PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA

35

SEMAINE D'ETUDE

SUR LE THEME

LES NOYAUX DES GALAXIES

13-18 AVRIL 1970

PONTIFICIA
ACADEMIA
SCIENTIARVM

EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA

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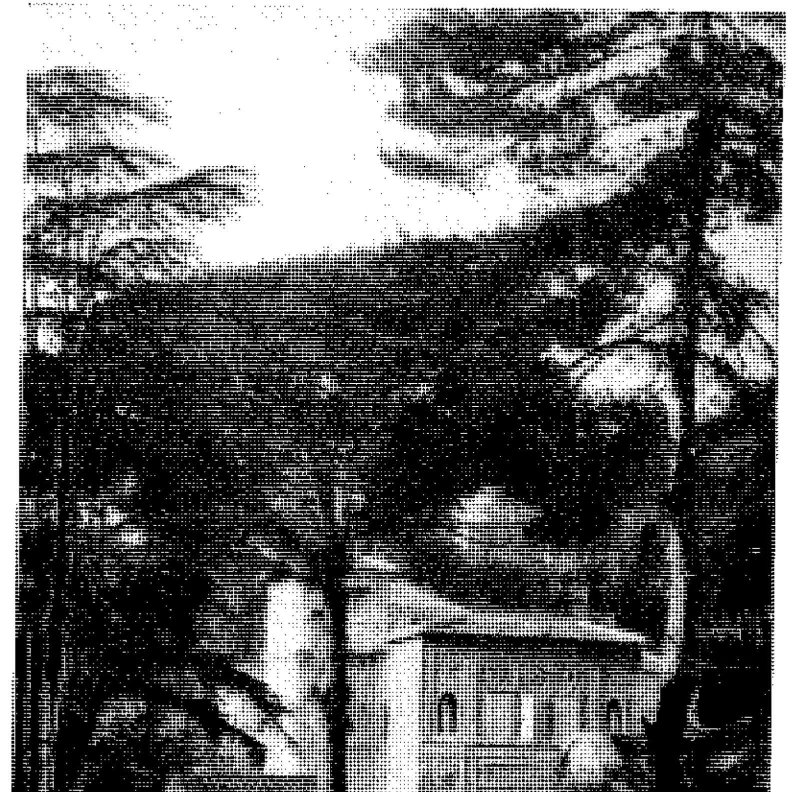

PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA
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STUDY WEEK
ON
NUCLEI OF GALAXIES

APRIL 13-18, 1970

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LA SEMAINE D'ETUDE
SUR
LES NOYAUX DES GALAXIES

Le but des « Semaines d'Etude » de l'Académie Pontificale des Sciences a été ainsi défini par son premier Président, S.E. le Rév.me Père AGOSTINO GEMELLI O.F.M.:

« Tandis qu'on fixait, après sa fondation, les travaux de l'Académie, un problème se présenta bien vite avec évidence: les sciences posent chaque jour des problèmes nouveaux qui donnent lieu d'ordinaire à divers essais de solution, souvent contradictoires. Il arrive ainsi constamment que parmi les représentants les plus autorisés d'une science et, en particulier, entre ceux qui se sont consacrés à l'étude d'une même question, on rencontre des opinions opposées. De pareilles divergences se maintiennent parfois pendant de longues périodes et constituent à la fois une grave difficulté pour l'enseignement des sciences et fréquemment aussi un obstacle considérable à leur développement. D'ailleurs, l'expérience montre que les méthodes actuellement pratiquées dans la discussion des problèmes scientifiques n'ont qu'une efficacité limitée au point de vue de l'établissement d'une unité de doctrine. Il serait hautement souhaitable de promouvoir tout ce qui pourrait favoriser une entente sur les points en discussion.

« Un tel procédé semble devoir être particulièrement utile sous ce rapport: à savoir établir des contacts personnels prolongés entre quelques représentants d'opinions différentes au sujet d'une question déterminée ».

Dans ce but, l'Académie Pontificale des Sciences a réalisé une nouvelle « Semaine d'Etude » ayant pour titre: « Les noyaux des galaxies » (1).

Bien que ces derniers temps un travail intense ait été fourni sur les divers aspects de ce problème, il restait cependant quelques questions de détail à résoudre, et de nouvelles questions s'étaient de plus posées pendant ces dernières années.

Etant donné qu'on n'avait pas encore provoqué un débat approfondi à ce sujet et que le moment semblait propice pour le faire, l'Académie Pontificale des Sciences s'est proposée de réunir un nombre restreint de savants, spécialistes de la question. Son but était de recueillir, au cours d'une discussion approfondie, les synthèses des nombreuses recherches effectuées dans ce domaine; de formuler clairement l'état des différents problèmes qui s'y rapportent; et par là de pouvoir fixer les directives de recherche les plus logiques, les plus persuasives et les plus prometteuses, étant donné l'état actuel de la science.

A cet effet ont été invités par l'Académie des experts qualifiés en photométrie et spectroscopie stellaire, en dynamique stellaire, des spécialistes de la distribution des étoiles dans notre galaxie et dans les autres, des mouvements et de la composition des étoiles, de radioastronomie, d'astronomie par moyen des rayons X, et même des spécialistes de physique nucléaire et de cosmologie, qui, grâce à la renommée des leurs études spécifiques et à leurs contributions scientifiques étaient les plus indiqués pour contribuer à éclaircir le sujet proposé par la Semaine.

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(1) Voir les « Semaines d'Etude » organisées jusqu'ici par l'Académie Pontificale des Sciences à la page XXXI.

La présidence de cette « Semaine d'Etude » sur « Les noyaux des galaxies » a été confiée au Président même de l'Académie Pontificale des Sciences, S.E. le Rév.me P. DANIEL J. K. O'CONNELL, S.J. Directeur de la Specola Vaticana de Castelgandolfo, et l'organisation générale au Chancelier de l'Académie Pontficale des Sciences Prof. PIETRO SALVIUCCI.

Ont été invités à la réunion les savants suivants:

Prof. Dr. VIKTOR AMAZASPOVIC AMBARTSUMIAN, Professeur d'Astronomie à l'Université de Jerevan; Président de l'Académie des Sciences de la RSS - *RSS d'Armenie* (URSS).

Prof. Dr. ELEANOR MARGARET BURBIDGE, Professeur d'Astronomie à l'Université de Californie - *San Diego, Calif.* (U.S.A.).

Prof. Dr. GEOFFREY RONALD BURBIDGE, Professeur de Physique à l'Université de Californie - *San Diego, Calif.* (U.S.A.).

Prof. Dr. WILLIAM ALFRED FOWLER, Professeur de Physique à l'Institut de Technologie de la Californie - *Pasadena, Calif.* (U.S.A.).

Dr. HERBERT FRIEDMAN, Superintendant de la Division Sciences Spatiales et Chef du Centre S.O. Hulburt de Recherche Spatiale aux Laboratoires de recherches de la Marine des U.S.A. - *Washington, D.C.* (U.S.A.).

Prof. Dr. FRED HOYLE, Professeur d'astronomie à l'Université de Cambridge - *Cambridge* (Grande-Bretagne).

Dr. KENNETH IRWIN KELLERMANN, Chercheur à l'Observatoire National de Radioastronomie - *Green Bank, W. Va.* (U.S.A.).

Prof. Dr. FRANK JAMES LOW, Professeur de Sciences Spatiales au département de Sciences Spatiales de l'Université Rice - *Houston, Tex.* (U.S.A.); professeur chargé de la recherche au Laboratoire lunaire et planétaire de l'Université de l'Arizona - *Tucson, Ariz.* (U.S.A.).

Prof. Dr. DONALD LYNDEN-BELL, Senior Principal Scientific Officer à l'Observatoire Royal de Greenwich, Sussex (actuellement en congé); Visiting Professor près l'Institut de Technologie de la Californie - *Pasadena, Calif.* (U.S.A.).

Prof. Dr. WILLIAM HUNTER McCREA, Professeur d'Astronomie théorique chargé de la recherche à l'Université du Sussex - *Brighton* (Grande-Bretagne).

S.E. le Prof. Dr. WILLIAM WILSON MORGAN, Académicien Pontifical, Président du Départment d'Astronomie de l'Université de Chicago - *Chicago, Ill.* (U.S.A.).

Prof. Dr. PHILIP MORRISON, Professeur de Physique théorique à l'Institut de Technologie du Massachusetts - *Cambridge, Mass.* (U.S.A.).

S.E. le R.P. DANIEL JOSEPH KELLY O'CONNELL S.I., Président de l'Académie Pontificale des Sciences; Directeur de l'Observatoire Astronomique du Vatican - *Cité du Vatican* (S.C.V.).

S.E. le Prof. Dr. JAN HENDRIK OORT, Académicien Pontifical; Professeur d'Astronomie à l'Université de Leyde (Pays-Bas) et Directeur de l'Observatoire de cette même ville - *Leyde* (Pays-Bas).

Prof. Dr. DONALD E. OSTERBROCK, Professeur et chef du département d'Astronomie à l'Université du Wisconsin - *Madison, Wisc.* (U.S.A.).

Prof. Dr. MARTIN JOHN REES, Membre du personnel scientifique de l'Institut d'Astronomie Théorique de l'Université de Cambridge, détaché temporairement auprès de l'Institut pour les Etudes Avancées de l'Université de Princeton, N.J. - *Princeton, N.J.* (U.S.A.).

Prof. Dr. ERWIN E. SALPETER, Professeur de physique et d'études nucléaires à l'Université Cornell - *Ithaca, N.Y.* (U.S.A.).

Dr. ALLAN REX SANDAGE, Astronome aux Observatoires du Mont Palomar et du Mont Wilson - *Pasadena, Calif.* (U.S.A.).

Dr. WALLACE SARGENT, Astronome aux Observatoires du Mont Palomar et du Mont Wilson - *Pasadena, Calif.* (U.S.A.).

Prof. Dr. MAARTEN SCHMIDT, Professeur d'astronomie à l'Institut de Technologie de la Californie - *Pasadena, Calif.* (U.S.A.).

Prof. Dr. HYRON SPINRAD, Professeur d'Astronomie à l'Université de Californie - *Berkeley, Calif.* (U.S.A.).

Prof. Dr. LYMAN SPITZER, JR., Professeur d'Astronomie à l'Université de Princeton, N.J., U.S.A., président du Département de Sciences Astrophysiques et Directeur de l'Observatoire de la même Université - *Princeton, N.J.* (U.S.A.).

Prof. Dr. HARRY VAN DER LAAN, Professeur de Radioastronomie à l'Université de Leyde - *Leyde* (Pays-Bas).

Prof. Dr. JOHN ARCHIBALD WHEELER, Professeur de physique à l'Université de Princeton - *Princeton, N.J.* (U.S.A.).

Prof. Dr. LODEWYK WOLTJER, Department of Astronomy de l'Université de Columbia - *New York, N.Y.* (U.S.A.).

Tous les invités ont participé à la Réunion.

Le Secrétariat scientifique de la Semaine d'Etude était composé par les Rev. Pères GEORGE V. COYNE, MARTIN F. MCCARTHY et PATRICK J. TREANOR, de l'Observatoire du Vatican.

Le « Règlement des Semaines d'Etude » prescrivant que le nombre des Participants doit être rigoureusement limité, a malheureusement empêché d'inviter d'autres illustres savants.

Ont aussi participé à la réunion: en qualité d'interprète et chef de Secrétariat M.lle JOSÉPHINE LUCAS; M.me HERMIONE MONTANER, M.me MAURA MARCHESE et M.me RITA MANZO en qualité de sténographes polyglottes de séance; M.lle RHODA BELL, M.me CARMEN FERRARA, M.lle JEAN MC EVOY, M.me PAULETTE ROSSALDI, M.lle MURIEL SADLIER. M.lle HEATHER SAUNDERS et M.lle ANNE SAUNDERS en qualité de sténo-dactylographes polyglottes chargées des Procès-verbaux; en qualité de technicien pour l'enregistrement et la projection, Mr MAURO ERCOLE, assisté par les opérateurs de Radio-Vatican Mr ANTONIO ALBERTINI et Mr ULDERICO MERLUZZI. Le Bureau de Presse était confié au Dr. FRANCESCO SALVIUCCI, Coadjuteur de Chancelier de l'Académie.

Le Comité de Réception pour les Dames dirigé par Mme HÉLÈNE LOTTI, était composé de la Comtesse KARINA CALVI DI COENZO, la Comtesse ISABELLA CALVI DI COENZO, M.me MARIÚ PUNZI POLLITZER, M.me CLELIA ROSTAGNOLI et M.lle JOSELLA BRUSCHI.

Le samedi 18 avril, tous les Participants ont été reçus en Audience Solennelle par le Souverain Pontife qui leur adressa un discours et après l'Audience a eu lieu, au Siège de l'Académie Pontificale des Sciences, une séance extraordinaire de l'Académie, à laquelle ont été invités également les Participants à la « Semaine d'Etude ».

Durant la Semaine d'Etude, chaque communication a été discutée en session plénière.

Dans les pages qui suivent, après le compte rendu de l'Audience du Saint-Père et le « Règlement des Semaines d'Etude », sont imprimés les rapports originaux présentés à la Réunion et les discussions qui les ont suivis, mis en ordre et publiés par les soins du Président de la Semaine d'Etude S.E. L'Académicien Pontifical et President de l'Académie le Rev.me P. DANIEL J. K. O'CONNELL, S.J.

Les séances se tenaient deux fois par jour, le matin de 9 h. 30 à 12 h. 30 et l'après-midi de 16 h. à 19 h.

La Note Collective Finale se trouve à la fin du présente volume.

La réussite de la « Semaine d'Etude » a pleinement satisfait les illustres Participants qui, à la fin de leurs travaux, ont tenu à exprimer au Saint-Père leur profonde gratitude et leur très sincère admiration pour cette manifestation scientifique si réussie, en envoyant à l'Auguste Pontife, animateur et mécène de l'Académie, le télégramme suivant:

« SA SAINTETÉ LE SOUVERAIN PONTIFE PAUL VI *-Cité du Vatican. — Les participants à la Semaine d'Etude sur les noyaux des galaxies Vous prient daigner d'accepter l'expression de leur admiration et de leur profonde gratitude pour leur avoir donné la possibilité de travailler dans les conditions les meilleures à l'étude des problèmes des noyaux des galaxies et d'échanger leurs idées en pleine liberté. Ils Vous expriment leur sincère reconnaissance pour l'honneur que Sa Sainteté a bien voulu leur accorder leur permettant de travailler sous les auspices de son Académie.* — AMBARTSUMIAN, E. BURBIDGE, G. BURBIDGE, FOWLER, FRIEDMAN, HOYLE, KELLERMANN, LOW, LYNDEN-BELL, MCCREA, MORGAN, MORRISON, O'CONNELL, OORT, OSTERBROCK, REES, SALPETER, SANDAGE, SARGENT, SCHMIDT, SPINRAD, SPITZER, VAN DER LAAN, WHEELER, WOLTJER ».

A ce télégramme d'hommage et de remerciement, le Saint-Père a daigné répondre par le message suivant, signé par Son Eminence le Cardinal Secrétaire d'Etat:

« *Professeur* PIETRO SALVIUCCI, *Chancelier Académie Pontificale des Sciences - Casina Pio IV, Città del Vaticano. — Saint-Père très sensible déférent message participants Semaine d'étude sur noyaux des galaxies remercie sentiments exprimés et se réjouit facilités rencontrées au sein Académie Pontificale pour étudier problèmes et échanger idées. Vous charge transmettre tous signataires paternels encouragements et assurance prière pour leurs personnes et leurs travaux en vue bien humanité.* — Cardinal VILLOT ».

Le matin du mercredi 15, les participants ont visité la Tour des Vents, qui fut le premier Observatoire astronomique du Vatican, construit par Grégoire XIII dans l'enceinte du Palais Apostolique, et l'après-midi ils se sont rendus à Castelgandolfo, où ils ont visité l'Observatoire astronomique du Vatican et le Laboratoire Astrophysique qui en dépend, institutions toutes deux équipées des instruments de recherche les plus modernes, selon les exigences techniques des programmes spécifiques de l'Observatoire.

Les Participants ont aussi visité la Bibliothèque Apostolique Vaticane et les Archives Secrètes Vaticanes sous la conduite des Rév.mes Préfets Mons. MARTINO GIUSTI et Père ALPHONSE RAES, S.I.

Enfin, le soir du samedi 18 avril, un dîner d'adieu a été offert par l'Académie, selon la coutume, aux savants participant à la « Semaine d'Etude ».

L'AUDIENCE
ET
LE DISCOURS DU SAINT-PERE

Le matin du samedi 18 avril, le Saint-Père a accordé dans la Salle du Consistoire du Palais Apostolique Vatican, une Audience Solennelle à l'occasion de la Session Plénière de l'Académie Pontificale des Sciences et de la « Semaine d'Etude » sur « Les noyaux des galaxies » tenue par l'Académie. Ont participé aussi à l'Audience de nombreuses éminentes personnalités.

Etaient présents Leurs Eminences les Cardinaux: Aloisi-Masella, Cicognani, Forni, Slipyj, Villot, Zerba, Garrone, Samorè, Grano, Staffa, Browne, Felici, Oddi, Paupini, Nasalli-Rocca di Corneliano.

De nombreux Académiciens Pontificaux sont intervenus, et spécialement Leurs Excellences: le Rév.me P. Daniel J. K. O'Connell Président, Charles Best, Keith Bullen, Carlos Chagas, Eduardo Cruz-Coke, Ernesto Gherzi, Sven Hörstadius, Bernardo Houssay, Alberto Hurtado, Jean Lecomte, Luis Leloir, Pierre Lepine, Manuel Lora-Tamayo, Giovanni Battista Marini-Bettolo, San-Ichiro Mizushima, William Morgan, Salimuzzanam Siddiqui, Arne Tiselius; les Académiciens surnuméraires: le Rev.me Mgr. Martino Giusti et le Père Josef Junkes; le Chancelier de l'Académie, prof. Pietro Salviucci et le Coadjuteur Dr. Francesco Salviucci.

Parmi le groupe des Académiciens assistaient les savants spécialistes « Participants » à la Semaine d'Etude sur « Les noyaux des galaxies ».

Avec le Corps Diplomatique au complet était présent S.E. Rév.me Monseigneur GIOVANNI BENELLI, Substitut de la Secrétairerie d'Etat, Nos Seigneurs AGOSTINO CASAROLI Secrétaire du Conseil pour les Affaires Publiques de l'Eglise, et SOTERO SANZ VILLALBA Assesseur de la Secrétairerie d'Etat; les Membres du Corps Diplomatique furent reçus par le Gr. Uff. MARIO BELARDO.

Une déférente manifestation d'hommage a accueilli l'arrivée du Saint-Père.

Après avoir gagné le trône, le Saint-Père donna son assentiment au Président O'CONNELL qui s'adressa alors au Souverain Pontife en ces termes:

« Très Saint-Père, j'ai l'honneur de présenter à Votre Sainteté mes hommages et ceux des membres de Votre Académie des Sciences réunis pour leur Session Plénière.

« Ce matin nous avons fini une Semaine d'Etude sur un thème astronomique "Les Noyaux des Galaxies". En 1957, nous avons traité un autre problème astronomique, les Populations Stellaires, avec la participation très active de l'auteur de cette découverte si féconde, le regretté Walter Baade. Nos travaux d'il y a treize ans ont produit des résultats de grande valeur pour le progrès de l'astronomie, et notamment pour nos connaissances de la structure de notre Galaxie.

« Cette fois nos travaux concernent un champ encore plus vaste, les galaxies en général. Pendant ces jours nous avons parlé des processus étranges qui se produisent dans les noyaux de galaxies, et nous avons assayé de pénétrer les secrets de l'origine et de l'évolution des galaxies et de l'univers même. Je regrette beaucoup que nous n'ayons pas eu parmi nous mon illustre prédecesseur, Georges Lemaître, celui qui a tant travaillé dans la domaine de la cosmologie et qui était en effet un des créateurs principaux de la théorie de l'expansion de l'univers. Nos discussions auraient été pour lui d'un interêt extrême.

« Au nom des Académiciens, qui ont travaillé dans les séances de la Sessione Plénière, et des astronomes illustres de divers pays qui ont participé à la Semainte d'Etude, je veux exprimer notre reconnaissance pour la munificence de Votre Sainteté qui nous a permis de réaliser cette importante manifestation scientifique ».

Le Saint-Père daigna répondre par le discours que nous reproduisons plus loin.

Le Saint-Père s'entretint ensuite, après avoir reçu l'hommage des Cardinaux, avec le Président O'CONNELL, les Académiciens Pontificaux, le Chancelier SALVIUCCI et les savants « Participants » à la « Semaine d'Etude », trouvant pour chacun d'aimables paroles de félicitations et de souhaits, pour eux, leurs familles et leur activité scientifique.

L'assistance exprima enfin ses remerciements au Saint-Père, sa reconnaissance émue et sa profonde gratitude, et le plus chaleureux hommage se manifesta de nouveau au moment où, l'Audience terminée, le Souverain Pontife quitta la Salle du Consistoire.

Excellences et chers Messieurs,

Nous vous remercions de tout coeur des sentiments si délicats que le Révérend Père O'Connell vient de Nous exprimer au nom de ses illustres collègues. C'est toujours une joie pour Nous, vous le savez, d'accueillir les membres de notre Académie Pontificale des Sciences, en présence du Corps Diplomatique et de personnalités distinguées, et aussi une certaine émotion de voir réunis des représentants aussi qualifiés de tout l'univers, véritable Sénat de savants, à la pointe de la recherche scientifique et de la réflexion qu'elle suscite dans l'esprit humain. Le thème de vos travaux, consacrés aux « noyaux des galaxies », n'en est-il pas le signe éclatant?

1. *Votre Session plénière marque un temps fort dans la vie de l'Académie, et Nous Nous en réjouissons. Car cette institution demeure hautement significative: elle peut apporter à notre monde un concours appréciable par la compétence et l'universalité de son témoignage, et fournir aussi à la réflexion des croyants une base solide pour un dialogue fructueux avec la pensée scientifique. Que de chemin parcouru depuis la fondation de l'Académie des « Lincei » en 1603, sa restauration par Pie IX, son élargissement sous Léon XIII, et surtout sa reconstitution par les soins éclairés de notre grand prédécesseur Pie XI, avec le* Motu proprio *du 28 octobre 1936* In multis solaciis, *sous la forme de l'Académie pontificale des sciences, constituée de soixante-dix Académiciens pontificaux, « veluti doctorum hominum Senatus seu "scientificus Senatus",... ad scien-*

tiarum progressionem fovendam », sous la présidence du regretté Père Agostino Gemelli.

D'illustres savants n'ont cessé d'honorer l'Académie de leur présence et de leurs travaux, et Nous avions Nous même, hier, la joie d'adjoindre à ce Cénacle choisi douze nouveaux membres, qui permettent de mieux représenter l'ensemble des maitres qui cultivent les disciplines scientifiques avec succès à travers le monde.

Vos études de sciences mathématiques et expérimentales, menées avec la liberté qui convient à la culture, ont certainement apporté leur contribution au progrès de la science pure et préparé le progrès des sciences appliquées. Mais un tel développement n'appelle-t-il pas aujourd'hui d'autres prolongements? Tout en continuant les recherches qui sont les vôtres dans une spécialité dont l'importance ne cesse de croître — les expériences des voyages spatiaux, dont nous avons suivi la plus récente ces jours derniers avec angoisse et, à la fin, avec joie et admiration émues, le démontrent suffissament —, ne serait-il pas désirable et opportun de promouvoir, en d'autres Académies, d'autres disciplines, essentielles elles aussi à l'esprit humain, telles que les lettres et les arts, la philosophie, le droit, l'histoire, l'économie, la sociologie et les sciences humaines qui marquent si profondément les hommes de notre temps? Nous aimons ce matin vous confier cette pensée que Nous méditons depuis longtemps déjà, et qui, dans notre esprit, est plus qu'un rêve: un véritable désir qu'il Nous plairait de réaliser.

2. *La nature même de votre travail Nous amène à souligner deux principes dont vous êtes déjà bien convaincus, que votre propre expérience, Nous pourrions dire: votre personnalité, atteste tous les jours.*

C'est que le savoir humain, si développé qu'il soit, n'est pas, et ne saurait être en opposition avec celui de la foi: « Scientia, quae vera rerum cognitio sit, numquam christianae fidei veritatibus repugnant ».

Bien plus, l'un et l'autre peuvent être intégrés dans l'unité de l'esprit humain, tout en gardant leur autonomie propre, comme *l'enseigne le premier Concile du Vatican: « Fides et ratio... opem quoque sibi mutuam ferunt ».*

Qu'on Nous entende bien en effet. Selon la Constitution pastorale Gaudium et spes, *qui « reprend à son compte l'enseignement du premier Concile du Vatican », l'Eglise « affirme l'autonomie légitime de la culture et particulièrement celle des sciences », avec « leurs principes et leur propre méthode en leurs domaines respectifs ». Mais ces disciplines, qui peuvent si bien « contribuer à ouvrir la famille humaine aux plus nobles valeurs du vrai, du bien et du beau, et à une vue des choses ayant valeur universelle », peuvent aussi préparer l'homme à reconnaître et accueillir la vérité en sa plénitude, pourvu qu'elles ne considèrent pas « à tort les méthodes de recherche qui leur sont propres comme règle suprême pour la découverte de toute vérité ». C'est le même Dieu qui a créé le monde avec ses lois que vous scrutez — « toutes choses dans les cieux et sur la terre, les visibles et les invisibles » — et qui se révèle aux hommes et leur apporte le salut en Jésus-Christ. C'est le même esprit humain qui est apte à scruter les secrets de la création et à « dominer la terre », et en même temps à reconnaître et à accueillir, « sous l'impulsion de la grâce », le don que Dieu lui fait de Lui-même: « le Verbe de Dieu qui, avant de se faire chair pour tout sauver et récapituler en lui, était déjà dans le monde » comme la « vraie lumière qui éclaire tout homme ». Comment l'Eglise n'encouragerait-elle pas l'investigation, la découverte et la conquête de cet univers qui, dans sa merveilleuse et admirable richesse, nous conduit, de l'infiniment petit à l'infiniment grand, vers l'invisible qui est la source du visible?*

3. *Mais le thème que vous venez d'aborder — « Les noyaux des galaxies » — mérite une attention particulière. Notre imagination se trouve confondue et nous laisse remplis de stupeur, comme débordés, écrasés presque par l'immensité des perspectives entrevues, « ce silence des espaces infinis » cher à Pascal. Nous suivons avec un profond respect et un grande intérêt votre patient travail d'observation, de coordination d'expériences, de formulation d'hy-*

pothèses scientifiques sur la genèse ou l'évolution des mondes astraux.

Est-ce à dire que la pensée humaine épuise toutes ses possibilités au niveau de ces investigations?

Derrière elles, il y a le problème de l'être même de ce cosmos, de cet univers; la question de son existence. Vous demeurez, en effet, dans l'observation expérimentale scientifique, d'ordre mathématique et cosmologique. Mais qu'est-ce qui empêche de reconnaître à l'esprit, sur le terrain philosophique, la possibilité de remonter au principe transcendant, au Créateur, « causa subsistendi et ratio intelligendi et ordo vivendi »? Trop souvent aujourd'hui, on doute de ce pouvoir. « Plus la science, perfectionnant ses méthodes, assujettit le monde à l'homme, plus, en revanche, l'être, qui ne se laisse pas assujettir, se dérobe... vient alors la tentation de l'agnosticisme ». Mais on ne saurait s'en tenir à pareille attitude. « L'intelligence ne peut absolument pas abdiquer; elle ne peut renoncer à sa loi formelle, qui est de juger, c'est-à-dire toujours d'affirmer ». C'est pour l'esprit humain comme un « besoin irrépressible de posséder en chaque moment de son aventure temporelle et en chaque état de ses connaissances une idée explicative de l'ensemble des choses ».

On parle souvent de la « mort de Dieu », mais ne serait-ce pas plutôt la mort de l'homme et de sa pensée en sa forme supérieure? Sans ce recours à Dieu, source de l'Etre, en effet, elle semble s'engloutir dans l'opacité et l'incompréhensibilité des choses, l'ignorance d'une unité qui y préside, et d'une finalité d'un ordre mystérieux qui en sont inséparables, l'amenant à trouver une absurdité qui n'est que dans sa propre démarche. Peut-être êtes-vous mieux préservés que d'autres contre ce qu'il faut bien appeler une véritable maladie de l'esprit, vous qui scrutez objectivement les sciences de la nature, de l'astrophysique, de la physique? Car l'intelligence, par son mouvement même, si elle n'en reste à l'écorce de la réalité, s'élève au niveau de sa cause transcendante, l'Absolu véritable, qui donne consistance à toute la création et d'abord à l'esprit humain, sans se confondre jamais avec eux. Comme on l'a dit si heureuse-

ment, l'intelligence est « nécessairement, en même temps qu'un pouvoir d'assimilation, un pouvoir de remontée... Elle saisit en toutes réalités ce par quoi elles sont, *c'est-à-dire sont ouvertes vers l'illumination de l'acte. Et ainsi, à juste titre, on peut dire qu'elle est le sens du divin, la faculté avide et habile à reconnaître les traces de Dieu ».*

Il y a là, il faut le redire, un développement naturel de la pensée, dans sa logique fondamentale, et non pas un saut indû comme le prétend une mentalité antimétaphysique abusivement qualifiée de scientifique. Le vraie science, bien loin d'arrêter l'élan de la pensée, constitue un tremplin qui lui permet de s'élever, dans cet élan même, vers Celui qui lui fournit généreusement son aliment. Car « l'esprit lui-même est un chemin qui marche... On ne peut faire l'économie de Dieu ».

Nous demeurons comme stupéfaits, disions-Nous, devant vos études sur les noyaux des galaxies. Le système solaire paraissait déjà si vaste et si mystérieux à nos devanciers! Mais nous ne sommes pas déconcertés pour autant, sachant que « Dieu préfère plutôt créer les êtres dans leurs germes pour les conduire ultérieurement à leur éclosion ». Le temps et l'espace, la matière et la forme peuvent se développer de façon démesurée, quasi indéfinie.

Tout en écoutant votre enseignement, nous trouvons certitude dans notre foi. Et à notre esprit, à nous qui sommes à l'école de la foi, reviennent les paroles de la sainte Ecriture: « Dieu créa le ciel et la terre... Et Dieu vit que cela était bon... Dieu vit tout ce qu'il avait fait, et tout cela était très bon ». Cette joie que Dieu a éprouvée devant ses créatures, comment ne l'aurions-nous pas, nous, pour notre Créateur?

A notre tour nous contemplons cette beauté et cette bonté mystérieuses de la création: tous ces êtres nous crient, comme à saint Augustin: nous ne sommes pas Dieu, mais c'est lui qui nous a faits. « Ecce caelum et terra clamant quod facta sint ». Et Lui, nous l'adorons! La rencontre avec Dieu s'opère devant la grandeur quasi illimitée de ses oeuvres — n'est-ce pas une grâce d'y être initié? —, dans la joie, dans l'admiration, dans la prière, dans l'adoration de

Celui qui « en répandant mille grâces... est passé à la hâte par ces forêts, et en les regardant... les a laissées revêtues de sa beauté ».

Au terme de cette contemplation des suprêmes réalités du cosmos dans leur rencontre avec les suprêmes vérités de l'esprit humain, Nous ne pouvons pas taire notre émotion, notre admiration, notre satisfaction, qui sont celles mêmes du monde entier, pour l'heureuse conclusion — oui, heureuse, très heureuse, même si le but principal n'a pas été atteint — du vol aventureux de l'Apollo 13. Tous certainement vous avez suivi, avec appréhension puis avec joie, le déroulement de cette entreprise extraordinaire. Et vous aurez sans nul doute à coeur de saluer chaleureusement avec Nous les valeureux astronautes qui ont échappé aux périls de ce grand vol, et de rendre hommage à tous ceux qui, par leurs études, leur action, leur autorité, ont une fois de plus manifesté aux yeux du monde la puissance illimitée des sciences et de la technique moderne. Avec Nous aussi, vous ferez monter un hymne ardent de reconnaissance à Dieu, Créateur de l'univers et Père des hommes, qui par ces voies aussi veut être cherché et trouvé par l'homme, adoré et aimé par lui.

Telles sont les pensées que Nous suggère, Excellences et chers Messieurs, cette rencontre qui Nous est très agréable. De tout coeur, Nous vous encourageons à poursuivre vos savants travaux, à les mettre en commun, de façon désintéressée, par-delà les frontières, et à aider tous vos frères à répondre aux questions que la science ou plutôt ses applications ne cesseront de poser. Vous le pouvez, et le devez, à la lumière de la foi que vous portez en vous. C'est notre voeu le plus cher. Nous l'accompagnons à votre intention d'une large Bénédiction Apostolique.

LES « SEMAINES D'ETUDE » ORGANISEES JUSQU'AU 1968

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La première « Semaine d'Etude » a eu lieu du 6 au 13 juin 1940; elle a été dédiée au « PROBLEME BIOLOGIQUE DU CANCER », et a été présidée par l'Académicien Pontifical S.E. Pietro Rondoni, Professeur de Pathologie Générale et expérimentale à l'Université de Milan; y ont participé personnellement 15 savants tandis que 3 autres ont envoyé des mémoires. Les comptes rendus de la « Semaine d'Etude » ont été publiés dans le 7ème volume des « Scripta Varia » de l'Académie; ils représentent un volume de 364 pages.

La deuxième « Semaine d'Etude » a eu lieu du 19 au 26 novembre 1961; elle a été dédiée au « PROBLEME DES MICROSEISMES », et a été présidée par l'Académicien Pontifical S.E. Francesco Vercelli, Directeur de l'Institut Thalassographique et de l'Observatoire Géophysique de Trieste; y ont participé personnellement 15 savants tandis que 4 autres ont envoyé des mémoires. Les comptes rendus de la « Semaine d'Etude » ont été publiés dans le 12ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 466 pages.

La troisième « Semaine d'Etude » a eu lieu du 24 avril au 2 mai 1955; elle a été dédiées au « PROBLEME DES OLIGOELEMENTS DANS LA VIE VEGETALE ET ANIMALE », et a été présidée par l'Académicien Pontifical S.E. Josè Maria Albareda Herrera, Directeur de l'Institut de Pédologie et de Physiologie végétale de l'Université de Madrid, Secrétaire Général du Conseil Supérieur des Recherches Scientifiques d'Espagne; y ont participé personnellement

19 savants tandis qu'un autre a envoyé un mémoire. Les comptes rendus de la « Semaine d'Etude » ont été publiés dans le 14ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 630 pages.

La quatrième « Semaine d'Etude » a eu lieu, du 20 au 28 mai 1957; elle a été dédiée au « PROBLEME DES POPULATIONS STELLAIRES » et a été présidée par l'Académicien Pontifical Surnuméraire le Rev.me Père Daniel J. K. O'Connell, Directeur de la « Specola Vaticana » de Castelgandolfo; y ont participé personnellement 21 savants. Les comptes rendus de la « Semaine d'Etude » ont été publiés dans le 16ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 615 pages.

La cinquième « Semaine d'Etude » a eu lieu du 23 au 31 octobre 1961; elle a été dédiée au « PROBLEME DES MACROMOLECULES D'INTERET BIOLOGIQUE AVEC REFERENCE SPECIALE AUX NUCLEOPROTEIDES », et a été présidée par l'Académicien Pontifical S.E. Arne Tiselius, Professeur de Biochimie à l'Université de Uppsala; y ont participé personnellement 18 savants. Les comptes rendus de la « Semaine d'Etude » on été publiés dans le 22ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 544 pages.

La sixième « Semaine d'Etude » a eu lieu du 1 au 6 octobre 1962; elle a été dédiée au « PROBLEME DU RAYONNEMENT COSMIQUE DANS L'ESPACE INTERPLANETAIRE », et devait être présidée par l'Académicien Pontifical S.E. Victor Francis Hess, qui n'a pas pu, en raison de son état de santé, être présent et la « Semaine d'Etude » a été présidée par l'Académicien Pontifical S.E. Georges Lemaître, Professeur de Mécanique et de Méthodologie mathématique à l'Université de Louvain et Président de l'Académie. Y ont participé personnellement 24 savants. Les comptes rendus de la « Semaine d'Etude » ont été publiés dans le 25ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 626 pages.

La septième « Semaine d'Etude » a eu lieu du 7 au 13 octobre 1963; elle a été dédiée au « ROLE DE L'ANALYSE ECONOMETRIQUE DANS LA FORMULATION DE PLANS DE DEVELOPPEMENT », et a été présidée par l'Académicien Pontifical S.E. MARCELLO BOLDRINI, Professeur de Statistique à l'Université de Rome; y ont participé personnellement 18 savants. Les comptes rendus de la « Semaine d'Etude » ont été publiés dans le 28ème volume des « Scripta Varia » de l'Académie; ils forment une oeuvre de 1260 pages en deux volumes.

La huitième « Semaine d'Etude » a eu lieu du 28 septembre au 3 octobre 1964; elle a été dédiée au « CERVEAU ET EXPERIENCE CONSCIENTE », et a été présidée par l'Académicien Pontifical S.E. Sir JOHN CAREW ECCLES, Professeur de Physiologie à l'Université de Canberra; y ont participé personnellement 18 savants. Les comptes rendus de la « Semaine d'Etude » ont été publiès dans le 30ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 885 pages.

La neuvième « Semaine d'Etude » a eu lieu du 18 au 23 avril 1966; elle a été dédiée aux « FORCES MOLECULAIRES », et devait être présidée par l'Académicien Pontifical S.E. PIETER DEBYE, Président du Department of Chemistry de la Cornell University de Ithaca, N.Y.; malheureusement l'Académicien PIETER DEBYE n'a pas pu, en raison de son état de santé, être présent et la « Semaine d'Etude » a été présidée par l'Académicien Pontifical S.E. SAN-ICHIRO MIZUSHIMA, Professeur émérite de Chimie à l'Université de Tokyo et Directeur de l'Institut des Recherches scientifiques « Yawata ». Y ont participé personnellement 17 savants. Les comptes rendus de la « Semaine d'Etude » ont été publiés dans le 31ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 824 pages.

La dixième « Semaine d'Etude » a eu lieu du 22 au 27 avril 1968; elle a été dédiée à la « MATIERE ORGANIQUE ET FERTILITE DU SOL » et devait être présidée par l'Académicien Pontifical S.E. Don José Maria Albareda Herrera, Directeur de l'Institut d'Edaphologie et de Physiologie végétale de l'Université de Madrid et Secrétaire Général du Conseil Supérieur des Recherches Scientifiques d'Espagne; malheureusement l'Académicien Pontifical José Maria Albareda Herrera mourut et la Semaine d'Etude a été présidée par l'Académicien Pontifical S.E. Manuel Lora Tamayo, Professeur de Chimie organique à l'Université de Madrid. Y ont participé personnellement 21 savants, tandis que 3 autres ont envoyé des mémoires. Les comptes rendus de la « Semaine d'Etude » ont été publiés dans le 32ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 1092 pages.

L'organisation générale de chaque « Semaine d'Etude » a été confiée au Chancelier de l'Académie Pontificale des Sciences, le Prof. Dr. Pietro Salviucci. Toutes les réunions se sont tenues au Siège de l'Académie à la « Casina di Pio IV » dans les Jardins du Vatican.

LES « SEMAINES D'ETUDE »

ET

LEUR REGLEMENT

Lorsque l'Académie Pontificale des Sciences fut fondée par le Souverain Pontifie Pie XI, de vénérée mémoire, par son « Motu Proprio » du 28 octobre 1936 « In multis solaciis », cette initiative suscita dans les milieux scientifiques un mouvement général de sympathie et d'admiration. Cette institution unique au monde, qui groupait en une même assemblée des représentants de toutes les Nations civilisées, était appelée, en effet, à de hautes destinées dans le développement de la pensée scientifique.

D'autre part, cette oeuvre de coopération fut accueillie avec un véritable soulagement par tous ceux que plongeait dans le désarroi le plus profond la période qui suivit la guerre 1914-18. On voyait, en effet, s'altérer profondément les caractères d'objectivité et de

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A general movement of sympathy and admiration was aroused in scientific circles when, in 1936, the Pontifical Academy of Sciences was founded by His Holiness Pope Pius XI, of venerable memory, by means of his « Motu Proprio » of October 28, « In multis solaciis ». This institution, the only one of its kind in the world, which brought the representatives of all civilized nations into touch with each other, was, in fact, called upon to play a leading role in the development of scientific thought.

This work of cooperation was, moreover, welcomed with a sense of real relief by all those who were plunged in a deep state of confusion in the period following the 1914-18 war.

Signs of drastic changes were, in fact, discernible in the objective and disinterested nature of scientific work and even a tendency to make science subject to pragmatic aims.

In his immortal « Motu Proprio » of October 28, 1936, Pope Pius XI.

désintéressement propres au travail scientifique, et s'affirmer même une tendance à asservir la science à des fins pragmatiques.

Tout au contraire, dans l'immortel « Motu Proprio » du 28 octobre 1936, le Pape Pie XI proclamait solennellement la dignité de la recherche de la vérité pour elle-même, et, élevant sa pensée au-dessus de toute préoccupation utilitaire, affirmait qu'il ne demandait rien d'autre aux nouveaux « Académiciens Pontificaux » que de se consacrer, avec une ferveur toujours plus grande, au progrès de la science et, par là, au culte de la vérité: « C'est Notre souhait ardent et Notre ferme espérance: que par cet Institut, à la fois Nôtre et leur, les "Académiciens Pontificaux" contribuent toujours plus et mieux au progrès des sciences. Nous ne leur demandons pas autre chose; car en ce dessein généreux et ce noble labeur consiste le service, qu'en faveur de la vérité, nous attendons de leur part» (*).

(*) « Nobis autem in votis expectationeque est, fore ut "Pontificii Academici" vel per hoc Nostrum suumque studiorum Institutum, ad scientiarum progressionem fovendam amplius excelsiusque procedant; ac nihil praeterea aliud petimus, quandoquidem hoc eximio praeclaroque labore famulatus ille nititur servientium veritati, quem ab iisdem postulamus ».

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on the contrary, solemnly proclaimed the dignity of the search for truth for its own sake and, raising his thoughts above all preoccupations of an utilitarian nature, asserted that all to be asked of the new « Pontifical Academy » and its members was that they should dedicate themselves, with increasing fervour, to the furthering of the progress of science and, consequently, to the cult of truth: « It is Our ardent wish and firm hope that, by means of this Institute, which is both Ours and theirs, the "Pontifical Academicians" will contribute to an increasingly great extent to the progress of science. We ask nothing more than that from them because the service in favour of truth that We expect from them consists in this generous intention and noble work » (*).

(*) « Nobis autem in votis expectationeque est, fore ut "Pontificii Academici" vel per hoc Nostrum suumque studiorum Institutum, ad scientiarum progressionem fovendam amplius excelsiusque procedant; ac nihil praeterea aliud petimus, quandoquidem hoc eximio praeclaroque labore famulatus ille nititur servientium veritati, quem ab iisdem postulamus ».

La consécration pratique de cette idée, par la nomination d'un certain nombre de non-catholiques parmi les nouveaux Académiciens Pontificaux, a fait une profonde impression sur beaucoup d'esprits, comme l'ont montré les réactions de la presse internationale de l'époque et de nombreux témoignages individuels d'hommes de science et des plus grands savants du monde.

Beaucoup de préjugés à l'égard de l'Eglise ont été fortement ébranlés par ce geste du Souverain Pontife qui a obligé à reconnaître la place éminente réservée aux valeurs purement intellectuelles dans l'Eglise Catholique.

Pour toutes ces raisons, la fondation de l'Académie Pontificale des Sciences a été hautement appréciée dans le monde scientifique et y a fait naître de grands espoirs quant aux possibilités d'action d'une institution si opportune.

Elle est placée sous la dépendance directe du Souverain Pontife et composée de soixante-dix « Académiciens Pontificaux » nommés par le Pape sur proposition du Corps Académique et choisis sans

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By including a certain number of non-Catholics amongst the new Pontifical Academicians, the practical application of this idea made a deep impression on many persons, as is proved by the reaction of the international press of the time and by the innumerable individual tributes paid by scientists and by the greatest scholars of the world.

Many prejudices against the Church were very deeply shaken by this gesture on the part of the Sovereign Pontiff, since it called attention to the lofty place reserved for purely intellectual values in the Catholic Church.

For all these reasons, the foundation of the Pontifical Academy of Sciences was greatly appreciated by the scientific world and aroused high hopes as to the prospects open to such a timely institution.

The Academy is directly subject to the Sovereign Pontiff, and it is composed of seventy « Pontifical Academicians », nominated by the Holy Father himself, proposed by the Academical Body and chosen aucune discrimination parmi le plus insignes spécialistes des sciences mathématiques et expérimentales de tout pays.

L'Académie Pontificale des Sciences est actuellement unique en son genre, étant la seule Académie scientifique à caractère supranational et à classe unique existant dans le monde.

Elle a pour but d'honorer la science pure, où qu'elle se trouve, d'en assurer la liberté, d'en favoriser les recherches qui constituent la base indispensable du progrès des sciences appliquées.

Le Saint-Père Pie XII, qui avait collaboré avec son Prédécesseur au projet et à la fondation de l'Académie et qui l'avait représenté comme Légat personnel lors de l'inauguration solennelle, ne se borna pas à maintenir à son égard ses sentiments de haute estime par sa présence à de solennelles séances académiques, où il daigna prononcer ses discours d'une haute portée scientifique; il a tenu en outre à lui donner un nouveau témoignage de son auguste satisfaction en accordant à ses membres le titre d'Excellence par le Bref Apostolique du 25 novembre 1940.

without any discrimination from amongst the most famous experts in mathematical and experimental sciences in all countries.

At the present time the Pontifical Academy of Sciences is unique, in the sense that it is the only Academy of Sciences in the world which is supra-national and which has only one class amongst its Members.

It has for its purpose to pay honour to pure science wherever it exists, to ensure its liberty and to further its researches, which are the necessary basis for the progress of applied sciences.

His Holiness Pope Pius XII, who had helped his predecessor to draw up the plan and to found the Academy, and who had represented him as his personal Legate at the time of its solemn inauguration, did not confine himself to the expression of lofty sentiments when attending solemn academic gatherings, where he deigned to make speeches of great scientific importance, but he also afforded proof of his august satisfaction by granting the title of Excellency to the members of the Academy, by an Apostolic Brief of November 25, 1940.

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Les sciences posent chaque jour des problèmes nouveaux qui donnent lieu d'ordinaire à divers essais de solution, souvent contradictoires. Il arrive ainsi constamment que, parmi les représentants les plus autorisés d'une science, et en particulier parmi ceux qui se sont consacrés à l'étude d'une même question, on rencontre des opinions opposées. Pareilles divergences se maintiennent parfois durant de longues périodes et constituent à la fois une grave difficulté pour l'enseignement des sciences et fréquemment aussi un obstacle considérable à leur développement.

Par ailleurs, l'expérience montre que les méthodes actuellement pratiquées dans la discussion des problèmes scientifiques n'ont qu'une efficacité limitée au point de vue de l'établissement d'une unité de doctrine.

Il serait dès lors hautement souhaitable de promouvoir tout ce qui pourrait favoriser un accord sur les points en discussion.

Un procédé semble devoir être particulièrement utile sous ce rapport: à savoir, l'établissement de contacts personnels prolongés

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Every day science raises new problems, which usually give rise to various, and often contradictory, solutions. Consequently it often happens that amongst the most authoritative representatives of a given branch of science, and particularly amongst those who are engaged in studying the same question, one meets with contrasting opinions. Divergences of this kind often exist over long periods of time and are a serious obstacle not only to the teaching of science but also to its development.

Experience shows, moreover, that the methods at present in use in the discussion of scientific problems have only a limited efficacy in so far as concerns doctrinal unity.

It would, therefore, be highly desirable if everything that could favour agreement on controversial points were to be promoted.

One process that would seem to be particularly useful from this point of view would be the establishment of prolonged personal contacts entre quelques représentants d'opinions différentes au sujet d'une question déterminée.

En effet, le contact personnel entre hommes de science constitue, sans aucun doute, le moyen le plus efficace de résoudre les controverses scientifiques.

Dans ce but, l'Académie Pontificale des Sciences a décidé de convoquer de pareilles rencontres. Pour la partie scientifique, ces rencontres seront présidées par un Académicien Pontifical versé dans la même discipline tandis que l'organisation générale en sera réalisée par le Chancelier de l'Académie.

Ces rencontres, qu'on a appelées « Semaines d'Etude » ont été réglées de la manière suivante:

RÈGLEMENT DES SEMAINES D'ÉTUDE

1. - L'Académie invite quelques illustres savants, parmi ceux qui, ayant étudié spécialement une question déterminée, sont arrivés à des conclusions différentes, à se rencontrer à Rome, à son siège, la

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between some of the representatives of different trends of thought on a given subject.

Personal contacts amongst scientists are, in fact, the most efficacious means of solving scientific controversies.

With this aim in mind, the Pontifical Academy of Sciences decided to organize meetings of this description. These meetings, for the scientific part, will be presided by an Academician versed in the same discipline while the general organization of these will be realized by the Chancellor of the Academy.

These meetings, known as « Study Weeks », were planned on the following lines:

STANDING RULES FOR « STUDY WEEKS »

1. - The Academy invites a number of illustrious scholars — comprising those who have especially studied a given question and have

« Casina di Pio IV », à l'intérieur de l'Etat de la Cité du Vatican, afin d'y procéder en commun, en dehors de toute autre préoccupation, à un examen général de toutes les données du problème.

2. - Le but essentiel de ces discussion est de chercher à formuler de façon précise les raisons qui sont à la base de la divergence des opinions. Les savants conviés aux réunions s'engageraient à l'avance à concentrer leurs efforts dans cette direction.

3. - Un examen critique de ces raisons aboutira soit à un accord sur une solution déterminée, soit à la constatation qu'à l'état actuel des connaissances, il est impossible d'établir une unité de doctrine au sujet du problème envisagé.

Dans ce dernier cas, les savants invités auront pour tâche:

a) de préciser les motifs pour lesquels un accord s'avère présentement irréalisable;

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arrived at different conclusions — to meet in Rome at its headquarters, the « Casina di Pio IV », situated in the Vatican City, so as to make a joint examination, free from all other preoccupations, of all data concerning the problem.

2. - The chief aim of these discussions is to endeavour to formulate precisely the reasons which are at the root of the differences of opinion. The scholars invited to these meetings undertake in advance to concentrate their efforts on this.

3. - A critical examination of these reasons should lead, either to agreement on a given solution or else to the conclusion that, on the basis of the information actually available, it is impossible to establish doctrinal unity on the problem envisaged.

In the latter event the scholars concerned will be called upon:

a) to define the reasons why agreement appears to be impossible for the present;

b) de définir le genre de recherches qu'il serait souhaitable d'entreprendre en vue de résoudre la question.

4. - L'invitation ne sera adressée par l'Académie qu'à un très petit nombre de représentants de chaque science: ceux-ci seront choisis exclusivement parmi les spécialistes de la question considérée, qu'ils soient membres ou non de l'Académie.

5. - Les discussions auront un caractère strictement privé; elles prendront la forme de conversations particulières.

Des interprètes polyglottes, des sténographes, des rapporteurs, etc., seront mis à la disposition des savants réunis.

6. - Les « Conclusions » des discussions seront publiées sous la forme d'une « Note Collective Finale » (à laquelle pourront éventuellement être jointes des annotations individuelles), mentionnant:

a) les points sur lesquels un accord aurait été réalisé;

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b) to specify the kind of research work it would be desirable to undertake with a view to solving the problem.

4. - The invitation will be addressed by the Academy to only a small number of representatives of each branch of science: these will be exclusively selected from amongst the specialists of the question being considered, either members of the Academy or not.

5. - The debates will be strictly private and will take the form of personal talks.

Polyglot interpreters, stenographers, reporters, etc. will be placed at the disposal of the participants.

6. - The « Conclusions » arrived at will be published in the form of a « Collective Note » (to which may eventually be added individual notes) mentioning:

a) the points on which agreement was reached;

b) les points sur lesquels un accord n'aurait pas paru réalisable;

c) les raisons pour lesquelles l'accord n'aurait pu être réalisé;

d) des suggestions relatives aux recherches paraissant les plus aptes à résoudre les difficultés.

7. - Les « Conclusions » seront ausitôt imprimées et communiquées, par les soins de l'Académie Pontificale des Sciences, à tous les centres scientifiques qu'elles seraient de nature à intéresser.

8. - L'Académie préparera, donc, la publication d'un volume officiel des Actes de la Semaine d'Étude contenant la chronique des journées, les rapports des participants avec les discussions correspondantes et la Note Collective Finale.

Le volume fera partie des publications officielles de l'Académie: il sera envoyé aux Institutions Scientifiques avec lesquelles l'Académie entretient des relations d'échange et toute personne pourra se le procurer.

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b) the points on which it was impossible to reach agreement;

c) the reasons why it was not possible to reach agreement;

d) suggestions regarding the research work which appears most suitable for arriving at a solution of the difficulties.

7. - The « Conclusions » reached will be immediately printed and transmitted, by the Pontifical Academy of Sciences, to all the scientific centres which might be interested therein.

8. - The Academy will publish an official volume of the Proceedings of the Study Week, containing an account of the sessions, the papers presented by the participants, together with the relevant discussions, and the final « Collective Note ».

This volume will form part of the official publications of the Academy and will be sent to the scientific institutions with which the Academy maintains exchanges. It can be acquired by anyone.

En vue d'étendre sa diffusion, le volume pourra aussi être confié à une organisation éditoriale pour être mis en vente, le Copyright demeurant toujours réservé à l'Académie.

9. - Toutefois, chaque participant reste libre de faire imprimer son propre rapport partout où il le juge convenable et à n'importe quel moment.

10. - L'Académie offrira en hommage à chaque participant une copie du volume officiel des Actes de la Semaine d'Étude, et des Extraits de son propre rapport suivant le nombre de copies qu'il souhaiterait avoir.

11. - Tous les frais de voyage et de séjour à Rome des personnalités invitées seront à la charge de l'Académie Pontificale des Sciences. L'hospitalité sera assurée dans l'un des principaux hôtels de Rome.

The volume may also be entrusted to a publisher, with a view to ensuring a wider distribution, but the Copyright will always be reserved to the Academy.

9. - Each participant remains free to print his own contribution wherever and whenever he thinks fit.

10. - The Academy will present to each participant a copy of the official volume of the Proceedings of the Study Week, as well as such number of reprints of his own communication as he may desire.

11. - All travelling expenses, and accommodation in one of the best hotels in Rome, of the persons invited to the meetings will be borne by the Pontifical Academy of Sciences.

L'Académie se fera un plaisir d'offrir la même hospitalité aux épouses des savants invités, à l'exclusion toutefois des frais de voyage.

12. - La participation à la Semaine d'Etude comporte de la part de chacun l'acceptation de toutes les clauses du présent Règlement.

The Academy will be pleased to offer similar accommodation to the wives of the scholars who are invited, but not their travelling expenses.

12. Participation in the Study Week implies on the part of each member the acceptance of all the clauses in these regulations.

TRAVAUX SCIENTIFIQUES

PREFACE

The aim of the Study Weeks conducted by the Pontifical Academy of Sciences is to take some topic of fundamental importance in a particular branch of science, a topic about which the experts have divergent, or even contradictory, views, and to invite a small group of scientists to discuss it as thoroughly as possible. The discussions may result in some agreed conclusions, or opinions may remain divided. In any case the formal papers, the discussions and the conclusions are published in full.

The subject of Nuclei of Galaxies is indeed a matter of lively discussion at the present day and seemed to be a very suitable topic for a Study Week in astronomy. The preparation of this Study Week was started during the Prague meeting of the IAU in August 1967 by discussions between MORGAN, RYLE, SANDAGE and the writer. A preliminary programme and list of participants were drawn up. Subsequently RYLE was unfortunately obliged to withdraw and the Organising Committee consisted eventually of G.R. BURBIDGE, W.W. MORGAN, J.H. OORT, A.R. SANDAGE, M. SCHMIDT, L. SPITZER Jr. and D.J.K. O'CONNELL (Chairman). The programme went through several revisions, mainly as the result of extensive correspondence. Although the whole committee met together for the first time in Rome just before the start of the meeting, various members of the committee had been able to meet each other from time to time to discuss details of the programme.

The choice of the participants was dictated by the desire to cover adequately the various aspects of the subject and to represent different points of view.

The meetings were held in the Academy building, the 16th century Casina of Pius IV in the Vatican gardens, on April 13, 14, 15, 16, 17, 18. There were in all ten sessions of about three hours each. At each session one of the members was invited to preside. The name of the Chairman is given at the beginning of each discussion. Professor E.M. BURBIDGE and Professor WOLTJER were asked to prepare summaries of the work of the Semaine, the former from the observational, and the latter from the theoretical point of view. These carefully prepared summaries formed the basis for the lively discussions about the conclusions. The preliminary draft of the conclusions is given at the beginning of each summary. The conclusions finally agreed on are given at the end of the volume, together with some suggestions for future researches.

The papers and discussions were recorded on magnetic tape and the tapes were brought every 15 minutes or so to the typists who transcribed them immediately. The transcripts were at once checked by Drs. G.V. COYNE, M.F. MCCARTHY and P.J. TREANOR of the Vatican Observatory, who attended the sessions, and the corrected scripts were then reduplicated. Thus the text of the discussions could be distributed to the speakers the same day or the following morning, so that they could correct them while the matter was still fresh in their minds. The corrected versions were then collated by the secretarial staff and a second revised draft was reduplicated and given to the speakers. Revised copies of the second draft were collated and the resulting third draft was sent to the speakers after the meeting. The corrections received from the speakers were incorporated in the final draft, proofs of which were sent to the participants together with the proofs of their papers.

Thanks are due to the above mentioned members of the staff of the Vatican Observatory, who contributed greatly to the correct recording of the discussions, and to Signora Josephine LUCAS and her staff of typists, who worked long hours in order to have the typescripts prepared rapidly. All the heavy work involved in the practical organisation, both before, during and after the Semaine, was conducted most efficiently by the Chancellor of the Academy, Professor PIETRO SALVIUCCI, and his coadjutor, Dr. FRANCESCO SALVIUCCI.

Finally I must thank all the participants who devoted so much time and trouble to the Semaine, and in particular the members of the Organising Committee, who were responsible for the scientific preparation of the meeting.

D.J.K. O'CONNELL, S.J.

I.

INTRODUCTION

INTRODUCTION

V.A. AMBARTSUMIAN

Burakan Observatory
Erevan - Armenia

1. The great majority of galaxies have a density-maximum somewhere near to their centre of inertia. This *region of maximum* density it is convenient to call *the central part* of the given galaxy.

Sometimes in the astronomical literature this *central part* is referred to as the *nucleus* of the galaxy. It is strongly desirable to avoid such ambiguity since it is not this maximum density region with very indefinite borders which we are going to discuss at this study week.

In some nearer galaxies, for example in M 31, M 32, M 33, we see that there is a starlike, or almost starlike, image superposed on this region of maximal density. In many distant galaxies the limits of angular resolution do not allow us to see similar starlike formation. They appear lost in the bright background of the central part. However, in some distant galaxies this superimposed starlike formation has sufficient luminosity to be observed even in the cases when the angular resolution of photographs are moderate ($1'' - 3''$). This is for example the case in Seyfert galaxies. Similar, but less prominent, starlike formation we observe in the photographic images of many other (mostly spiral) galaxies. It is much more convenient to apply the term "nucleus" just to these formations, since they have shown us a number of exceptionally interesting phenomena, the discovery of which affected the whole outlook of modern extragalactic astronomy.

2. The spectroscopic study of the more prominent nuclei shows that there are processes within the nuclei which differ from phenomena taking place in the other parts of galaxies. We are going to speak about these processes a little later. Let us mention here only some of them: the violent motions of gaseous clouds, considerable excess of radiation in the ultraviolet, relatively rapid changes of brightness, expulsion of jets and of condensations.

The presence of one or of several of these processes is described by the word *activity* of the nuclei. Now there are cases when no starlike discrete image is seen at the center of a galaxy, but there are clear signs of the nuclear activity. It is natural to suppose that in such cases a nucleus exists in the galaxy, but its total luminosity in the visible light is so low that its image is not visible owing to the presence of the bright background of the ordinary stellar population. The higher resolution can show us in such cases the presence of the small nucleus.

Nevertheless no sign of a nucleus has been found in some of the *nearest* galaxies. Examples: S M C and the Sculptor System. We can only speculate on the possible presence of the nuclei in the past history of these systems or on the possibility to find now the remnants of what at some time was the nucleus of a galaxy of such type.

At the same time all existing data make it almost certain that all spiral galaxies as well as all ellipticals of high and intermediate luminosity have nuclei of different prominence. Putting it in another way, we can say that almost all galaxies of high and intermediate luminosity have nuclei, but it is possible that a large proportion of dwarf galaxies are deprived of nuclei.

Of course we do not know exactly where lies the boundary between the galaxies with and without a nucleus. Perhaps there is no clearcut border and the difference is only in the luminosity and significance of nuclei of different galaxies. In any case here is a problem for study which is very difficult.

3. It is widely known that there is a great measure of similarity between quasars or QSRSs and active galactic nuclei. It is known also that parallel to QSRSs, which are comparatively rare objects, we observe optical QSOs. According to Dr Sandage and his collaborators the number of QSOs of *a given apparent magnitude* is more than a hundred times larger than the number of quasars of the same apparent magnitude.

The ratio is much higher when we take the corresponding spatial *concentrations* (densities) of the same objects. We know that quasars have optical (photographic) luminosities between —24 and —26 absolute. The QSOs have apparently a somewhat larger dispersion of luminosities and their mean luminosity must be of the order of —23. This makes it very probable that the spatial density of QSOs is more than one thousand times higher than that of quasars. This means that the optical QSOs are in some respects much more important than quasars. We can formulate the situation in the following way:

The QSOs have considerable dispersion of luminosities. The most luminous of them are emitting also intense radio-frequency radiation and are known as Quasars.

Such a large population of QSOs in the universe is an evidence against their short life time. It seems to me that the assumption that QSOs live in the average a time shorter than 10^9 years is connected with many difficulties. However, if we consider the state of quasars as a special active phase in the evolution of QSOs then it is possible to suppose that the total duration of such phase is much shorter (of the order of 10^7 years - 10^8 years, but hardly less).

For a QSO or a quasar of high luminosity ($M_M = -25$) such a long lifetime means that the total amount of energy emitted in the form of electromagnetic radiation including the strong infrared radiation must be of the order of 10^{63} ergs, which quantity is equivalent to about 5.10^8 $M_\odot$. It is true that we can suppose that the lifetime of very *high luminosity QSOs* is shorter than 10^9 years, but even in the case of objects with $M_M = -22.5$ the problem of the energy sources seems very difficult.

4. One of the most important things to be done in the studies of active nuclei and of QSOs is to find the connection between the different forms of activity.

It is true that the study of radio-galaxies has opened the way to discovery of the phenomena we are now discussing, but it is now clear that the radio-sources form only a small part both of galaxies with active nuclei and of QSOs. In any case this is the case when we speak about strong radio-sources. It is quite possible that all active nuclei emit something in radio-frequencies, but apparently we are not able to detect such weak sources.

Much more widespread among nuclei of galaxies is the activity in the form of presence of ultraviolet excess radiation of non-thermal and *non-stellar origin* and the presence of emission lines. Since in almost all cases the strong emission lines originate by mean of fluorescence processes similar to that in gaseous nebulae of our own galaxy it is possible to concentrate our attention on the continuous emission in the ultraviolet. In the case of QSOs, owing to very large redshifts the presence of ultraviolet excess is quite clear. However, for the majority of galaxies the total radiation of the nucleus (both absolutely and apparently) is weak and only a small part of galaxies shows an ultraviolet excess coming from the nucleus. A careful search of galaxies with bright ultraviolet continuum covering several thousands of square degrees has been made at Burakan Observatory. As a result it has been found that about 2% of galaxies in the interval of apparent magnitudes 13.5 and 17.5 have comparatively bright ultraviolet continuum. About 400 of such "ultraviolet" galaxies have been already found by

MARKARJAN and three lists comprising 300 galaxies with u.v. excess are already published. About one hundred galaxies of these lists were already observed by different observers (KHATCHIKJAN, WEEDMAN, SARGENT, ARAKELJAN, DIBAJ, ESIPOV) and it is now clear that not less than 80% of MARKARJAN's galaxies have strong emission lines. Thus the observations support the idea that the strong emission lines are strongly correlated wtih u.v. excess.

Now there is every reason to believe that the excess observed in the near-ultraviolet of these galaxies expands to the far-ultraviolet, as in the case of QSOs and that there exists a maximum of spectral distribution when we consider the intensities in wavelength scale [I (λ)]. Let us connect this fact with the observations of galaxies made by orbiting astronomical observations launched by American astronomers. They have indicated that some normal galaxies (for example M 31) show an increase of intensity to the far ultraviolet, which suggests a maximum of intensity beyond 2000Å. Apparently we may guess that the nuclear region of every galaxy is a source of non-thermal and non-stellar radiation, which has its maximum in the far ultraviolet. What we observe from the earth's surface is only a relatively faint wing of this radiation. In the cases when the excess is *large* (as in the case of Seyfert or of some N galaxies) *we can* distinguish this wing. However, in the majority of cases the u.v. excess is faint and its near-ultraviolet wing is still fainter and we cannot detect it.

If this extrapolation is valid, we may suppose that all nuclei emit this kind of u.v. radiation, but in galaxies with active nuclei such emission is much more intense. It seems therefore that the observation of radiation of nuclei in the far ultraviolet is becoming very important for understanding the activity of nuclei.

All these questions are connected with the problem of low-level activity of the nuclei of normal galaxies. But even in normal galaxies we have apparently from time to time violent events. The Dutch astronomers have shown recently from

21 cm observations that there are outward motions of some isolated clouds diverted from the nucleus of our Galaxy at a considerable angle to the plane of galaxies.

As regards the source of ultraviolet radiation there is no doubt that this continuum usually comes from a source of small diameter (less than 10^{17} cm) and very characteristic irregular variations are evidence in favour of this. How can we explain these variations? If the mechanism of radiation is of synchrotron nature, then probably the variations of radiation intensity are caused by variation in the flow of particles which are ejected from a central body which has a still smaller volume.

The infrared emission represents another form of activity of some nuclei, however a very important form. There are evidences that dust is present in the nuclei some of the galaxies of Markarjan, but it is not the real cause of infrared emission.

5. Another form of the nuclear activity is the ejection of gaseons clouds. In the case of less active nuclei we have apparently steady outflow of matter from the nucleus. We have some possibilities to estimate the loss of mass by active nuclei.

In the case of NGC 4151 ANDERSON and KRAFT (*Ap. J. 158*, 859, 1969) have calculated that the loss of mass is somewhere between 10 and 1000 $M_\odot$ per year. If we suppose the duration of the Seyfert phase to be 5.10^7 years and take the lower value for the loss per year, we obtain the total loss of the order of 5.10^8 $M_\odot$. Thus the activity must be connected with great changes in the state of the nucleus.

Another example is NGC 1275. Apparently the giant filamentary gaseous structure which we observe in this galaxy has a mass of the order of several times 10^8 $M_\odot$.

Thus the outflow of gas from nuclei, either in the form of clouds or of shells, indicates essential evolutionary changes in the masses of nuclei. At the same time we must suppose that in the initial stage of evolution the mass of the active nucleus forms a considerable part of the mass of the whole galaxy.

We can only guess about the further history of the gases.

Where the motions are extremely violent (more than 1000 km/sec) the galaxy loses these gases. In the case of low velocity of outflow from the nucleus the gases can form some system of clouds around the nucleus.

Perhaps the constant escape of mass from such galaxies as NGC 4151 and Markarjan 9 is the cause of the extreme faintness of the envelope surrounding the nuclei of these galaxies.

As you know, the Seyfert galaxies were defined as a class of objects in which the permitted lines have much larger width than the forbidden lines (especially N_1 and N_2). However, it is necessary to say that, if the emission line spectra of Seyfert galaxies are to be explained as the radiation of many gaseous clouds expelled from the nucleus, then the spectral property just mentioned means only that a considerable part of the emission line radiation comes from clouds of small masses. The expanding cloud of small mass can give an appreciable amount of radiation only when it is dense, since the luminosity is proportional to M^2/V.

But at high density and small volume it cannot radiate the forbidden lines. When however, owing to the expansion, the density diminishes, the total radiation is too faint to be observable. Thus in such clouds we do not see any forbidden lines. The opposite is true for the clouds of high masses. When we have only clouds of large mass then we shall observe for a considerable length of time both the permitted and forbidden lines. Now everything depends on the velocity of expansion of these large clouds. If they have low velocity of escape, they produce narrow forbidden lines. If their expansion velocity is high we must observe wide forbidden lines. Now it is important that *there is a group of galaxies which show both the permitted and forbidden lines equally widened*. Examples are Markarjan 3, 6 and 39. But this is exactly opposite to what we have in the case of Seyfert type spectra. At the same time the physical causes are the same. Only the values of the masses of the clouds are different. Thus many other galaxies have active nuclei of the same kind as the nuclei of Seyfert galaxies.

Sometimes one speaks of the spiral structure of Seyfert galaxies. It seems to me that this property is not essential to them. More important from the point of view of morphology is the prominence of the nucleus. We can notice that many galaxies with Seyfert spectra are similar in their structure to N galaxies introduced by Professor MORGAN. Therefore it seems that it is more appropriate to discuss their morphology in connection with morphological properties exhibited by N galaxies. Professor MORGAN has some important new ideas on this matter and I hope that he will tell us more on this matter later. But in this connection I would like to dwell only on one point which has been emphasised by MARKARJAN and ARAKELJAN recently.

In his survey of uv galaxies MARKARJAN has divided all uv objects in two classes. First, s-galaxies which are strongly concentrated objects of spheroidal form, which have a spectral distribution like QSOs, and the second the d-objects which have diffuse borders, where the emission lines are radiated from a large volume of corresponding galaxies.

The redshifts of 42 CS objects (concentrated, spheroidal) are known at this stage, but only for 25 objects have the photoelectric measurements been made. Therefore only for them we can determine more or less reliable absolute magnitudes.

For the mean absolute magnitude and colour of CSOs MARKARJAN and ARAKELJAN give $M_B = -19.2$, $B - V = +0.57$, $U - B = -0.28$ compared with mean values which have been obtained from published data on N galaxies $M_B = -21$, $B - V = +0.9$, $U - B = -0.27$.

The s-galaxies of MARKARJAN, though generally much nearer to us than N galaxies, as a rule were not observed as radio sources.

Therefore we can say that the CSOs of MARKARJAN form together with N galaxies one major class of objects. The optically most luminous of these objects often are radio galaxies.

The number of CSOs in a given volume is several hundred times larger than the number of N galaxies.

We have the same situation in the case of QSOs and QSRs, and D - E galaxies and corresponding radio sources.

6. *Radio-frequency emission.* Here we have one of the most important problems. We understand that a strong radio-frequency emission is always connected with the activity of nuclei. But the type of connection between the activity of nuclei and of radio-frequency emission must be different in different cases.

Apparently in the case of Quasars and of N galaxies the connection is a direct one since the optical radiation in these cases is the radiation coming from the nucleus. However, in the case of D or E radio galaxies, in which in many cases the radio emission comes from the clouds of relativistic gas situated outside the galaxy and the optical luminosity is caused by the light of the stellar population, the connection is indirect and the explanation is to be found in the deep connection between the nucleus and the stellar population of the whole galaxy. Every theory which explains the activity of the nuclei and the origin of radio galaxies must explain also these simple facts.

Another important question is connected with the process of formation of clouds of relativistic electrons. The models supposing that the clouds were ejected directly from the nucleus meet some difficulties. It is much easier to suppose that the clouds have been formed by coherent bodies ejected from the nucleus. In this case we must assume that each of these ejected bodies behaves as an active centre, radiating the relativistic electrons. Here is a challenge for theoreticians.

7. *Dense bodies ejected from nuclei.* On several occasions I had the opportunity to speak on jets originating in the nuclei of some giant galaxies. The galaxy NGC 4486 is only one example. The jets in NGC 3561 and IC 1182 are similar in form but consist mainly of classical gas. The condensations

10. As usually happens in astronomy when great new discoveries are made, the theoreticians try to give the explanation of new facts almost immediately. However this time we deal with very complex phenomena. It is even difficult to understand what is going on in the external parts of a nucleus which are transparent and open to our observations. Therefore, some patience is necessary.

At this stage we shall try to undestand better the external manifestation of the activity of nuclei and to obtain a correct general picture of the processes under consideration. Only then will come the second stage when the theoreticians will give the explanation of the deep processes and of the physics of energy generation.

To make the first stage shorter we must put the emphasis on the observations and on the systematization of the results of observations.

The systematization and classification of objects is as important as the classification of relations we discover between different facts and forms of activity.

Nature is endlessly more complicated and diverse than it seems to us, who until recently had no information on these wonderful processes. Let us study them with patience and base our conclusions mainly on the observational data.

DISCUSSION

Chairman: D. J. K. O'Connell

Morgan

I should like to second the remark of Prof. Ambartsumian concerning the need to select a single point of view — a criterion of classification with the greatest prospect of significance. Then the preliminary classification should be carried through without being diverted by other spectacular phenomena.

Low

I would like to make a comment about the strength of the ultraviolet continunm. In trying to make models of the infrared phenomenon the problem is to suppress the ultraviolet. There is no difficulty in building a model of the infrared phenomenon phenomenon the problem is to suppress the ultraviolet. There is difficult to make the IR without producing more high energy radiation than is observed.

Osterbrock

In connection with the ultraviolet continuum observations of galaxies, I should like to say that I discussed them specifically before this meeting with my colleagues at the University of Wisconsin, who made the Orbiting Astronomical Observatory measurements. Their first material on M 31 seemed to show a very strong ultraviolet excess. However, the data at that time were not completely reduced. It now seems that the *UV* excess is not quite as large as it first appeared. On the other hand, the data continue to show a *UV* excess for the center of M 31, in the sense that between 3000Å and 2000Å there is considerably more radiation than from main-sequence type stars with the same spectral type or *B-V* colour index. The complete reduction in absolute energy units is not yet complete.

OORT

Prof. AMBARTSUMIAN spoke about the possibility of making a whole galaxy from a nucleus by eruption. There is one great difficulty, which is to get angular momentum. Angular momentum is such a characteristic thing everywhere in the universe, especially for spiral galaxies, that to me this forms a very great difficulty.

AMBARTSUMIAN

On the angular momentum which Prof. OORT mentioned: of course, I also keep this problem always in my mind. However, I think that there are many possibilities to explain the angular momentum now observed. Let us consider, for simplicity, how we can have an apparent violation of the law of conservation of momentum. If we have a nucleus from which two jets of equal mass and velocity are being ejected in opposite directions, in this case the nucleus will not change its velocity. But if one of the jets consists of material which, for some reason, will remain long in the condensed form, and the material of the second jet will easily disperse after some time, we shall have only one remaining jet and we shall have an *apparent* violation of the momentum law.

For example, in the case where a nucleus is drawn out into a jet which gives a dense visible condensation, we would expect that the nucleus itself would receive an impulse in the opposite direction. But there may be a diffuse undetected ejection in the opposite direction which carries away this impulse. So it is possible to imagine cases where there is an apparent violation of angular momentum but where there is some unknown compensation. The observations of ARP suggest something of this kind.

OORT

But not angular momentum?

AMBARTSUMIAN

It is easy to build an example of the same type, leading to the apparent violation of angular momentum. I agree that what I have said is not a real explanation. The situation is dark but there are many possibilities.

OORT

I agree that often quite unexpectedly things which we cannot imagine have turned up.

E. M. BURBIDGE

I worried a lot about this angular momentum problem also, because in some ordinary spiral galaxies when one measures the rotation in the outer parts one finds that a lot of the angular momentum resides in the outer part. I wondered if outflow from the nucleus might not be combined with the acquisition of material from outside the galaxies; perhaps the infall of the material coming in an asymmetrical way, or with a small effective rotation far out, could provide angular momentum.

OORT

It would need a lot of matter, the velocities of which would have to be beautifully oriented.

HOYLE

I think here one has to distinguish between the spiral galaxies and the elliptical galaxies. Take the spirals first, where we can be fairly sure that angular momentum is involved. To make a system with angular momentum by a process of ejection, a material with essentially zero total angular momentum, it is necessary for separation to occur, with a part of the material retained to form the galaxy and a part being expelled to infinity. Then there is conservation of angular momentum, with a plus for what stays and a minus for what goes away, making a zero total.

[1] I - *Ambartsumian* - p. 16

II.

OBSERVATIONS AND THEIR INTERPRETATION

AN OPTICAL FORM MORPHOLOGY OF SEYFERT GALAXIES

W.W. MORGAN, N.R. WALBORN and J.W. TAPSCOTT
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Chicago - U.S.A.

ABSTRACT

The optical forms of five Seyfert galaxies [NGC 4051, 1068, 4151, 3516, and 1275] are related to the forms of a standard sequence of giant spirals and ellipticals [NGC 4303 (fS), 4501 (gS), 2841 (kS), and 4472 (E)] on the Yerkes form-classification system.

The form-relationship is described in terms of an operator F, which, when acting on a normal spiral, produces a Seyfert galaxy. Successive applications of the operator F on gS and kS normal spirals generate a surface which can be used for an integrated classification of Seyfert Galaxies, radio N-type galaxies, and some of the Markarian and Zwicky blue compact galaxies.

1. *Introduction. Definition of "Seyfert Galaxy".*

The classical paper by CARL K. SEYFERT (*Ap. J.*, *97*, 28, 1943) on nuclear emission in spiral galaxies lists twelve systems considered to have certain spectroscopic characteristics. SEYFERT's own spectroscopic investigation, however, refers to only six [NGC 1068, 1275, 3516, 4051, 4151, 7469] of the twelve; and the very great majority of recent investigations are concerned with one or more of the six. For the purposes of the present paper, we shall consider the term "Seyfert Galaxy" to be defined by these six.

The spectroscopic discriminant given by SEYFERT is: emission features similar to those found in planetary nebulae, superposed on a solar-type absorption spectrum. He describes their forms as "... intermediate-type spirals with ill-defined amorphous arms, their most consistent characteristic being an exceedingly luminous stellar or semi-stellar nucleus which contains a relatively large percentage of the total light of the system".

It is the aim of the present investigation to relate the optical forms of the Seyfert galaxies to those of normal spirals and ellipticals, in a more precise manner. For this purpose, the Yerkes classification of the forms of galaxies will be used.

2. *The Yerkes Form-Classification.*

The Yerkes form-classification system (*P.A.S.P. 70*, 364, 1958; *P.A.S.P. 71*, 394, 1959) is based on one of the two principal criteria of the Hubble system: the degree of central concentration of luminosity. This criterion has been found to be rather closely correlated with the kinds of stars contributing most to the luminosity in the photographic region (see W. W. MORGAN and N. U. MAYALL, *P.A.S.P. 69*, 291, 1957; W. W. MORGAN and D. E. OSTERBROCK, *A. J. 74*, 515, 1969).

The relationship of the Yerkes system for the giant spirals to that of Hubble is not single-valued. The relation between MK spectral type of the nuclear region, Yerkes form type, and Hubble types as listed by HUMASON, MAYALL and SANDAGE (*A. J. 61*, 97, 1056) is shown in Figure I. The classes Sa and Sb overlap over their entire range in MK spectral type; and in the Yerkes form classes fgS and gS the relation with the Hubble class is triple-valued.

However, there is not a completely smooth relationship

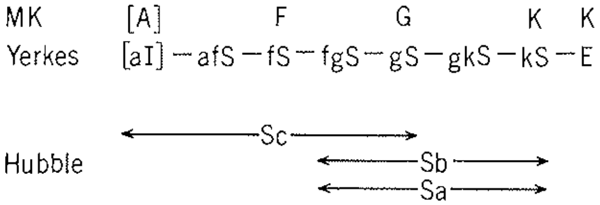


FIG. 1 — The relationship between MK spectral type, Yerkes form-class, and Hubble form-class.

between MK spectral types and Yerkes form types; and there is, in addition, a considerable variation in the appearance of the inner region of spirals of the same Yerkes type. For example, among the fS spirals the nucleus itself can be single [NGC 4303] or multiple [5248, 1808]. There are other major differences in the forms of the inner regions of galaxies of similar nuclear concentration of luminosity; some of these have been described by SANDAGE, DE VAUCOULEURS, and others.

From these considerations, we state an important characteristic of the Yerkes form-classification system: *The single criterion for the Yerkes form-classification system is the one most closely correlated with the stellar population of the inner region of the main body; this criterion is intrinsically coarse, and does not recognize the wide variety of phenomena observed in the inner regions of the giant spirals. The coarse Yerkes form-classification is a classification according to a physical characteristic: the stellar population.*

3. *The Frame of Reference for the* fS, gS, kS, *and* E *Systems.*

In what follows, we shall consider these four galaxies to be representative of their Yerkes form-types: fS, NGC 4303; gS, NGC 4501; kS, NGC 2841; E, NGC 4472. Three of the four are members of the Virgo Cluster, and the fourth (NGC

2841) is of a size and distance similar to the other spirals. The three spirals are of the "giant" category, which have the characteristic of having remarkably similar sizes, as far as their easily-photographed "main bodies" are concerned. The general characteristics of the four standard galaxies can be summarized as follows:

fS (NGC 4303). Small, bright nucleus. The MK spectral type of the nuclear region from McDonald spectrograms is F7, in the range λλ 3720-4120.

gS (NGC 4501). Inner part of main body considerably brighter, relative to the outer part, than NGC 4303. Single nuclear condensation. The MK spectral type in the violet region is G5.

kS (NGC 2841). The large, bright, amorphous nuclear bulge characteristic of the kS class is present. The violet MK spectral type of gK0 is characteristic of spirals of this class.

E (NGC 4472). This galaxy is similar in form to other giant ellipticals in the Virgo Cluster, and in many other clusters of galaxies. We describe such ellipticals as of the "giant" category, because they are far larger and more lumiuous than the dwarf ellipticals of the M 32 class. The giant ellipticals as defined here are much smaller and less luminous than the cD galaxies described by Matthews, Morgan and Schmidt, 1964, (*Ap. J.*, 140, 35), and have a different radial distribution of luminosity. The blue-violet MK spectral types of all of the brightest ellipticals of the Virgo Cluster are near gK0; this is also true for the elliptical-like galaxy NGC 4374.

We may summarize the form-categories represented by the standard galaxies as follows: (1) The three giant spirals NGC 4303, 4501 and 2841 define a sequence of increasing relative brightness of the inner region, with a corresponding progression in violet MK spectral type from F to G to gK; and (2) There is a major change between form classes gS and kS in the main body;

the bright detailed structure visible in the nuclear region at gS progresses to a large, amorphous, nuclear bulge in class kS. The distinction between form classes gS and kS is therefore very great, *when photographs of short exposure and normal contrast are used.*

4. *The Problem of the Degree of Form Resolution.*

There is one additional subject that must be considered before proceeding to the application of the standard form-sequence: the optimum degree of resolution (or the number of picture elements) in galaxy photographs. The obvious desire to record as many details as possible leads to a progressive diminution in image size on passing to progressively more distant galaxies – and, therefore, to a progressively smaller number of picture elements. Such a procedure is likely to introduce systematic differences in form classification as a function of distance; and a serious complication can result for investigations which depend on the intrinsic identity of near and far objects; in addition, the possibility of recognizing progressive changes in galaxy form-type with distance is lessened. For these reasons, there are advantages in defining normal types in terms of a limited number of picture elements from photographs with small telescopes; such photographs can then be compared with plates of distant galaxies obtained with large telescopes, with better probability of classifying the latter on a comparable system.

For this reason, the photographs of the present investigation were obtained with the new Yerkes 41-inch reflector at its *f*8 Cassegrain focus. This procedure – together with the equally important one of use of short ($1^{min}-8^{min}$) exposures for the clear delineation of the crucial inner regions – results in photographs of optimum classifiability for galaxies at the distance of the Virgo Cluster. Such photographs have several hundred picture elements in the main bodies of normal spirals, with faint-star diameters of the order of 2″ to 3″ of arc.

5. *The Form Type of the Seyfert Galaxy NGC 4051.*

Short exposures of the fS standard NGC 4303 and the Seyfert Galaxy NGC 4051 are shown in Figure 2. The former is one of the giant spirals of the Virgo Cluster; the latter is a member of the Ursa Major Cloud. The two are located at comparable distances, with NGC 4051 probably somewhat nearer.

On photographs of higher resolution (for example, see: *P.A.S.P. 70*, 364, 1958), the nucleus of NGC 4051 is seen to have a sharper, harder edge than the nuclei of normal fS spirals; however, in Figure 2 it can be seen that this discriminant has effectively disappeared for resolutions ∾3″. The 2^{min} exposures illustrated show that with this low angular resolution the appearance of the nuclei, and the relative surface brightness of the inner arms, are similar. We are therefore unable to discriminate, *from these criteria*, the Seyfert Galaxy from the normal fS spiral. In this case, with the resolution illustrated, we are thrown back on spectroscopic evidence; and this last is quite convincing: the spectrum of the nucleus of NGC 4051 differs markedly from that of NGC 4303, and confirms that it is a proper member of the Seyfert Galaxy group (McDonald spectrograms, unpublished).

6. *The Seyfert Galaxies NGC 1068, 4151, 3516, and 1275.*

Series of short exposures of these four galaxies are shown in Figure 3 - together with the gS, kS and *E* standards. All but one of these are from Yerkes 41-inch plates; the longest

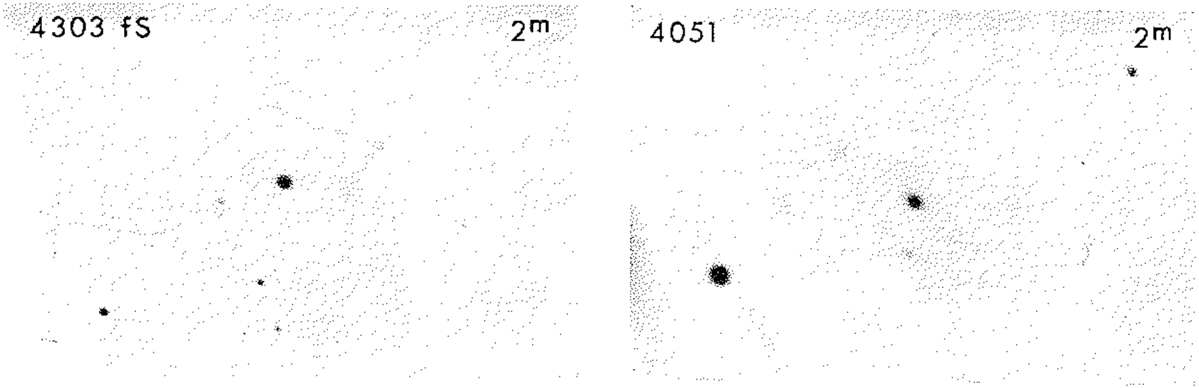


FIG. 2 — Photographes of the fS standard NGC 4303 and the Seyfert GalaxyNGC 4051. Eastman 103-a-G plate, unfiltered; exposure times 2^{min}; Yerkes41-inch reflector.

exposure of NGC 3516 is from the Yerkes glass copy of the blue plate from the National Geographic Society-Palomar Observatory Sky Survey. We are indebted to Dr. H. W. Babcock for permission to reproduce this exposure. The angular scale of all prints is the same, except for the two of NGC 1275, which have been enlarged more. The four Seyfert Galaxies are arranged vertically in order of relative luminosity of the inner region to the outer. The inner regions of NGC 1068 and 4151 are compared below with those of the gS standard NGC 4501, NGC 3516 with the kS standard NGC 2841, and NGC 1275 with the giant Virgo elliptical NGC 4472:

> *NGC 1068.* The surface brightness of the inner part is much higher than that of the gS standard NGC 4501; the 2^{min} exposure of NGC 1068 is brighter than the 3^{min} exposure of NGC 4501. The linear diameter of the visible main body of NGC 1068 is considerably smaller than that of NGC 4501. A faint, outer, arm structure for NGC 1068 has been shown by Sandage in the Hubble Atlas; this increases the size to a dimension comparable to that of the main body of NGC 4501.
>
> *NGC 4151.* Here the differences in form structure compared to the gS standard are marked. The 1^{min} exposure of NGC 4151 is hazy-stellar in appearance; the contiguous region has grown bright in the 4^{min} exposure — completely different in appearance from the 3^{min} exposure of the gS standard. The 12^{min} exposure of NGC 4151 shows strongly the much fainter main body. This main body is considerably smaller in absolute dimensions than that of NGC 4501. But again, there are faint outer spiral arms visible on the Yerkes glass copy of the National Geographic Society-Palomar Observatory Sky Survey; and these outer

arms expand the size of NGC 4151 to dimensions comparable to those of the gS standard.

NGC 3516. This Seyfert Galaxy is considerably more distant than those already discussed; and the apparent dimensions in Figure 3 should be approximately doubled for comparison. The appearance of the three shortest exposures (1^{min}, 3^{min}, 12^{min}) is strikingly different from that of the two exposures (2^{min}, 8^{min}) of the kS standard; and the outer part of the main body of NGC 3516 is only visible on the long exposure image reproduced from the second negative of the National Geographic Society-Palomar Observatory Sky Survey. The shortest exposures resemble a hazy star – very similar in appearance to the 1^{min} exposure of NGC 4151.

NGC 1275. This strong radio source is much more distant; the two exposures in Figure 3 differ in scale from the others. The 2^{min} exposure from the unfiltered 103aG plate is strikingly similar to the shortest exposures of NGC 4151 and 3516, and differs from the 2^{min} exposure on the elliptical NGC 4472. The spectacular eruptions in NGC 1275 (W. BAADE and R. MINKOWSKI, *Ap. J.*, *119*, 215, 1954; E. M. BURBIDGE, G. R. BURBIDGE and A. SANDAGE, *Rev. Mod. Phys.*, *35*, 947, 1963; E. M. BURBIDGE and G. R. BURBIDGE, *Ap. J.*, *142*, 1351, 1965; R. LYNDS, *Ap. J.*, *159*, *L151*, 1970) are not visible on this scale and exposure time (the image near the galaxy on the 2^{min} exposure is due to a star). The 8^{min} exposure shows the elliptical-like structure – which is even more striking on the National Geographic Society-Palomar Observatory Sky Survey glass copy.

7. *The Structural Morphology of the Seyfert Spirals:* (a) *The Diagonal Relation.*

A comparison of the 4^{min} exposures of NGC 1068 and 4151, illustrates why the two spirals were arranged in the vertical order shown: the spiral arms are strong in the first and weak in the second. Similarly, a comparison of the 12^{min} exposures of NGC 4151 and 3516 shows the arms strong in the former and absent in the latter. *the sequence order of the three Seyfert spirals is similar to that for the standard spirals;* and they can be used to define a standard sequence for the form-classification of separable Seyfert Galaxies. At one extreme is NGC 1068; at the other is NGC 3516.

8. *The Structural Morphology of the Seyfert Spirals:* (b) *The "Nucleus-Shoulders-Arms" Structures.*

The development in appearance with exposure time of the three Seyfert spirals in Figure 3 can be described in terms of three substructures. The hazy star-like nucleus is outstanding in the shortest (1^{min}) exposures. The exposures in the second column (1068, 2^{min}; 4151, 4^{min}; 3516, 12^{min}) illustrate the development of a second, brilliant substructure, which we label the "shoulders" (at the suggestion of V. AMBARTSUMIAN); here the brilliant nucleus is lost in the overexposed image. In the third column (1068, 4^{min}; 4151, 12^{min}; 3516, PSS) the outer arm structure has become visible [discrete arm structure is often not visible with the low resolution used; but it seems very likely that with higher resolution all similar galaxies would show spiral structure].

A classification of Seyfert Galaxies in terms of these substructures is shown in Figure 4, the left-hand parts of which are similar in arrangement to the photographs illustrated in Figure 3. The three columns under "Seyfert Galaxies" are

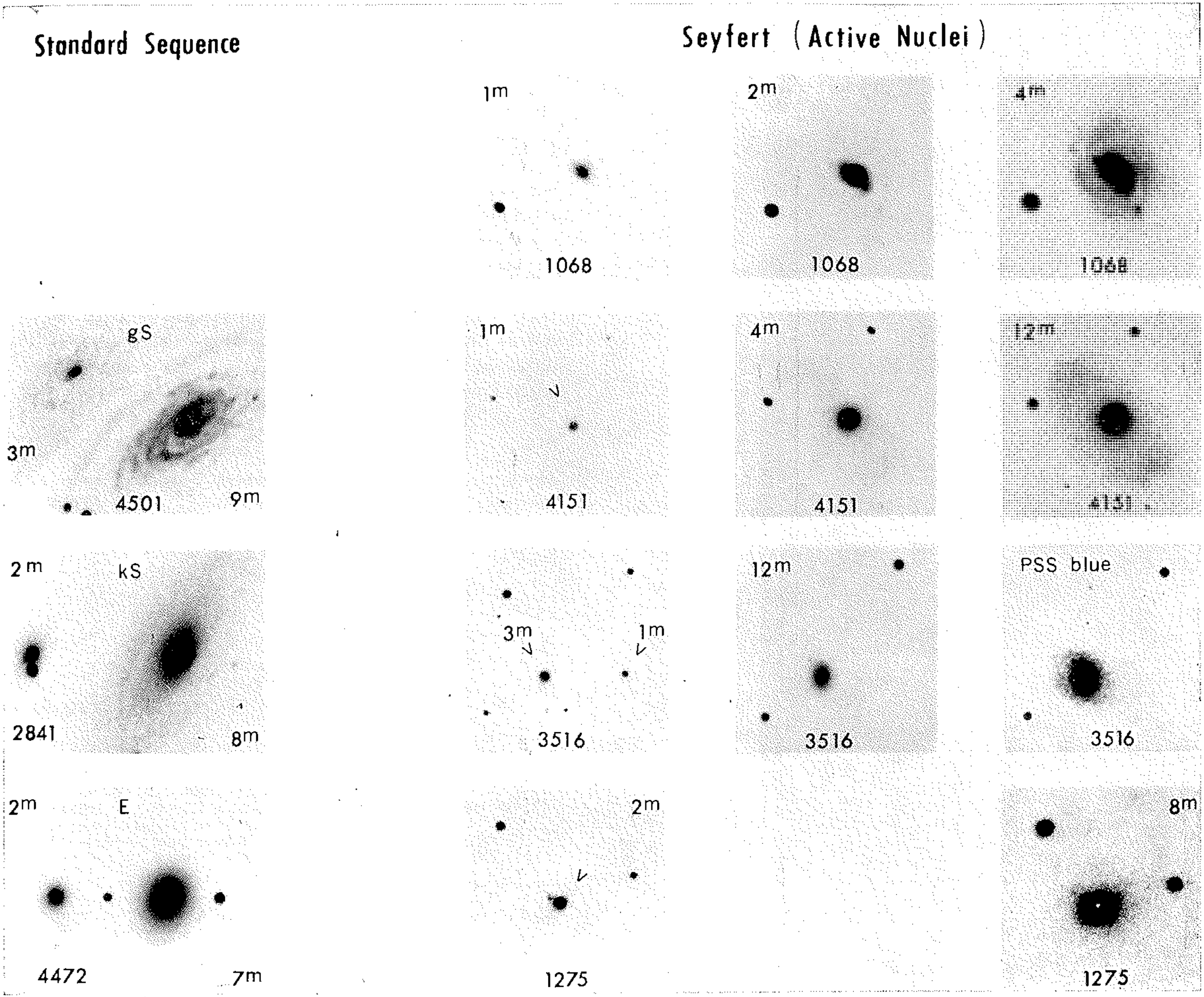
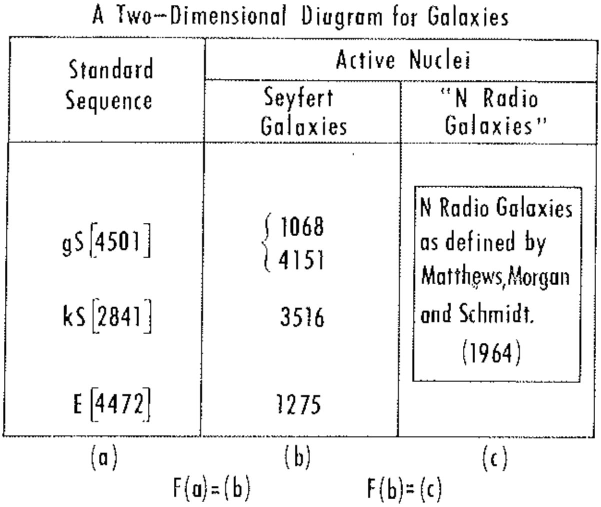


FIG. 3 — Photographs of the standard sequence gS — E (two exposures for each), and four Seyfert Galaxies. Eastman 103-a-G plate, unfiltered; exposure times as marked; Yerkes 41-inch reflector. "PSS blue" exposure on NGC 3516 from National Geographic Society-Palomar Observatory Sky Survey blue plate [Yerkes glass copy].

4151 (K. S. ANDERSON and R. P. KRAFT, *Ap. J.*, *158*, 859, 1969; R. CROMWELL and R. WEYMANN, *Ap. J.*, *159*, *L147*, 1970) as well as other eruptive processes apparently going on in more distant (and more luminous) radio galaxies.



A Two-Dimensional Diagram for Galaxies

Standard Sequence	Active Nuclei	
	Seyfert Galaxies	"N Radio Galaxies"
gS [4501]	1068 4151	N Radio Galaxies as defined by Matthews, Morgan and Schmidt. (1964)
kS [2841]	3516	
E [4472]	1275	
(a)	(b)	(c)

F(a)=(b) F(b)=(c)

FIG. 5 — Diagram illustrating result of successive applications of operator *F* to standard sequence of spirals.

10. *The Limitations of the Optical-Form Morphological Approach.*

We have noted certain family regularities in the appearance of the optical forms of standard spirals and Seyfert Galaxies. With short exposures, like those illustrated in Figure 3, a useful classification can be carried out; but it is necessary to combine such a classification with one based on the spectroscopic phenomena peculiar to the Seyfert phenomenon. There are certain combinations of emission lines which permit the formation of "natural spectroscopic groups" similar to those described for stellar spectra (see: *Pubs. Obs. Univ. Michigan, 10,* 33, 1950). When such a spectroscopic approach is combined with a form morphology such as that outlined here, it should be possible to strengthen the morphological structure for these objects.

11. *Allocation of Activities. Conclusion.*

All of the photographs discussed here (with a single exception) were obtained by WALBORN with the Yerkes 41-inch reflector. The photographic work, including laboratory experimentation on comparable photographic reproduction of the forms illustrated in Figure 3, was carried out by TAPSCOTT. The paper was written by MORGAN.

One of us (W. W. M.) is indebted to Professor DIMITRI MIHALAS for a series of discussions. He also is indebted to Dr. W. F. VAN ALTENA for providing the camera used in the direct photography. We are indebted to Director H. W. BABCOCK of the MOUNT WILSON and Palomar Observatories for permission to reproduce the long exposure of NGC 3516 from the Yerkes glass copy of the National Geographic Society-Palomar Observatory Sky Survey.

This investigation was supported by a grant to MORGAN from the National Science Foundation.

Note added in proof

An important paper by E. A. DIBAJ ("Luminosities of Seyfert Galaxies and their Nuclei", *Astronomical Circular* No. 481, p. 4, 1968) introduces a classification based on a non-dimensional ratio of nuclear to galaxy luminosity. He points out that this ratio increases continuously along the sequence:

Ordinary galaxies → most Seyfert galaxies
→ 3C 120 → Ton 256 → QSS.

DISCUSSION

Chairman: D. J. K. O'CONNELL

SANDAGE

May I ask if there is an apparent difference between Seyfert galaxies and N galaxies only as the function of distance? Would you say that these galaxies which you, SCHMIDT and MATTHEWS identified as N's would look like Seyferts if they were closer?

MORGAN

The strong radio sources classified as N in that paper might resemble some of the bright Seyferts in a general way, but the distant N's would represent a much more extreme departure from "normal" spirals in the luminosity of the nuclear region.

SANDAGE

NGC 4151, perhaps, has the brightest nucleus of the classical Seyferts compared to the total magnitude. Does it seem likely that if NGC 4151 were removed to a distance corresponding to, say $z = 10{,}000$ km/sec, you see very little fuzz around it, and would it then be classed as an N?

MORGAN

Yes, probably.

KELLERMANN

I would just like to make a brief comment which I intend to discuss more fully tomorrow: M 87 does, in fact, have a small flat-spectrum radio source in the center with similar properties to the other objects that Dr. MORGAN discussed. This, in fact, appears to be a fairly common property of elliptical galaxies and other galaxies. These small sources are not confined to the quasi-stellar objects or to Seyfert galaxies.

MORGAN

This is very interesting. I believe still that there is a marked difference in the gradient of the images on the slides we have seen here.

SANDAGE

In M 87 it is interesting that optically although the centre is exceedingly bright, it is not abnormal in the *U-B*. The *B-V* is about 1.1 and *U-B* is moderately normal, and that has always been very strange. So here's a case where you have a bright Seyfert-like optical appearance, but where the non-thermal radiation does not dominate as in Seyferts and N's.

MORGAN

I actually was using M 87 as a standard, because Dr. HEESCHEN remarked in a private conversation that it has a "normal" radio spectrum.

KELLERMANN

I should clarify the radio situation. It is certainly true that 99% of the radio emission from M 87 has a normal spectrum. It happens that the small high frequency flat-spectrum object is buried in this more extended source. By itself it is no different from the other objects which you have discussed, where the small object exists alone.

MCCREA

I'd like to ask Dr. MORGAN about the spiral he showed in which there were multiple condensations in what seemed to be the nuclear region and I'd like to ask him what the condensations are and whether there are other examples as well.

MORGAN

I can answer the second part. There are other instances, for example, NGC 1808.

E. M. BURBIDGE

Yes, we have spectra of NGC 1808. We studied that galaxy for rotation and came to the conclusion that those hot-spots really seem to be H II regions, and there are some other galaxies whose nuclei are like that, with hot spots, that appear to be H II regions containing OB stars.

MORGAN

Are all the hot-spots H II regions?

E. M. BURBIDGE

Well, the emission line intensities, relative intensities, seem to fit with that. Recently BERTOLA told me he had some other spectra along the minor axis and found some rather strange velocity gradients in that direction. I think it is an active nucleus.

AMBARTSUMIAN

Apparently this is true for hot spots only, but not for the nuclear condensation. Probably the spectrum of the nucleus is different from the other condensations.

E. M. BURBIDGE

The very central knot: on our spectra it was very hard to disentangle that from the surrounding knots.

MORGAN

May I ask Dr. SANDAGE if he has information with high resolution on the nuclear region of NGC 1808?

SANDAGE

Only that the hot spots are there. I believe that spectra by ARP and BERTOLA indicate to them that matter has been ejected along the minor axis.

LYNDEN-BELL

I've read somewhere in SERSIC's work that active nuclei come more commonly in systems with some sort of bar structure, that is in DE VAUCOULEURS' types SB or SAB rather than type SA. Is there, in your opinion, real truth in this or is it largely a matter of observational selection still?

E. M. BURBIDGE

I think may be SERSIC was referring to these two southern galaxies NGC 1365 and 1097. He drew attention to the strange blobby structure in a ring in the nucleus of NGC 1097 and it turns out to have emission lines which again look like H II regions. But here there is a central nucleus which can be clearly distinguished and which has a stellar population, I believe. NGC 1365 does not have such a central stellar nucleus; its whole nuclear region is bright and has strong emission lines with velocity gradients that indicate non-circular velocities.

MORGAN

There is at least one bright barred spiral having a nucleus with hotspots.

THE STELLAR CONTENT AND EVOLUTION OF GALAXY NUCLEI

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I. Nuclear m/l Values

Before beginning the discussion of the present stellar content of galaxies, and especially their nuclei, I wish to discuss briefly the current status of the dynamic M/L ratios applicable to the galaxies discussed here. In particular I would like to emphasize the few available *nuclear* M/L values which we can compare to the purely stellar population models at the end of my talk.

A classic approach used for E galaxies and the centers of big spirals, the virial theorem, coupled with an assumption on the random directions of star motions near the centers, lead Poveda (1961), Minkowski (1962), Burbidge, Burbidge and Fish (1961) and Brandt and Roosen (1969) *to total mass determinations*, and when photometry was available, M/L ratios, which apply to the whole body of an E galaxy or to the amorphous central bulge of an Sb. The analysis ignores possible circular motions due to rotation.

On the other hand, if we have a system with small central velocity dispersion and a well-determined rotation cnrve (true in some Sc galaxies) we can assume circular motions to be dominant; total M/L values for a large number of spirals have been determined optically by the BURBIDGES and their collaborators (c.f. BURBIDGE and BURBIDGE 1970 and RUBIN and FORD 1970) while radio astronomers, notably ROBERTS (1969), have employed the 21-cm H line as a rotation measure which can lead to total galaxy masses. However, if in the central parts of an Sb galaxy like M 31 say, $\sigma^2 > v^2_c$, then use of circular motions and an ordinary rotation curve will greatly underestimate the internal mass. The "pressure term" [BURBIDGE, BURBIDGE, and PRENDERGAST (1959)] cannot be ignored. This omission is typified by LALLEMAND, DUCHESNE, and WALKER'S (1960) work on the very center of the Andromeda spiral. Their M/L ratio is probably at least a factor of 5 too low!

Another way to obtain total masses is through the statistical attack on radial velocities of galaxy pairs; when PAGE'S (1962) total M/L values are corrected to $H_0 = 75$ km sec^{-1} Mpc^{-1} and expressed in terms of *V* light, we find for the pure E galaxies, $\overline{(M/L)}_v = 52 \pm 35$. The pure spirals in PAGE'S sample have *total* $\overline{(M/L)}_v \simeq 2$ under these assumptions.

The most relevant new computations — and the ones which really should apply to the discussions in this conference — are new work done in Berkeley by KING and MINKOWSKI (1970). The basic formula is:

$$(1) \qquad (M/L)_c = \frac{0.105\sigma^2}{f_o\, r_c\, d} \, (*) \; ;$$

it yields a nuclear M/L, after corrections for seeing and a flattening factor are made. Then a rather uncertain correction for galactic absorption must also be attempted.

They use this self-contained analysis of a small central region without recourse to the implied assumptions of uniform

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(*) Where, σ = vel. disp. (km/s); d = distance in Mpc; f_0 is central surface brightness, and r_c = core radius.

mass and light distribution, which is inherent to the virial theorem technique. The observational data are MINKOWSKI'S velocity dispersions and new central photometry for 18 elliptical galaxies, 2 SO's and 2 Sb's. KING and MINKOWSKI arrive at three general results:

a) There is no clear difference in M/L between the centers of E and So and Sb galaxies.

b) Systems with M_v fainter than - 19 have lower M/L.

c) For luminous galaxies there is no $(M/L)_c$ correlation with M_v.

M/L values from 15 - 40 for their giant galaxies probably represent a real range.

In summary, the nuclei of luminous Sb and E galaxies *always* seem to have $(M/L)_v > (M/L)$ near the sun ($\backsimeq 2$) and *never* seem to be as high as 90 or 100. The inner portion of M 31 is the same as the big E galaxies.

II. GALAXY SYNTHESIS — STARTING POINTS

Together with Dr. B. J. TAYLOR, I have been attempting to synthesize the spectra of galaxy nuclei with groups of relatively nearby stars.

Photoelectric scanner observations with 16 and 32 Å resolution on about 90 field and cluster stars, three kinds of globular clusters, and the nuclei of the galaxies M 31, M 32, M 81, NGC 4594 and NGC 3379 have been made at Lick Observatory with the objective of synthesizing model galaxies from stars observed locally.

The models presented here employ up to 30 groups of stars, each with $\geqslant 1$ star representing different segments of the H-R diagram, to represent the galaxy scanner spectra at 36 independent wavelengths from λ3300 in the ultraviolet to λ10700 in the near-infrared. Both lines and continua are included. The spectral features measured, in both stars and galaxies, include three TiO bands, three CN bands, one weak CaH band, the D-lines of NaI, the MgI 'b' triplet, CaI λ4227, CaII λ8662, NaI λ8190 doublet, the G-band of CH plus the hydrogen lines Hα, Hγ, and Hδ.

The galaxies selected were chosen to be as nearly normal as possible; in the context of this *Semaine* they are a "silent majority". We tried to exclude nuclei with obxious non-stellar continua, strong emission lines and those with obvious large tracts of dust. The original screening was only partly successful; our lack of complete success in synthesizing the center of M 81 (with WADE'S small radio source, and considerable optical emission) may be blamed on this fact. The discussion here centers mainly on M 31, M 32, M 81 and to some degree on NGC 3115, 3379 and 4594 and 5194. Scans are complete for only the first three nuclei.

An important problem is the selection of the nearby stars for use in the synthesis. The range of spectral types represented is broad; main sequence O9 to M8, subgiants G0 - K2, giants G8 - M8. A dense grid in the H-R diagram was observed for stars cooler than the sun. As mentioned before (SPINRAD 1966) Super-Metal-Rich (SMR) stars — individual strong line giants and dwarfs — have been scanned [see SPINRAD and TAYLOR (1969)]. They are used in distinct metal-rich star groups — alternatives for normal giants. Not enough SMR dwarfs are known, so the procedure for G0 - M8V stars was to use the strongest line stars found, thus just enriching the mean metallicity of the m.s. stars. Opening up a third parameter is an important result but leads to different operational strategy — where does one stop observing SMR stars? We return to this topic later.

Metal-poor stars are also available for inclusion in the synthesis, when necessary. These were represented by three metal-abundance levels of halo galactic nuclear globular clusters: *a*) M 15 + M 92; *b*) M 3 + M 5; and *c*) NGC 6356.

III. The Astrophysical Constraints on the Galaxy Models

A few model-building constraints are imposed from current astrophysical opinion; they are in order of importance in practice. We demand that there be:

1) Continuity of the main sequence,

2) Evolved giants follow tracks consistent with those suggested for galactic clusters,

3) Any Hα emission ought to be consistent with the number of O-B stars, and

4) That only one generation of star formation be considered.

The continuity condition is probably the only important constraint; we do not permit large gaps in the main sequence.

IV. Rules for Goodness of Fit and Model Building (Operationally)

We have used the following "rules of matching" for deciding about the goodness-of-fit for our galaxy population models; these guide lines are rather like those suggested by D. B. Wood (1966).

a) First we match with the galaxy continuum colors — hopefully from λ3300 - λ10700 or to K (2.2μ) and L (3.4μ).

b) Match the line pseudo-equivalent widths (w's). The lines from F-G and perhaps early K stars are given highest weight at $\lambda < 4500$A in cases where arbitrary decisions must be made; conversely the very late stellar type spectral features (TiO bands) are most important in the infrared.

The CN bands ($\lambda 3880$, $\lambda 4200$, $\lambda 9200$) are sentive to abundance and are a positive luminosity discriminant. The MgI + + MgH blend ($\lambda 5175$) is somewhat abundance-sensitive and is the strongest negative luminosity discriminant in the visible spectrum. The D-lines are likewise strongest in late K dwarfs, and have considerable abundance-sensitivity (SPINRAD and TAYLOR 1969) (hereafter abbreviated ST).

V. RESULTS FOR THE BEST MODELS OF M 31

We have scanned the M 31 nucleus with a 10″ diaphragm at the 120-inch reflector at Lick; this entrance hole corresponds to a linear radius of 15 pc at M 31's distance, so the spherical volume element is about 1.4×10^4 pc^3, a tiny volume compared to the entire amorphous M 31 nuclear bulge.

The M 31 scan is rather precise [errors about 1% at the ST (1969) wavelengths]; it has been corrected for a galactic reddening of $E\,(B\text{-}V) = 0.^{m}11$. We note that the M 31 *line* spectrum is clearly composite; Hδ is present with a strength comparable to about a G6V star, CN and CaI absorptions resemble K stars and the red TiO bands are as strong as those in early M stars. The infrared TiO band suggests a contribution by stars later than M3. The curvature of the continuum is also indicative of a quite composite source. The complexity of the integrated galaxy spectrum is one reason to attempt model-building comparisons for solution of the stellar content of M 31's center.

A major thrust of this paper is to compare the goodness-of-fit of different population models for M 31. We pass over the solar vicinity van Rhijn luminosity function quickly — it has far too much hot young star light, giving a model with far too much ultraviolet and blue light and too strong Balmer lines compared to the M 31 nucleus. This result is, of course, consistent with MORGAN'S (1960) equivalent blue region spectral type of about F0 for the solar neighborhood.

Other M 31 models we consider in more detail have been based upon old stellar groups usually modeled after the moderately old galactic cluster M 67 (c.f. MORGAN and MAYALL 1957, BAUM 1959, WOOD 1966). The previous workers in this field have all found a reasonably good color match with their old star group models and M 31 and giant E galaxies; here we ask an important question — need a good color match over a long λ baseline insure a model galaxy which has appropriate absorption line strengths?

Unfortunately the answer is negative. The non-uniqueness of galaxy models based upon broad-band colors alone has been recognized before (SPINRAD 1962); for example, SPINRAD (1966) has computed line indices for a color-match model suggested by JOHNSON (1966). This was an extreme case, with broad-band colors moderately well satisfied from 0.36μ to 3.4μ, but with very different stellar line indices in the model and the real galaxy (M 31 nucleus again).

The degree of uniqueness achieved in model-fitting depends upon the sharpness of the empirical criteria; that is, the stellar-mix discrimination possible with the available *line* and *continuum* intensities and, naturally, the precision of the galaxy intensity data. Looking ahead somewhat we consider the galaxy models chosen here to be close to unique as far as the general representation of nearby stars to simulate the M 31 nuclear mix is concerned. And our limits against certain types of very red or blue objects are quite strong. But with the approximate 1% observational uncertainty at most λ's we can say little about contributions by any star groups giving $< 1\%$ of the total M 31 nuclear light at most wavelengths. Our hold on the proportion of stars with colors roughly like the M 31 center itself is weakest.

One of the purposes of this paper is to discuss the inadequacies of previous M 31 population models based upon less complete spectroscopic evidence. The usual clarity of hindsight which we express here suffices to show the limitations of models based upon spectra taken over a very limited λ range; we do not wish to denigrate some of these pioneering efforts which provided early stimulus to this field, but they now can be considered improved upon.

We discuss first the MORGAN and MAYALL (1957) giant model. MORGAN and MAYALL suggested that normal-abundance CN giants (G8 - K3III) contributed most of the blue light to the M 31 center and dominated other *k*-nuclei. Their schematic H-R diagram indicated that M giant stars were major red and near-IR contributors. Contribution from an old main sequence (G - M) was minimal.

We have computed several MORGAN and MAYALL type models, using our own proportions of stars in the subgiant and giant branches of an M 67 type array to satisfy the continuum colors of the M 31 nucleus. The main sequence is present with a G0V turnoff position and an approximate van Rhijn luminosity function — it provides only a tiny fraction of the visible or even infrared light in this model.

These giant-dominated models are slightly weaker-lined than the M 31 center in the blue (including blue CN also), and fail badly to match the large MgI and NaI line strengths in the yellow-green. Their worst and telling fault is found at $\lambda > 7000$Å. Here we cannot match continua intensities and line indices simultaneously. If the continua to $\lambda = 3.4\mu$ were matched fairly well by adding red stars, we find the model has a λ7100 TiO index too weak and NaI index strong in apparent "emission" — caused by TiO and VO blanketing at the surrounding wavelengths. This large residual is caused by having 23% of the λ8190 flux contributed by *M giants* in the giant-dominated models. If we attempt to fit the red and IR TiO we arrive at a model with even more sodium "emission" and a continuum which is far too red. If we attempt to fit the subordinate λ8190 NaI lines, with no regard to TiO band matching, our model continua intensities at $\lambda > 9000$Å are far too weak — down by 14% at λ8800, 24.5% at λ10700 and by about $0\overset{m}{.}56$ at L band (3.4μ). This disastrous situation is typical of M giant IR contributory models. The M/L for these models are about 3.0 to 3.5 — depending upon whether some number of white dwarfs (wdA) are added.

The inclusion of SMR giants (ST 1969) in place of normal ones helps the blue and green region indices somewhat — although the metallic lines are still stronger in the real galaxy nucleus than the enriched M + M models. However, the IR discrepancy will remain — to get the model continua sufficiently red one requires M4 - M6III stars which have strong apparent "emission" at the λ8190 Na lines (see Figure 4 in SPINRAD 1966). We would expect this situation to continue even if the SMR giant metal abundances were increased by a factor of ten, if all the metals were raised in phase.

More specific but similar models based upon stellar contributions computed by ELLIOTT MOORE (1968) seem to have the same general drawbacks as the M + M models (see Figures 1 and 2). MOORE used measured equivalent widths in the blue region to constrain his galaxy population mixes and developed models based upon the shapes of the "tracks" of the old galactic clusters M 67 and NGC 188. We find MOORE'S models red star deficient — i.e., they are deficient in red and infrared light. The IR intensity residuals are very great at $\lambda > 9000$Å. Such a problem is not to be unexpected as studies of details in the blue ($\lambda < 4500$Å) are not likely to yield accurate data on M stars. Addition of M giants as implied by MOORE creates

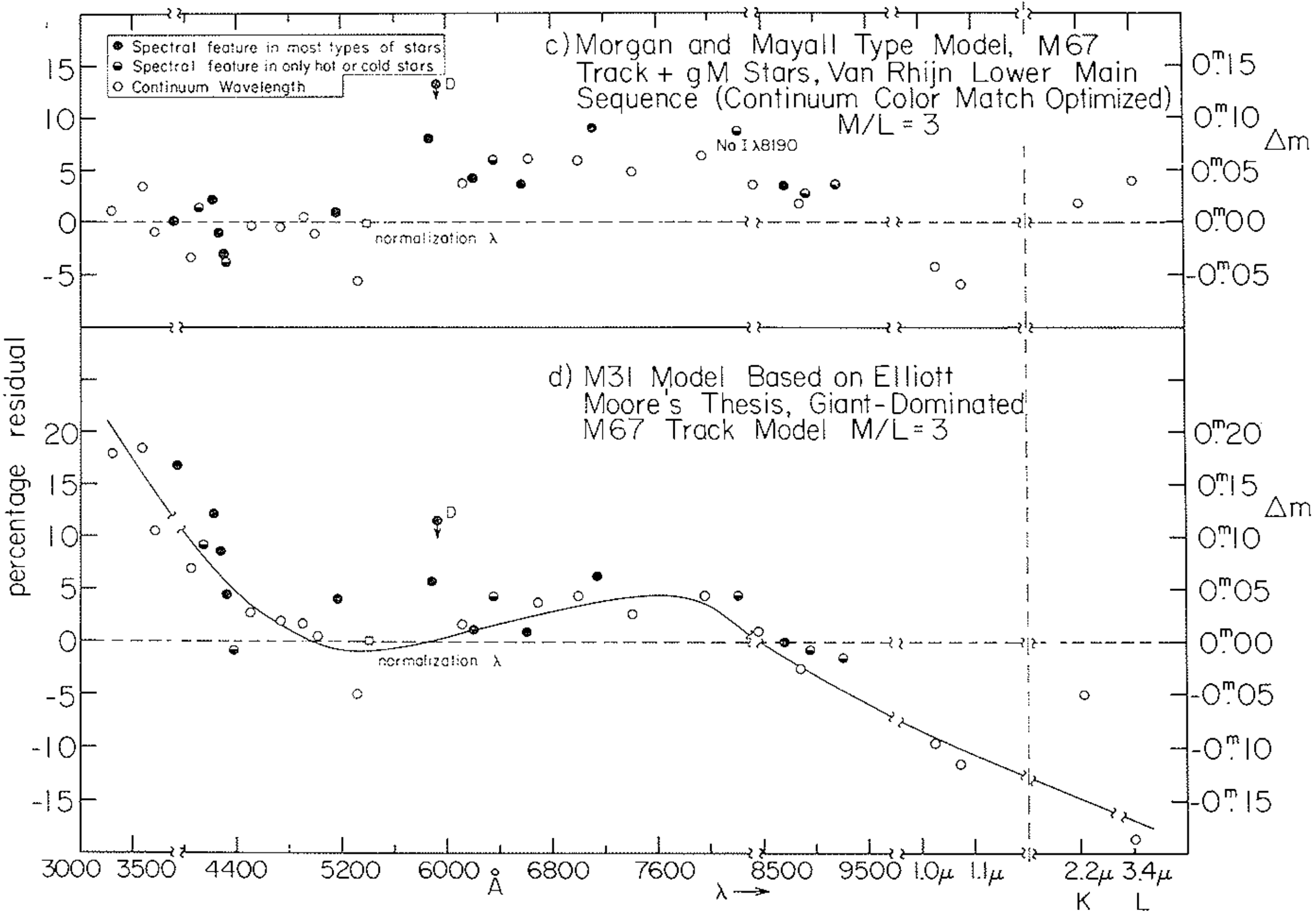


FIG. 1 (above) — A residual diagram for a galaxy model based upon the MORGAN and MAYALL (1957) concept of an M 67 giant branch plus van Rhijn lower main sequence. Plotted is the M 31 intensity residual, $R(\lambda) = \dfrac{\text{model - observed nucleus}}{\text{observed galaxy}}$ as a function of wavelength from the ultraviolet to the 3μ infrared. λ5360 is always the normalization wavelength at which $R(\lambda) = 0.00$. The model chosen has been optimized to fit the galaxy continuum over the long baseline; note that the strong absorption lines (especially Na D, the NaI λ8190 doublet and the red TiO bands) fit quite poorly. The sense of the residuals in spectral features is positive for lines too weak in the model to match the real galaxy center. The arrow at D indicates the change in R(λ5893) for the expected 400mÅ interstellar absorption in our galaxy.

the NaI emission residual, as discussed previously. We find M/L = 3.1 for MOORE'S models, including wdA stars.

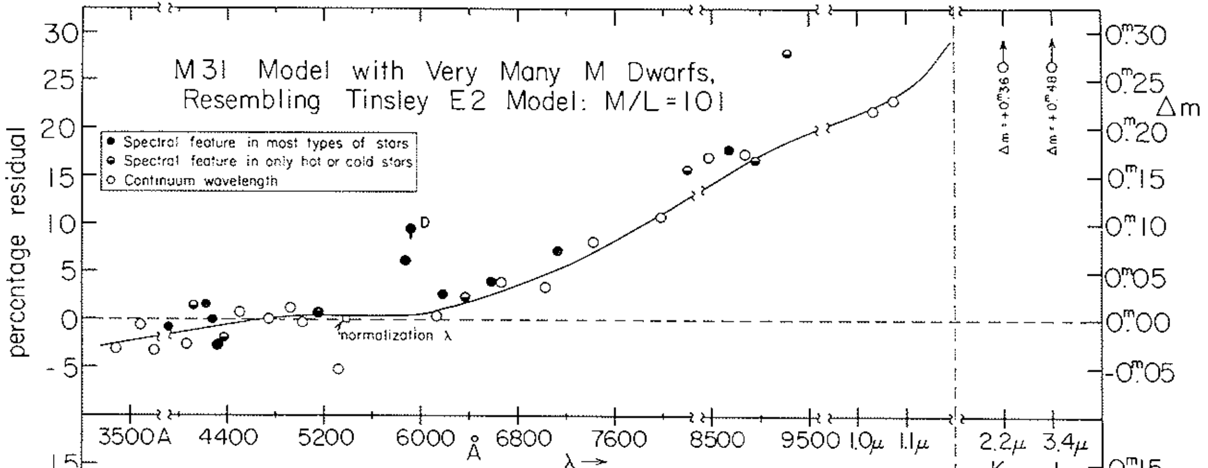
The galaxy models of DAVID WOOD (1966) are rather better approximations to M 31 on our system, for $\lambda < 7000$Å. With normal-abundance stars they have too weak lines of MgI and NaI and red TiO, but the continua match from $\lambda\lambda 3300 - 7000$ rather well. This is to be expected as WOOD'S observed continua were obtained with photoelectric precision. However, for $\lambda > 7000$ (not observed by WOOD) the residuals grow (see Figure 3); they reach 20% at $\lambda 10700$ and $0\overset{\mathrm{m}}{.}50$ at L (3.4μ). WOOD'S models are too blue — the real galaxy has more very late-type stars. Now this red-light deficiency in WOOD'S M 31 model prescription is indicative and causal to a more deep-seated discrepancy. WOOD'S model M/L ratios were consistently a factor of 3 lower than available *dynamic* M/L ratio estimates for his galaxies. We claim that this is a natural consequence of his lack of M7 and M8 dwarf stars, which we will later show are necessary to match the IR continua and lines and bring the M/L up dramatically. This point was also noted by TINSLEY (1968). However, her E2 model with very many M dwarfs and M/L = 100 is too red (see Figure 4).

Our best models, determined through trial and error experience, are relatively satisfactory. One is illustrated graphically in Figure 5, where again we plot intensity residuals, $R(\lambda)$ vs. λ. A similar plot can be made for any alternate solution, say one including hot stars (Figure 6).

The reader will note the following main characteristics of the acceptable model for M 31's nuclear stellar content:

a) A very dwarf-heavy luminosity function, with measurable light contributions all the way down to M8V (all the mass in late M dwarfs);

b) SMR stars employed when possible, all over the H-R diagram (SMR giants, "spiked" mixture of strong line and normal m.s. stars);



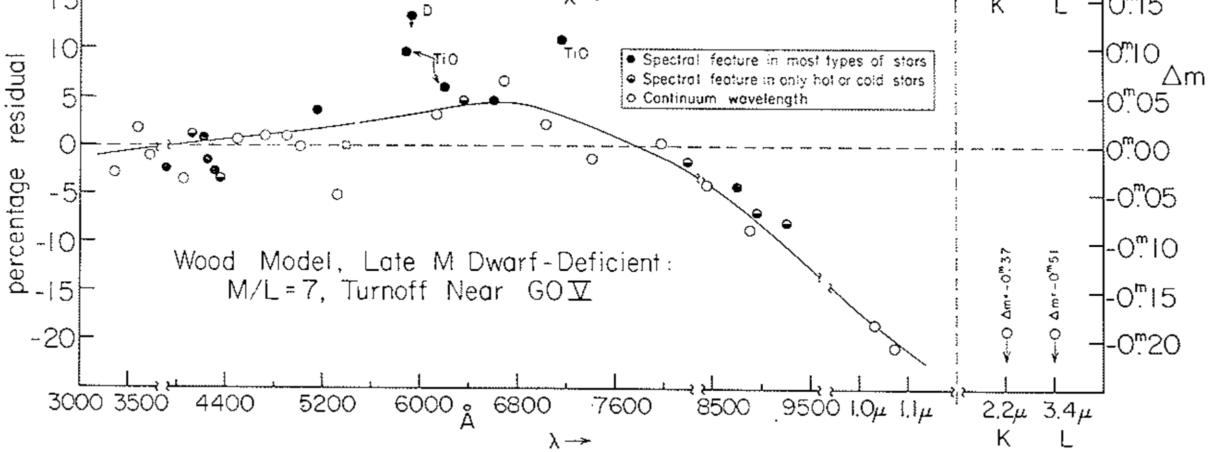


FIG. 3 (below) — The lower panel shows the R(λ) vs. λ diagram for a model suggested by D. B. WOOD (1966). Note the modestly good match for λ < 7600Å (WOOD's photometry stopped at λ7300) and the increasing run of residuals for λ > 8000Å. WOOD's model (with M/L = 7) is too blue in the IR — it has insufficient M dwarfs.

FIG. 4 (above) — The upper panel shows a very dwarf-rich, very red model — based upon TINSLEY's (1968) E2 model. The residuals become very large at λ > 6800Å; this model has far too many M dwarfs (note M/L = 101).

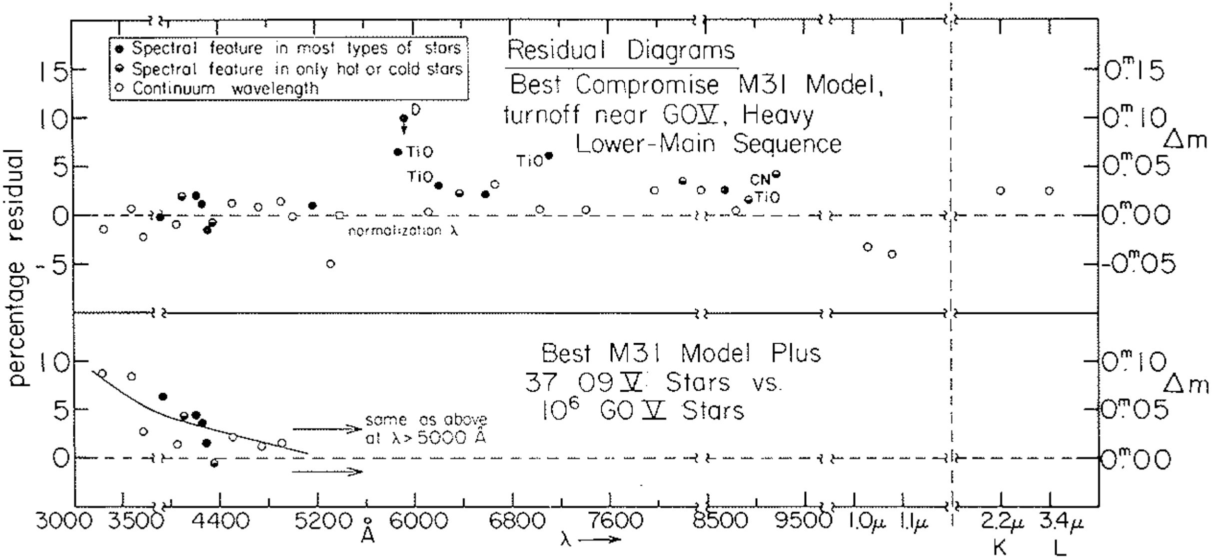


FIG. 5 (above) — The upper panel illustrates the best compromise M 31 model. This R (λ) vs. λ diagram still shows the strong lines in the model too weak compared to the real nucleus of M 31. Note especially the weakness of D, red TiO bands and the infrared CN bands at λ9200.

FIG. 6 (below) — The lower panel shows the best M 31 model (as in Fig. 5) with the addition of 37 O9V - B1V stars per 10^6 G0V (and $> 10^9$ M8V) stars. This small numerical addition affects the ultraviolet continuum of the model drastically; R(λ) goes to an unacceptable + 8% at λ3300Å! Such a model illustrates the excellent sensitivity of the procedure to a few anomalous ingredients.

c) A main-sequence turnoff near GoV;

d) A giant branch dying out at K5III (presumably a result of rapid time-scale for low-mass, high-luminosity evolutionary phases (c.f. IBEN 1967); and

e) A stellar M/L = 43.5, in approximate agreement with the dynamical M/L ratios of KINMAN (1965) and KING and MINKOWSKI (1970) for the very nucleus of M 31.

We shall now discuss the model characteristics in a detailed way, for they are probably typical of most large spiral galaxy nuclei, and also are very similar to the central region of giant E galaxies.

The large amount of dwarf-enrichment (compared to van Rhijn luminosity function) is striking. The necessity of matching both the red and IR colors and keeping w of NaI λ8190 $\geqslant$ $\geqslant$ 0.00 demands large numbers of K7 - M8V. It is here that a clear distinction between M dwarf and M giants may be made — c.f. SPINRAD (1966) Figure 4. The K dwarfs aid in reaching a closer match for NaI "D" and MgI 'b' lines in the yellow and green, respectively.

The main sequence (now *excluding* slightly evolved G subgiants) contributes 26% to λ5360 *V* light, 28% to λ4040 in the blue, and 46% at λ10700 and 54% to the 2.2λ (K-band) flux of M 31. The steepness of the model's luminosity function produces the very high stellar M/L, and leads to other consequences which we discuss later. However, our red scanner colors and the *V-K, V-L* colors exclude the possibility of galaxy model M/L > 80, if the stellar mass is in M dwarfs (see Figure 4 again). The M/L = 80 trials with the present M 31 model as a base-building block turn out to be far too red at λ > 1μ. There is no obvious distinction for λ < 8000Å, the usual region studied optically.

The need for super-metallicity (see ST 1969) in the stellar mix for M 31 can be seen most easily in the line w's of Table 2, which follows.

TABLE I — *Abbreviated Population Model for the Nucleus of M 31.*

Star Group Name	% *V* Light	% Total Mass
Late F dwarfs	0.99	0.02
Early GV	6.44	0.15
Late GV	4.26	0.22
K1 - K2V	4.26	0.25
K3V - K4V	3.17	0.28
K5V - K7V	1.49	0.47
M0V - M2V	1.19	1.09
M3V - M4V	1.19	3.90
M5V - M6V	1.19	12.70
M7V	0.99	13.65
M8V	0.50	66.92
Early G Subgiants	11.78	0.12
Late G Subgiants	9.60	0.10
SMR K0 - K1 IV	13.86	0.09
SMR K2III - IV	18.12	0.03
SMR K3III	16.04	0.02
SMR K4 - 5III	4.95	0.01
wdA	0.0	0.0
Later M Giants	0.0	0.0
Sum	100.00	100.00

TABLE 2 — *M 31 Galaxy and Best Fitting Model Line Strengths.*

Feature	w (M 31 Observed) $E(B-V) = 0.11$	w (Normal G) "Spiked" Dwarfs	w (SMR G) "Spiked" Dwarfs	Further Increase → Approximate Abundance Factor to Reach M 31
UV CN λ3880	+0.37	+0.36	+0.37	1.0
B1 CN λ4215	0.20	0.17	0.18	1.5 x ? in N
CaI λ4227	0.19	0.17	0.19	— 1.0
CH λ4300	0.29	0.31	0.31	—
MgI MgH λ5175	0.28	0.23	0.25	1.1x
D-NaI λ5893	0.13* (0.12)	0.08	0.10	1.4x
TiO λ6180	0.05	0.03	0.03	3x
TiO λ7100	0.11	0.06	0.06	3x
NaI λ8190	0.01	0.00	0.00	—
CaII λ8662	0.10	0.08	0.09	1.5 in Ca
TiO λ8900	0.03	+0.03	+0.02	
IR CN λ9200	+0.05	—0.01	+0.00	3x ? in N

(*) Corrected for $W_\lambda = 0.3Å$ galactic interstellar D.

In other words, we may obtain the same red colors for the model galaxy, and nearly the same blue colors, with stars of different line strength. Yet we do not quite achieve M 31 line and band intensities, especially in red CN and TiO. As is often the case, we can learn much from the deficiency of a computed model. From observations of individual galactic stars we can assure ourselves of the reality of *galactic examples* of old stars with extraordinary strong lines. With particular relevance to the TiO deficiency of our models we list in Table 3 below some examples of TiO-strong, K giant stars in old galactic clusters. Normal K giants show detectable TiO in our scanner bands if their types are cooler than about K4III ($T > 540$). The notation is that of ST (1969). One bright field example is ν Peg, K4III.

TABLE 3 — *Strong TiO in Old Galactic Cluster K Giants.*

Star	*V*	T_0*	Equiv. Sp. Type	Σ w (TiO)	Normal Σ w (TiO) for color
M 67, M1465 **	8.9	616	K5.5III	0.24	0.16
M 67, M793 **	9	547	K4III	0.08	0.06
NGC 188, III-18	9	566	K4III	0.14	0.09
NGC 6791, No. 1	13.7	540	K4III	0.25	0.05
NGC 6791 No. 3	14	519	K3.5III	0.11	0.03

(*) With the following cluster color excesses: M 67, $E = 0.^m06$; NGC 188, $E = 0.^m10$; NGC 6791, $E = 0.^m22$.

(**) MURRAY, C.A. (1967, unpublished) and MURRAY, C.A., and CLEMENTS, E.D. (1968, *Royal Obs. Bull.* 139).

If we could obtain scans at all wavelengths for these faint stars they could be included in the appropriate synthesis SMR groups. Unfortunately, only the M 67 giants are within range for the difficult wavelengths at $\lambda < 4000$Å and, more importantly, $\lambda > 9000$Å with the S-1 photomultiplier.

So actually achieving the great M 31 TiO bands strength with relatively hot stars (K3III) of high abundance is possible in principle — but extremely impractical with the amount of 120-inch observing time available. The increase in metallicity of the SMR M 31 nucleus over the average star near the sun is probably of the order of a factor of six!

The improvement (increase) of 0.05 in w(IR CN λ9200) may be more difficult. We already have used rather strong line giants from the field in the late SMR giant groups of this synthesis. However, at λ9200, 31% of the model's light originates in *M dwarfs* and here our selection of stars with strong lines and relatively strong CN bands is probably inadequate. The total number of M dwarfs observed completely to date is not very large and the abundance-selection criteria for M dwarfs are only beginning to be understood. We may have about solar or slightly above solar abundances for the Mo - M8V stars so far observed — a few metal-poor stars having been already removed from the groups. If the lower main sequences of M 67 and NGC 188 could be observed to M8V (a quite impossible task) and included in this synthesis they would likely strengthen the IR CN index. A more realistic hope might be the dwarf M companion of ρ'Cnc A [a SMR dwarf studied by TAYLOR (1970) and GREENSTEIN and OINAS (1968)]. An important desideratum for the future will be a search for and an examination of individual M dwarfs with atypically strong lines. Probably such a major effort would improve the λ9200 CN residual in these models.

We note that the CN strengths in the blue which suggested giant branch domination to MORGAN and MAYALL (1957) are best explained both by CN-rich *giants* and strong line *dwarfs*; otherwise we get the correct CN strength with luminous stars whose damping lines of MgI and NaI, etc. are much too weak. This conclusions was also reached by MCCLURE and VAN DEN BERGH (1968). To summarize, the degree of super-metallicity in the M 31 nucleus is known with low precision, but perhaps would be at about twice the level of our SMR models, or at about $[M/H]_{\odot} \simeq + 0.8$. MCCLURE (1969) and SPINRAD, GUNN, TAYLOR, MCCLURE and YOUNG (1970) have found that the M 31 metal-abundance decreases rapidly outwards from the semi-stellar nucleus. This is especially noticeable in the blue λ4200 band, which decreases by some 5-7 times over the first inner kpc of M 31. In fact, our 10″ entrance aperture at Lick might even have a small dilution effect on the abundances of the stars in the innermost region (say of radius 5 pc). A contribution by BAADE'S Population II stars may become noticeable at $r \simeq 3'$ from the center (some 600 pc on the major axis); implicit in our battle to attain M 31 superline strengths with our nuclear models is the statement that classic metal-poor Population II stars contribute very little to the integrated spectrum at $r < 3'$. At the nucleus they must be near zero in their V light contribution.

V. THE SPECTRAL TYPE AND AGE OF THE MAIN SEQUENCE TURNOFF STARS IN M 31

Our models fit best at $\lambda < 4500$ with no stars at all hotter than a few late F dwarfs, and very few earlier than G0 - G2V. It might be thought that horizontal branch O9V's would be hard to distinguish from G0V in the near *UV*; however, the extension to λ3300 provides enough baseline to give us a continuum shape difference between these alternatives. OAO continua observations to λ2000 would be even better, *if* they could be secured with a very small entrance diaphragm to isolate the M 31 nucleus. A hypothetical 1% V light contribution by O stars gives a peculiar tilt to near-*UV* continua (see Figure 6); moreover, the lack of noticeable Hα emission at the very center of M 31 would tend to rule out the presence of many hot O-type horizontal branch stars or a few O9V main-sequence stars. The argument is valid and strong unless there is now low density gas there — however, the presence of [OII] λ3727 emission lines almost to the very center (MÜNCH 1959) of M 31 would argue for at least a little gas, presumably in the form of H II.

Trial M 31 models attempted with turnoff at middle or late GV were clearly too red, as these require the deletion of early G IV's also, from our astrophysical constraints. Evolved stars are assumed to be at the same or lower Te in their immediate post-main-sequence phases. Our conclusion for this statement is contingent upon the assumed M 31 galactic reddening ($E = 0.11$) to be approximately correct. In summary, a G0 - G2V turnoff seems appropriate for M 31 center.

The age or a single generation coeval-birth group of stars of normal abundance and G0V turnoff is about 10×10^9 years. However, if extreme "SMR-ness" prevails, as we suggest, then the chronological age of the stars is decreased to about the revised NGC 188 age — some 4×10^9 years (c.f. AIZENMANN, DEMARQUE and MILLER 1969, S. PEIMBERT 1969). Thus there is little doubt that the *nucleus* of M 31 is really quite young! That is, star formation has continued until about 4 billion years ago. The M 31 disk may be much older — it has approximately the same turnoff and solar abundances (at approximately 200 pc S of the M 31 center) (SPINRAD *et. al.* 1970).

A possible explanation for the apparently relatively young SMR stars at the nucleus of M 31 may be the tendency for gas liberated by evolving stars or stellar collisions in the M 31 disk to collapse toward the center and form highly concentrated younger generations of high angular momentum at the very nucleus. Whether conventional stellar evolution and mass loss from normal-abundance disk stars would produce any supermetallicity is in some doubt (ST 1969). We are indebted to discussion with Drs. KING and SASLAW on the subject (and see paper by SPITZER in this volume).

VII. MODELS FOR THE NUCLEUS OF THE DWARF E2 SYSTEM M 32

M 32 observations are first-class data like the M 31 scans. We have used again $E_{B-V} = 0^m.11$ to remove galactic reddening in front of M 32. Also, 0.01 of w(D) may be considered as interstellar in our own galaxy.

The scanner spectrum of M 32 is distinctly different from the M 31 scans. M 32 doesn't have very strong metallic absorption lines. It is also rather bluer than M 31. M 32 also has noticeably stronger Hγ and Hδ lines than does the M 31 core, so the question might be raised — does M 32 have an earlier equivalent spectral type because of an F5V main sequence turnoff point, or could it be metal-poor and partially simulate the integrated characteristics of weak-line globular cluster (c.f. MORGAN 1956)? The latter alternative has been suggested by McCLURE and VAN DEN BERGH (1968). We try to answer the question by model making and adjustment and comparison. The choice here becomes rather difficult. Passing to longer λ in the scans we note that M 32 is composite; the TiO at λ7054 is visible —insuring some red contribution by M stars. The IR NaI λ8190 w is negative, so there is no obvious *a priori* demand for many middle and late M dwarfs, as necessary for M 31. However, many red stars are needed as the λ10700 intensity is not very much lower than found for the M 31 nucleus. *V-K* and *V-L* would be extremely useful additional future data!!

We have tried a number of models to fit the M 32 population; these are basically of two types — a younger stellar system with a F5V turnoff position, normal abundance giants (and dwarfs) and, as an alternative, a moderately metal-poor globular cluster base (usually NGC 6356, sometimes M3 + M5) plus an old galactic cluster track resembling M 67 or NGC 188 in character. The M dwarf and M giant ratio continues to be set by the intensities of infrared continuum colors, w(TiO) and w(NaI λ8190). Table 4 below summarizes the results of these trials.

TABLE 4 — *M 32 Model Descriptions.*

Model Description Name	(M/L)	Good Points	Possible Weaknesses
a) NGC 6356 base, $V = 34\%$ Normal Giant Stars, Turnoff G0V; Some M3 + M5 contribution, $V = 12\%$	6	Best continuum fit, lines also are reasonably matched.	Large range in stellar abundances in center M3 → normal [Fe/H] No Hα emission from M3 hot stars-possibly some expected.
Rather few late dwarfs		Low M/L fits KING and MINKOWSKI dynamics.	
b) Turnoff at F5V SMR giants, 6356 = 38%	7	Continuum *fairly good*, lines fair, IR indices excellent match.	SMR stars and metal-poor big range. Very young gp - F5V, SMR $\tau \leqslant 1 \times 10^9$ years, SMR makes Na, Mg too strong.
c) 6356 = 26% Normal Giants, some M8V's.	$\leqslant 20$	M/L $\leqslant 20$ if M8V $\leqslant 0.4\%$ V.	Only useful in setting crude upper limit to stellar M/L. Infrared continuum too red.
d) 6356 = 26% V F5V, early turnoff = 9% V. Normal abundance giants.	7	Good IR indices. Only small abundance range.	Only fair continuum match. Still rather young stars, $\tau \backsim 3 \times \times 10^9$ years.

The first model, which employs weak-line stars from NGC 6356, M3 + M5, and normal giant stars, without great dwarf enrichment, fits best, but it is only slightly better than the others. There is no need for SMR stars in these models; model *b* is worse for including them! The only decision one might wish to make astrophysically — on better theoretical grounds than we can now offer — would be a choice based upon stellar "age" at the nucleus. Really what is meant here is the epoch of last burst of star formation. If that might have been as recent as 3 billion years ago — and we see no way to outlaw this — then model (*d*) is only a slightly worse fit to M 32 observations than is (*a*), our first choice. Clearly the models are not as unique as we would like in the case of M 32.

VIII. SOME CRUDE INFORMATION ON THE STELLAR CONTENT OF SC NUCLEI

Sc galaxies often have early type spectra (HUMASON 1936, HUMASON, MAYALL and SANDAGE 1956, MORGAN and MAYALL 1957); our partially complete scans of NGC 5194 and NGC 2903 show a blue continuum in each case with Hδ and Hγ (corrected for weak emission in NGC 5194) strong in absorption. TIFFT'S (1963) photometry is quite consistent with ours. A rough model for NGC 5194 suggests an extended main sequence gap up into the late B stars in 5194 and perhaps to B0V in NGC 2903. Late-type stars are also needed in NGC 5194 — the spectrum is quite composite. However, the requisite data on the infrared spectra of these galaxies has not yet been obtained, so that no strong decisions on the lower main sequence are possible at this time.

IX. EVOLUTIONARY CHANGES IN THE BRIGHTNESS OF A MODEL E OR SB GALAXY

SANDAGE (1962, 1968), TINSLEY (1968, 1970), and others have computed the evolution of the integrated brightness of a model giant galaxy over some 4 billion years time. This is approximately the look-back time to the distant cluster containing 3C 295 at $z = 0.46$. We could use our nuclear M 31 model as typical of the centers of a big Sb and Sa and probably giant E Systems. However, when we observe a galaxy at a great distance, the actual photometry involves almost the whole galaxy — not just the central region. This leads to a problem of integration; the nuclear models are too metal-rich for the integral galaxy, and little is known about the stellar content of the halo of giant E systems (c.f. DE VAUCOULEURS 1969).

A compromise solution, using a model for the M 31 disk (SPINRAD, GUNN, TAYLOR, MCCLURE and YOUNG 1970) gives a very small evolutionary correction: $dL/dt = 0\overset{m}{.}00 \pm 0\overset{m}{.}03$ per 10^9 years (up to 4×10^9 years in the past). This is true because of a fortunate counterplay of two factors as we look back in time to the models, when they were younger. We note that:

a) The steep m.s. luminosity function of the models yields *fewer giants* resulting from their earlier main sequence progenitors;

b) The turnoff point stars, subgiants, and giants are brighter at a given color, this earlier stage; and

c) The lower unevolving main sequence, accounting for some 30% of the *V* light, is unchanged.

The lack of a large luminosity correction was computed for the present *V* wavelength; at emitted *B* band there may be a modest correction, but it is really negligible for the present epoch of faint galaxy photometry. However, it is likely that observations in *R* band (referring to emitted *V* light in a distant source) would be the easiest ones to interpret. If we eventually measure distant galaxies at $z \geqslant 0.6$, the simple extrapolations discussed here will require improvement.

X. OTHER PROPERTIES OF THE MODELS: GAS GENERATED BY "STAR DEATHS"

Following a computation by Mr. WILLIAM BROWN, I have computed the mass of stellar matter lost to the interstellar medium as red giants of present representative turnoff point masses ($\sim 1.2\ M_\odot$ in our current day models) evolve to white dwarfs of mass $0.6\ M_\odot$. No physical discussion or justification is in order here; the computation obviously relies on the "standard" theory of mass loss in evolving stars. The fractional mass generated by star deaths in this way will depend upon the ratio of evolving stars to unevolved stars — and will be much lower in our best M 31 model than in the solar vicinity. The equation used is:

$$\mathrm{M}_{gas} = \sum_{M_v = +17}^{-4} \mathrm{M}\ (M_v)\ \Psi_0\ (M_v)\ .$$

Note that the lower limit to the luminosity integral now goes all the way down to smallest mass stars — including many stars which do not appreciably evolve in 10^{10} years.

Conceptually, the ratio $\mathrm{M}_{gas}/\mathrm{M}$ computed in this way is very dependent on the initial stellar luminosity function; if the $\Psi_0\ (M_v)$ is very dwarf-heavy, the gas ejected will be only a tiny fraction of the total mass. BROWN has computed this ratio as a function of the shape of Ψ_0; he finds the SALPETER initial luminosity (SALPETER 1955) yields a large gas fraction — $\mathrm{M}_{gas}/\mathrm{M} \cong 1/3$, while using SPINRAD's (1966) now dated but very dwarf-rich function for Ψ, he obtained a ratio of 3×10^{-4}. We have computed the ratio for the best M 31 model; $\mathrm{M}_{gas}/\mathrm{M} \cong 10^{-3}$ with an uncertainty of at least a factor of three due to the necessary extrapolation to masses above 1.3 $M_\odot$. White dwarfs would only amount to 10^{-3} M_{total} in this exercise. These computations are schematic, but indicate a way in which a little gas may be found in "dead" galaxy centers — we note that the giant E galaxy NGC 4472 may have neutral H in the ratio $M_{HI}/M_{total} = 2 \times 10^{-4}$ (ROBINSON and KOEHLER 1965).

XI. CORRELATION OF GALAXY NUCLEAR SPECTRAL FEATURES AND ABSOLUTE MAGNITUDE

Finally we mention that the strength of some absorption lines and bands in the spectra of galaxy nuclei seems to correlate fairly well with the integrated magnitude *of the whole system*.

M_v of E and So galaxies correlates with the DDO system CN band measure C (41-42), as observed by Mc CLURE and VAN DEN BERGH (1968). The CN is considerably stronger in the giant E's ($M_v < -20$) than in dwarf galaxies like M 32 and NGC 205. SPINRAD and TAYLOR'S scans confirm this. M_v also nearly correlates fairly well with Q (McCLURE and VAN DEN BERGH 1968) and rather well with the sodium D lines (unpublished scans by SPINRAD, and SPINRAD 1962, DEUTSCH 1964).

These correlations imply to me a chemical composition difference between the centers of big E, SO and Sa-Sb system compared to the smaller galaxies of these morphological classes. Why the little ones have been inefficient in metal production is not clear — perhaps the small absolute amount of gas processed and falling to the center in dwarf systems is the key.

In conclusion, although the *normal* galaxy nuclei are relatively inactive by definition, it may be necessary to understand their stellar content if the active phases are side products of normal galaxy evolution — as stressed by some of the speakers in this *Semaine*.

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DISCUSSION

Chairman: W. W. MORGAN

SANDAGE

May I ask what the sensitivity of your model continuum energy distribution is to slight changes in the ingredients? That is, what can you allow the turnoff luminosity difference to be to produce, say, a 5% difference in I (λ)? The point is to see within what range the giant ellipticals are the same age, in which observation shows the I (λ) to be the same within error limits of about 5%.

SPINRAD

The sensitivity of the models, of course, depends upon which ingredients are changed; if you wiggle the extremely hot and cold ones they are terribly sensitive. However, I assume that's not your question. The turnoff point is moderately sensitive; let me discuss it first of all from the empirical point of view, before getting to the physical side, which is harder. You certainly can immediately detect inclusion of stars as hot as F7 instead of G0, because the ultraviolet end of the model gets blue. The inverse thing happens if you go down and then break off the main sequence at G5 instead of G0. What would be more realistic is, say, take the turnoff down to G5 so it would be something terribly old, then the ultraviolet colors in the model turn too red, but let us try to preserve them by putting in some slightly metal-poor globular cluster. This is actually a suggestion of SIDNEY VAN DEN BERGH. I tried to play that game - it looks as though one can constrain it moderately well, so I think the turnoff point is determined to rather high precision, I would hope to about two or three tenths of a class. On the other hand, to equate this in terms of absolute age is awkward, because if you believe the turnoff point stars are super-metal-rich then they come out to be quite young.

SANDAGE

It is not the absolute age that is important. It is the differential age for galaxies which observations show to have the same I (λ) to within 5%. What can you say of the equality of age from the variation you can allow from the main sequence turnoff point?

SPINRAD

Now I understand your question; I wish I could answer it betted. I really don't have exactly the best kind of observation one would like: for example, it would be great for me to do the ten top galaxies in the Coma cluster. I don't have nearly that extensive material. I have scanned a few ellipticals (excluding the dwarfs, which I don't count in this). They are more or less the same, but unfortunately the one for which I have the best scans, NGC 3379, has a rather bluish center (by about 10% in the base line from 5300 to 4000Å). I don't know exactly what to make of it — it is purely stellar — a very quiet galaxy. Hδ is also slightly strong. Other than that, I think all that has been said by using *UBV* photometry on the large galaxies, especially those in clusters, indicates them to be homogenous and I don't really quite understand what the NGC 3379 difference is. Perhaps it is just a fluke, but perhaps it means that one can't be so categorical about saying that the turnoffs are all the same, although it is my personal prejudice that they are not very different.

SANDAGE

By how much though in $\Delta T/T$?

SPINRAD

It's just an impossible thing for me to answer in my head now. But I'll do it before the day is over and give it to you privately. (The answer is approximately a 40% age variation limit).

HOYLE

I'd like to follow up the 5% that SANDAGE has just mentioned. Isn't that of the order of the difference between your best fit to M 31 and the MORGAN distribution with K Giants?

SPINRAD

I think that that is right, but what I think he is talking about are systematic effects which presumably will be functions of wavelengths. For example, if you change the turnoff point luminosity you also change the color in a systematic way, so you have F8 instead of G4's or G2's, and that is a cinch to find whether you like MORGAN's HR diagram or mine. It wouldn't matter in this particular case.

HOYLE

The point is that a change of 5% in the I (λ) curve would permit a change from your best distribution.

SANDAGE

Yes, but God hasn't said that half the galaxies are built by MORGAN and half by SPINRAD. They are all built presumably on the same model and then you are looking for differences as a function of age, i.e. main sequence turnoff points. It has always been stated that the equality of colours or I (λ) says something about the spread that you can allow in the giant ellipticals, and I'm asking from SPINRAD's ingredients how much can he allow and let I (λ) be the same to within 5%?

HOYLE

It may well be so.

SANDAGE

The type of galaxies I am talking about (giant E) is the same in many rich clusters of galaxies. That is, the first rank cluster member is so homogeneous a class in all its properties, that we want to know what are we allowed in the age spread for this group alone.

HOYLE

I am saying that so far as the observational situation is concerned there is uncertainty.

SANDAGE

I do not agree, if we are talking about giant E galaxies.

SPINRAD

What little I can add to this is that homogeneity is certainly pretty good in the upper end of the galactic luminosity function. This applies to the big Es and the big Sbs. When you get a little fainter, they start to jump around and appear more individualistic. Of course, the Scs which I talked about not at all, are a completely different kettle of fish. They've got young stars in them — as hot as you like. That isn't relevant to SANDAGE's question.

MORGAN

The violet spectrum of the inner part of M 31 seems to have a continuous veiling of the strong K-type features. This veiling is not observed in the case of the elliptical-like NGC 4374. Have you considered the possibility of the presence of a stratum of white dwarfs as the cause of the veiling in M 31?

SPINRAD

I've played the white dwarf game to the following degree. After the Prague IAU I went out and observed one. It's one of the A type ones with a continuum like an O star but hydrogen lines stronger than an A4 main-sequence: the classic thing. Those can be constrained in my models fairly well because they show up in the deep ultraviolet very rapidly at 3300 Å. They also show up in the higher members of the Balmer series, so they are pretty easily constrained and I don't think they are a terrible hazard. I didn't put them in this particular model because I didn't need them at a level where it mattered. For example, if you put them in at the level where you can start to see them (and say you don't like them because they distort the spectrum), they increase the mass-light ratio for the best M 31 model from about 44 to 47, so they are quite inconsequential that way.

However, what is probably more important and what I haven't done, is to look into the problem of the cold white dwarfs, things like Van Maanen 2, and even cooler stars. I just simply haven't observed them and really cannot deny that they are there. What they would do to the ultraviolet continuum in the K type spectrum I'm not really sure - they certainly do not have a spectrum as full of details as a K giant.

MORGAN

I would question the statement that the higher numbers of the Balmer series show in white dwarfs of the o^2 Eri B class.

SPINRAD

Yes, you are correct, Hδ is the last line which, in fact, I have measured. My mistake.

MCCREA

I asked Dr. SPINRAD after his talk this morning about the age as seen from a different point of view: if he had evidence that all the stars in the nuclear region are about the same age, and whether that age can be taken to be the age of the galaxy concerned. I wish to ask if Dr. SANDAGE's question implies that the age is, in fact, the age of the relevant galaxy?

SPINRAD

Let SANDAGE answer first.

SANDAGE

We don't know, but the thing that is so impressive, I think, about members of the local group, which you can study in great detail, is the resolution of what BAADE always calls the background sheet of population II. This resolves in all members of the local group at the same absolute luminosity, about M_V —2.8 to—2.9. The globular clusters resolve at the same level. This applies not only in the nucleus of M 31 but in the disk of the Large and Small Magellanic clouds, in M 33, in IC 1613 and NGC 205. So at least in those galaxies where we can see something that we can age date from the top end of the globular clusters, the age seems to be the same to within about 20%. Then the energy distribution of the central regions of M 31 (not just the nucleus but, say, the central 400 parsecs) is the same (to within the measuring accuracy) with the energy distribution of the giant ellipticals in all clusters of galaxies. This has always been very impressive, at least to me, and was BAADE's main argument that all galaxies where we can see something are the same age.

SPINRAD

Well, I think my models are not sensitive enough to discriminate 10 or 20% age differences, if we take the maximum age to be 12 billion years or something that. I don't think I can tell the difference between 9 and 12, for example. The sensitivity occurs when the turnoff point begins to change rapidly and it is just a function of mass dependence of the stellar evolution, so I really would not like to say anything about the maximum age. I can say something of course, about the last date of star formation where the models do have some sensitivity.

MORGAN

I have one more short question: In the nuclear region of our own galaxy, at a distance of about 4 degrees from the actual galactic centre, the brightest objects in the near infrared are late M giants. Does this agree with SANDAGE's remark in regard to the brightest resolved stars?

SANDAGE

I don't know whether we've really identified the same type of populations in our galaxy at the place you mention as, say, in M 31, but the knowledge that there are RR Lyrae stars in the centre of our galaxy shows, in any case, that there is an old population there. If we allow the RR Lyrae stars to vary in absolute luminosity by, say, 0.4 of a magnitude according to metal abundance, then we can't tell what $\Delta T/T$ is exactly, but we know that there are old stars in the center of our galaxy.

FOWLER

This morning, did I understand you to give a figure for the abundances of the central regions relative to the solar system?

SPINRAD

In a moment of foolish boldness, I said 6 or 7 times solar. I think that's probably O.K., in a bold sense of the word. Also, it is not at all clear that I've resolved the maximum.

FOWLER

But you say that the central region of M 31 has 6 to 7 times as much nitrogen as in the sun. How do you know the value in the solar system in the first place?

SPINRAD

It's clearly relative. The elements studied are sodium, calcium, magnesium, and indirectly oxygen, nitrogen, and carbon. I don't know them in an absolute sense in the solar system. This is a wild extrapolation which is probably not so very bad in the context of this meeting. It comes from the factor of three enrichment which TAYLOR and I have suggested for the old galactic clusters, and another factor of two above. That's where the factor 6 comes in.

FOWLER

But which elements are the key ones now?

SPINRAD

Sodium, magnesium, probably nitrogen through the CN bands also through the emission lines that Mrs. BURBDIGE and OSTERBROCK will talk about (N II λ6584). I don't have any iron information directly, for example, which would be difficult to get. I have no information of helium in the nucleus of M 31 and that would clearly be a crucial observation. Observations have been made by PEIMBERT and others for other nuclei, and the helium does not seem to vary much.

MORGAN

When you speak of super metal-rich, just what do you include under the category of metals?

SPINRAD

The Categories include the things that I measure: Na, Mg, Ca, N.

MORGAN

Is carbon a metal?

SPINRAD

In this context, yes.

THE OPTICAL LINE AND CONTINUOUS SPECTRA OF RADIO GALAXIES, COMPACT GALAXIES, AND SEYFERT GALAXIES

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I. INTRODUCTION.

This survey of the spectroscopic properties of Seyfert galaxies, N-type galaxies, compact galaxies, and radio galaxies (1) is not intended to be a balanced review. Instead we shall pay particular attention to two topics which are new. First, in the discussion of ZWICKY's compact galaxies, we shall dwell particularly on the properties of two dwarf emission line galaxies which may be examples of young galactic nuclei. Secondly, in the section on Seyfert galaxies, we shall summarize recent evidence for the existence of very small components in their nuclei - objects of order 0.001 parsecs in diameter.

These two topics relate to two of the most fundamental problems discussed at the Symposium. A few authors, particularly AMBARTSUMIAN, seem to regard galactic nuclei as primary components of the Universe, relicts of a very early phase in its

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(1) Due to lack of time, the section on radio galaxies was not presented at the Semaine d'Etude. It is included here for completeness. Other parts have also been expanded, in some cases (indicated in the text) because new information became available shortly after the meeting.

plot for the objects in ZWICKY's lists by FAIRALL (1970) indicates that they are substantially complete down to magnitude 15.

Spectra of a few compact galaxies have been described by ZWICKY (1964, 1966, 1967), ARP (1968), FAIRALL (1968, 70) BARBON (1969) and by DE VENY and LYNDS (1969). The writer (SARGENT 1970a) recently completed a more extensive survey in which low dispersion spectra were obtained of 141 Zwicky objects, of which 126 turned out to be galaxies. (The rest were Galactic stars, presumably superimposed by chance on the image of a distant galaxy, and one planetary nebula). The main results of SARGENT's survey are shown in Table 1 which summarizes the statistics relating to redshift and absolute magnitude for the objects divided up according to the character of their spectrum. Before discussing some of the more interesting individual objects, we note that 60 of the galaxies show only absorption lines, 20 have both emission and absorption lines and 43 have only emission lines. The remaining two objects are lineless; they probably have non-thermal continous spectra similar to the rapidly varying radio source BL Lac.

a) *Objects with emission-line spectra.*

In this paper we shall concentrate on the Zwicky galaxies with emission line spectra. These fall into two categories - objects with broad emission lines similar to those observed in the spectra of Seyfert nuclei, and objects with sharp emission lines. The galaxies with broad emission lines will be described in section III. SARGENT found that while the 33 galaxies with sharp emission lines encompassed a wide range in both absolute magnitude and redshift, their emission line spectra did not depart from the range in excitation exhibited by H II regions in galaxies. That is, none of these 33 objects had emission lines of He II and [Ne V] which are found in the spectra of Seyfert galaxies, some planetary nebulae, and some radio gal-

TABLE I — *Statistics of redshift and absolute magnitude.*

Spectrum	No. of Objects								
	Compact	Compact Part	Other	$\langle V_R \rangle$	Min. V_R	Max. V_R	$\langle M_p \rangle$	Min. M_p	Max. M_p
Broad em.	7	1	—	13942	6241	26934	—21.2	(—19)	—23.2
Broad em.?	1	1	—	21360	15590	27130	(—21.5)	(—21)	(—22)
Sharp em.	13	9	7	6988	517	12287	—19.8	—14.9	(—22)
3727 em.	4	—	—	15688	9266	20619	(—19.5)	(—19.5)	(—19.5)
Sharp em., Ca II abs.	1	1	1	6796	4985	5980	—19.9	—19.2	—20.6
3727 em., Ca II abs.	1	1	—	9376	5388	13363	(—20.4)	(—19.5)	—21.3
Sharp. em., Ca II + Hyd. abs.	3	2	—	7758	4374	12309	—20.1	—18	—21.4
Sharp em., Hyd. abs.	3	4	1	5728	789	10482	—19.4	—15.2	—21.6
3727 em., Hyd. abs.	—	—	2	9973	6986	12960	—20.5	—20.3	—20.7
Hyd. + Ca II abs.	1	3	1	11489	4028	17353	—20.8	—19	—21.6
Hyd. abs.	—	1	—	9867	—	—	—20.2	—	—
Ca II abs.	31	22	1	11473	1270	21843	—20.3	(—18)	—22.1
All objects	65	45	13	9994	517	27130	—20.2	—14.9	—23.2

axies (see section IV). A similar result has been found in the case of the galaxies discovered on very low dispersion objective prism plates by MARKARIAN (1967, 69a, 69b). These objects were selected according to the abnormal strength of their ultraviolet continuum. Many of them are compact in the sense used by ZWICKY and indeed some of the objects isolated by MARKARIAN on the basis of an abnormal *spectrum* are included in ZWICKY's lists on the basis of an abnormal *appearance*. (A particularly interesting example is I Zw 0930 + 55 which is described later on in this section. It is object No. 116 in MARKARIAN's (1969a) second list). Most of MARKARIAN's galaxies have sharp emission line spectra. Extensive surveys by WEEDMAN and KHACHIKIAN (1968, 69), SARGENT (1970b) and by ARAKELIAN, DIBAI and ESIPOV (1970) have shown that the spectra of these objects also invariably exhibit the same range in excitation as galactic H II regions. As a result the writer has proposed that in both the Zwicky and Markarian galaxies the emission lines are excited by hot stars.

The fact that the emission lines in most of the compact galaxies are probably not excited by non-thermal radiation does not make them less interesting. Figure 1, taken from SARGENT's (1970) paper, shows 200-inch direct photographs of six sharp emission line galaxies and illustrates their great range in absolute size and morphological appearance. The scale at the top of Figure 1a shows 20 second of arc, it is common to all six sections of the Figure. The other scale, at the bottom of each section, shows the quoted distance in kiloparsecs. The six galaxies are identified in Table 2; the table also lists the redshift, apparent magnitude and absolute magnitude for each object. Brief descriptions of these galaxies are given in the writer's paper. Here we merely point out a few conspicuous features. For example II Zw 0447 + 03 (b) is intrinsically very bright and has four faint straight jets extending out to 25 kpc from the main compact body of the object. II Zw 0459 + 03 (c) is an example of a "ring" galaxy. Two similar objects of this kind are illustrated in ARP's (1966) *Atlas of*

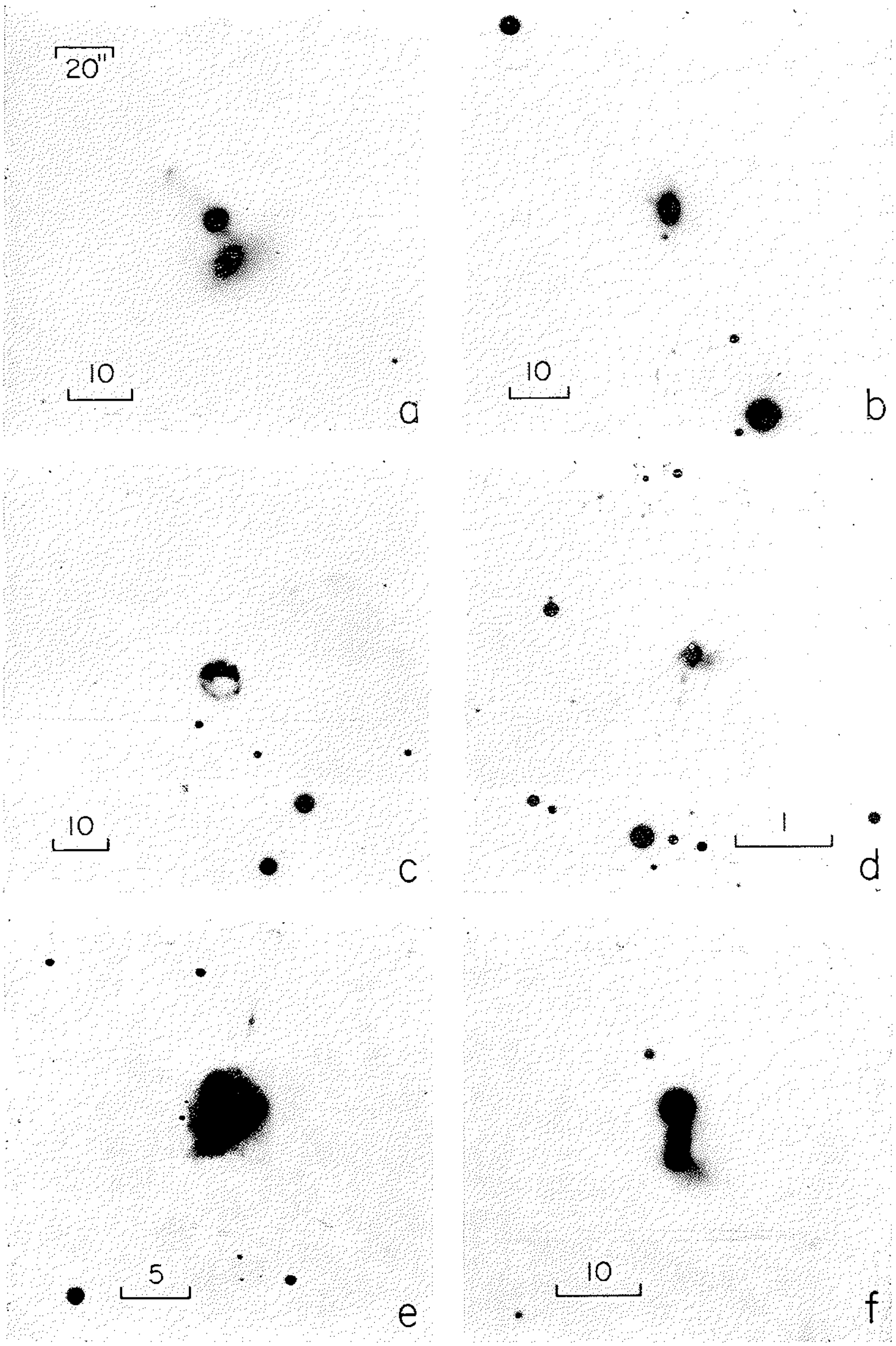

FIG. 1 — Direct photographs of some typical emission-line compact galaxies from the paper by SARGENT (1970a). The objects are identified in Table 2. Detailed descriptions are given in the paper cited above. The scale in the upper left corner of Figure 1a shows 20 seconds of arc; the same scale applies to all six photographs. The scale at the bottom of each section shows the quoted distance in kpc.

Peculiar Galaxies. The centres of these rings are apparently empty and the ring structures consist of condensations which appear to be H II regions. Object d in Figure 1 is II Zw 0553 + 03; it will be discussed extensively later on. IV Zw 2325 + 23 (e) is NGC 7973, an intrinsically luminous galaxy with $M_p = -21.0$. It consists of a number of bright spots in a fainter luminous matrix, the whole being about 6 kpc. in diameter. These "hot spots" are evidently H II regions. The last object f, in Figure 1 is IV Zw 2327 + 25, a pair of emission line galaxies only 3 kpc apart and very close to a brighter foreground star.

TABLE 2 — *Properties of the galaxies in Figure 1.*

Galaxy	Name	V_R (km.sec^{-1})	m_p	M_p
a	II Zw 0338 — 01	7378	16.1	— 19.2
b	II Zw 0447 + 03	8320	14.8	— 21.0
c	II Zw 0459 + 03	8548	15½	— 20½
d	II Zw 0553 + 03	750	15.6	— 14.9
e	IV Zw 2325 + 23	3255	12.7	— 21.0
f	IV Zw 2327 + 25	5530	15.0	— 19.8

b) *Possible young galactic nuclei.*

The photographs in Figure 1 show the great variety of emission line objects in ZWICKY's lists. However, as we mentioned, there is reason to believe that in all cases the emission lines are excited by hot stars. Some of the forms exhibited in Figure 2, particularly the highly luminous jet object (b) and the ring object (c) appear to be unstable. On the other hand, the object with "hot spots" (e) while giving the appearance of stability is intrinsically bright for its size. It is possible and perhaps likely that all these objects are early phases in the evolution of more normal galaxies; they certainly deserve more detailed study with this idea in mind.

Perhaps the best candidates for young galaxies, however, are certain dwarf emission line compacts from which 21 cm neutral hydrogen emission has recently been detected; II Zw 0553 + 03 (d in Figure 1) is such an object. Normal galaxies with emission line spectra are common; Sc galaxies and irregulars of Type 1 frequently show emission lines which arise in their numerous H II regions. However, a new development in the last few years has been the dissovery of very compact emission line systems with very small diameters (of order 100 pc) and very low absolute luminosities (around $M_p \sim -14$). Individual examples have been found by ARP (1965) and by KINMAN (1965). The recent systematic work on the Zwicky and Markarian galaxies has shown that these dwarf systems are very common. Table 3 gives a list of six dwarf Zwicky galaxies with emission line spectra. All have absolute magnitudes fainter than $M_p = -17$ and all have redshifts below 1500 km.sec^{-1} so that 21 cm emission is in principle detectable with multichannel receivers of the type at Nançay, for example.

TABLE 3 — *Dwarf emission-line galaxies in Zwicky's lists.*

Object	V_R km.sec^{-1}	m_p	M_p	Spectrum
II Zw 0553+03	750	15.6	—14.9	Sharp em.
I Zw 0930+55	764	15.6	—14	Sharp em.
II Zw 1448+55	1217	14.5	—16.6	Sharp em.
II Zw 1449+35	1301	14.2	—16.9	Sharp em; Hyd. abs.
I Zw 1531+46	789	15.2	—15.2	Sharp em; Hyd. abs.
I Zw 1545+54	783	15.2	—15.3	Sharp em.

Recently, CHAMARAUX, HEIDMANN and LAUQUÉ (1970) have searched for 21 cm emission from three of the objects in Table 3. Their main results, obtained with a new receiver on the radio telescope at Nançay are summarized in Table 4. We see that 21 cm emission has been detected from two galaxies, I Zw 1531 + 46 and II Zw 0553 + 03. In each case the observed signal implies a mass of neutral hydrogen of about 10^8 solar masses; there is an uncertainty in this number arising from the use of the Hubble constant to estimate the distances of objects with fairly low redshifts. CHAMARAUX *et al's* original paper shows a bump at the correct redshift on their record obtained while observing the third galaxy, I Zw 0930 + 55. If real, this would also imply a neutral hydrogen mass of 10^8 solar masses; however, the authors prefer to interpret their result for this object as an upper limit (²).

TABLE 4 — *Results of neutral hydrogen search in dwarf emission-line compacts* (*).

Object	Neutral Hydrogen		Hydrogen mass to light ratio
	Mass (suns)	velocity disp. (km.sec⁻¹)	
I Zw 0930+55	$\lesssim 1.4 \times 10^8$	40±40	12
I Zw 1531+46	1.0×10^8	35±35	1.0
II Zw 0553+03	2.3×10^8	55±20	0.33

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(2) In a preliminary version of their paper, which was described at the Semaine, CHAMARAUX *et al.* found that the neutral hydrogen around II Zw 0553 + 03 was extended, reaching out to about 5 kpc from the optical nucleus. Later observations did not confirm this result so we shall not discuss its implications here. It is extremely important that the angular extent of the neutral hydrogen be determined.

(*) From the paper by CHAMARAUX *et al* (1970).

Independently of CHAMARAUX et al, the writer and L. SEARLE had for the past 3 years been making optical observations (photoelectric scans and spectroscopic measurements) of several sharp emission line Zwicky galaxies, including two of the three objects for which 21 cm data has been obtained, I Zw 0930 + 55 and II Zw 0553 + 03. These objects have quite different optical appearances.

I Zw 0930 + 55. This object is illustrated in Figure 2 which is taken from the paper by ZWICKY (1966). It consists of a double galaxy in which the components are separated by $5''.6$ or 211 pc with a pair of very faint luminous patches about $30''$ away to the N.W. Galaxy 1, the brighter of the pair, has $m_p = 15.6$ which leads to an absolute magnitude of $M_p = -13.8$. This galaxy has a diameter of 246 pc with a bright core of diameter 66 pc. Galaxy 2 is fainter with $m_p = 17.6$ and $M_p = -11.8$. It has a diameter of only 147 pc with a bright core again of diameter 66 pc. A spectrum obtained by ZWICKY

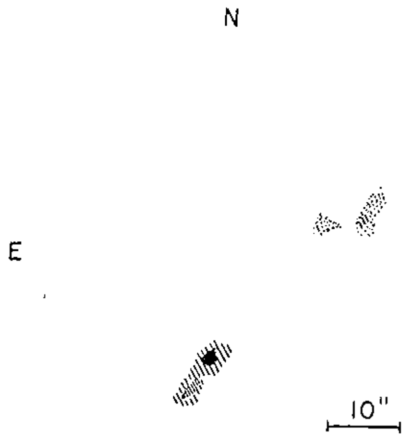

FIG. 2 — A sketch of the dwarf emission line system I Zw 0930 + 55 taken from the paper by ZWICKY (1966). ZWICKY's paper also has a direct 200-inch photograph of the system.

(which is illustrated in his paper) with the slit along the line joining Galaxies 1 and 2 shows that emission lines came from both components *and from the space between them.* The emission lines are tilted, with a redshift difference of 150 km.sec.$^{-1}$ between Galaxies 1 and 2. ZWICKY pointed out that if this difference is interpreted as being due to a rotation of the system, then it has a total mass $M_t \geqslant 7.2 \times 10^8$ suns and a mass-to-light ratio $M/L_p \sim 14$. We note that M_t is greater than the upper limit to M_H determined by CHAMARAUX *et al.* and given in Table 4. It is hard to account for the extra mass in the form of old red stars; perhaps this indicates that the object is not stable.

II Zw 0553 + 03. We have already referred to this galaxy; it is illustrated in Figure 1d. It consists of a bright core only 3″ × 5″ or 110 × 190 pc in size with very faint plumes extending out to 1 kpc, particularly to the South and South-East. The spectrum of II Zw 0553 + 03 is shown in Figure 3. This and other spectrograms show that the object has a smooth continuum with no discernable absorption lines. The emission lines are strong and are not resolved at the dispersion

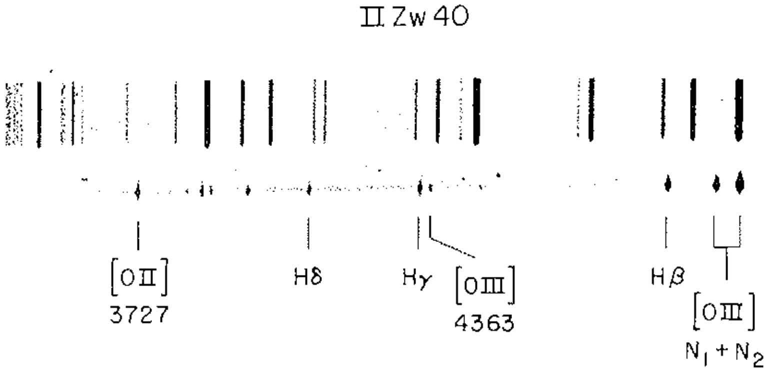

FIG. 3 — The spectrum of II Zw 0553 + 03 (II Zw 40). The original spectrogram had a dispersion of 190 Å/mm. and was obtained at the prime focus of the 200-inch telescope.

used (190 Å/mm). This means that the velocity dispersion in the emitting gas is less than about 200 km.sec^{-1}. The spectrum of II Zw 0553 + 03 is very similar to ZWICKY's spectrum of I Zw 0930 + 55. The [O III] lines λ4363 and N_1 and N_2 are unusually strong relative to Hγ and Hβ, respectively, while [O II] λ3727 is relatively weak.

Unlike I Zw 0930 + 55, II Zw 0553 + 03 lies at a low galactic latitude, (b^{II} = − 11 deg.) Consequently it is in an obscured region and no other galaxies are seen anywhere near it on the *Sky Survey prints*. Despite this, its colors are very blue; SARGENT (1970a) measured $(B - V) = 0.69$, $(U - B) = - 0.11$. The amount of space-reddening may be estimated in two ways. First, CHAMARAUX *et al.* have shown from the Lick counts (SHANE *et al.* 1959) that galaxies are about 50 times less frequent in the field around II Zw 0553+03 than at high galactic latitudes. From this they estimate a photographic absorption of about 3 magnitudes. Alternatively, SEARLE and the writer have made photoelectric spectrum scans of II Zw 0553 + 03. We found that the observed emission line ratios Hα : Hβ : Hγ could be corrected so as to give the values predicted for radiative recombination (Case B) if we assumed an absorption of 2.5 magn. at Hβ. This corresponds to a visual absorption of 2.1 magn. and, using the normal relationship, to a value of $E\ (B - V) = 0.7$ magn. Hence the reddening corrected colours of II Zw 0553 + 03 are $(B - V)_0 \sim 0.00$, $(U - B)_0 \sim - 0.60$. This is very blue indeed; if this object is composed of stars they must be predominantly young, with ages less than about 10^7 years.

The photoelectric continuum scans of II Zw 0553+03 and I Zw 0930 + 55 made by SEARLE and the writer show that, after correction for Galactic absorption, their continuous energy distributions are almost identical. Both have flat continua in the observed wavelength range (λλ3300 - 8000) on a plot of the logarithm of the flux per unit frequency interval against frequency. Hence the *UBV* colours of I Zw 0930 + 55 must be similar to the values given above for II Zw 0553 + 03. The overall energy distributions and emission line strengths strongly resemble those of large H II regions in nearby galaxies, M 31, M 33, NGC 2403 and M 101, according to unpublished observations recently made by SEARLE. The observed continua show no sign of the Balmer jump in emission. This means that most of the continuum radiation at all wavelengths is emitted by the hot stars that illuminate the H II region. We have recently used these photoelectric observations to estimate the physical properties of the emitting gas in the dwarf galaxies. We find from the ratio of the [O III] lines λ4363 : λ5007 that in both cases the electron temperature T_e is about 12,000°K. The equivalent width of Hβ in II Zw 0553 + 03 is 208Å and the flux in Hβ at the source is 1.65×10^{38} ergs.sec.$^{-1}$. We may then use the recombination formula by PENGELLY (1964) to estimate that $N_e^2 V = 2.5 \times 10^{64}$ cm^{-3} where N_e is the electron density and V is the emitting volume. The mass of ionized gas is $M_g = 2 \times 10^7 \times n_e^{-1}$ solar masses. We can put only crude limits on the density, n_e. The fact that strong [O II] lines are observed implies that $N_e \lesssim 10^5$ cm^{-3}. On the other hand, the volume of the nucleus of the object, from which most of the emission comes, is about $V = 4.5 \times 10^{61}$ cm^3. From the value of $N_e^2 V$ above we estimate that the mean smoothed out electron density is $N_e \sim 500$ cm.$^{-3}$. Hence the mass of ionized gas is in the range $200 \lesssim M_g \lesssim 4000$ solar masses, the higher value being applicable if the gas fills most of the volume of the nucleus. SEARLE and the writer have estimated similar values of the above quantities for I Zw 0930 + 55. Moreover, we have shown that the relative abundances of the elements H, He, O and Ne in these dwarf galaxies are the same as in the Orion Nebula to within about a factor of two.

From the optical point of view the two dwarf galaxies resemble giant O-associations with their associated H II regions. We may use the Zanstra theory and the observed total emissivity in Hβ to estimate that the ionized gas in II Zw 0553 + 03 is excited by about 10^{51} Lyman continuum photons per second.

This number of photons would be radiated, for example, by either 50 O5 stars or 500 O7 stars or 5000 O9 stars. For comparison, a giant O-association in the Galaxy, the Orion I association, for example, contains about 100 OB stars, has a radius of about 100 pc and a mass in the form of stars of $10^3 - 10^4$ solar masses.

The coexistence in I Zw 0930 + 55 and II Zw 0553 + 03 of a population of young massive stars with a much larger mass of neutral gas makes these objects excellent candidates to be young galaxies. In fact there are only two straightforward interpretations of the combined optical and radio data. Either these objects have only lasted in their present form for an order of 10^7 years or *they have only made massive stars during most of their lives*. This last possibility is not implausible. If the stars are of such a mass as to shine for only 10^7 years or less, then we may estimate that there is sufficient neutral gas to last for 10^{10} years, the characteristic expansion age of the Universe. This possibility could only be eliminated if, for example, it could be shown that the systems are unstable on a shorter timescale. The evidence that I Zw 0930 + 55 may not be a bound system is interesting in this context; however at present this evidence is not sufficiently conclusive.

In summary, the hypothesis that objects like II Zw 0553 + 03 and I Zw 0930 + 55 are young systems rests on four observed facts:

1) Their blue *UBV* colors imply that the optical emission is produced by a dominant population of young, massive stars.

2) The photoelectric scans show that their continua are very similar to those obtained of the integrated light of large O-associations in other galaxies.

3) Both the spectra and the scans show that there are no absorption lines detectable (This is also the case with the integrated spectra of distant O-associations. The hot stars

which dominate the optical radiation have few and weak absorption lines. Moreover, many of the absorption lines which do exist in the spectra of hot stars, the Balmer lines for example, are swamped by emission lines from the hot gas).

4) The objects contain a large mass of neutral hydrogen (3).

Since work on these dwarf objects is still in progress it is perhaps unwise to go into further detail about their possible interpretation. However, there is one interesting consequence of the hypothesis that objects like II Zw 0553 + 03 and I Zw 0930 + 55 are young. Rough counts indicate that the space density of these objects is about 0.008 Mpc^{-3}. However, the space density of objects which have been through this brief flash, or which are going to do so, must be 1000 times higher – the ratio of 10^7 years to 10^{10} years. That is, there should be 8 per cubic megaparsec and, in consequence, several inside the local group. None of the known dwarf galaxies in the local group could possibly have evolved from such compact dwarf systems. However, it is conceivable that clouds of neutral hydrogen with the required mass and size could have gone undetected. Perhaps here we have a connection with the infalling neutral hydrogen clouds described by OORT.

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(3) Since the Semaine d'Etude, observations of II Zw 0553 + 03 have been made in the near infrared, at 2.2μ and 1.6μ, by Dr. G. NEUGEBAUER of the Hale Observatories. These measurements, which were generously made at the request of L. SEARLE and the writer, show that the continuum of II Zw 0553 + 03 stays flat out to at least 2.2μ. The most natural interpretation of this red radiation would be that it comes from faint red (and therefore old) stars in the system. With a mass to light ratio $M/L = 50$ it turns out that there could be roughly 300 times as much mass in these old red stars as in the young, massive stars which produce the visible part of the spectrum.

However, this obvious interpretation is not necessarily correct. A few red supergiants or luminous protostars could also produce this near infrared radiation. At the time of writing NEUGEBAUER was attempting to make similar observations of the integrated radiation from a giant O-association in a nearby spiral galaxy - NGC 5471 in M101 is one such object. If the integrated spectrum of an O-association also proves to be flat out to 2.2μ, this will make the interpretation of the infrared radiation from II Zw 0553 + 03 in terms of old red stars much less plausible.

III. GALAXIES WITH BROAD EMISSION LINES

a) *Emission spectra.*

We mentioned in the Introduction the problem of the distinction between the terms Seyfert galaxy and N-type galaxy. Here we shall discuss the line spectra and continua of that class of galaxies which have broad Balmer emission lines in their spectra. This kind of spectrum is confined to galaxies which have star-like nuclei. The class of objects includes the classical Seyfert galaxies, NGC 1068, 1275, 3227, 4051, 4151, 5548 and 7469 as well as more distant objects which have been discovered since radio observations drew attention to the N-type galaxies. In Table 5 we give a list of some newly discovered galaxies

TABLE 5 — *Some new Seyfert galaxies.*

Object	$z = \frac{\Delta\lambda}{\lambda_0}$	m_p	M_p
3C 120	0.033	14.2	— 21.8
III Zw 0008 + 10	0.090	15.4	— 22.6
I Zw 0051 + 12	0.061	14.0	— 23.2
II Zw 0119 — 01	0.054	15.1	— 21.8
II Zw 2130 + 09	0.061	14.6	— 22.8
Markarian 9	0.039	14.8	— 21.2
Markarian 10	0.029	14.7	— 20.7
Markarian 34	0.051	15.8	— 21.0
Markarian 42	0.024	16.2	— 18.8
Markarian 50	0.023	15.5	— 19.6
Markarian 69	0.076	16.5	— 21.2

with broad emission lines in the spectra of their nuclei. It will be observed that the new more distant objects are, on average, much more luminous intrinsically than the classical Seyfert galaxies mentioned above.

Figure 4 shows several spectra of NGC 4151. This object and NGC 1068 are archetypes for the two main kinds of spectrum observed in Seyfert galaxies. In the case of NGC 4151 the forbidden lines and the permitted lines (notably those of hydrogen) have quite different profiles. The forbidden lines are relatively sharp, with widths at half maximum intensity of about 450 km.sec^{-1}. On the other hand the hydrogen lines have cores with the same width as the forbidden lines but with much wider wings. In NGC 4151 the wings of Hβ have widths at half intensity of about 6000 km.sec. Measurements by OKE and SARGENT (1968) show that in this object 82 percent of the Hβ emission is in the wings and only 18 percent in the sharp core. In the spectrum of NGC 1068 the forbidden lines and the Balmer lines have the same widths. All the known Seyfert galaxies follow one of these two patterns. No case is known in which the forbidden lines are wider than the permitted lines.

Objects like NGC 4151 are more common than ones like NGC 1068. This is particularly true among the distant, highly luminous objects which almost always have very broad Balmer lines and very sharp forbidden lines.

High resolution studies of NGC 4151 by WALKER (1968) show that while the profiles of the broad wings are smooth, the cores have considerable structure which WALKER has plausibly attributed to the presence of discrete clouds in relative motion with speeds of a few hundred km.sec^{-1}. WALKER's observations (and more recent ones by M.V. PENSTON and the writer with the Mount Wilson 100-inch coudé spectograph) show that the structure of the *core* of Hβ is the same as the structure of the nearby [O III] lines.

The emission spectra of Seyfert galaxies are remarkable for their richness and for the great range in ionization potential of the ions observed. Thus, in the case of NGC 4151, OKE and

SARGENT (1968) listed H, He I, He II, [N II], [O I], [O II], [O III], [Ne III], [Ne V], [S II], [A IV], [Fe III], [Fe IV], [Fe X] and [Fe XIV]. OSTERBROCK and PARKER (1965) drew attention to the fact that the Bowen fluorescence lines of permitted O III were absent in NGC 1068. These lines are strong in the spectra of high excitation planetary nebulae. They are produced by a coincidence in the energy of a highly excited level in O III with that of the Ly α emission line of He II. WEYMANN and WILLIAMS (1968) have since shown that the Bowen fluorescence lines are weakly visible in the spectrum of NGC 4151.

In general the emission spectra of Seyfert galaxies do not exhibit great diversity in the lines observed. However, recently the writer found two broad emission line galaxies, I Zw 0051 + 12 and II Zw 2130 + 09, which have many permitted emission lines of Fe II in their spectra. The most extreme case is I Zw 0051 + 12 (SARGENT 1968). Its spectrum contains only lines of H, He I (4) and Fe II. The Fe II emission lines and the Balmer lines have the same half-widths, about 3000 km/s. None of the normal forbidden emission lines are seen in the spectrum of this object. Moreover, there are no detectable lines of Fe II. These same Fe II emission lines were identified as broad bands in the spectrum of 3C 273 by WAMPLER and OKE (1967).

The second galaxy, II Zw 2130 + 09, has the normal broad H and He permitted lines and the usual sharper forbidden lines in its spectrum, although these are weaker than normal. The Fe II lines must be broad in this galaxy, like the Balmer lines. Both I Zw 0051 + 12 ($M_p = -23.2$) and II Zw 2130 + 09 ($M_p = -22.8$) are abnormally luminous for Seyfert galaxies; there is a distinct possibility that Fe II emission is correlated in some way with luminosity in these objects.

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(4) The presence of He I in this object was not mentioned in SARGENT'S original paper. However, photoelectric scans secured by J.B. OKE clearly show a broad feature due to He I λ5876.

In understanding the origin of the emission line profiles in Seyfert galaxies, an important question is whether all the permitted emission lines behave in the same way. Permitted lines have only been observed from four ions — H, He I, He II and Fe II. As we just mentioned, in the two "iron galaxies" the Fe II emission lines are certainly broad like the Balmer lines. OKE and SARGENT's photoelectric scans also suggest strongly that the He II λ4686 line is broad in the spectrum of NGC 4151. Unfortunately, in most Seyfert galaxies, the He I lines are too weak for us to be certain of detecting a broad component in such lines as λ4471 or λ5876. However, in one object, III Zw 0008 + 10, which has abnormally broad Balmer lines, ARP (1968) reported the existence of a very broad emission feature which is almost certainly He I λ5876. Thus there is strong evidence, in my view, that in Seyfert galaxies all the observed permitted lines have a broad component. We shall discuss the implications of this conclusion later on.

b) *Variability in emission lines.*

It is well established that the continua radiated by Seyfert nuclei vary by as much as a magnitude. It is not so clear that the emission lines vary, either relative to one another or as a whole. ANDRILLAT (1968) claimed that a comparison of her spectra of NGC 3516 obtained at Haute Provence in 1967 with the spectra described by SEYFERT (1943) and by DIBAI and PRONIK (1967) show changes in, for example, the ratio of the sharp [O III] lines and the broad Hβ line. In our view these claims are not convincing. The ratio of the emission lines to the continuum can be influenced by the way in which a spectrum is taken (for example, on whether the nucleus of the galaxy is stationary on the slit during the exposure or "trailed" along it to produce a widened spectrum) as well as on real changes in the continuum emission. Moreover, the *relative* visibility of broad and sharp emission features on photographic spectra can also be influenced by changes in the continuum. Walker (1968) has made a much more convincing case that changes in the ratio of the emission lines as a whole to the continuum have occurred in NGC 4151. Walker's observations have the advantage that they were made with the Lallemand electronic camera, which has a linear response. An observational proof that changes occur in the relative intensities of emission lines must be based either on very careful photographic photometry with the same instrument being used on each occasion, or, to be really certain, on photoelectric photometry.

c) *Absorption lines and changes.*

Most of the classical Seyfert galaxies show absorption lines in their spectra due to the background of stars in and around the nucleus. An exception among the nearby Seyfert galaxies is NGC 4151, whose nucleus is abnormally bright relative to the rest of the galaxy. This object is variable in light. At times of light maximum the absorption lines due to stars are swamped and only a few non-stellar absorption features remain in an otherwise smooth continuum. The most noticeable feature is a dip in the continuum between the He I emission line at λ3889 and the [Ne III] line at λ3870. O.C. Wilson (reported by Oke and Sargent 1968) identified it as a blue displaced absorption line of He I; this is plausible since the lower level of the transitition responsible for λ3889 is metastable. There is another, less certain, dip in the continuum at λ3732 (Sargent 1962) which is unidentified.

Recently Anderson and Kraft (1969) reported that there are absorption lines immediately to the blue of the sharp cores of the Balmer lines in NGC 4151. They interpreted these features together with the blue-displaced He I 3889 absorption as being evidence for outflow of gas from the nucleus of

NGC 4151 (5). The hydrogen absorption features discovered by ANDERSON and KRAFT may be seen particularly at Hβ in two of the spectra (b and c) illustrated in Figure 4, which is taken from a paper by CROMWELL and WEYMANN (1970). In their paper CROMWELL and WEYMANN present fairly convincing evidence that these blue displaced Balmer absorption features come and go. The top spectrum, Figure 4a, was taken by SARGENT in 1961 with the B-spectrograph at the Newtonian focus of the Mount Wilson 100-inch telescope. This spectrogram shows no sign of the Balmer absorption features which are clearly visible on the spectra illustrated in Figure 4b and c,

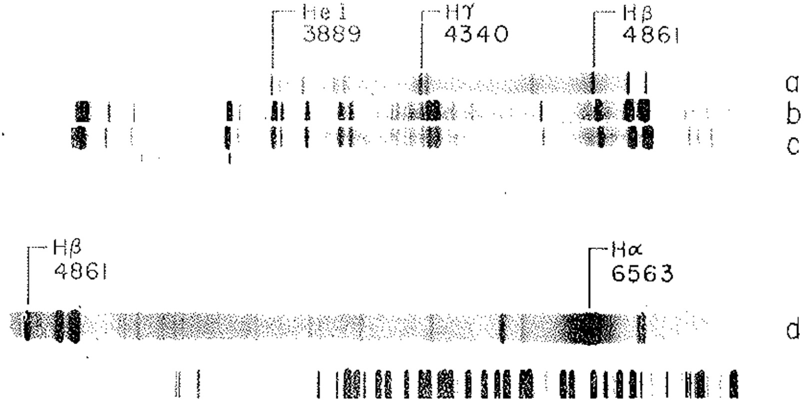

FIG. 4 — Spectra of the Seyfert galaxy NGC 4151, taken from the paper by CROMWELL and WEYMANN (1970). The top spectrum (a) was taken by SARGENT in 1961 with the Mount Wilson 100-inch telescope; it shows the wide wings to Hβ and that the sharp core of Hβ has the same width as the O III, N, and N_2 lines to the right. Spectra (b), (c) and (d) were obtained by CROMWELL and WEYMANN in 1970 with an Image tube spectrograph on the Steward Observatory 90-inch telescope. These spectra show more faint emission lines than SARGENT's older plate. This is presumably due to a change in the brightness of the non-thermal continuum. Spectra (b), (c) and (d) also show the absorption line on the short wavelength side of the emission core of Hβ which is not present on spectrum (a).

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(5) This interpretation was also suggested by SARGENT (1962) on the basis of the displaced He I λ3889 absorption alone.

which were obtained by CROMWELL and WEYMANN in 1970 with an Image Tube spectrograph on the Steward Observatory 90-inch telescope. The spectra in Figure 4b and c were obtained in different ways; both show absorption features clearly, as do ANDERSON and KRAFT's spectrum and a spectrogram obtained by PENSTON and SARGENT with the Mount Wilson 100-inch coudé spectrograph in March 1970. CROMWELL and WEYMANN point out that no spectrogram obtained before March 1969 showed these features, including one obtained by WILLIAMS and WEYMANN in January 1968. They conclude that the features can develop on a time scale of about 1 year. The center of the Balmer absorption is displaced by about 900 km.sec^{-1} from the center of the emission line. Thus a time scale of a year (3.10^7 seconds) corresponds to a distance scale of about 3×10^{15} cms.

No doubt Dr. OSTERBROCK will say more about the implications of the variability of the Balmer absorption features in his talk. However, we may remark here that three alternative interpretations of the Balmer line-profiles in objects such as NGC 4151 have been proposed. First, it is generally accepted that the forbidden emission lines and the sharp cores of the Balmer lines arise in a region having a diameter of about 50 pc, in which the gas has an electron temperature $T_e \sim 20{,}000°$K and an electron density $N_e \sim 5000$ cm^{-3} (see, for example, OKE and SARGENT 1968). These last authors then suggested that the broad wings to the Balmer lines are produced by electron scattering, also in this extended region. Their idea was that if the optical depth for self absorption in the Balmer lines is sufficiently high then the path length traversed by a Balmer line photon in the extended region will be increased, thus raising the probability that the photon scatters off a free electron. This idea has been criticized by WEYMANN (1970) and no longer seems tenable. Earlier, WOLTJER (1959) suggested that the broad components of the permitted lines in Seyfert galaxies arise in a region where the electron density is so high ($N_e \gtrsim 10^6$ cm^{-3}) that forbidden lines are suppressed. In WOL-

TJER's picture the broad wings were produced by Doppler motions (rotation or more chaotic motions) in the region of high electron density. This idea was criticized by BURBIDGE, BURBIDGE and PRENDERGAST (1959) who showed that the central mass of 10^{11} suns, required by WOLTJER's model to hold in this rapidly moving gas, was in conflict with the general rotation curve observed in NGC 1068. Lastly, KANEKO and OHTANI (1968) and WEYMANN (1970) retained the idea of a high density region to suppress the forbidden lines, but suggested that the Balmer lines are broadened by electron scattering in this region of high electron density. WEYMANN's model requires the high density region to have $N_e = 3 \times 10^9$ electrons per cm^3 and a radius of about 7.5×10^{15} cms (6).

CROMWELL and WEYMANN pointed out that their discovery of changes on a timescale of one year in the displaced Balmer absorption components leads to a distance scale (3×10^{15} cms) which is compatible with that required for the Balmer emission lines to be broadened by electron scattering in a region of high electron density. Arguments based on the total energy radiated by a Seyfert galaxy in its lifetime indicate that if the ultimate source of energy in these objects is a "black hole" then its mass must be at least of order 10^6 solar masses. The Schwarzschild radius of such an object is about 3×10^{11} cms, so that at a radius of 3.10^{15} cms gas which is bound to the system must experience Doppler motions of order $10^{-2}c$ or 3000 km.sec.$^{-1}$, comparable to the observed line widths. We are led to the idea that more refined observations of changes in the optical spectra

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(6) At the time of writing M.J. REES and the author are exploring the possibility that a model similar to WOLTJER's (1959) proposal may be compatible with the observations after all. WOLTJER was led to an unreasonably high mass because he attributed too large a radius to the dense region. If one takes a radius of order 10^{16} cm. and an electron density of order 10^9 cm^{-3}, then a central mass of only 10^8 suns is required to hold in matter moving at around 3000 km.sec^{-1}. We therefore suggest that the broad wings in objects like NGC 4151 are caused by the *rotation* of a small, high density gas cloud. We hope to publish the details of this work elsewhere.

of Seyfert galaxies will enable us to set meaningful upper limits on the amount of matter in a gravitational singularity at the center.

c) *Optical continua of Seyfert nuclei.*

The best studied optical continuum is that of NGC 4151. As we have seen, this object is variable and at times of light maximum the continuum is smooth with no absorption lines due to the stars in and around the nucleus. Figure 5 is taken from OKE and SARGENT's (1968) paper. It shows the continuum of NGC 4151 in the wavelength range λλ3300 - 11000 Å. The bump at the ultra-violet end of the spectrum is the Balmer jump in emission which is produced by the hot gas which radiates the emission line spectrum. OKE and SARGENT's detailed observations enabled them to subtract out the part of the continuum emission contributed by the hot gas. The lower curve in Figure 5 shows the continuum that remains. Within the

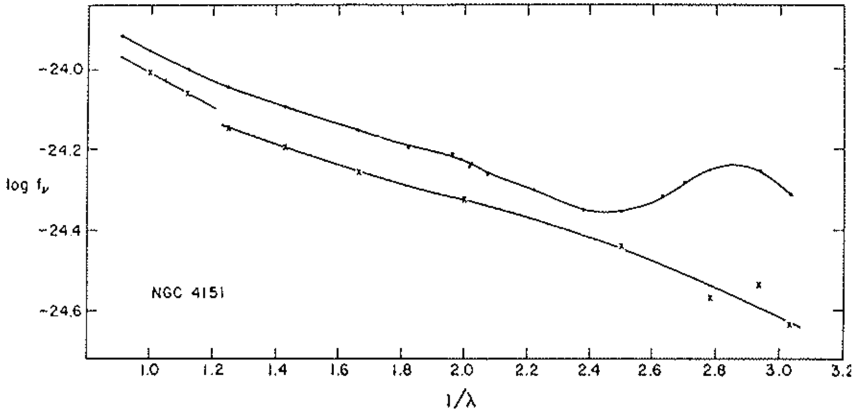

FIG. 5 — The continuous spectrum of NGC 4151 measured photo-electrically in the wavelength range λλ3300 — 11000 by OKE and SARGENT (1968). The observed continuum is shown by the upper line on a plot of the logarithm of the flux per unit frequency interval against the reciprocal wavelength in μ^{-1}. The lower curve shows the continuum (presumed to be non-thermal) which remains when the hydrogen recombination spectrum has been subtracted.

errors of observation it is a straight line on a plot of the logarithm of the flux per unit frequency interval against frequency; this would imply a law of the form $f_\nu \sim \exp(-\nu/\nu_c)$ for the supposed non-thermal continuum. WEYMANN and WILLIAMS (1968) showed that a law of the form $f_\nu \sim \nu^{-1.2}$ is also compatible with the observations over this restricted range of wavelength.

For comparison, we show in Figure 6 the continuum of NGC 1275 taken from the paper by OKE (1968). This con-

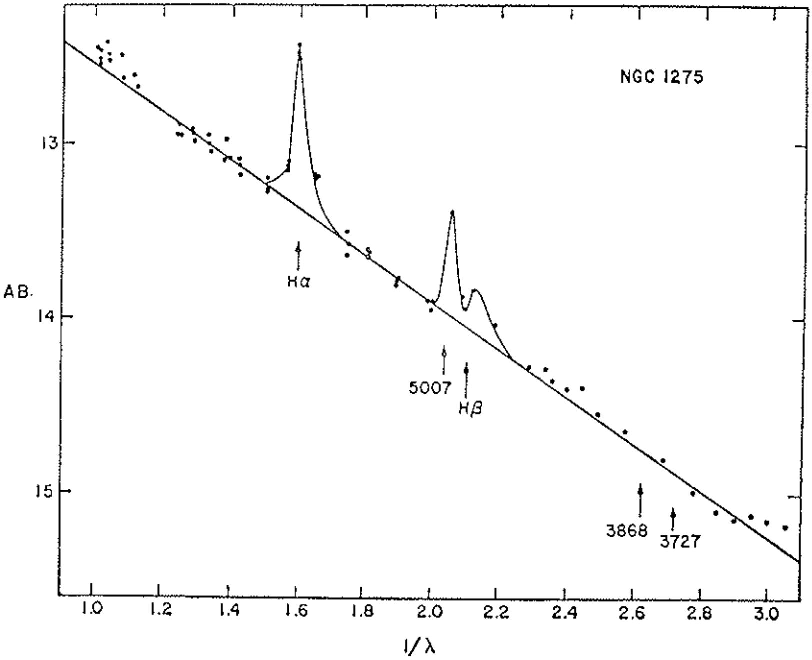

FIG. 6 — The continuous spectrum of NGC 1275 measured photo-electrically in the wavelength range λλ3300 — 11,00 by OKE (1968). The observed continuum is a straight line on a plot of apparent magnitude against the inverse wavelength in μ^{-1}. Note that the emission lines are relatively weak and that, unlike the case of NGC 4151 in Figure 5, there is no sign of the Balmer discontinuity.

tinuum shows no sign of the Balmer discontinuity and, according to OKE, it is almost identical to that of NGC 1068. In this case the emitted flux varies with frequency approximately accordin to the law $f_\nu \sim \nu^{-2.0}$. Continuum observations have been reported for a few other Seyfert nuclei including 3C 120 (OKE, SARGENT, NEUGEBAUER and BECKLIN 1967, WAMPLER 1968) and the N-galaxy 3C 371. In each case studied so far the continuum rises to the red on a plot of flux per unit frequency interval against frequency. The objects NGC 4151 and NGC 1068 roughly span the range of observed continuum slopes.

IV. RADIO GALAXIES.

The optical spectra exhibited by radio galaxies are exceedingly diverse. There is no particular spectroscopic quality invariably associated with radio-emitting galaxies. This fact, together with the existence of double radio sources in which the components are some distance away from their parent galaxy, means that the optical identification of distant radio galaxies is not straighforward.

The main lists of redshifts of radio galaxies have been published by SCHMIDT (1965), SANDAGE (1966), WILLS (1967) and by BURBIDGE (1967). SCHMIDT's paper gives the most extensive systematic account of the spectra of such objects. In it he studied 31 radio galaxies, mostly objects in the 3CR catalogue. SCHMIDT found that all but 3 of his radio galaxies had emission lines in their spectra; at least 10 of the objects with emission lines also exhibited absorption lines which are more difficult to find than emission lines on low dispersion spectrograms.

All of SCHMIDT's objects showed sharp emission lines at the low dispersion (400 Å/mm) used in his survey. Many of the known Seyfert-type galaxies would be easily detectable from the width of their Balmer emission lines as this dispersion. SCHMIDT's paper contains a set of reproductions of typical spectra which indicate the range in the character of the emission line spectrum. From SCHMIDT,s work the following general results may be stated concerning the emission spectra of radio galaxies:

1) There is come correlation between the strength of their degree of excitation. Objects with many strong emission lines tend to have the [O III], N_1 and N_2 lines strong relative to Hβ and to have detectable lines of He II and [Ne V] (Cygnus A has this type of spectrum). On the other hand if only one weak line is visible it is almost always [O II], λ3727.

2) It follows from the above description that the range in excitation exhibited by radio galaxy spectra is greater than that encountered in galactic H II regions. The spectra of objects such as Cygnus A superficially resemble those of high-excitation planetaries.

3) Strong radio galaxies are mostly supergiant D (cD) galaxies or N-type galaxies. The N-type galaxies do not always have broad emission lines and some have no emission lines.

4) SCHMIDT showed that there is a rough correlation between the strength of the emission lines and the intrinsic strength of the radio source.

Practically no observations have been published of the optical continuum of radio galaxies. A few Seyfert galaxies which are also radio sources, for example 3C 120, have been studied. OKE (1968) mentions that the continuum of Cygnus A has a very steep slope, with the flux varying as $f_\nu \sim \nu^{-3.2}$. A detailed study of the source of ionization in this object will be of great interest.

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DISCUSSION

Chairman: W. W. MORGAN

MORRISON

I suppose it is evident that there is no field galaxy near the direction and depth of those odd Zwicky objects, which might be blamed for having emitted them in the past?

SARGENT

No. One of the objects (II Zw 40), is close to the galactic plane and it would be rather hard to find surrounding galaxies. The other one is at high galactic latitude and is in a fairly empty region and there are certainly no large galaxies around that could produce this material.

HOYLE

First a comment, then a question. The comment is that I am not sure that one can make the inference about the size of the absorbing region that you made if the source of the emission is less than 15″. If you imagine a point source of light shining through a cloud, then the light just pierces the cloud along the line of sight. Only the gas intercepted by the line of sight need change in the two years. And now my question. I seem to remember at one time, when we considered the possibility that the broadening of the wings of the lines could be due to electron scattering, you had an argument against it arising from the work of WALKER. Do you remember it?

SARGENT

Yes, I do have an argument against electron scattering but WEYMANN claims that my argument is incorrect. My earlier argument against electron scattering was that, if the hydrogen lines are broadened by this mechanism the picture was that an Hβ photon emitted from the middle of an extended region could be scattered by other hydrogen atoms before it got out of the cloud and therefore would have a longer path length for electron scattering than a forbidden line photon which could go straight out. It turns on whether or not hydrogen lines always have a little pip on them, corresponding to the same width as the forbidden lines. Now WEYMANN claims that if you look hard enough you always find a small pip on the top of the permitted lines. I think that I've seen cases in which a pip did not exist. WEYMANN's picture is that the permitted lines are produced primarily in a small high density region and then there is a much bigger low density region around, which forms the forbidden lines, and clearly this low density region must produce a little pip.

SANDAGE

Could the absence or presence of the Hβ absorption line be due to increase or decrease of contamination of the non-thermal component? It's known that NGC 4151 varies by a magnitude in periods like a year.

SARGENT

I was pretty well convinced that it was not; that this feature had appeared because the whole continuum level had fallen.

SANDAGE

But have observers obtained the apparent magnitude at the times the spectra were obtained?

SARGENT

No.

SPITZER

In the case of NGC 4151, do you happen to know whether OKE's determination of the diameter was based on the forbidden lines or on Hβ?

SARGENT

It was based on the forbidden lines, because it was not possible to measure the tilt of the broad component of Hβ.

MORGAN

Is it possible that some of the difference in the appearance of the Hβ absorption component on your plate and those of WEYMANN can be due to the differing densities and plate characteristics?

SARGENT

I think not. In fact, WEYMANN's were image-tube spectra and mine were ordinary photographic spectra, so that it was not a very good comparison, but looking carefully at them I was convinced that there had indeed been a real change.

E. M. BURBIDGE

I think one can make a distinction between the helium line λ3889 and the Balmer lines because I have the impression that the helium line has always been visible. It was visible on those old plates of WILSON as a broad shallow absorption and it might come from a more extended region of the shell type that gives rise to lines from a metastable level.

OSTERBROCK

The absorption line He I λ3889 was observed by KRAFT and ANDERSON to consist of three components, one of which had roughly the same red shift as the single absorption component of Hβ. This component is presumably the one closest to the source of continuum, because the greater metastability of the He 2^3 S level means that the He absorption can persist under conditions of less frequent ionization followed by recombination.

E. M. BURBIDGE

WILSON's line looked broad so that one could convince oneself that there could have been several components there that hadn't been resolved. That was my impression.

OORT

You were referring to the evidence for neutral gas falling into the plane of our Galaxy. If I understood you correctly you suggested that in the case of II Zwicky 40, the entire galaxy might have been formed recently by collecting intergalactic gas. This, I think, would certainly be possible.

As far as your principal suggestion is concerned I think it is quite possible that galaxies would still be forming in these recent times. This is plausible in view of all the gas there is still in the universe apparently.

SARGENT

I think that the surprise to me is that there are so many of these clouds. If we assume that there are as many clouds as emission-line galaxies with low red shifts then, as I said, there are at least ten within ten megaparsecs, and if they only last 10^7 years that means there are 10^4 within 10 megaparsecs.

OORT

But they have low masses?

SARGENT

The mass is low but it is as high as the total neutral hydrogen mass in our galaxy.

OSTERBROCK

I was quite interested in the material on the two compact galaxies. You emphasized in the one case the difference between the mass of H I that was observed and the gravitational mass that is derived from the measured rotational velocity. Is there any chance that there are stars present in the system that can account for the derived mass?

SARGENT

Well, SEARLE and I have done rough calculations and it turns out that in order to get enough mass in, say, cool stars, they have to have a mass to light ratio which is larger than 300, so this seems to us a little implausible, but it is not entirely out of the question. It would demand that the luminosity function of the stars would have to be very peculiar, with a few very bright hot stars and then nothing further down and more very, very cool, low-mass stars.

G. R. BURBIDGE

You say that it's hard to account for any mass in the form of stars. I take it you can't exclude the possibility of mass in the form of molecular hydrogen or even of dust in these clouds?

SARGENT

No. May I add a remark? There is a velocity dispersion measurement which I forgot to discuss — the velocity dispersion of the gas in II Zw 0553+03 is about 60 km/sec. If you ask what sort of distribution of mass would give this kind of dispersion, or if you ask, if you have 10^8 solar masses of gas, how extended does it have to be to give this kind of velocity dispersion, it comes out to be of the order of 300 parsecs.

G. BURBIDGE

But that velocity is surely comparable to the velocity of ejection of this matter, if you believe it has been ejected from its centre.

SARGENT

Yes.

G. BURBIDGE

So these may not be stable clouds and the whole system may be expanding.

SARGENT

That's right.

AMBARTSUMIAN

I would like you to clarify two things: first, is it a good coincidence between the radial velocity of the H II regions in Zwicky 40 obtained from optical observations, with the radial velocities obtained from 21 cms?

SARGENT

Yes, the coincidence is within about 30 km/sec for both of the galaxies studied.

AMBARTSUMIAN

The second question is, can you see any stars in this galaxy, which is very near to us?

SARGENT

No. Both galaxies have very small angular extent and all one sees is a blob which radiates an emission line spectrum. In neither case is there any direct evidence for stars, and this is also the case if you obtain an integrated spectrum of an H II region of a distant galaxy - one does not see the individual stars. There is in principle a way in which one could find evidence for stars and that is by finding the Wolf-Rayet bands in emission which are radiated by hot O stars. These are occasionally found in the integrated spectrum of distant H II regions. Of course, the absorption lines that you would expect to be produced by hot stars are all filled in by emission lines.

McCrea

I would like to ask how these objects compare with quasi-stellar objects in any respect.

Sargent

The only similarity they have probably is in colour. I cannot quite remember the colours unfortunately and the colour I have was obtained from scans, but we estimated the colours were roughly B-V about -0.2 and U-B -0.8, so they're exceedingly blue objects and they could be discovered from colours more easily than from their appearance on photographs as Zwicky has done. I'm sure that some of the objects in Markarian's lists will turn out to be such things.

Spinrad

Can you say how the more or less indeterminate amount of stars cooler than the sun in II Zw 40 compare with the Pleiades which would be a cluster in our galaxy with a slightly greater age than you suggest? The relevant number of Gs and Ks compared to the Os and Bs?

Sargent

Could you rephrase the question please?

Spinrad

Let me rephrase it and break it up also. Is there any evidence whatever for any special type later than B5 and, if so, can you say anything about proportions?

Sargent

There is no evidence from the spectrum of any stars at all, but it would appear from the continuum that they are all early B or O stars - if there are any stars there at all. That is, that these objects are the same as the stars that radiate the light in H II regions or O associations.

SPINRAD

But in NGC 604 the continuum-producing stars are certainly detectable.

SARGENT

Well, yes. These objects, as you saw, have strong continuum but they have no absorption lines and this just what you find in distant O associations.

SPINRAD

Right, and then you have to use the curvature of the continua to infer anything about the stellar content if indeed it is stellar. Is that correct?

SARGENT

Yes, and all one can say is that these are like the bright O associations in distant galaxies and I don't know what they contain, that's one of the problems. One doesn't know whether an O association contains a lot of low-mass stars that are still contracting.

SPINRAD

What is the longest wavelength observed?

SARGENT

8,000 angstroms.

WOLTJER

When you say that to stabilize the system with stars you need M/L ratios in excess of 300 is that assuming that the stars are concentrated in the optical image or that they fill the whole region from which there is 21-cm emission?

SARGENT

That is from the binary object which, if you remember, has two components which are only ten seconds of arc apart and the mass estimate was obtained from the relative motion. In that case, one knows that whatever mass one has to put in has to be in a small volume and it was for that case that I quoted the mass to light ratio of 300. In the other case, you require a similar mass to light ratio if you put all the mass in the optical object, but of course if you put low-mass stars throughout this very, very large volume then it would be hard to do the calculations, particularly as the object is in an obscured region at low galactic latitude.

AMBARTSUMIAN

I think that you must put the dynamical mass in these compact objects, since the influence of the extended gaseous cloud of H I on the dynamics of the pair inside it cannot be appreciable even when the mass of the extended cloud is very large.

SARGENT

Yes, into one of these small objects we have to put a large mass. This was the assumption. I should like to emphasize again that we did some work on the composition of the gas in these two galaxies and we could only get the abundance ratios of helium to hydrogen, oxygen to hydrogen and neon to hydrogen, and they were all the same as the Orion nebula, within a factor of two. Now, this was very surprising. If these objects are young galaxies, then how is it that they could have made exactly the same proportion of these elements as our Galaxy and have done it all in 10^7 years?

OORT

Isn't that always the way? For instance, many objects in the galactic halo have almost normal abundances, and yet they have presumably been formed in the early stages of the collapse leading to the formation of the Galactic System, which would have lasted less than 10^8 years.

OPTICAL SPECTRA
OF QUASI-STELLAR OBJECTS

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I. INTRODUCTION.

This description of the observations on the optical spectra of the QSOs will be divided into an account of the emission lines, followed by a more detailed discussion of the absorption-line spectra, and finally a necessarily brief (because of time limitations) account of the optical continua. This is a natural division because the three types of spectra arise in different situations in the objects, where different physical conditions must prevail. I shall include both radio-emitting and radio-quiet QSOs, since there appears to be no distinction in their optical spectra, and I shall include objects at all abserved redshifts. The only point to note here is that some objects which have been classified as QSOs but which have very small redshifts, are probably better grouped with the compact or N-type galaxies. A distinction can be drawn primarily by means of the properties of the continuum radiation, and secondarily by the nature of the emission-line spectra.

II. EMISSION-LINE SPECTRA.

1. *Identification of lines.*

The emission lines found in spectra of QSOs are those expected to be produced in a hot gas at fairly low density with a chemical composition similar to that of the sun and the stars and gaseous nebulae in the solar neighborhood. Since the redshifts of QSOs generally fall in the range $z = 0.2 - 2$, the most easily observable optical wavelength region encompasses lines of rest wavelengths in the range about 1200 — 5000 Å. A table of ultraviolet lines to be expected in the spectra of planetary nebulae of normal composition, which was prepared by OSTERBROCK (1963) in anticipation of satellite observations of the spectra of planetary nebulae, proved to be most helpful in identifying lines in the early spectroscopic observations of QSOs with big redshifts. OSTERBROCK and PARKER (1966) later compared calculated line strengths with observed lines in order to derive an estimate of the physical conditions in the emitting gas, and published a table of observed and predicted lines.

A useful table which groups lines according to electron configuration in the emitting ions was published by LYNDS (1968). All possible transitions were listed between about 1000 and 7000 Å, in the various ionization stages of all elements having a solar-neighborhood ("normal") relative abundance greater than 10^{-6} hydrogen, and those transitions which had actually been observed were noted.

BURBIDGE and BURBIDGE (1967) gave a compilation of emission lines observed in 60 QSOs, with eye estimates of intensity. An updated version of this table has been prepared, but the conclusions to be drawn from it are unchanged; no new identifications are indicated. OSTERBROCK (1969) published an updated list of calculated line strengths for the elements H, He, C, N, O, Ne, and Mg in "normal" abundances, and also a further list of weaker lines from Mg, Si, S, Ar, some of which have been observed.

Table 1 lists most of the emission lines observed in the range about 1200 — 5000 Å. A few lines identified only rarely have been omitted, e.g. Fe II and Na I features seen in 3C 273 (Wampler and Oke 1967) and [Mg VII]. A line observed in several QSOs at 2974 Å, originally identified as [Ne V], has been suggested by Véron (1967) to be due to [O I]. The lines marked with asterisks in Table 1 are generally the strongest and the most useful in determining redshifts. Because of the overall similarity of most QSOs, two strong lines visible in the spectrum of a newly-observed QSO will usually suffice to determine its redshift, although the observers try to obtain confirmation from the presence of other less strong lines.

Table 1 — *Principal Emission Lines Seen in Spectra of QSOs, 1200 — 5000 A.*

Ident.	λ (A)	Ident.	λ (A)
Ly - α	1216*	Mg II	2798^{*+}
N V	1240^{+}	[Ar IV]	2854, 2869
Si IV	1397^{+}	[Mg V]	2931
O IV]	1406	He II	3203
C IV	1549^{*+}	[Ne V]	3346, 3426
He II	1640	[O II]	3727^{+}
O III]	1664	[Ne III]	3869, 3968
C III]	1909*	[O III]	4363, 4959, 5007*
C II]	2326	Balmer series	4102, 4340, 4861*

* Strongest transitions.
$^{+}$ Blends of doublets.

2. *Widths of Emission Lines.*

The emission lines are characteristically broad, 50 — 100 Å or more in the redshifted frame of reference. Little quantitative work on line profiles has been done; widths have mostly been roughly measured or estimated during wavelength measures for the determination of redshifts. Sometimes, particularly for QSOs of fairly small redshift, the forbidden lines are quite narrow while the Balmer lines are broad; this effect is characteristic of the spectra of nuclei of Seyfert galaxies, and in fact the generally large line widths in QSOs are an indication that similar physical processes are at work in both classes of object.

In PKS 1217 + 02, with $z = 0.240$, an illustration by LYNDS (1968) shows [O III] λλ4959, 5007 no wider than the instrumental profile; the nearby Hβ is about 50 Å wide, and [O III] λ4363, the transition which comes from an upper level of higher excitation than the other two [O III] lines, is of intermediate width. In other QSOs, however, the forbidden lines are all broad, but the general tendency is for the permitted lines, especially the resonance lines, to be the broadest. In QSOs with the very smallest redshifts all lines can be quite sharp, and this is one indication that such objects are probably better classed as small compact galaxies rather than as QSOs. The question of the mechanism for causing line broadening — electron scattering or Doppler broadening — falls outside the province of this descriptive talk.

3. *Observed Range of Ionization.*

A large range of ionization is represented in the spectra of the QSOs, from 7.6 ev which is required for single ionization of Mg, to 97 ev required to produce Ne^{+4} or 109 ev for Mg^{+4} (or even 186 ev for Mg^{+6} if [Mg VII] is indeed present in a few spectra).

4. *Spectroscopic Differences between Objects; Case of N V λ1240; New Observations of Large-Redshift QSOs.*

Although the emission-line spectra of the QSOs examined so far show great similarity one to another, there are distinct differences between some objects and eventually, when more quantitative work on line intensities and profiles has been done, it may be feasible to group them into different classes. Even the first two objects to be studied spectroscopically, 3C 48 and 3C 273 (GREENSTEIN and SCHMIDT 1964), clearly showed differences which led to different electron densities for the two.

The emission feature N V λ1240 is quite variable from one object to another. For example, the radio-quiet QSO PHL 3424 (SANDAGE and LUYTEN 1967) has N V nearly as strong as Ly α, while N V is absent in many QSOs of about the same redshift as PHL 3424. Another good example of an object with strong N V is 5C 2.56. I had earlier obtained a tentative redshift of 2.38 for this object, but was somewhat puzzled because Ly α was very broad and appeared to be blended with N V λ1240. I was unable to confirm this redshift as the object dropped in brightness, becoming around 20th magnitude. After two years, however, it brightened again this spring and spectrograms obtained at Lick have given $z_{em} = 2.388$; N V λ1240 is indeed present and is nearly as strong as Ly α and almost blended with it. Figure 1 shows this portion of the spectrum of 5C 2.56 on three spectrograms, taken in 1968, 1969 and 1970.

Rather weak Ly β emission is also visible in 5C 2.56; the big redshift brings it into the easily observable region. No quantitative measures have yet been made on the intensities. BAHCALL (1966) has given a theoretical discussion of the way in which the ratio of Ly α to Ly β can give information on physical conditions in the emitting region.

The recent discovery by LYNDS and WILLS (1970) of the very big redshift of the QSO 4C 5.34 is also interesting in this respect. It has less broad, very strong emission lines (see Figure 2), and study of Ly α, Ly β, and the Lyman limit will be possible and should give interesting results. I return to a discussion of the continuum of 5C 2.56 and 4C 5.34 in Section IV.

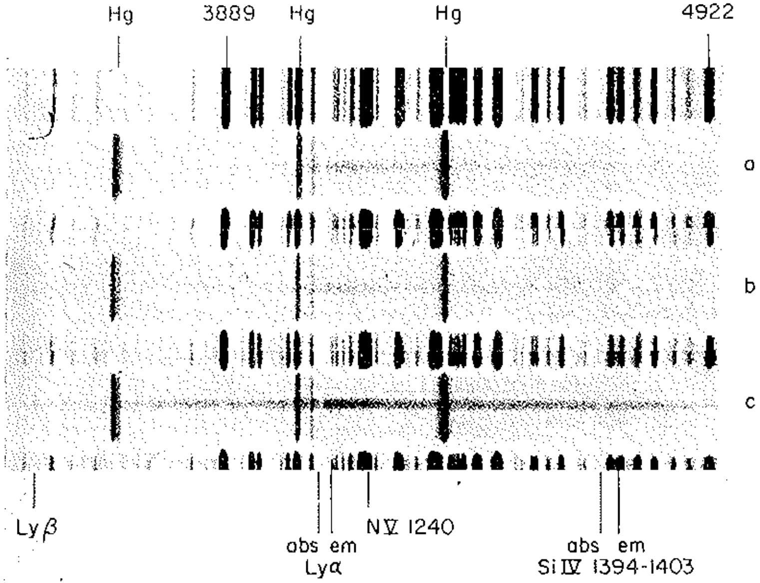

FIG. 1 — Three spectrograms of the QSO 5C 2.56 ($z_{em} = 2.388$), obtained with the 120-inch telescope at Lick Observatory. *a*: April, 1968; *b*: March, 1969; *c*: April, 1970. Object was very faint in 1969, but had brightened by 1970. Note strength of N V λ1240, presence of Ly-α and Si IV absorptions, and Ly-β at 3476 Å. Strong night-sky Hg lines, and two comparison lines to indicate wavelength scale, are marked at top.

III. ABSORPTION-LINE SPECTRA.

1. *3C 191; Analogy With Hot Galactic Supergiant Stars.*

The first QSO in which a set of many absorption lines was detected was 3C 191 (BURBIDGE, LYNDS, and BURBIDGE 1966; STOCKTON and LYNDS 1966). This object has the usual broad emission lines with a redshift $z_{\text{em}} = 1.953$. Its absorption lines are much narrower than the emissions, and proved to be easily identified, at a redshift $z_{\text{abs}} = 1.947$, with transitions out of the ground levels of various ions to be expected on the basis of the features already known to occur in emission in QSOs. Of the lines listed in Table 1, Ly α, N V, Si IV, and C IV were all found in absorption in 3C 191, together with other ground-level lines arising from lower stages of ionization.

Since 3C 191 still provides the best example of a normal absorption-line spectrum, the absorption lines found in it are listed in Table 2. In Section III (3) the occurrence of absorption lines of longer wavelengths in QSOs with multiple redshifts is discussed, and a table appropriate to that wavelength region is given there; in order to make the listing of absorption lines more complete, Table 2 also lists some lines possibly present in 3C 191, and some lines present in PKS 0237-23 [see Section III (3)].

Some of the Si II lines in Table 2 are transitions arising from excited fine-structure levels in the ground state of Si^+, and these have provided the basis for an analysis by BAHCALL and WOLF (1968) of the physical conditions and location of the absorbing gas. It must be quite near the QSO, for these levels would have a negligibly small population in clouds of gas in intergalactic space.

It is interesting that the discovery of the absorption lines in 3C 191 came at about the same time as SHKLOVSKY, BAHCALL and SALPETER predicted that resonance absorptions from certain atoms and ions might be produced in the spectra of QSOs by intergalactic gas lying between the object and the observer. However, the lines in 3C 191 could all be identified at a single redshift, close to the emission-line redshift, and because of the fact that the excited fine-structure ground levels were populated, they clearly arise in gas close to the regions producing the continuum and the emission lines.

TABLE 2 — *Absorption Lines in Spectrum of 3C 191.*

Ident.	λ (A)	Ident.	λ (A)
Si II	1190.4	C II	1335.3
Si II	1194.2	Si IV	1393.8
Si III	1206.5	Si IV	1402.8
Ly α	1215.7		
N V	1238.8	Si II	1526.7
N V	1242.8	Si II	1533.4
Si II	1260.4	C IV	1548.2
Si II	1264.8	C IV	1550.8

Possible Lines in 3C 191, or Additional Lines in PKS 0237-23.

Ident.	λ (A)	Ident.	λ (A)
S III	1190.2	S II	1259.5
S III	1194.1	Al II	1670.8
S II*	1231.8	Si II	1816.9
S II	1250.5	Al III	1854.7
S II	1253.8	Al III	1862.8

* From metastable level.

The difference between the absorption and emission line redshifts in 3C 191, if taken as a Doppler difference, gives a velocity of some 600-1000 km/sec for the outward motion of the shell. This is quite small compared with some of those found subsequently.

A direct comparison can be made between the spectrum of 3C 191 and the far-ultraviolet rocket spectra of O and early B stars in Orion, obtained by MORTON (1967a, b) and MORTON, JENKINS, and BOHLIN (1968). The stars δ Ori (O 9.5 II), ε Ori (B0 Ia), and ζ Ori (O 9.5 Ib) show the resonance lines of C IV, N V, Si III and Si IV which appear in 3C 191, and they are shifted to shorter wavelength by some 1800 km/sec with respect to the stars themselves. LUCY and SOLOMON (1970) accounted theoretically for these P Cygni-type profiles by the effect of radiation pressure in hot supergiant stars, leading to continuous mass loss from the stellar surfaces. It is not surprising that something similar should occur in QSOs.

Concerning the possbile occurrence of intergalactic absorption lines, it is worth noting that the only certain interstellar absorption seen in the spectra of these hot stars in Orion was Ly α, although interstellar lines of C I, O I, Al II, and Si III were possibly present. Interstellar lines of C II, O I, Al II, and Si II were, however, found by STONE and MORTON (1967) in the rocket spectra of δ and π Scorpii. Table 3 lists these lines with their measured equivalent widths.

As I shall discuss, it is likely that all the absorption lines found so far in the spectra of QSOs are produced in gas that is or has been associated with the objects themselves. Therefore this phenomenon would appear to be connected with the activity of the QSOs, which has led to the ejection of gas from them, and is therefore of great interest in the general study of violent activity in compact objects. As the next step in this line of argument, we turn now to various objects where large differences in redshift and multiple absorption redshifts have been found.

TABLE 3 — *Interstellar Lines in the Spectra of δ and π Scorpii.*

δ Sco	π Sco	Ion	λ (Lab) (Å)	Multiplet	$J_l - J_u$	$(gf)_{mult}$	W_λ (Å)	
							δ Sco	π Sco
1302.77	1302.44	O I	1302.174	$2p^4\ {}^3P - 3s\ {}^3S^o$	2 – 1	0.32	1.2	1.1
1334.69	1334.40	C II	1334.515	$2p\ {}^2P^o - 2p^2\ {}^2D$	$\frac{1}{2}\ \frac{3}{2}$	0.68	0.9	0.9
1525.76	1525.55	Si II	1526.719	$3p\ {}^2P^o - 4s\ {}^2S$	$\frac{1}{2}\ \frac{1}{2}$	0.78	0.6	0.45
1671.65	. . . . .	Al II	1670.81	$3s^2\ {}^1S - 3p\ {}^1P^o$	0 – 1	1.5	1.2	. .

2. *PHL 5200 and RS 23.*

PHL 5200 was identified with the radio source 4C-5.93 by SCHEUER and WILLS (1966), and LYNDS (1967) found it to have a spectrum unlike that of any other QSO so far found. The spectrum resembles that of a supernova; very wide absorption bands of C IV, Si IV, N V, and Ly α lie on the short wavelength side of somewhat narrower emission features, with a very sharp boundary between the emission and absorption features, and LYNDS found structure within the broad emission bands. He suggested that the very broad absorptions were produced in an expanding shell of gas around the central energy source, with a large velocity gradient in this shell. BURBIDGE (1968, 1969) found that the structure in the Si IV absorption band appeared to have taken the form of fairly sharp minima in the small residual intensity within the very broad absorption bands — absorption "dips" — corresponding to Si IV $\lambda\lambda 1394, 1403$ at $z = 1.950, 1.891$.

The total width of the absorption bands corresponds to a range of outward velocity in an expanding shell from 0 — 10,000 km/sec. Gas expanding outward under the action of radiation pressure in resonance lines of abundant atoms and ions might acquire stable velocities at particular values, governed by the incidence of *other* strong resonance lines at different redshifts but coincident wavelengths. One can see qualitatively how this mechanism can lead to a discrete and fairly stable pattern of outflow velocities whose observational consequence would be the appearance of absorption lines at a number of separate, and even widely different, redshifts. This idea has particular application to the multiple-redshift objects described in Section III (3).

RS 23 is a radio-quiet blue stellar object suggested by RICHTER and SAHAKJAN (1965) to be a candidate QSO from its *UBV* colors; it was confirmed as such by BURBIDGE (1970), and the redshift $z_{em} = 1.908$ was found. It has strong rather broad absorptions adjacent to and on the short wavelength side of its emission lines, resembling what is seen in PHL 5200 except that the absorptions in RS 23 are less broad. SCARGLE, CAROFF, and NOERDLINGER (1970) have studied the profiles of the absorption features in both PHL 5200 and RS 23, and have concluded that they are produced by pure scattering in an outward-moving thick shell, probably driven by radiation pressure.

3. *The QSOs With Multiple Absorption Redshifts: Ton 1530, PHL 938, and PKS 0237-23.*

The radio-quiet QSOs Ton 1530 and PHL 938, and the radio source PKS 0237-23, with a radio spectrum that has a maximum and turns over at low frequencies, have very interesting optical spectra with large emission-line redshifts and many sharp absorption lines, which could not be identified until a new concept was accepted — that the absorption lines can appear at multiple values of the redshift, some very different and much less than the emission-line redshift. As well as their unusual optical spectra, these three objects are unusual because two of them are radio-quiet (which may mean that they have synchrotron spectra that turn over at fairly high frequencies), and one of them exhibits directly the signs of synchrotron self-absorption. Further, all are optically fairly bright.

BURBIDGE, LYNDS, and STOCKTON (1968) analyzed these three objects and found that some of the many sharp absorptions in Ton 1530 could be identified at three separate redshifts. Almost all the absorptions in PHL 938 could be identified at two redshifts, one $z = 0.6128$, being very much smaller than the emission-line redshift; the lines identified in this system are listed in Table 4. Meanwhile, the lines in PKS 0237-23 required some seven separate redshifts to explain them and still a considerable number of lines were left unidentified. BAHCALL, GREENSTEIN, and SARGENT (1968) independently analyzed PKS 0237-23 and came to the same conclusion that multiple redshifts had to be invoked to explain the absorption lines; they adopted five separate values. BAHCALL, OSMER, and SCHMIDT (1969) subsequently added two more redshifts to the values found by BURBIDGE *et al.* in Ton 1530. All these separate redshifts are listed in the last column of Table 5, which is a compilation of QSOs with emission-line redshifts greater than 1.8.

TABLE 4 — *Identified Absorption Lines in PHL 938.*
(BURBIDGE, LYNDS and STOCKTON 1968)

Measured λ Å	Identification		Redshift
3533.2	Ly α	1215.7	1.9064
3644.2	Fe II	2260.1	0.6124
3779.1	Fe II	2343.5	0.6126
3818.6	Fe II	2366.9	0.6134
3827.1	Fe II	2373.7	0.6123
3841.6	Fe II	2382.0	0.6127
4171.2	Fe II	2585.9	0.6131
4193.0	Fe II	2599.4	0.6131
4509.1	Mg II	2795.5	0.6130
4520.1	Mg II	2802.7	0.6128

Most of the lines still left unidentified in both Ton 1530 and PKS 0237-23 lie on the short wavelength side of the Ly α emission lines in each spectrum, and BURBIDGE *et al.* (1968) suggested that they might actually be Ly α absorption at a multiplicity of redshifts, produced by gas of insufficient optical depth to yield measurable absorptions in other, less abundant, atoms and ions.

Historically, the first case discovered of a QSO with absorption lines at more than one redshift was PKS 1116+12, with $z_{em} = 2.118$. Lynds and Stockton (1966) found a strong absorption component in the short-wavelength wing of the broad Ly α emission, about 26Å from the center of this emission. It was apparently not seen by Schmidt (1966) on his spectra of PKS 1116+12, but Bahcall, Peterson, and Schmidt (1966) detected two other absorptions, probably Ly α and C IV λ1549, at $z_{abs} = 1.947$, i.e. a redshift corresponding to some 17,000 km/sec less than the respective emission-line centers.

However, what led Burbidge, Lynds and Stockton to the concept of multiple absorption redshifts was the spectrum of PHL 5200, where, as described in Section III (2), the broad absorption bands show signs of incipient breakup into discrete narrow absorptions. We were also struck by the near-coincidence of the strongest lines at one redshift to an expected transition from a different ion at another redshift — e.g., the Mg II λλ2796, 2803 lines at $z_{abs} = 0.6128$ lie on the short wavelength side of the C IV λ1549 emission line at $z_{em} = 1.955$. In fact, the Mg II absorption, which was visible on the first spectrograms of PHL 938 obtained by Kinman (1966), was originally thought to be due to C IV λλ1548, 1551 at a redshift of about 1.914, because there is strong Ly α absorption at $z = 1.906$, and this seemed the obvious interpretation, despite the poor agreement in z. It was only the clear resolution of the doublet on our higher-resolution spectrograms that showed the absorption could not be the C IV doublet, which has the wrong separation, and this led to the correct interpretation. This is shown in Figure 2, where the spectra of the three QSOs under discussion are reproduced along with that of 4C 25.5, another object with a large emission-line redshift and a complex absorption spectrum (Schmidt and Olsen 1968). The absorption lines in 4C 25.5 have not yet been fully identified.

TABLE 5 — *QSOs with Redshifts Greater than* $z = 1.8$ (*absorption and emission*).

Object	α 1950	δ 1950	z_{em}	z_{abs}
PKS 2146 – 13	21 46 46	– 13 18.7	1.801	1.785
3C 432	21 20 24	+ 16 51.7	1.805	
PKS 2354 + 14	23 54 44	+ 14 29.5	1.810	
PHL 3424	01 31 12	+ 05 32	1.847	
B 194	12 56 08	+ 35 44.9	1.864	1.8366, 1.8946
RS 23	13 33 55	+ 28 40.3	1.908	1.873
PHL 1222	01 51 12	+ 04 48	1.910	1.934 (one line assumed to be Ly α)
4C 29.50	17 02 11	+ 29 51.0	1.927	
PKS 2134 + 004	21 34 04	+ 00 28.2	1.936	
PKS 0119 – 04	01 19 56	– 04 37.3	1.955	1.965
PHL 938	00 58 12	+ 01 56	1.955	1.9064 (one line assumed to be Ly α), 0.6128
3C 191	08 02 04	+ 10 24.1	1.956	1.947
BSO 6	12 59 30	+ 34 27.2	1.956	
PHL 5200	22 25 54	– 05 34	1.98	1.90 – 1.98; 1.9502, 1.8910
PKS 1148 – 00	11 48 10	– 00 07.2	1.982	
PHL 1127	01 41 30	+ 05 14	1.990	1.95 (one line assumed to be Ly α)
LB 8755	08 48 05	+ 15 33.5	2.010	
3C 9	00 17 50	+ 15 24.3	2.012	
Ton 1530	12 22 57	+ 22 53	2.046	2.0553, 1.9798, 1.9362, 1.9215, 1.8866
PHL 1305	02 26 24	– 03 52	2.064	
PKS 0229 + 13	02 29 02	+ 13 09.7	2.065	
B 189	12 56 51	+ 36 48.2	2.075	
BSO 11	13 11 22	+ 36 16.5	2.084	2.028
PKS 2254 + 024	22 54 44	+ 02 27.3	2.09	
PKS 0106 + 01	01 06 02	+ 01 19.1	2.017	
PKS 1116 + 12	11 16 20	+ 12 51.0	2.118	1.947
PKS 0424 – 13	04 24 48	– 13 09.6	2.165	
QS 1108 + 285	11 08 26	+ 28 57.9	2.192	
PKS 0237 – 23	02 37 53	– 23 22.1	2.228	2.2017, 1.9556?, 1.6744, 1.6715, 1.6564, 1.5958, 1.5132, 1.3646.
4C 25.5	01 23 56	+ 25 43.9	2.358	2.3683
5C 2.56	10 55 18	+ 49 55.6	2.388	2.370
4C 5.34	08 05 21	+ 04 41.4	2.877	2.475

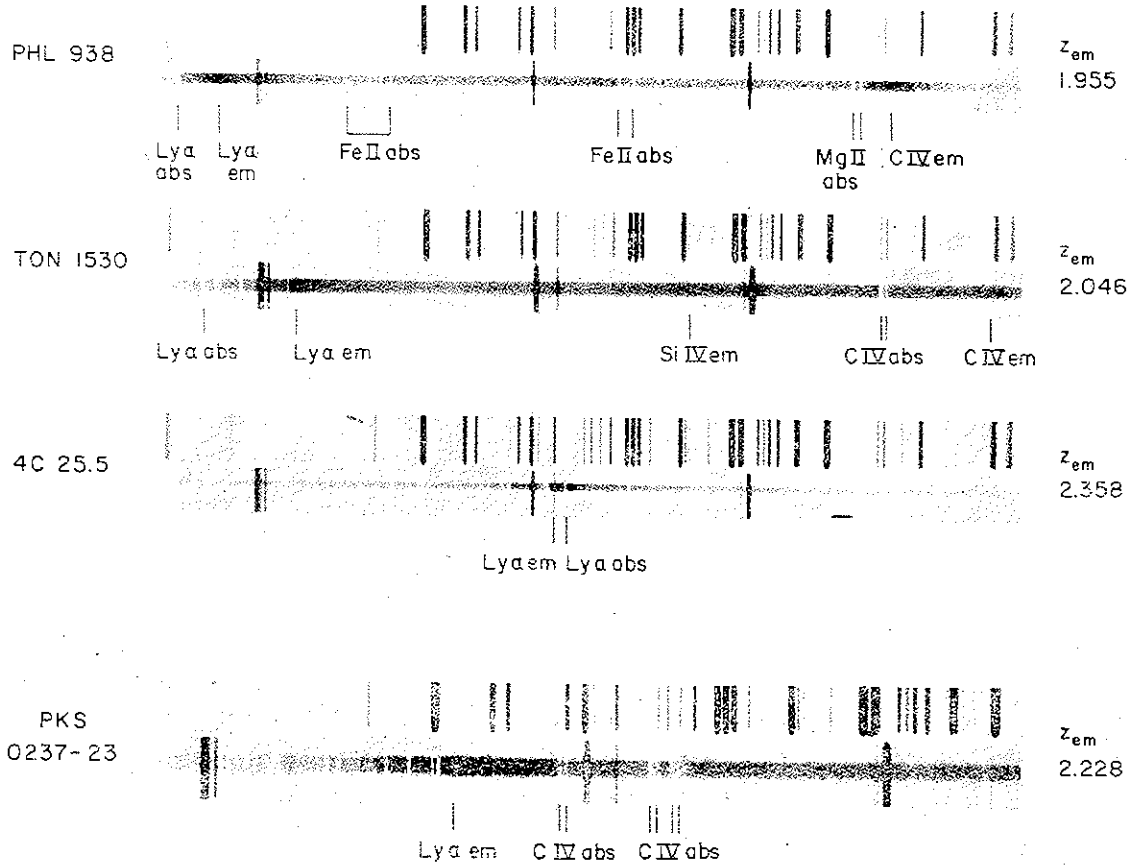

FIG. 2 — Selected regions of spectrograms of four QSOs with complex absorption spectra, obtained with 120-inch telescope at Lick Observatory, with a resolution of about 2Å. Wavelength region: 3480—4740 Å on upper three, 3580—4500 Å for PKS 0237—23. A few absorption-line identifications are indicated; more details of absorption-line redshifts are given in Tables 4 and 5. Note different separations of Mg II doublet in PHL 938 and C IV doublet in Ton 1530, and three sets of C IV doublet in PKS 0237—23.

Table 4 lists the absorption lines identified in the system with $z = 0.6128$ in PHL 938. Equivalent widths of the lines have been measured on Lick spectrograms, and there are enough for some attempt to be made at determining physical conditions in the absorbing gas; this has been discussed by DEMOULIN and DORAS (1970) and by CHAN and BURBIDGE (1970). The lines are strongly saturated, with small Doppler widths corresponding to only about 50 km/sec velocity dispersion. The numbers of absorbing ions along the line of sight are

$$N(Fe^{+}) = 7 \times 10^{14}\ \mathrm{cm}^{-2}$$
$$N(Mg^{+}) = 4 \times 10^{14}\ \mathrm{cm}^{-2}$$

according to CHAN and BURBIDGE, using STRÖMGREN's doublet method.

4. *Comparison Between NGC 4151 and QSOs with Multiple Absorption Redshifts.*

The multiple absorption redshifts in QSOs have been found recently to have a remarkable counterpart in the spectrum of the nucleus of the Seyfert galaxy NGC 4151. ANDERSON and KRAFT (1969), using Lick coudé spectrograms, found discrete narrow absorption components in He I λ3889 arising from the metastable 2^3S state at three distinct velocities. Relative to the nucleus itself these were − 280, − 550, and − 840 km/sec; weaker components were also visible in the Balmer lines, the largest velocity difference being − 970 km/sec at Hβ. These lines can best be interpreted as arising in gas ejected from the nucleus of NGC 4151, which is known to be variable in optical light. CROMWELL and WEYMANN (1970) observed that these components are variable, so that clouds, filaments, or shells are produced on a time scale of order one year. The multiple nature, and the displacements toward shorter wavelength, when combined with the many analogies between QSOs and Seyfert nuclei, strongly suggest that the phenomenon of the absorption components has a basically similar cause in the two classes of object.

5. *Compilation of Results on Absorption Lines; Discussion.*

Table 5 shows all QSOs with $z_{\mathrm{em}} \geq 1.8$ which possess absorption lines (or all available in the literature). This list includes the multiple-redshift objects and all the separate absorption redshifts are tabulated. The majority of QSOs having absorption lines are the objects of large redshift, and one may ask whether this is a real effect or a selection effect due to the greater number of resonance lines in the further ultraviolet. WEYMANN and WILCOX (1968) thought it to be due to selection, but LYNDS (1968) looked at QSOs with redshifts in four very different ranges, such that different resonance lines come into view, and tentatively concluded that the absorption-line phenomenon is more common among objects of large redshift. BURBIDGE and BURBIDGE (1969a), when additional redshifts had been measured, concluded that the effect is not due to selection.

Three possible interpretations for the absorption lines come to mind:

1) they arise in gas around the QSO and moving relatively to it;

2) they are produced by intervening objects lying between the observer and the QSO — either intergalactic clouds or galaxies;

3) if a model of a QSO could be constructed giving large gravitational redshifts, then shells of gas further out from the central object might lie in a lower gravitational potential.

All three suggestions are designed for absorption redshifts that are smaller than the emission-line redshifts, yet a significant number — about 1 in 3½ of all cases — have $z_{\rm abs} > z_{\rm em}$, as shown in Figure 3.

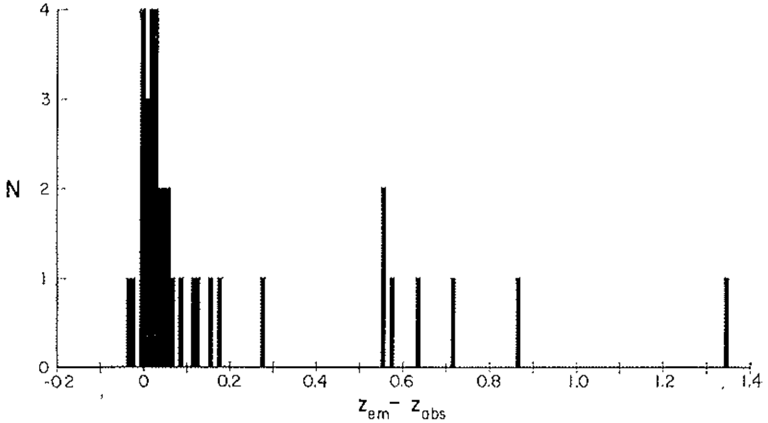

FIG. 3 — Histogram showing distribution of values of $z_{em}-z_{abs}$ for those QSOs having both absorption and emission lines. N = number with given $z_{em}-z_{abs}$, in intervals of 0.01.

We believe that the first explanation is the correct one (see also BURBIDGE and BURBIDGE 1969b). It does require, however, very large ejection velocities in some cases — 90,000 km/sec for the smallest redshift in PKS 0237-23 and 160,000 km/sec in PHL 938. The occurrence of several redshifts in a very few objects, while many QSOs have only one set of absorption lines or none at all, argues against the second explanation; further, the histogram of $z_{\rm em} - z_{\rm abs}$ in Figure 3 shows that in the majority of cases this difference is not large and the absorbing gas is most likely to be associated with the QSO. The similarity of the phenomenon in NGC 4151 is another argument in favor of the first explanation. Cases in which $z_{abs} > z_{em}$ could be due to infalling gas; in the QSOs Ton 1530 and B 194, where both $z_{abs} \lesseqgtr z_{em}$ are simultaneously present, one wonders whether the shells will collide.

Before leaving the discussion of the line spectra, it may be of interest to see a histogram of the distribution of all redshifts, from both absorption and emission lines. This is shown in Figure 4, where the growth of knowledge of these is demonstrated by the three histograms plotted for data available in three different years. This includes objects of small redshift that are related to the QSOs. The growth of the much-discussed peaks at $z = 0.061$ and $z = 1.95$ is to be noted (BURBIDGE and BURBIDGE 1969a, b).

III. CONTINUA.

The early work on colors of QSOs by SANDAGE and his colleagues (e.g. MATTHEWS and SANDAGE 1963) showed that their continuous energy distributions in the optical region were unlike hot stars and were in fact best explained either by a power-law, $F(\nu) \propto \nu^{-\alpha}$, as in synchrotron radiation, or by an exponential law, $F(\nu) \propto e^{-\nu/\nu_0}$. The characteristic features are a strong ultraviolet flux, first used by SANDAGE as a means of identifying QSOs, and, in many objects, a strong infrared flux, first discovered in 3C 273 by JOHNSON (1964) and JOHNSON and LOW (1965). At long wavelengths this infrared flux peaks above a power-law curve joining the radio and optical fluxes. The high flux in the near infrared has been used, e.g. by BRACCESI, LYNDS, and SANDAGE (1968), as a means of discovering QSOs; stellar images found to be unusually strong in both *UV* and *IR* are almost certain to be valid QSO identifications.

Since SANDAGE will discuss *UBV* measures of QSOs and variability, I shall not cover these topics here. SANDAGE's composite average continuum with broad bumps on it, con-

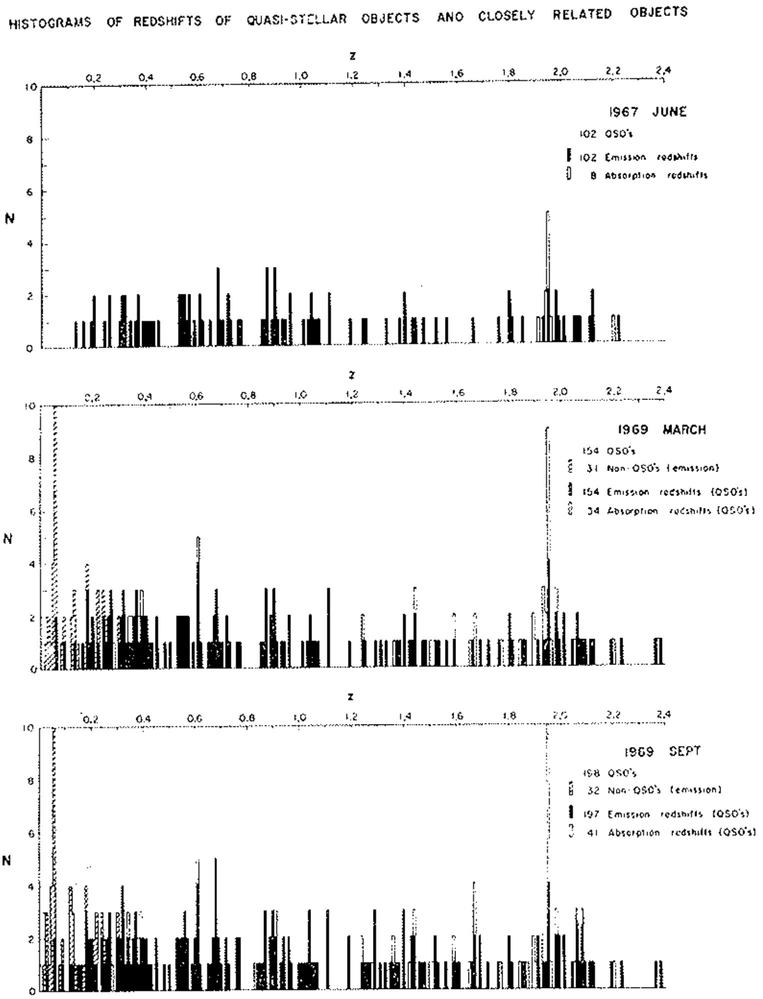

FIG. 4 — Distribution of redshifts of QSOs at three different times (QSOs only in 1967; closely related emission-line objects also in 1969 data). Shows growth of data and peaks at $z = 0.061$ and 1.95. N = number with given z, in intervals of 0.01.

structed from his *UBV* measures of many QSOs at various redshifts, and the correlation between *UBV* colors and redshift discovered independently by several workers, were shown by STRITTMATTER and BURBIDGE (1967) to be due to a smooth continuum of the power-law or exponential form with the strongest characteristic emission lines superposed on it.

Scanner observations giving absolute spectrophotometric data have been made at Lick by WAMPLER and by OKE at Palomar. The most recent body of data consists of a study of 28 QSOs between 0.32 — 2.2μ, by OKE, NEUGEBAUER, and BECKLIN (1970). These objects clearly do not have one single common form for the energy distribution; they have power-law spectra with indices ranging from - 0.2 to - 1.6. No difference between the radio-quiet and the radio-emitting QSOs was found. For the QSOs which are strongly variable in visual magnitude, the energy distributions have not been found to change during the variations.

Figure 5 shows a Hubble-type plot of log z against magnitude; the enormous scatter in this diagram has been the subject of much discussion and has been one of the factors leading some people to question the cosmological nature of the redshifts. There is still much work to be done on the magnitudes; many of the values used in this plot are very approximate eye estimates made from the Palomar Sky Survey prints.

An interesting question has been whether there is a sharp drop in continuum radiation shortward of the Lyman limit. It has, for example, been suggested that a cutoff or steep drop here might account for the very marked falling off in numbers of QSOs having $z > 2.2$, shown in Figure 4, and the lack of QSOs with very large redshifts. The usual method of finding QSOs, by looking in accurate radio source positions for stellar objects appearing blue on the Palomar Sky Survey prints, or for objects with *UV* excess, would lead to a strong observational selection effect against objects with large redshift, if there

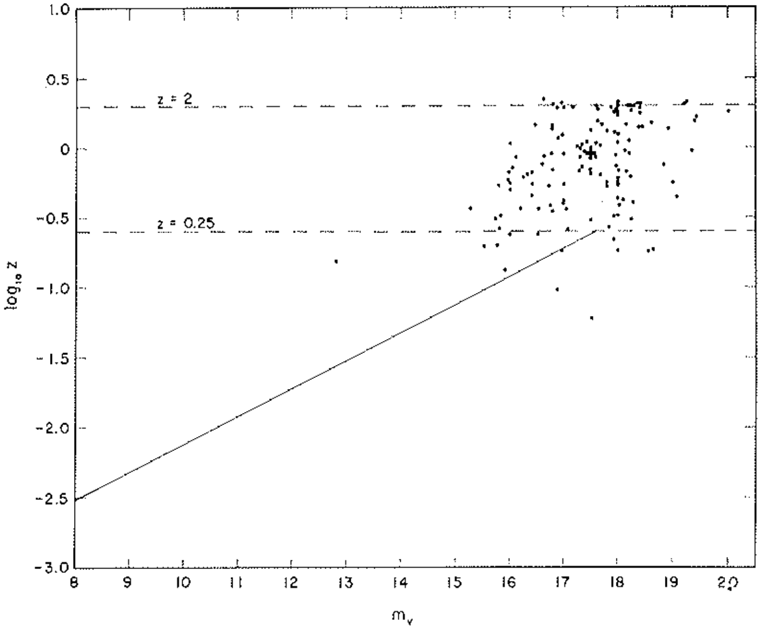

FIG. 5 — Redshift-apparent magnitude relation for 136 QSOs (taken from BURBIDGE and BURBIDGE 1969b). Full line is the Hubble relation for normal galaxies.

were little or no radiation escaping shortward of the Lyman limit.

However, LYNDS and WILLS (1970) recently found a QSO with $z = 2.88$, and there appears to be no observational reason why more such objects should not have been found if they did in fact exist. This object, 4C 5.34, was picked as a blue stellar object on the Palomar Atlas, it is a shade brighter than 18th magnitude, and it does have radiation shortward of the Lyman limit, which is brought to the easily observable redshifted wavelength of 3536Å. Figure 6 shows Lick spectrograms of 4C 5.34, and it will be seen that Ly α and C IV λ1549 are

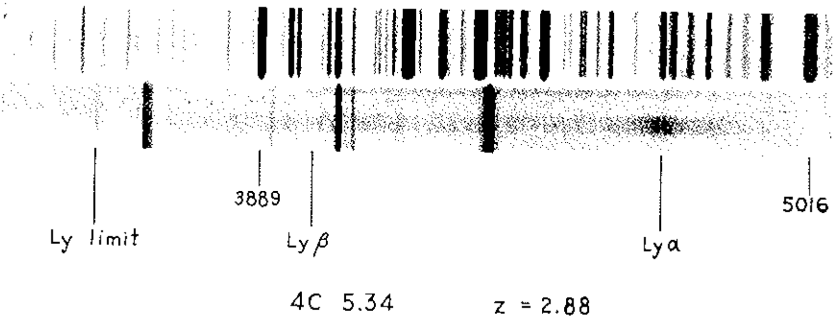

FIG. 6 (a)

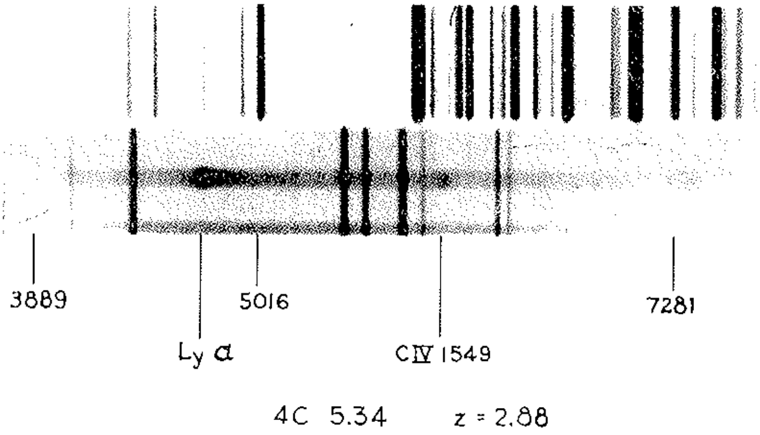

FIG. 6 (b)

FIG. 6 — Spectrograms of 4C 5.34, obtained with Lick 120-inch telescope, showing wavelength regions (a) 3700—5000 Å and (b) 4000—7000 Å (wavelengths of comparison lines at 3889, 5016, 7281 Å are marked for reference). Note great strength of emission lines of Lyα and C IV λ1549. Object was photographed low in western sky through large air mass, features from night sky and city light contamination are therefore very strong and spectrum is heavily absorbed shortward of Hg λ3650 lines.

strong, broad, easily-observable lines. Thus the lack of QSOs with redshifts much greater than 2.2 must be accepted as a real effect.

In conclusion, let me return to the QSO of second largest known redshift — 5C 2.56. Figure 1 shows the spectrum on three different dates, during the period when the luminosity varied. It is not possible from photographic data to make an accurate comparison between the flux emitted in the emission lines, relative to the continuum. It is well known that in 3C 446, which is strongly variable, the emission lines became much less distinct at maximum light, because their flux remained constant while the continuum varied. Yet the third spectrogram of 5C 2.56 shows the emission lines quite distinctly. It will be interesting to carry out absolute spectrophotometry on this object to see whether its emission lines also remain constant while the continuum varies.

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DISCUSSION

Chairman: W. W. MORGAN

SALPETER

You mention that one possibility for the multiple absorption lines are gravitational shells which then would have to be very thin to make the line sharp, and therefore of high density. Did you estimate roughly how high the density would have to be inside such a shell with a gravitational redshift?

E. M. BURBIDGE

No. I have not made an estimate.

AMBARTSUMIAN

I would like to ask Mrs. BURBIDGE; can you find any systematic change of absorption lines, of their intensities or of the number of components, with the distance (redshift)?

E. M. BURBIDGE

I did not have time to show the correlation of number of absorption line appearances with redshift, but the histogram showed all redshifts, all sets of absorption lines that had been seen in any object. There are three main resonance features that you can look for, that is the Mg II, the C IV and Lyman α. They are valid as indicators of absorption lines over different ranges of redshifts. The tendency is to get more objects with absorption at high redshift. The proportion of objects that show any absorption at all increases steeply with redshift. I did not mention that the white spaces in the main histogram which I showed (of the buildup of the distribution of z over 3 different years) — these white spaces were the absorption redshifts. Yes, I would say that the increase of absorptions with z is not a selection effect. One could argue that Mg is less abundant than C and H, and so might be harder to see, but in those QSOs which show Mg II absorption it looks quite strong. It is difficult to make a direct comparison because of the very different wavelengths, but in PKS 0237-23 (the best multiple-z object), Mg II shows quite strongly in the absorption system of smallest z (1.36), on LYNDS's spectra, and C IV can also be seen in that system and then in the systems at greater z C IV looks about as strong as it did in the $z = 1.36$ system. Lyman α does not show in that, of course, but can just be seen (again on LYNDS's spectra) right down in the *UV* in the 1.67 system. Therefore, I conclude that Mg II 2798, which shows always so strongly in emission, is indeed a good indicator of whether absorption is present. Incidentally, SHKLOVSKY expected it to be the best feature to look for in intergalactic space.

AMBARTSUMIAN

Is the number of components also increasing? Is there a tendency for an increase in the number of components with red

E. M. BURBIDGE

Yes, because consider the 3 QSOs out of the 4 on the composite slide of 4 QSOs with multiple z which I showed (one of them is not sorted out yet). Of the three that have been sorted out, they all have an emission line redshift between $z = 1.9 - 2.2$.

SALPETER

I just want to understand your answer a bit better. If I understood the statement about selection effects, these effects are absent if you go to a fixed difference in velocity between emission and absorption lines; say up to a red shift difference of Δz 0.2 to 0.3.

If you stick to $\Delta z \gtrsim 0.2$, is it still true that there are more cases for high emission redshifts than for low emission redshifts?

E. M. BURBIDGE

Yes.

SANDAGE

How do you interpret this? Do you interpret it as radiation being absorbed between us and it, with the path length increasing with increasing z?

G. R. BURBIDGE

Of course not, but we are not allowed to talk theory here. Small Δz means that the gas is close to the QSO; for $z_{abs} > z_{em}$ it could not be intergalactic.

MORGAN

You are allowed to answer any question that is put to you. But I think that there really is a tendency for high emission-redshift objects to have more absorption in them than the lower redshift objects; this at least is the impression; it is not a selection effect, and I think the multiple absorptions confuse the issue somewhat. If you look at all of the absorption lines which you see in all objects — essentially three objects, as I recall, which have multiple absorption, give rise to half of the absorption lines which you ever see. In all of the other cases the absorption is very close to the emission. There is a tendency for those to be low redshift objects.

SPITZER

I had the impression that the number of spectra available with enough dispersion to show these narrow absorption lines was so small that one really didn't have a sufficiently adequate sample to make any firm statement. Do you agree with this or is my impression exaggerated?

E. M. Burbidge

The absorption line objects that I described all showed their absorption on the very first survey spectra that were taken, the low dispersion survey spectra. In the case of PHL 938 they were wrongly interpreted at that stage, but it was already realised that there was some kind of a lack of fit, there was something a little bit wrong with the "obvious" identification.

Oort

Have you thought about any models of the expulsion of these very high velocity shells? Can one make a model in which a shell is expelled with a z difference of the order of one, and still present a narrow line.

G. R. Burbidge

Well, Dr. Rees is indeed just just trying to make such a model. Maybe he will speak of that.

Rees

I could express it more quickly if I talked after Dr. van der Laan's talk tomorrow.

Morrison

Is there any connection between the absorption line entries near $z = 1.95$ and the estimated absolute luminosity?

E. M. Burbidge

Well, I don't really know. I can say that along the line of redshift $z = 2$ in the magnitude-log z plot, the objects that have the most absorption line redshifts are at the bright end of this line. For example, PKS 0237-23 is a little bit brighter than $m = 17$ and so is Tonantzintla 1530 brighter than 17th magnitude. There may be some correlation there I think, but of course 5C 2.56 is around 19 (that is the object in Fig. 1), and 4C 25.5 is about mag. 17.7.

PHYSICAL CONDITIONS IN THE ACTIVE NUCLEI OF GALAXIES AND QUASI-STELLAR OBJECTS DEDUCED FROM LINE SPECTRA

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As is well known the Seyfert galaxies are characterized by their spectra consisting of a continuum plus very wide emission lines, ranging up to a relatively high level of ionization, including [Ne V] and [Fe VII]. The first spectrophotometric work on these objects was due to SEYFERT [1] himself, and the first interpretation to WOLTJER [2]. Later many more spectrophotometric measurements have been published, by OSTERBROCK and PARKER [3], DIBAI and PRONIK [4], OKE and SARGENT [5], and SOUFFRIN [6], and in addition there are the very recent as yet unpublished measurements of WAMPLER and of ANDERSON. I have combined all of the later spectrophotometric results to form weighted average values that are used for each Seyfert galaxy throughout the discussion in this paper.

One of the most puzzling spectral features of several Seyfert galaxies, particularly in NGC 1068, was the very steep Balmer decrement for which no good physical interpretation was available until WAMPLER [7] showed that it results (at least in part) from interstellar extinction. He measured the [S II] line ratios suggested by MILLER [8], comparing the ^2D — ^2P λ10320 multiplet with the ^4S — ^2P λλ4069, 4076 doublet, all of which arise from the same upper ^2P term. Thus the emission rates in these two multiplets depend almost entirely on transition probabilities alone, and their intensity ratio can be accurately calculated. WAMPLER's measurements show very clearly that the observed values of this ratio in Seyfert galaxies are redder than the computed ratios, that the observed ratios differ from one galaxy to another, and that they are closely correlated with the observed Hα/Hβ and P7/Hδ ratios in these galaxies in the sense expected from interstellar extinction.

Therefore I have corrected all the measured relative emission line strengths for interstellar extinction. This was done using the standard WHITFORD [9] reddening curve for the wavelength variation of the extinction and the calculated radiative recombination relative line strengths of H at $T = 2 \times 10^4$ ° for the intrinsic color (since the [S II] ratios have not been measured for all the Seyfert galaxies). The amount of extinction was then calculated by comparing the observed and calculated Hβ/Hγ and the Hβ/Hδ ratios, adopting the mean of the two determinations. The results are listed in Table 1. For a few Seyfert galaxies the extinction was also calculated independently from the [S II] lines. It can be seen from Table 1 that there is quite good agreement for two of these galaxies but not for NGC 4151, in which the extinctions calculated from the H I lines and the [S II] lines disagree badly. The discrepancy is somewhat reduced if instead of the mean [S II] measured line strengths we adopt the measurement of this ratio made by WAMPLER, which differs by a factor of 2 from the measurement by ANDERSON. This illustrates the possible inaccuracies that can be encountered in measuring broad weak emission lines in faint objects with continuous spectra. The intermediate amount of extinction, $A_V = 0.9$: , calculated from WAMPLER'S measurement of the [S II] lines, has been adopted for NGC 4151.

TABLE I — *Derived interstellar extinction in Seyfert galaxy nuclei.*

	A_V (H lines)	A_V [S II]
NGC 1068	2.3	1.6
NGC 1275	2.3	2.5
NGC 3227	0	—
NGC 3516	0	—
NGC 4051	2.0	—
NGC 4151	3.3	0.2:
NGC 5548	0	—
NGC 7469	0	—
3C 120	0	—

The procedure used to correct for interstellar extinction is certainly not correct in detail, because the reddening curve is derived from observations that give the effects of scattering plus absorption by interstellar dust along the light path from a distant star, while in the case of a Seyfert galaxy nucleus the dust is observed in the photometer diaphragm or spectral scanner slit along with the emitting gas, and only absorption reduces the observed number of photons. However theoretical work by MATHIS [10] shows that the effects of absorption in this case are pretty well reproduced by the WHITFORD reddening curve. In addition of course the dust in Seyfert galaxy nuclei may be different from the dust in our Galaxy near the sun, where the reddening law is derived. Thus the corrections must be regarded as having a significance that is more qualitative than quantitative.

These extinctions were used to correct the observed Balmer decrements for extinction, with the results shown in Table 2, where it can be seen that the corrected Hα strength is generally somewhat higher than the strength calculated on the basis of recombination alone. This increased strength of Hα is perhaps partly due to some collisional excitation, though it may indicate that the interstellar extinction correction is not correct in detail.

TABLE 2 — *Balmer decrements in Seyfert galaxy nuclei corrected for interstellar extinction.*

	Relative Line Strengths			
NGC	Hα	Hβ	Hγ	Hδ
Observed Galaxies				
1068	36.	10.	5.1	2.3
1275	49.	10.	4.1	3.0
3227	52.	10.	4.0	2.9
3516	45.	10.	4.9	3.0
4051	20.	10.	4.5	2.9
4151	21.	10.	3.9	1.5
5548	50.	10.	5.5	2.6:
7469	37.	10.	4.7	2.7
3C 120	42.:	10.	5.1	2.8
Radiative Recombination Theory				
$T = 2 \times 10^4$				
$N_e \rightarrow 0$	28.	10.	4.7	2.6
$N_e > 10^8$	27.	10.	5.1	3.0
$T = 1 \times 10^4$				
$N_e \rightarrow 0$	29.	10.	4.7	2.6

As is well known, average values of the electron density N_e and temperature T can be derived from various forbidden line ratios such as [O II], [O III], [S II], [A IV], etc. Published results include $N_e = 10^4$ cm^{-3}, $T = 10^4$ in NGC 1068 [3], and $N_e = 5 \times 10^3$ cm^{-3}, $T = 2 \times 10^4$ in NGC 4151 [5]. There is no doubt that the degree of ionization, T and N_e vary with position within a Seyfert galaxy nucleus, and therefore that the spectral lines observed are not all produced in one and the same region. The derived values of N_e and T must be understood as very approximate representations of the average conditions in the ionized gas.

The observations of the larger number of Seyfert galaxies that are now available show that [O III] λ4363 is quite strong in many of these objects. This can occur at high T (see Fig. 1), but in many of the objects the observed intensity ratio (λ4959 + + λ5007)/λ4363 is so small that it is clear the electron density is rather high, of order 10^6 cm^{-3}. The detailed numerical results are listed in Table 3.

Another interesting line ratio is [S II] λ6717/λ6731, which measures N_e in the region of relatively low ionization, since the ionization potential of S^0 is only 10.4 ev. WEEDMAN'S measurements of this ratio give electron densities $N_e = 2.5 \times \times 10^3$ cm^{-3} in NGC 4151 and $\approx 4 \times 10^2$ cm^{-3} in NGC 1068. Combining this with the [S II] λ4069 + λ4076 doublet strength then gives T in the same region. In NGC 4151 this method would give $T = 1.2 \times 10^4$ if the measured line strengths uncorrected for reddening were used, but $T = 2.0 \times 10^4$ from the corrected line strengths. In NGC 1068, $T = 1.0 \times 10^4$ would be deduced from the uncorrected line ratio, but $T \to \infty$ from the corrected ratio. Even in NGC 4151 the temperature calculated from the corrected line strengths, which surely should be used, seems too high. One possible interpretation is that there is a wide range of electron densities in the [S II] region,

TABLE 3 — *Derived electron densities and temperatures from [O III] line ratios.*

	Observed $\frac{\lambda 4959+\lambda 5007}{\lambda 4363} = I_o$			Corrected $\frac{\lambda 4959+\lambda 5007}{\lambda 4363} = I_c$		
NGC	I_o	T (if $N_e = 10^5$)	N_e (if $T = 2 \times 10^4$)	I_c	T (if $N_e = 10^5$)	N_e (if $T = 2 \times 10^4$)
1068	80.	1.5×10^4	$<1 \times 10^5$	54.	1.9×10^4	$<1 \times 10^5$
1275	15.:	7×10^4:	2×10^6:	10.:	7×10^4:	3×10^6:
3227	>51.	$<1.9 \times 10^4$	—	>51.	$<1.9 \times 10^4$	—
3516	7.9:	$>7 \times 10^4$:	4×10^6:	7.9:	$>7 \times 10^4$:	4×10^6:
4051	8.6	$>7 \times 10^4$	4×10^6	6.1	$>7 \times 10^4$	5×10^6
4151	38.	2.3×10^4	1.5×10^5	32.	2.6×10^4	3×10^5
5548	21.	4.1×10^4	1.0×10^6	21.	4.1×10^4	1×10^6
7469	12.	$>7 \times 10^4$	2.5×10^6	12.	$>7 \times 10^4$	2.5×10^6

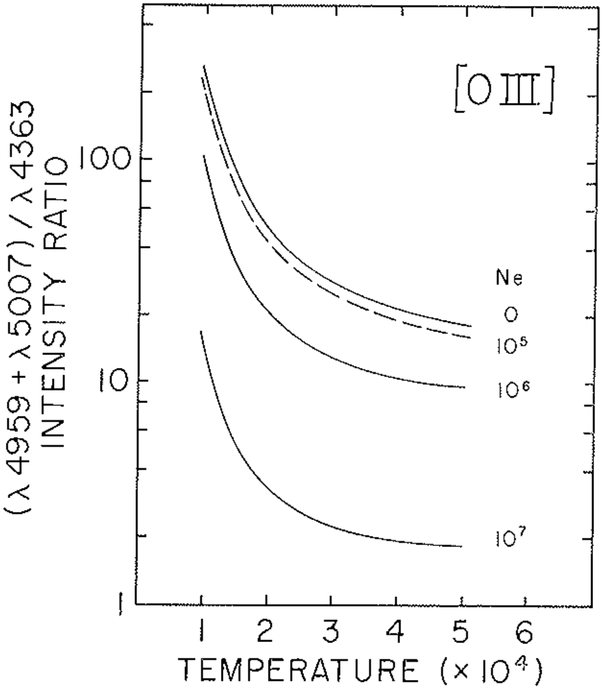

Fig. 1 — [O III] (λ4959 + λ5077)/λ4363 intensity ratio as a function of temperature and electron density.

for then the λ6717, 6731 lines would come preferentially from the low density regions, and the λλ4069, 4076 from the high density regions.

The total luminosity in a line, e.g. Hβ, is directly determined for a Seyfert galaxy nucleus from the measured flux in the line and the known distance of the galaxy. A selection of these values of L(Hβ) are listed in Table 4, along with other data that will be discussed below. They provide good evidence for strong density fluctuations in the ionized gas in Seyfert-galaxy nuclei through the following argument. The luminosity

TABLE 4 — *Luminosities and masses of Seyfert galaxy nuclei.*

NGC	N_e (cm^{-3})	Not corrected for extinction L(Hβ) (erg/sec)	M/M$_\odot$ (ionized gas)	Corrected L(Hβ) (erg/sec)	M/M$_\odot$ (ionized gas)	t_{KE} (*yr*)
1068	10^4	4.1×10^{40}	8×10^4	3.4×10^{41}	6×10^5	1×10^5
1275	10^6	7.7×10^{40}	1×10^2	6.4×10^{41}	1×10^3	1×10
3227	10^4	8.7×10^{39}	2×10^4	8.7×10^{39}	1×10^4	3×10^5
3516	10^6	5.4×10^{40}:	1×10^3:	5.4×10^{40}:	1×10^3	1×10^2
4051	10^6	2.8×10^{39}	5×10	1.7×10^{40}	3×10^2	1×10^2
4151	10^5	1.3×10^{41}	2×10^4	2.8×10^{42}	5×10^5	2×10^3
5548	10^4	3.5×10^{41}	6×10^5	3.5×10^{41}	6×10^5	1×10^4
7469	10^6	4.8×10^{41}	9×10^3	4.8×10^{41}	9×10^3	3×10^4
3C 120	10^4	2.1×10^{41}	4×10^5	2.1×10^{41}	4×10^5	2×10^4

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can be written in terms of the emission coefficient per unit volume, the total volume of the nucleus, and the fraction ε of this volume filled by ionized gas

$$L\,(H\beta) = \varepsilon\, N_e\, N_p\, f_{H\beta}\,(T)\, \frac{4\pi\, R^3}{3} \quad , \tag{1}$$

where $f_{H\beta}\,(T)$, the emission rate per proton per electron, depends only weakly on T. In NGC 4151 $R \approx 25$ pc, while in NGC 1068 $R \approx 50$ pc; then with $N_e \approx N_p$ we find $\varepsilon \approx 10^{-2}$ or 10^{-3}. Thus a large fraction of the nucleus does not contain ionized gas at the mean density – these regions must either contain lower density ionized gas or else neutral gas. High-resolution searches for H I would perhaps clarify this problem, though the neutral gas might also be H_2.

The relative abundance of helium may be derived from the relative strengths of the H I, He I and He II recombination lines. I have used the recombination coefficients given by SEATON [11] for H I and He II, and by ROBBINS [12] for He I, all interpolated approximately to $T = 2 \times 10^4$, $N_e = 10^5$ cm^{-3} to derive the results listed in Table 5. The results are quite insensitive to the assumed conditions, and the spread in helium abundance for the objects in Table 5 seems larger than the expected observational errors. Thus it seems there may be variations in relative helium content by factors of 2 or 3 around a mean value of order 0.1. The abundances of the heavier elements appear approximately normal, though the details depend critically on N_e, T and the ionization structure, which, as mentioned above, are only approximately known. At any rate, there is no evidence for large abundance anomalies in Seyfert galaxies.

TABLE 5 — *Relative helium abundances.*

	Line Strength ($H\beta = 10$)				Relative Abundance ($H^+ = 1$)		
	Observed		Corrected				
NGC	He II $\lambda 4686$	He I $\lambda 5876$	He II $\lambda 4686$	He I $\lambda 5876$	He^+	He^{++}	$He^+ + He^{++}$
1068	3.7	1.5	4.2	0.9	0.08	0.04	0.12
1275	0.6	0.4	0.6	0.2	0.02	0.01	0.03
4151	2.5	0.4	2.6	0.3	0.03	0.03	0.06
7469	3.1	3.0	3.1	3.0	0.26	0.03	0.29
3C 120	2.1	2.0	2.1	2.0	0.17	0.02	0.19

If the observed blue continuum spectrum in some Seyfert galaxies is extrapolated into the ultraviolet as a power law as $\nu^{-0.6}$ (determined from the radio spectrum) in NGC 1068 or $\nu^{-1.2}$ (determined from the optical spectrum) in NGC 4151 there are approximately enough ionizing photons to produce all the ionization of H observed in these objects, that is

$$\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} \, d\nu \geq Q \text{ (Balmer)} \;, \tag{2}$$

where L_ν is the luminosity of the nucleus per unit frequency interval, $h\nu^o$ is the ionization potential of H, and Q (Balmer) is the total number of Balmer photons (= the total number of ionizations of H) emitted by the nucleus per unit time. This is the basis for the detailed photo-ionization models calculated by WILLIAMS and WEYMANN [13] for Seyfert-galaxy nuclei. They suppose that the source of radiation is a central "point" source with the gas distributed in clouds around it, and the filling factor $\varepsilon \approx 0.01$. On these assumptions the ionization of each element is calculated as a factor of position, taking account of the weakening of the radiation field by geometrical dilution and by absorption. The temperature is computed at each point from the thermal equilibrium between photo-ionization heating and radiative cooling. Then integrating over the entire volume of the model gives the total emission in each line. These photo-ionization models agree approximately (but far from perfectly) with observations, as shown in Table 6. The Aller mixture of abundances was assumed in the calculation of these models, and to a first approximation the true abundances may be found from the ratios of calculated and observed line strengths. This leads to the approximate abundance ratios $\mathrm{Ne/H} = 6 \times 10^{-5}$ and $\mathrm{O/H} = 1 \times 10^{-4}$. A detail the models do not match is the great observed strength of the lines of the neutral atom lines [O I] λλ6300, 6363 and [N I] λ5200. These conceivably could arise in very dense condensations (WILLIAMS) or as a result of motion of gas clouds past the source of ionization (COX).

More recently NUSSBAUMER and OSTERBROCK [14] have analyzed the observed strength of the [Fe VII] lines, an ion which has nearly the same ionization potential as [Ne V]. The Fe/Ne abundance ratio can thus be determined, and it leads in turn to the abundance ratio $\mathrm{Fe/H} = 1.5 \times 10^{-5}$.

Another interesting problem is that of the [Fe X] λ6374 and [Fe XIV] λ5303 emission lines first discovered in NGC 4151 by WILSON [5]. It should be noted that there is some question whether the second line is actually [Fe XIV], or perhaps [Ca V] λ5309 as reported by SOUFFRIN [6]. The interpretation proposed by OKE and SARGENT is that these lines are produced under conditions of collisional ionization as in the solar corona, requiring $T \approx 10^6$. If the entire nuclear volume (outside the $T \approx 10^4$ condensations that produce the rest of the emission-line spectrum) is filled with this gas a density of $N_e = 10^2 \text{ cm}^{-3}$ is required. A somewhat more quantitative analysis by NUSSBAUMER and OSTERBROCK confirms this estimate and shows that if (as is likely) a range of temperatures is present they may rum up to $T = 5 \times 10^6$.

TABLE 6 — *NGC 4151 photo-ionization models.*

	Line	Single-cloud model	Multiple-cloud model	Observed	Corrected
Hα	λ6563	28.6	28.6	29.4	22.1
Hβ	λ4861	10.0	10.0	10.0	10.0
He I	λ5876	1.7	1.8	0.4	0.3
He II	λ4686	2.5	2.4	2.5	2.4
[N II]	λ6583	0.8	1.0	2.9	2.2
[O I]	λ6300	2.9×10^{-3}	3.6×10^{-2}	1.5	1.2
[O II]	λ3727	2.6	2.8	4.7	3.7
[O III]	λ5007	270	272	21.2	20.6
[Ne III]	λ3869	36.0	36.0	2.9	2.3
[Ne V]	λ3426	32.0	28.6	3.0	2.2

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However an alternate interpretation is that the [Fe X] and [Fe XIV] lines are formed under conditions of photo-ionization by the same assumed power-law continuous spectrum that produces the other ions. The very high stages of ionization of course only occur close to the central point source of radiation. However the calculated strength of [Fe XIV] λ5303 is considerably smaller than the observed strength and if the identification of this line is confirmed the photo-ionization model is probably ruled out.

A well-known feature of typical Seyfert-galaxy spectra is the very wide wings of the H and He emission lines. The cores of these lines often have profiles much like the forbidden lines, which however do not have the same broad wings as the H lines. Though these broad H wings occur in most Seyfert galaxies, NGC 1068 does not have them and in NGC 1275 they are relatively weak. Table 7 summarizes the available data on the widths of cores and wings of H lines and of forbidden lines. One interpretation of the wings is that they actually represent high turbulent velocities. WOLTJER has suggested that these could occur in a region of such low temperature that none of the collisionally excited (forbidden) lines could occur, while SOUFFRIN has suggested that the high turbulence occurs in a region of such high density ($N_e \gtrsim 10^7$ cm^{-3}) that all the forbidden lines are collisionally de-excited.

Another interpretation of the wings that was suggested by OKE and SARGENT and worked out quantitatively by WEYMANN [15] and MATHIS [16] is that electron scattering produces the broad wings. According to this idea there are high-density condensations in which the forbidden lines are suppressed, but in which the H lines are emitted and broadened by electron scattering before escaping. Plausible conditions for these condensations in NGC 4151 are $T = 2 \times 10^4$ and τ (optical depth in electron scattering) $= 10$, requiring, for instance $N_e = 2.5 \times 10^9$ cm^{-3} and diameter 0.0045 pc, or $T = 4 \times 10^4$, $\tau = 5$, with $N_e = 2.2 \times 10^8$ cm^{-3} and diameter 0.003 pc. Note that the sizes of these condensations together with the measured velocities of order 500 km/sec lead to lifetimes of the order of 10 years. Quite rapid variations are thus possible. Furthermore if such small dense knots occurred near the ionization source the radiation pressure on them would be considerable.

TABLE 7 — *Line widths in Seyfert galaxies.*

	Forbidden lines (km/sec)		Hydrogen Lines (km/sec)	
NGC	FWHM	FWOI	FWHM	FWOI
1068	1400	4000	1200	4000
1275	600	3000	600	6000
3227	800	2500	2000	11000
3516	400	1800	4800	10000
4051	500	1400	1100	6000
4151	600	1800	600	12000
5548	500	1800	900	12000
7469	800	2700	1900	11000

Note: FWHM = full width at half-maximum intensity
FWOI = full width at zero intensity

There is good evidence that the nuclei of Seyfert galaxies each contain many clouds or turbulent elements. This is most clearly shown in the coudé spectra of NGC 1068 and NGC 4151 taken by WALKER [17]. In NGC 3227, according to RUBIN and FORD [18], there is fine structure in the profile extending far out into the wings. If this is confirmed by other observations it will be a strong argument against the electron scattering model, which should result in smooth profiles.

It is interesting to test whether the observed turbulence, as indicated by the forbidden lines and the cores of the H lines, can provide the energy radiated in the emission lines. The observed luminosities in Hβ are listed in Table 4 above. To find the total energy emitted in all emission lines together we use the measurements by OKE and SARGENT of NGC 4151, the best observed sample object, and apply them to all the other Seyfert galaxies. Their measurements give L(Balmer) / L(Hβ) = 3.5 (measured) or 5.2 (calculated) and L(forbidden lines)/L(Hβ) = 4.7. Another major source of line radiation that is unobserved is the Lα emission lines. On the assumption that every Balmer photon is accompanied by at least one Lα photon we find L(Lα)/L(Hβ) $\approx$ 20. Therefore to estimate the total emission in all emission lines together we adopt L(all emission lines)/L(Hβ) = 40. This gives an idea of the rate of energy loss by the ionized gas in Seyfert galaxy nuclei.

Furthermore the total of ionized gas may easily be calculated from the observed L(Hβ) and the electron density estimated from relative forbidden line strengths, using equation (1) to find the product $4\pi\varepsilon R^3/3$, and then

$$M = \frac{4\pi\varepsilon R^3}{3} N_p m_H . \tag{3}$$

The estimated electron densities used and the resulting masses are listed in Table 4. From the observed widths of the cores of the lines the kinetic energy of mass motion can be calculated as $\frac{1}{2} Mv^2$, and thus finally the time scale t_{ke} that would be required for the gas to radiate this kinetic energy. These time scales are also listed in Table 4, where it can be seen that they range from 10^2 to 10^5 years. Note they are independent of the extinction correction, because $M \propto L(H\beta)$ in this method of using the observational data. Comparing these with the estimated lifetime of Seyfert galaxies, 10^8 years, it is immediately apparent that a continuing input of energy to the ionized gas is required.

The idea that the kinetic energy of mass motions in Seyfert-galaxy nuclei may be converted into observed optical radiation was first suggested by SARGENT, and was emphasized by OSTERBROCK and PARKER. The basic picture is that the individual clouds of gas have random velocities, and that collisions between these clouds transform kinetic energy into heat. In its most primitive form this interpretation cannot be correct, because the high temperatures that occur in the collisions between clouds would produce forbidden lines much stronger than those observed, as pointed out by WOLTJER [19] and by SOUFFRIN [20]. The observed high velocities mean that quite high initial temperatures are produced behind the shock (500 km/sec yields $T = 5 \times 10^6$). The shock-heated gas then cools by radiation and expansion, but at these high temperatures considerable energy is radiated in the ultraviolet as resonance-line photons of higly ionized stages of O, Ne, C, N, etc., and these high-energy photons can escape from the shock region and can ionize H and other atoms in the gas that has not yet entered the front. In fact, if the observed [Fe X] and [Fe XIV] in NGC 4151 are interpreted as resulting from hot collisionally ionized gas, then the total radiation from this gas amounts to about 7×10^{42} erg/sec, mostly in the ultraviolet. This is considerably larger than the total optical radiation observed to be emitted by the same nucleus, namely $L(\text{forbidden}) = 4 \times \times 10^{41}$ erg/sec, $L(H\beta) = 3 \times 10^{41}$ erg/sec, or even $L(L\alpha) \geq \geq 1.5 \times 10^{42}$ erg/sec. Thus we can adopt the picture that the collisions between gas clouds produce heating to high temperatures, which leads to emission of ultraviolet photons from the heated region, that in turn cause pre-ionization of the neutral gas that has not yet entered the shock. Thus we have a possible photo-ionization model of Seyfert galaxies in which the ionizing radiation is a complicated emission-line spectrum, and in which in addition some of the observed radiation comes from regions directly heated by the collision. More detailed calculations of such models are obviously necessary before the picture can be qualitatively accepted.

At the present time the only available detailed calculations of interstellar shock fronts are those by Cox [21], which however were intended to apply to the Cygnus Loop, and therefore involve considerably lower velocities and densities than are observed in Seyfert galaxies. A comparison of the calculated and observed relative line strengths is shown in Table 8, and it can be seen that qualitatively the features agree fairly well, particularly the strength of the [O I] and [N I] lines that are not reproduced by the photo-ionization models. A higher density shock-wave model would tend to have weaker. [O II] λ3727 because of collisional de-excitation, and would further improve the agreement. Much further model work, covering a range of densities and velocities, is necessary.

A most interesting new discovery is the measurement by Anderson and Kraft [22] of three absorption-line components of He I λ3839 in NGC 4151. This line arises from a metastable level and has been observed in absorption in the Orion nebula and in at least one planetary nebula, IC 418. The measured velocities of the three absorption-line components, relative to the emission-line velocity, are − 280 km/sec, − 550 km/sec and − 840 km/sec. Anderson and Kraft also observed one absorption-line component each in Hβ and Hγ at − 970 km/sec, which probably actually correspond to the − 840 km/sec component of He I λ3889, since the profile of this line is somewhat affected by the strong [Ne III] λ3869 line. Cromwell and Weymann [23], have also obtained spectrograms of NGC 4151 showing the Hβ absorption-line component, and have compared them with earlier spectrograms (taken in 1962 by Sargent) which do not show this absorption. They therefore conclude that good variation in the strength of the absorption-line component has occurred in a time scale of a few years, and they present this as evidence that a small cloud or puff of gas has been shot out from the continuum source within the nucleus of NGC 4151.

TABLE 8 — *Shock-wave model.*

$V = 141$ km/sec		$n_0 = 4$ cm^{-3}	$B = 3 \times 10^{-6}$ gauss NGC 4151	
Line		Model	Observed	Corrected
Hα	λ6563	28.6	29.4	22.1
Hβ	λ4861	10.0	10.0	10.0
He I	λ5876	0.7	0.4	0.3
He II	λ4686	—	2.5	2.4
[N I]	λ5200	6.5	0.3	0.3
[N II]	λ6584	28.	2.9	2.2
[O I]	λ6300	7.6	1.5	1.2
[O II]	λ3727	102.0	4.7	3.7
[O III]	λ5007	23.0	21.2	20.6
[Ne III]	λ3869	14.	2.9	2.3
[Ne V]	λ3426	3.2	3.0	2.2

The analysis of the conditions in the small cloud responsible for the absorption-line is not straightforward, because a wide range of densities is possible. However the fast time scale shows that small distances and correspondingly high densities are involved. CROMWELL and WEYMANN suggest as a possibility $N_e \approx 5 \times 10^7$ cm^{-3}, which could also explain the electron-scattering emission-line profiles mentioned previously. They then calculate the size the condensation must have to produce the observed He I absorption, and thus finally derive the rate of mass flow out from the nucleus in these dense condensations. Their result is 0.6×10^{-3} M$_\odot$/yr, though it seems to me that making allowance that the flow probably occurs in all directions, and not just in direction toward the sun, increases this estimate to 0.6 M$_\odot$/yr.

Let us next turn our attention to the nuclei of ordinary galaxies that have emission lines in their spectra. Statistics assembled in radial velocity surveys show that a large fraction of the spiral galaxies have this property, and that some ellipticals share it. The emission lines observed [O II], [N II], [O III], [S II], and H I, etc., are generally of a lower average level of ionization than in Seyfert galaxies, and more like the lines observed in H II regions. In addition [O I] λ6300 is observed in many nuclei. All the emission lines are relatively weak, and still weaker lines such as [O III] λ4363 have not been measured in any of these nuclei so there is no direct observational evidence on the temperature.

TABLE 9 — *Relative abundances in nucleus of NGC 4278.*

Ion	Assumed Temperature	
	1.0×10^4	2.0×10^4
H^+	1.0×10^4	1.0×10^4
N^+	0.25	0.062
O^+	1.3	0.14
O^{++}	0.31	0.054
Ne^{++}	0.19	0.024

The two bright elliptical galaxies with the strongest emission lines, NGC 1052 [24] and NGC 4278 [25], have been fairly well studied. In NGC 4278 the abundances of several elements have been approximately determined from the emission-line strengths, with the results shown in Table 9. Since the temperature is unknown there is some indeterminacy, and it can be seen from the table that approximately normal T and abundances agree with the observations, as do also somewhat higher T and somewbat lower abundances of the heavy elements (which in fact could occur together because decreased abundance of the heavy elements leads to decreased radiative cooling and therefore a higher equilibrium temperature). Thus a decisive statement about the heavy-element abundance cannot be made on the basis of the available data. The measured L(Hβ) of NGC 4278, listed in Table 10 shows that its ionized gas nucleus is a factor of 10 to 100 less luminous than tbe nuclei of Seyfert galaxies. The total mass of ionized gas in the nucleus of NGC 4278 is comparable with that in Seyfert galaxy nuclei.

TABLE 10 — *Luminosities and masses of nuclei of normal galaxies.*

Nucleus	L(Hβ) (erg/sec)	N_e (cm^{-3})	M/M$_\odot$ (ionized gas)
NGC 4278	6×10^{38}	10^2	6×10^4
M 31	—	5×10	—
M 51	7.2×10^{37}	5×10^2	1.4×10^3
M 81	5.1×10^{38}	10^3	5.0×10^3

One of the interesting problems of interpretation of the emission-line spectra of the nuclei of galaxies is that in many of these objects the intensity ratio [N II] λ6583/Hα $>$ 1, while further from their centers and in most H II regions λ6583/Hα $<$ 1 [26]. The high [N II] λ6583/Hα ratio in the nuclei of many galaxies might possibly be due to high abundance of N, or to high T, or conceivably to decreased ionization of N^+ to N^{++}, so that more N^+ is present to emit the [N II] lines. Table II shows calculated values of the [N II] λ6583/Hα intensity ratio computed on the assumption that $N^+/H^+ = 1 \times 10^{-4}$, using the best available collision strengths [27]. According to published general abundance tables $N/H \lesssim 1 \times 10^{-4}$, which would thus be an upper limit to the ratio N^+/H^+. However, in the Orion Nebula PEIMBERT and COSTERO [28] have found a lower nitrogen abundance, $N/H = 4 \times 10^{-5}$, directly from an analysis of the [N II] λ6583/Hα intensity ratio.

TABLE II — *Calculated [N II] λ6583/Hα intensity ratios.*

(Assumed abundance ratio $N^+/H^+ = 1.0 \times 10^{-4}$)

T	λ6583/Hα
6.0×10^3	0.4
8.0×10^3	1.2
1.0×10^4	2.3
1.2×10^4	3.5
2.0×10^4	9.1

The best spectrophotometric data on the emission-line intensities in normal galaxies are from the recent work of PEIMBERT [29], who observed the nuclei of the spiral galaxies M 51 and M 81. In addition, spectra of the nucleus of M 31 show that its strongest emission lines are [O II] λ3727 [30] and [N II] λ6583 [31], which shows that it is quite similar to M 51 and M 81, though at an even fainter level of activity. Observationally determined values of Ne, L(Hβ) and the mass of ionized gas of these three nuclei are included in Table 10.

PEIMBERT'S measurements clearly show that there is some abundance anomaly in the nuclei of M 51 and M 81. If it is assumed that the N abundance is normal, then high values of T are required (see Table 11) but as the [O II] and [O III] lines are not particularly strong this requires an abnormally low abundance of O (down by a factor of 10 to 20). Alternatively if it is assumed that the O abundance is normal, then the line strengths can be fitted with $T \backsimeq 1000^\circ$ but with the N overabundant by a factor of 3 to 5. This last hypothesis seems fairly plausible from the viewpoint of stellar evolution and is adopted as the most likely by PEIMBERT, though there is no strong observational evidence favoring it over the opposite assumption, or over any intermediate assumption of somewhat higher than normal N abundance, somewhat lower than normal O abundance, and somewhat higher than normal T.

The full widths of the permitted and forbidden emission lines in the elliptical galaxies NGC 1052 and NGC 4278 are approximately 600 km/sec (at half maximum intensity). This width results from a combination of rotation (the effects of which can clearly be seen in the interstellar gas just outside the nucleus) plus turbulent broadening (the effects of which are confined to the nucleus). In the spiral galaxy M 51 [32] there are local deviations from the circular rotational velocity ranging up to ± 100 km/sec. Also M 31 (which is observed with the largest scale [30, 31]) the rotational velocity spread is 250 km/sec within 500 pc of the center, and there are superimposed noncircular motions again of the order of ± 100 km/sec.

The source of ionization for the emission in the nuclei of these ordinary galaxies is probably (though not necessarily) related to the source of ionization in Seyfert galaxies. One possibility is that photo-ionization is caused by radiation from hot stars. Small numbers of faint hot blue stars (comparable to the relative proportion of such stars in the globular cluster M 3 for instance) would be sufficient to provide all the observed ionization [25]. Likewise a small number of ordinary OB stars with temperatures in the range 2.5×10^4 to 4.0×10^4 would provide sufficient ionization, but would escape detection in the ordinary photographic region [29]. Ultraviolet observations in the region λλ912-2000 would of course easily show the presence of such blue stars. If this stellar photo-ionization source is assumed correct, the question of why some galaxies have emission-line nuclei but others do not then must be raised. Probably all nuclei contain gas, and the differences would be due to the ionization source. Another possibility is that the emission-line nuclei contain a photo-ionization source weaker in intensity but similar in kind to the source in Seyfert galaxies, and that it is an optical synchroton source with a power-law continuous spectrum. The main difficulty with both these photo-ionization sources is that they do not predict the observed strength of [O I] λ6300.

It seems to me that a shock-wave model might be able to explain all the observed data. There may or may not be a small source within the nucleus that projects out small dense clouds with high kinetic energy, but at any rate the widths of the emission lines show that there are motions with velocities of the order of several hundred km/sec. If these motions are not highly organized, collisions between elements of gas must occur. The resulting shock-waves do not maintain an equilibrium cloud of hot ionized gas; instead the heated mass immediately begins to cool and to recombine. The [O I] emission occurs in a region in which there is both neutral gas and ionized gas providing free electrons, that is, in the recombining region. The observed lower velocities in the nuclei of these galaxies imply that lower temperatures are reached in the shock wave than in the Seyfert-galaxy shock-wave models discussed above. For instance a relative velocity of 100 km/sec leads to $T_{max} \approx 10^5$, while 500 km/sec leads to $T_{max} = 5 \times 10^6$. Note that these temperatures are not simply proportional to the square of the velocity, because at the lower velocities a larger fraction of the energy is stored in the ionization of H.

The calculated models dne to Cox show fairly reasonable agreement with the small amount of observational data, as shown in Table 12. A crucial observation would be the measurement of [O III] λ4363, because on the shock-wave model no appreciable photo-ionization of O^+ is expected and the [O III] emission should therefore arise in a zone with $T \approx 5 \times 10^4$. This would lead to a line ratio $\lambda 4363/\lambda 5007 \approx$ ≈ 0.1, which might conceivably be detectable (given sufficient observing time), while on the photo-ionization models $\lambda 4363/\lambda 5007 \lesssim 0.02$.

TABLE 12 — *Nuclei of normal galaxies.*

Line		Measurements		Shock-wave Models	
		M 51	M 81	71 km/sec	141 km/sec
[O II]	λ3727	2.8	2.0	13.9	10.0
Hβ	λ4861	—	1.1	1.0	1.0
[O III]	λ5007	3.2	1.4	3.0	2.3
[O I]	λ6300	0.5	0.7	0.2	0.7
Hα	λ6563	2.9	2.9	2.8	2.8
[N II]	λ6584	7.2	4.1	2.8	2.7

Finally we shall discuss briefly the emission-line spectra of quasars and QSOs. The absorption lines in these objects are of course also very important for understanding their structure, but as they have been discussed thoroughly by Dr. E.M. BURBIDGE at this Semaine d'Etude I shall not include them in the present paper. The quasars are particularly interesting because their large red shifts bring the ordinarily unobservable ultraviolet spectral region into the range of transmission of the earth's atmosphere. Thus many new lines, including permitted transitions such as C IV 2^2S — 2^2P λ1549 and Mg II 3^2S - 3^2P λ2800, as well as intercombination (semiforbidden) transitions such as C III] 2^1S — 2^3P λ1909 are observed in quasars.

To calculate the intensities of collisionally excited lines under conditions of known T, N_e and ionization, the collision strengths Ω (proportional to excitation cross-sections) must be known. These collision strengths are available for essentially all forbidden lines from the work of SEATON [27], CZYZAK [33], and their collaborators. Collision strengths are available also for nearly all permitted lines of interest in quasars from the work of BELY [34], TULLY, REGEMORTER [35], and others, while for the few transitions not computed in detail, good estimates have been made from SEATON'S radiative approximation [36]. A selection of these collision strengths is included in Table 13 below. For the intercombination lines, until quite recently only rough estimated values of Ω based on the conservation theorem were available. However I have recently calculated the collision strengths for the C III] isoelectronic sequence by solving the detailed coupled quantum-mechanical equations [37]. These semiforbidden transition collision strengths, which are also included in Table 13, should have accuracies comparable to the forbidden-line collision strengths of SEATON, CZYZAK, *et al*, as the main approximation in both sets of calculations is that configuration interaction is neglected.

No accurate calculations are as yet available for the inter-

ABLE 13 — *Collision strengths for ultraviolet emission lines.*

Ion	Transition	Lines	Ω	Reference
II]	$2p\ {}^2P - 2p^2\ {}^4P$	2326.3, 2327.9, 2325.6, 2329.0, 2324.4	(9.1)	See text
II	$2p\ {}^2P - 2p^2\ {}^2D$	1335.7, 1334.5	6.4	Osterbrock 1963
III]	$2s^2\ {}^1S - 2p\ {}^3P$	1908.7, 1906.7	1.24	Osterbrock 1970
III	$2s^2\ {}^1S - 2p\ {}^1P$	977.0	6.02	Osterbrock 1970
IV	$2s\ {}^2S - 2p\ {}^2P$	1548.2, 1550.8	9.76	Bely 1966
II]	$2p^2\ {}^3P - 2p^3\ {}^5S$	2143.4, 2139.7	(3.8)	See text
III]	$2p\ {}^2P - 2p^2\ {}^4P$	1749.5, 1752.0, 1753.8, 1746.7, 1748.5	(5.0)	See text
IV]	$2s^2\ {}^1S - 2p\ {}^3P$	1486.5, 1483.2	0.75	Osterbrock 1970
V	$2s\ {}^2S - 2p\ {}^2P$	1238.8, 1242.8	7.08	Bely 1966
III]	$2p^2\ {}^3P - 2p^3\ {}^5S$	1666.5, 1661.2	(2.1)	See text
IV]	$2p\ {}^2P - 2p^2\ {}^4P$	1401.2, 1404.8, 1399.8, 1407.4, 1397.2	(3.0)	See text
V]	$2s^2\ {}^1S - 2p\ {}^3P$	1218.4, 1213.9	0.49	Osterbrock 1970
VI	$2s\ {}^2S - 2p\ {}^2P$	1037.6, 1032.0	5.28	Bely 1966
g II	$3s\ {}^2S - 3p\ {}^2P$	2796.4, 2803.5	20.2	Burke and Moores 1968
g II	$3p\ {}^2P - 3d\ {}^2D$	2798.8, 2791.6	4.10	Burke and Moores 1968
II]	$3p\ {}^2P - 3p^2\ {}^4P$	2335.3, 2344.9, 2329.2, 2350.9, 2335.1	(9)	See text
II	$3p\ {}^2P - 3p^2\ {}^2D$	1817.1, 1808.2, 1817.6	0.86	Roberts 1970
II	$3p\ {}^2P - 4s\ {}^2S$	1533.6, 1526.8	3.2	Roberts 1970
II	$3p\ {}^2P - 3p^2\ {}^2S$	1309.3, 1304.4	1.6	Roberts 1970
II	$3p\ {}^2P - 3d\ {}^2D$	1264.8, 1260.5, 1265.1	11.3	Roberts 1970
II	$3p\ {}^2P - 3p^2\ {}^2P$	1194.5, 1193.3, 1197.4, 1190.4	5.1	Roberts 1970
III]	$3s^2\ {}^1S - 3p\ {}^3P$	1892.0, 1882.7	(2)	See text
III	$3s^2\ {}^1S - 3p\ {}^1P$	1206.5	6.4	Osterbrock 1963
IV	$3s\ {}^2S - 3p\ {}^2P$	1393.8, 1402.8	19.1	Bely, Tully, Regemorter 1963

combination transitions of the other isoelectronic sequences. However the general distorted-wave program being developed by EISSNER at University College London will soon be able to provide all these collision strengths. Comparison of preliminary results derived from it with coupled-equation results for the C III] isoelectronic sequence shows that the distorted-wave approximation is correct to approximately 30% for singly ionized ions, and that as expected its accuracy improves with increasing ionization, being better than 10% for doubly ionized ions, and better than 1% for six times ionized ions. In addition the general program will take configuration interaction into account accurately in the calculations. However until the results derived from it become available the best interim procedure for estimating collision strengths for other semiforbidden transitions seems to be to correct the estimate based on the conservation theorem by a factor derived from the C III] sequence that depends on the degree of ionization. Collision strengths estimated in this way are also included in Table 13, where they are indicated to be estimates by the parentheses. Finally, semiforbidden-transition collision strengths for various ions of Si have been derived by scaling the corresponding strengths for C by a factor derived from the permitted-transition strengths, which are computed. These estimates for Si are probably the least reliable values in Table 13, but at the present time they are the best available for these particular ions.

The first theoretical interpretations [38, 39] of quasars were concerned with finding the T, N_e, degree of ionization, and relative abundances that give the best fit to the observed mean emission-line spectra. These studies led to estimates $T \approx 1.5 \times 10^4$, $N_e \approx 3 \times 10^6$ cm^{-3}, a considerable range of ionization, from once to five times ionized ions in approximately equal proportions, and approximately normal abundances of the elements except for an indicated very low abundance of He.

The widths of the emission lines in many quasars are comparable with or wider than those in Seyfert galaxies. Forbidden lines often have full widths at half-maximum of order 1000 to 1500 km/sec. The permitted resonance lines such as Mg II and C IV are often wider, indicating that resonance-line scattering or electron scattering is important in determining the profile of these lines.

The luminosities of quasars, if they are at the "cosmological" distances indicated by their red shifts, are considerably larger than the luminosities of Seyfert-galaxy nuclei. For instance 3C 48 has $L(H\beta) = 1.7 \times 10^{43}$ erg/sec, while the mass of the ionized gas in it is approximately $1.8 \times 10^4 M_\odot$, comparable with many Seyfert galaxy nuclei. If the quasars are closer both these figures are of course reduced.

There is good observational evidence that the ionized gas in quasars is concentrated in dense condensations. As Dr. SANDAGE has indicated in his review at this Semaine d'Etude, practically all quasars vary in brightness. These variations, presumably originating in the central source, would be damped by electron scattering [38] in an assumed homogeneous envelope of ionized gas in which the emission lines are produced, since the size of the envelope required is typically of order several light years, and the electron-scattering optical depth of order 10. However if the ionized gas is all in concentrations filling only a fraction ε of the volume the optical depth is smaller, since N_e and

$$L\,(H\beta) = \varepsilon\, N_e\, N_p\, f_{H\beta}\,(T)\ \frac{4\pi\, R^3}{3} \tag{4}$$

are fixed observationally, so that

$$\tau = \varepsilon\, N_e\, \sigma\, R = \varepsilon^{2/3}\, N_e^{\,1/3}\, L\,(H\beta)^{1/3} \frac{3}{4\pi}\ ^{1/3} \tag{5}$$

can be made arbitrarily small. For any $\tau < 1$ the bulk of the emitted optical radiation of the central source is transmitted by the envelope and light variations can be observed.

The most detailed models of quasars are those of BAHCALL and KOZLOVSKY. They assume photo-ionization, with the source of radiation a power-law spectrum $F_\nu = C\nu^{-\alpha}$ with α chosen to give the best fit to the optical continuum or to the emission-line data. For the 3C 273 model that we shall discuss they take $\alpha = 0.7$, and the filling factor $\varepsilon = 10^{-3}$. The ionization is calculated from the radiation field, modified by absorption by the intervening material. However in these models the thermal balance equation is not solved, but instead for the sake of simplicity T is assumed to be a constant ($= 1.7 \times 10^4$). However since collisional ionization is included in their equations, this means that outside the H II region in which all the ionizing photons are absorbed, H is still 90% ionized as a result of collisional ionization, Mg is completely ionized to Mg II, etc. The assumed spherical model is then terminated at the correct radius so that the calculated Mg II line strength matches the observational data. This model, which provides a good representation of the observed emissionline spectrum of the relatively low z quasar 3C 273 has $N_e = 3 \times 10^7$ cm^{-3}, $R = 14$ pc, $\varepsilon = 10^{-3}$, (electron scattering) $= 0.15$ and $M = 10^5 M_\odot$.

Furthermore, this model has a more general significance. Using the collision strengths listed in Table 13, I have calculated the entire ultraviolet emission-line spectrum of this model, and in Table 14 this model is compared with the mean emission-line spectra for quasars, adapted from a table by BURBIDGE [41]. It can be seen there is good qualitative agreement, except that the helium lines are observed to be much weaker than the calculations predict. Note that in this table the relative numbers of photons are listed (rather than energy fluxes) as the best measure of relative line strength over a wide frequency interval.

TABLE 14 — *Comparison of 3C 273 model with mean observed quasar spectrum.*

Line		Relative Photon Rate	Observed	Line		Relative Photon Rate	Observed
Lα	λ1216	166.	S	Mg II	λ2799	3.6	S
C IV	λ1549	42.	S	N V	λ1240	2.8	—
He II	λ1640	22.	W	[Ne V]	λ3426	2.4	W
Hβ	λ4861	20.	M	O III]	λ1664	2.1	—
He II	λ4686	18.	—	Si IV	λ1397	1.7	—
Hγ	λ4340	10.	M	[O III]	λ5007	1.6	M
C III]	λ1909	9.4	M	Si III]	λ1892	1.2	—
C II]	λ2327	8.0	obs	[Mg VII]	λ2632	1.1	—
O IV]	λ1402	6.0	M	[O III]	λ4363	1.0	obs
Hδ	λ4101	6.0	obs	[Ne V]	λ3346	0.9	obs
O VI	λ1034	5.6	—				

S = strong M = medium W = weak obs = observed

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TABLE 15 — *Comparison of 3C 273 model with mean observed quasar line ratios.*

	Relative Photon Numbers	
	Model	Observed
Mg II/Hβ	0.2	∼0.7 (mean)
C III]/C IV	0.2	0.06 0.06 0.2
Lα/C IV	4.0	5.1 6.3 6.6

Most of the available observational data on line strengths in quasars is confined to qualitative statements that lines are strong, weak, absent, etc. as used in Table 14. Obviously quantitative data provide a far sharper test of the model, but as quasars are faint and have broad weak lines, the observational problems are difficult. Very recently a large list of measured line intensities have been provided by OKE, NEUGEBAUER and BECKLIN [42], and in Table 15 we compare some of the observed ratios with the calculated ratios of the 3C 273 model. It can be seen that in most cases the agreement is relatively good, showing that the model is a fairly accurate first approximation to the observed emission-line spectra of quasars. However the Mg II doublet is relatively weak in 3C 273 compared with the mean observed quasar spectrum. Note that the C III]/C IV ratio, for which the deviations between calculated and observed ratios are large in two of the quasars, is the ratio which depends most critically on the assumed radiation field. Further observations of relative emission-line strengths in quasars can be expected to add to our understanding of the far ultraviolet spectra in these objects.

In their work on quasar models BURBIDGE, BURBIDGE, HOYLE and LYNDS [43] have particularly emphasized the importance of dense condensations for the formation of Mg II emission. They assumed the dense condensation to be at the center of their model, in order to avoid the prediction that there should be Mg II absorption lines in all quasars, but it seems to me it is also possible to think in terms of many small dense condensations scattered through the quasar in such a way that they do not produce absorption lines in the spectrum of the central source.

Resonance fluorescence is a process that is responsible for the excitation of some of the emission lines in quasars and also in compact galaxies. WAMPLER and OKE [44] identified the diffuse features at λλ4450-4650 and λλ5100-5400 in 3C 273 as groups of permitted Fe II lines broadened so that the individual components overlap. These emission lines are excited by absorption of continuum radiation in the near ultraviolet region around λ2500 (it is interesting to note that the ground state Fe II absorption lines observed in PHL 938 are among those that contribute to this excitation process, but in 3C 273 many of the excited levels of the ground configuration are also populated and contribute to the absorption). The same Fe II emission lines have also been observed by SARGENT [45] much narrower and completely resolved in the compact galaxy I Zw 0051 + 12. The emission of the observed Fe II lines leads to population of high excited even levels of Fe^+, but the [Fe II] lines that can be emitted by these levels are not observed. This indicates that the electron density in the emitting region is sufficiently high ($N_e > 10^7$ cm^{-3}) so that the collisional de-excitation tends to suppress these lines. This numerical value of the electron density depends on estimated values of the collision strength, and may therefore be in error by as much as a factor of 10.

Finally, although absorption lines are not discussed in detail here, the possibility of interpreting the absorption-line components that have $z_{abs} \asymp z_{em}$ as self-absorption in the emitting gas itself should be kept in mind.

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DISCUSSION

Chairman: W. W. MORGAN

HOYLE

How far is it relevant that you get good agreement in the two places where the elements are different and the abundances are in some degree adjustable, whereas in the case where the discrepancy is bad the element is the same?

OSTERBROCK

The model of BAHCALL and KOZLOVSKY was calculated to apply to 3C 273. They assumed the "normal" (Aller table) abundances of the elements, and cut off the size of the ionized region to match the H/Mg II ratio in 3C 273. The fact that the calculated Lα/Mg II ratio approximately agrees with the mean observed value of this ratio shows the typical quasars are fairly similar to 3C 273. The Lα/C IV and the C IV/C III] ratios are not observed in 3C 273 and the agreement of calculated values of the ratios with observational data for other quasars should be regarded as evidence favoring the model. The C IV/C III] ratio depends most strongly on the assumed spectrum of the ionizing radiation.

LOW

Have you thought of what happens when you put the infrared source at the centre?

OSTERBROCK

I have thought about it but not in a very quantitative way. It seems to me that the shock-wave model (generated by clouds coming out of a central source with high velocities) can probably explain the excitation of the emission lines. I thought the same general origin, from kinetic energy of clouds of gas coming out and striking other gas, might explain the optical radiation as well as the infrared. However, I don't really know your ideas on the origin of the infrared radiation.

LOW

Prof. OSTERBROCK, maybe we can continue that separately.

WOLTJER

Dr. OSTERBROCK discussed the evidence for dust in Seyfert galaxies, is there similar evidence in the case of the quasi-stellar objects?

OSTERBROCK

No, I don't know of any. By analogy with the Seyfert galaxies it may be there and should be looked for. The infrared [S II] lines have not been observed in any quasars. Probably the $H\alpha/H\beta/H\gamma$ ratio would be the best lines to use.

ABSORPTION REDSHIFTS IN QSOs

W.H. McCREA
University of Sussex
Falmer, Brighton - England

This is a very brief account of a model that may possibly account for the properties of the absorption lines in quasi-stellar objects that Prof. MARGARET BURBIDGE described yesterday. The features that came out in her talk were:

1. In most cases there are no absorption lines.
2. When there is absorption, the lines are in general narrow.
3. There can, however, be broad absorption lines as in the example discovered by LYNDS, of which we were shown a slide.
4. In general, the absorption redshift is less than, or equal to, the emission redshift.
5. Cases do occur, however, in which the inequality goes the other way.
6. There are cases of multiple absorption redshifts.
7. If there are any absorption lines, the probability of more than one redshift is quite high.

We often think of a QSO schematically as having a small number (perhaps 2 or 3) intense sources of continuous radiation, and we think of the spectral lines as being formed in filaments of gas. Now we may think that these filaments are actually jets coming out of one or more of these sources. If no jet lies between one of the sources and ourselves, there are no absorption lines, in agreement with feature 1.

In general, there must be a velocity gradient along a jet. However, if we view one of the sources of radiation through a jet coming from a different one of the sources, then in general the velocity-gradient along the sight-line where it traverses the jet must be small. This means that in general we must get narrow absorption lines, in agreement with 2. However, if by chance we view one of the sources through its own jet, we see it through a large velocity gradient. In that case we get broad absorption lines, as in 3.

Now if we see a jet with a source behind it, the jet is more likely to be pointing towards us than away from us, and so to give an absorption redshift less than the (emission) redshift for the whole system. This is feature 4. Nevertheless, we can obviously have cases where we view a source through a jet that is pointing away from us, and then we shall get feature 5. Again, if we have several jets coming from one or more of the sources, we can easily get multiple redshifts, in agreement with 6.

If we adopt a model like this, if we get any absorption at all, it seems quite likely that we shall have a case of multiple redshifts, in accordance with 7. On the other hand, this is one of the difficulties in accounting for the absorption lines by absorption in intergalactic clouds. For in that explanation, since the chance of getting any absorption is small, the chance of getting multiple absorption is almost negligible.

DISCUSSION

Chairman: M. SCHMIDT

SPINRAD

Dr. McCREA, is it not intuitively correct from the geometry that in this model the larger the difference between the absorption redshifts and the conventional emission redshift, the broader would be the absorption feature? In other words, you would see the major axis of the jet in your direction. You would then get large Δz. Correct?

McCREA

I didn't hear the beginning of your question.

SPINRAD

If the absorption redshift is smaller than the emission redshift by a large amount, in other words, with a substantial fraction of Δz emission, then I would think that you would need to have the jet sort of coming at you, and that would, I think, give you a rather broad line.

McCREA

Yes, I think there are various features like that that could be used to test the model.

E. M. BURBIDGE

I think that this is rather a nice idea, and maybe in order to get the very large range of differences of velocity that are measured, it might be combined with Dr. REES' model. I don't know whether he is going to say something about that? The single *very* broad line object, PHL 5200, is the only one known of this kind (RS 23 does not have such broad lines), so that this phenomenon is certainly rare.

McCREA

Yes, it would be rare.

REES

The suggestion I want to make is based on the evidence which will be discussed later this morning from the variable radio sources. The most natural interpretation of these variable radio sources involves the ejection of clouds of relativistic particles with bulk speeds exceeding half the speed of light in some cases. Now if one considers the likely situation 10^5 — 10^6 years later, the debris from all these radio outbursts will occupy a large volume in intergalactic space. It will also have cooled adiabatically by a big factor so that the initially relativistic particles will no longer be relativistic, and indeed could have cooled down to thermal energies. Moreover, if you start off with an equi-partition magnetic field and then expand by a big factor so that the matter becomes non-relativistic (and then has a gamma of 5/3 not 4/3) you will end up with magnetic pressures which dominate the particle pressure. Under these conditions the material may be compressed by large density enhancement factors at places where the magnetic field reverses. This seems a natural way of getting the matter in these regions to concentrate into a number of cool discrete filaments whose dimensions may be thousands of times smaller than the overall dimensions. If this situation can be achieved then the velocity dispersion across a single filament may also be thousands of times smaller than the velocity dispersion through the cloud as a whole, so in this way it may be possible to explain why the absorption lines produced by a single filament can be narrow, even though the velocity dispersion through the whole cloud is large. So one could attribute the absorption redshifts one sees in a particular object to the filaments that happen to lie along our particular line of sight. The whole cloud contains perhaps millions of these filaments (This model is described more fully in *Astrophys. J. 160,* L. 29).

Low

Is it physically impossible that the sources can have high velocity?

McCrea

I think in the reply to both Dr. Rees and Dr. Low, I would say that this is just a model; it is not a theory. It is, of course, the velocity-difference between the source and the absorber that is the essential feature of the model, but I think it is easier to have a range of velocities associated with the jets rather than with the sources. Further, in reply to Dr. Rees, I should be inclined to reverse his argument and appeal to the compression of the magnetic field as a way to produce relativistic particles rather than the other way round.

Morrison

I would like to enquire, isn't it so, even on your picture, Dr. Rees, that the need for multiple continuum sources is still present if we have a few inverted cases: i.e. redshifts in absorption?

Rees

If the absorption is due to matter ejected from the objects you would not be surprised by blue-shifted absorption lines. In the cases where the absorption redshifts are larger than the emission redshift, you can either say that there is a particular filament that has an inward peculiar motion despite the overall expansion, or you could invoke transverse velocities which are a sufficiently large fraction of c for the transverse Doppler effect to be important.

MORRISON

How big is the velocity difference in the redshifted absorption?

REES

The observations do not show any case where the absorption redshift is *much* larger than the emission redshift.

E. M. BURBIDGE

There are cases where $z_{abs} > z_{em}$ run up to $z_{abs} - z_{em} = 0.03$ (e.g. in B 194, where $z_{em} = 1.86$ and there are two sets of absorption, at 1.83 and 1.89, about equally strong).

INFRARED EMISSION OF GALAXIES

F.J. LOW

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University of Arizona

Intense infrared emission from the central regions of galaxies has been observed. It has been shown that this phenomenon is associated with the "nuclei" of galaxies and the infrared power levels, 10^{41} to $> 10^{46}$ erg/sec, are orders of magnitude higher than the optical and radio emission of galactic nuclei. Extraordinarily energetic phenomena were already known to occur in the "active nuclei" of galaxies, manifested chiefly by continuous and discontinuous ejection of matter. Now we find infrared radiation on a similar energy scale. Conventional physical explanations for the radiative mechanism and for the fundamental energy source responsible for the infrared emission have not been found. The stress placed on conventional psysics is sufficiently great that consideration of unconventional solutions involving fundamentally new principles seems justified.

The observational data concerning the 15 objects now known to display this phenomemon will be reviewed. Most of the results are published; however, a number of important unpublished results were obtained just after the Semaine d'Etude and these are included here. For example, application of angular resolution on the order of one arcsecond at 10 microns has revealed structure in the nucleus of our galaxy and has shown that the source in M 82 extends about 200 pc outward from its center.

Between 5 and 25 microns the spectra of galactic nuclei resemble the 230°K thermal spectrum found in several galactic infrared sources. LOW and KLEINMANN [1] suggested that a common physical mechanism might be responsible for this similarity. In the galactic sources, chiefly H II regions and planetary nebulae such as M 17 and NGC 7027, it is possible to account for the observed infrared emission by thermal reradiation from dust heated by a strong central sources of ultraviolet radiation. In the extra-galactic sources it now appears that this simple mechanism may be present but that it cannot account for all the properties that are observed.

It has been suggested [2] that an ensemble of discrete sources called irtrons produces the observed infrared radiation from galactic nuclei by a non-thermal mechanism such as coherent synchrotron emission. RIEKE [3] has investigated several non-thermal models which are appropriate for the galactic nucleus and are consistent with the observed radio, infrared, optical and high energy spectral data. He finds that conversion efficiencies from relativistic particles to infrared radiation are of the order of 10 percent or less even under extremely special conditions. All models imply large fluxes at x-ray and γ-ray energies.

Infrared Sources in the Galactic Center Region

BECKLIN and NEUGEBAUER [4] reported the detection of near infrared emission from an extended source coincident with the radio source Sagittarius A. Interpretation of this near infrared source in terms of starlight heavily reddened by interstellar dust is strongly supported by analogy with the nucleus of M 31, a large spiral galaxy thought to be similar to our galaxy in a number of other characteristics. BECKLIN and NEUGEBAUER degraded their high angular resolution profile of the 2.2 micron emission of the galactic nucleus to the same scale of linear distance obtained in scans of the M 31 nucleus at 2.2 microns. Almost exact correspondence between the two spatial distributions of 2.2 emission was found. Since the 2.2 micron emission from M 31 is clearly produced by ordinary stars in the central region of the galaxy, the same is taken to be the case in our galaxy. Based on this result the visual interstellar extinction is found to be ∼ 27 magnitudes and it is possible to construct a model for the optical output of the galactic nucleus by direct analogy with M 31. An unexpected result of these near infrared observations was the detection of a bright "point source" near the center of the extended source. The apparent temperature and luminosity of this source, if it is near the center of the galaxy, are 1700°K and $10^5\ L_\odot$.

Observations in the 5, 10 and 22 micron atmospheric windows revealed the existence of a small but resolvable source about 0.7 parsec in diameter [5, 6]. The angular diameter was found to be about the same at all three wavelengths, although the results of BECKLIN and NEUGEBAUER [5] indicated a more extended source when larger beam sizes were used at 5 and 10 microns. We do not find an increase in flux at 10 microns with beam sizes between 30 and 120 arcseconds. We have observed at 10 microns with a sharp sided beam 5 arcseconds in diameter and find small scale structure less than 0.25 parsec in size.

At 10 microns the linear polarization was found to be less than 3 percent [6].

The spectrum of the source coincident with the radio source Sgr A was extended to 300 microns and an upper limit was obtained at 1000 microns [6, 7]. These data are summarized in Figure 1. Far-infrared observations have now been carried

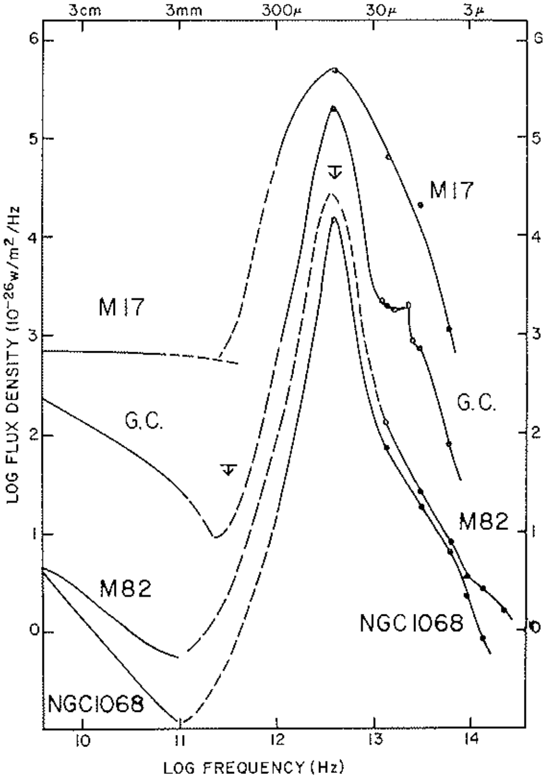

FIG. 1 — Radio and infrared spectra of NGC 1068, M 82, the Galactic Center (Sgr IRA), and M 17. Flux densities at the peak near 4 × 10^{12} Hz are approximate. Two upper limits are shown, one for M 82 and the other for the Galactic Center.

out with several filter systems and beam sizes ranging from 2 arcminutes to 10 arcminutes [8]. The angular extent and distribution of the source at the peak near 70 microns is still not well determined. The spectrum is drawn through the flux obtained with the 2 arcminute beam since beams of that size were used at 10 microns without increasing the flux. The location of the peak at 70 microns (ν max $= 4 \times 10^{12}$ Hz) is now well established [8].

In addition to the sources already described we must take note of the observations, reported by HOFFMANN and FREDERICK [9], of an extended 70-100 micron source 2 by 6 arc-degrees, oriented along the galactic equator and centered roughly on Sagittarius A. We have failed to confirm the existence of this source within this same region. North of Sagittarius A, near but not coincident with Sagittarius B2, there is a discrete source perhaps somewhat colder and brighter than the nucleus itself! Almost an equal distance along the equator to the south, there is another source about one-third as bright. The Sagittarius B2 source is at 1950 coordinates $\alpha = 17$ hr 44.5 m $\pm .2$ m, $\delta = -28^\circ 27' \pm 2'$; we have not been able to detect this source at 10 microns, so the spectrum is still quite uncertain. However, observations using several filters which divide the 50 to 300 micron range into overlapping bands suggest a continuum rather than one or two bright emission lines. It seems quite possible that the extended source of HOFFMANN and FREDERICK was caused by the discrete sources within their large 2 degree beam. Further observations are needed to determine whether a diffuse source exists in addition to the discrete sources.

It is not certain that the discrete sources are all near the galactic center; there may be many such sources throughout the galaxy. Approximate luminosities are given in Table 1 for the various sources in the galactic center region assuming they are all at a distance of 10 kpc; location and size are also included.

Extra Galactic Sources

The first extra galactic infrared source, 3C 273, was detected at 10 microns in June 1964 and remains the most luminous infrared source discovered so far [10]. In addition to this single quasar and the sources near the center of our galaxy, 13 galaxies have been detected at 10 microns, the wavelength which produces the highest signal/noise.

TABLE 1 — *Sources in the Galactic Center Region.*

Source	Galactic Coordinates		Angular Diameter (arcminutes)	Linear Diameter (pc)	Luminosity (L_0)
	l^{II}	b^{II}			
2.2μ pt. Source	−0.05	−0.05	<0.02	<0.06	8×10^4
1.6-3.4μ Ext. Source	−0.05	−0.05	2	6	8×10^6
5-25μ Nucleus (IRA)	−0.05	−0.05	0.25	0.7	2×10^6
70-100μ Extended Sources					
IR A	−0.05	−0.05	2-10	6-30	8×10^7
IR B	0.64	−0.05	2-10	6-30	2×10^7
IR C	−0.6	−0.1	∽10	∽30	1.2×10^7
Sgr A	−0.05	−0.05	12	36	5×10^2

Marginal detections or upper limits have been obtained for 38 other galaxies. Table 2 lists new unpublished data which supplements the data published previously [11, 12].

The spectrum of NGC 1068 has been extended to 300 microns and a far infrared upper limit was obtained for M 82 [8]. These results are plotted in Figure 1 where the spectra may be compared to the galactic center and to M 17. In all cases where there are data, the infrared spectra of extra galactic sources have the same character, rising steeply above

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[8] II, 7 - *Low* - p. 6

the radio and optical continua to a peak at wavelengths inaccessible from the ground. Only by observing at these difficult wavelengths near 100 microns can we obtain full knowledge of the spectra.

TABLE 2 — *Recent Infrared Observations of Galaxies.*

Source	J.D.	2.2μ Flux	± error	10.2μ Flux	± error	Average 10.2μ Flux	± error
NGC 3031 ≡ M 81	40643			− 1.5	2.0	−2.7	1.4
	40626	0.9	0.4	−11.6	3.1		
	40624	1.95	0.4	1.4	2.6		
NGC 3115	40690	0.45	0.65	0.0	0.2		
NGC 3227	40687	1.0	0.3	0.37	0.07	0.42	0.06
	40686			0.55	0.10		
NGC 3516	40730			0.17	0.15		
NGC 3675	40742			0.35	0.15	0.26	0.07
	40689	0.07	0.03	0.20	0.08		
NGC 4051	40634			0.35	0.30		
NGC 4151	40740			1.20	0.10		
3C 273	40741	0.18	0.07	0.23	0.10	0.43	0.04
	40740			0.29	0.08		
	40687	0.3	0.3	0.58	0.06		
NGC 4594^{+} ≡ M 101	40658	0.6	0.2	— 0.1	0.1		
NGC 4736 ≡ M 94	40741			0.28	0.05	0.30	0.04
	40714			1.10	0.50		
	40689	0.35	0.06	0.35	0.10		
NGC 4826^{+} ≡ M 64	40741			0.0	0.1	0.15	0.1
	40690	1.25	0.20	0.3	0.1		
NGC 5055^{+} ≡ M 63	40689	0.17	0.06	0.0	0.1		
NGC 5194^{+} ≡ M 51	40713			0.55	0.25	0.2	0.1
	40690	0.9	0.6	0.00	0.15		
NGC 5195^{+} . . .	40742			0.26	0.06	0.30	0.05
	40741			0.40	0.10		
NGC 5548	40650			0.2	0.1		

Given their complete spectra we have computed total luminosities for NGC 1068 and the galactic nucleus. Assuming a similar spectrum for the other objects, we have extrapolated the groundbased results to obtain estimates of their total fluxes and luminosities; the results are given in Table 3. The last column gives the luminosities in terms of equivalent mass loss rates. It is quite possible that this method of extrapolation produces an underestimate of the total power output, since in our own galaxy there are powerful 100 micron sources which are not detected at 10 microns. However, the far infrared power levels are so much higher than in radio or optical sources, that there is some reason to suspect these extrapolations might lead to over-estimates of the total luminosities. If this is the case the error could be as large as one order of magnitude.

TABLE 3 — *Infrared Luminosities.*

Source	Distance (*) mpc	Mean 10μ Flux 10^{-26}w/m²/Hz	Infrared Luminosity 10^{44} ergs/sec	Equivalent Mass-Loss Rate 10^{-3} $M_{\odot}$/yr
Gal. Cen.	0.010	550	.003	.005
NGC 1068	13	26	300	500
NGC 1275	70	1	300	500
3C 120	120	0.4	300	500
NGC 2782	33	1.6	100	160
M 82	3.2	40	20	30
NGC 3077	4.3	3	3	50
NGC 3227	13.4	0.4	4	7
NGC 4151	13	0.9	9	15
3C 273	630	0.4	9000	15000
NGC 4736	6	0.3	0.6	1
NGC 5195	2	0.3	0.07	0.1
NGC 5236	4.3	6	6	10
NGC 7469	68	0.9	200	300
NGC 7714	39	0.3	30	50

(*) H = 75 km/sec/Mpc.

The new observations included here provide important information about the range of infrared luminosities. Note that NGC 4736 and NGC 5195 have luminosities which are intermediate between the high values found for Seyfert galaxies and the much lower value found for the galactic nucleus. NGC 5195, the small interacting companion to M 51, is only 20 times more luminous than the galactic center. These results imply that many galaxies will be found with luminosities in this intermediate range. This is important in determining the lifetime of the infrared phenomenon.

We have resolved the source in M 82 at 10 microns and find an angular extent of at least 25 arcseconds along the plane of the galaxy and about 10 arcseconds toward the poles as shown by the contours plotted in Figure 2. The center of this source agrees well with our earlier position [11] for the 2 micron source and with radio positions. Photographic and optical polarization studies have been used to predict positions for the nucleus of M 82 which are in rough agreement with the center of the 10 micron source.

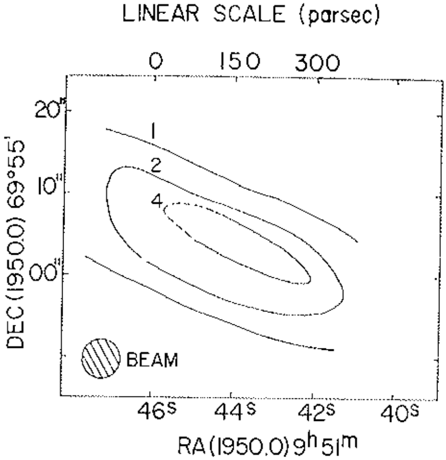

FIG. 2 — Ten micron contour map of the source at the center of M 82. Size, shape and location agrees with radio source.

It is now possible to compare the 10 micron surface brightness at the center of M 82 with the surface brightness of the 10 micron source in Sagittarius A. Observations of both sources were made with the same size beam, 5 arcseconds. These results are given in Table 4. The source in the nucleus of NGC 1068 is smaller than 5 arcseconds in diameter and must be physically smaller and have higher surface brightness than the M 82 nucleus. The galactic H II region M 17 is included for comparison. NGC 4151 is of special importance since it appears that both the 10 and 22 micron flux densities have decreased more than a factor of 10 in 1000 days [11]. If we assume that this apparent variability in the infrared is real, the light travel time argument can be used to place a limit on the size of the source. Of course, this limit applies strictly to the variable component only and it is quite possible that the quiescent component may be much larger in size.

TABLE 4 — *Physical Parameters at 10 Microns.*

	M 17	Galactic Nucleus	M 82	1068	4151
Beam Size (arcseconds) .	35	5	5	5	(1.3×10^{-2})
Flux (f.u.)	225	80	4	30	1.2
Surface brightness (10^{-17}w/m²/Hz/ster) . .	10	180	8.5	>64	4×10^5
Equivalent Emissivity . .	2×10^{-4}	4×10^{-3}	2×10^{-4}	$>1.5 \times 10^{-3}$	10
Total Linear Size (pc) . .	3	0.7	400	<300	1
Total Infrared Luminosity ($L_\odot$)	5×10^6	10^8	6×10^{11}	6×10^{12}	2×10^{11}

Shorter term variations of a magnitude or more may be real in NGC 4151, 3C 273, NGC 1275 and NGC 1068; however our data are still not conclusive on this important question. Our most recent data show that the signal/noise has now been improved enough to permit frequent monitoring of these objects at 10 microns. Of course, only about 10 percent of the total luminosity is represented by groundbased observations, therefore it will be necessary to monitor at 100 microns in order to answer the question unambiguosly. All of the variability phenomena observed at optical, infrared and microwave frequencies can be understood in terms of outbursts in a small part of the total source.

Concluding Remarks

The mass loss rate equivalent to the observed far infrared luminosity of NGC 1068 is about 0.5 $M_\odot/yr$. Disregarding all discussions of the radiative processes and their probable efficiencies, it is clear that if NGC 1068 has been emitting at this level for 10^8 years or longer, the mass in the nucleus must have been replenished. The distribution of mass within the nuclear region of NGC 1068 should be studied with great care to determine, if possible, what fraction of the total mass ($\sim 5 \times 10^9 M_\odot$) [13] lies within the infrared source. The problem is more serious if NGC 1068 has maintained its present luminosity over a larger fraction of its lifetime. The fact that 3C 273 is much more luminous than NGC 1068, and is probably much younger, suggests that this may well be the case.

The total energy released in the form of infrared radiation during the lifetime of a galaxy is still quite uncertain; values much higher than 10^{62} ergs seem likely in some galaxies, and there are indications that the true value may be 10^{65} ergs for a galaxy of $10^{11} M_\odot$ [2]. It is clear that the 15 galaxies detected at 10 microns do not represent the full range of infrared luminosities. Observations of sources in our own galaxy show that 100 micron radiation need not be accompanied by detectable fluxes at 10 microns. This suggests that true "infrared galaxies" may exist which emit exclusively in the far infrared. These problems will be difficult to solve by observing individual objects; however, our present knowledge indicates that in the 70 to 500 micron spectral region there must be a bright diffuse cosmic background [14]. The question may be put as follows: How does the far infrared radiation produced in the nuclei of galaxies compare in energy to the "primordial" 3°K blackbody radiation which is thought to be the residual radiation produced in the fireball which accompanied the creation of all the matter and energy in the Universe? If, as suggested here, each galaxy emits $> 10^{62}$ ergs in the far infrared the energy density at these wavelengths will be $> 10^{-12}$ erg/cm^3, larger than the energy density produced by the 3°K background. A direct radiometric measurement of the cosmic background at far infrared wavelengths, although technically difficult, would answer these questions raised by present observations.

Future Direction of Extra Galactic Infrared Astronomy

This subject, which deals directly with the principle energy source in galactic nuclei, is still in its infancy and the new techniques seem foreign to most astronomers. It should be noted that all the results obtained so far were accomplished by a few people working with a small fraction of the support afforded to those working in other fields such as high-energy or ultraviolet astronomy. The scientific return on investment in people and equipment has been extraordinary; and, as others join the field, even greater returns lie ahead if support is shifted from conventional lines of research to build infrared instruments and facilities.

Groundbased observations have progressed to within a factor of ten of fundamental limits to their sensitivity. These fundamental limits should be reached in the next year. Progress beyond that point will be slow and more costly just as in optical astronomy where significant improvements in sensitivity have not occurred in recent years. Fortunately, the number of extragalactic sources detectable at 10 microns is already quite high. The importance of high resolution should not be overlooked but it is not known whether high spectral resolution will be important in the study of galaxies.

Observations beyond 25 microns are more difficult since they require the use of aircraft, balloons, rockets or spacecraft. Results obtained so far with aircraft suggest that much progress is needed before this part of the spectrum can be fully exploited. In principle, the highest signal/noise should occur at these wavelengths. Technical innovations will speed progress but a more adequate level of support is badly needed for this difficult and sometimes hazardous work.

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DISCUSSION

Chairman: M. SCHMIDT

MORRISON

Is the time variability really certain in NGC 1068? As I looked at it I saw a factor of about two in 1068 over several years.

LOW

Well, perhaps I did not state it very well. My own view is that 1068 requires more work. If NGC 4151 has varied, then NGC 1068 probably has too, but this is a circular argument.

MORRISON

But the GC does not show any variation.

LOW

It has not, but this is not a strong statement. The galactic center is very hard to observe in the northern hemisphere. It comes in the summer time and is low in the sky.

MORRISON

And 3C 273?

LOW

It has been very difficult to improve the data on 3C 273 since the early work in 1964. This, despite the fact that our sensitivity has improved a great deal. However, the existence of strong IR flux is well established; take the 17 independent observations at 5.10 and 22 microns listed by KLEINMANN and Low, and average them. The result, 4 ± 0.5 flux units, clearly indicates a non-spurious result. This average includes several observations which are several standard deviations outside the indicated distribution. To me, this strongly implies, but does not prove, substantial variability at these wavelengths. (*Note*: Recent results bear strongly on this point).

MORRISON

When the dot appears in the later measurements of 1068 or 4145, that refers to a statistical error only — there are possible systematic variations?

LOW

The errors in the absolute calibration amount to about 15 or 20% and are not included; nor is there an estimate made of systematic errors, only statistical errors are shown.

MORRISON

I see, the calibration varies from time to time?

LOW

Stars used as calibration standards may vary.

MORRISON

It isn't the calibration, it is just the reliability of the relative values of the time sequence of points.

LOW

The techniques of infrared photometry have changed greatly over the last few years. For example, we now use only those stars which we know are constant.

MORRISON

Sure, but the ratio in 1068 between the observation at time T and the observation at time $T + \tau$ was, I estimate, 50 times the standard deviation. Do you think that is unmistakably real?

LOW

The rapid changes indicated in NGC 1068 may be real; only further observation will tell. The variability of M 82 is even less certain, but it is a very interesting case because of its lower luminosity.

G. R. BURBIDGE

There are two points. The first is about variations. STEIN and GILLETT have been looking at NGC 4151 in the infrared, and they also believe that there are variations which are possibly taking place in shorter time scales but the data are uncertain. The second question I wanted to ask you concerns M 82, namely, the galaxy is filled with dust yet the source appears to be a small one, and maybe a variable one. Can you set any limits to the amount of thermal infrared radiation that is coming from M 82, its main body? It looks as if it should be a thermal infrared source.

LOW

As far as we can tell, M 82 is a point source at 10 microns. The Hoffman type radiation would not be seen at 10 microns. (*Note*: The most recent results show M 82 to be extended at 10μ).

SANDAGE

Can you say where your infrared source is in M 82 compared with SOLINGER's explosion centre which he determined from the direction of the polarisation vectors?

LOW

As far as I can tell, our present observations do not differentiate clearly between any of the several positions suggested for the nucleus by SOLINGER and others. We are still working or this point.

SANDAGE

SOLINGER thought he had an accuracy to the order of 10 seconds of arc.

MORRISON

Maybe Dr. OSTERBROCK would care to help too. I would like to know what is the optical luminosity of 1068, and what is the absorption indicated by Balmer decrement in terms of that number of watts? I think that is an interesting number to compare with the infrared strength.

OSTERBROCK

I do not have the optical luminosity, but I do have the emission line luminosity, namely for NGC 1068 $L(H\beta) = 3 \times 10^{41}$ ergs/sec, corrected for interstellar extinction. It should be multiplied by a factor of order 30 to account for all the other emission lines, giving L (em) = 10^{43} ergs/sec., which would mostly be absorbed by the dust and re-radiated in the infrared. That is considerably less than the infrared luminosity of NGC 1068 which I believe is about 10^{46} ergs/sec.

(Note added later) - The optical luminosity of the nucleus of NGC 1068, corrected for interstellar extinction, is about 2×10^{43} ergs/sec. In addition, a contribution must be added for the continuum between the atmospheric limit at 3500Å and the Lyman limit at 912Å, amounting to perhaps another 2×10^{43} ergs/sec. It may be greater than this, as the extinction correction tends to flatten the assumed spectrum. Thus, the total optical and ultraviolet luminosity of the nucleus is about 10^{44} erg/sec.

REES

Are there any data on the polarisation of any of the extragalactic infrared sources?

Low

We made a polarisation measurement of 3C 273 at 1.6 microns with the 200″ in twilight time and we got the extremely high value of 30%. It has not been confirmed.

Schmidt

Is it true that the characteristic shape of the infrared radiation comes essentially from only two objects, the galactic centre and NGC 1068?

Low

No, there are 6 objects which have the same spectrum from 5 to 22 microns.

Schmidt

But it is true, isn't it, that if you integrate up to 25 microns rather than 70 microns you find energies that are more than 10 times smaller?

Low

About 30 times smaller.

Fowler

What data do you actually have on 3C 273?

Low

We have the data published in the Astrophysical Journal Letters by Kleinmann and myself, taken over the last 6 years.

Fowler

But you keep saying that sometimes it is emitting infrared and sometimes it is not; I do not understand whether you believe the data or not.

Low

The existence of a very large IR flux seems well established. The mean value, in view of the apparent variability, is not well established. The spectrum is also uncertain, although the results are consistent with the behaviour of the galaxies.

Fowler

But that, of course, is what worries me, that the more modern data do not seem to substantiate the number that you give, namely 6×10^{48} ergs/sec.

Low

I think they do.

Morrison

If we take the peak of the observed values for 3C 273, by how many standard deviations was that above the mean noise at the time?

Low

Unity instantaneous S/N at best for 3C 273. Integration times ranged from 20 minutes to 4 hours.

Hoyle

I understood you to say that in sources such as 4151 you thought there would be a number of emitting regions contributing to the total emission. Was this correct?

Low

If you believe the coherent synchotron model for the galactic centre, then you must have about 10^4 sources; NGC 4151 would have 10^9.

HOYLE

Then I do not understand how you get variability.

LOW

I am not saying that any of the events that have so far been observed represent explosions of individual sources. I am suggesting chain reactions to account for the wide range of outburst phenomena.

HOYLE

That brings me to the comment that you need such a tight coupling between your individual units that it is a question as to whether you should speak about them being discrete.

LOW

I think there is a rough analogy to a large atomic nucleus.

SANDAGE

Was it true from your slide that the amplitude of the NGC 4151 IR variation is a factor of 20 over three years?

LOW

That is correct.

SCHMIDT

Since the theoretical aspects will undoubtedly come up again later, could I ask for perhaps one or two highly urgent questions about this matter?

SPINRAD

I don't know how urgent this is — I'd like to ask what galaxy nuclei (active or inactive) were looked for hard and not detected?

Low

We have not noted any unpleasant surprises.

Rees

I'd just like to make the point that NGC 4151 did peak optically in about July 1967, which is around the beginning of your run of observations. A dust model radiating at a temperature of 200 degrees like a black body need only have a radius of about 1 parsec. The time-scale of the 20 micron decline which you observed is consistent with this estimate of the size of the emitting region, and would indeed be *expected* if the infrared flux resulted from re-radiation of the light which peaked at the beginning of the period and then died away.

Low

I agree, I don't think the slow variability of NGC 4151 is inconsistent with dust.

Van der Laan

You said that your estimate of the power level of 3C 273 was conservative (the one given in the table), but perhaps that's neither here nor there; the crucial point is whether you have really detected it or not and if you detect it at all then the power level is two orders of magnitude greater than anything else, and you'd almost be forced to drop the cosmological distance.

Low

No, I don't think that follows: I don't think it follows that if the power level in 3C 273 is two orders of magnitude greater than in a relatively nearby galaxy, we have to put the powerful source at the same distance as a relatively nearby galaxy. The time scales are not necessarily equal.

COMPACT RADIO SOURCES IN THE NUCLEI OF GALAXIES

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Summary: Compact radio sources are often found in the nuclei of galaxies, particularly the Seyfert and N-type galaxies which have optically active nuclei, but sometimes in normal elliptical, spiral, or irregular galaxies as well. These compact sources or compact components of sources appear similar to the compact radio sources associated with quasi-stellar objects, although they are less luminous than the identified quasi-stellar sources.

The smallest radio nuclei have dimension of 0.1 pc or less. The maximum brightness temperature found is about 10^{12} °K, a limit set by inverse Compton cooling.

Many of the compact radio nuclei show flux density variations on time scales as short as a few months, suggesting the repetitive production of relativistic particles. The magnetic field strengths deduced from measurements of the surface brightness and self absorption cutoff frequency are typically $10^{-4\pm1}$ gauss, and are nearly 1 gauss in some sources.

It is not clear what relation there is, if any, between the compact radio sources found in the nuclei of galaxies and the intense, and often variable, optical and infrared flux from the same regions. Nor is it clear how radio nuclei are related to the more extended radio galaxies.

Introduction

Among those extragalactic radio sources whose coordinates are well known, about one third are identified with some type of galaxy and a similar fraction with quasi-stellar objects. The

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(*) Operated by Associated Universities, Inc., under contract with the National Science Foundation.

remainder are located in either blank or in heavily obscured regions, and no optical identification has been possible.

The identified radio galaxies whose distances are known from optical measurements of red shift have a wide range of absolute luminosity extending from those like our own Galaxy with a luminosity of about 10^{38} ergs/sec to the very strong radio galaxies such as Cygnus A and 3C 295 with luminosities near 10^{45} ergs/sec. Although the fainter sources are much more common, neither the detailed radio luminosity function, nor the relation between radio emission and galaxy type is clearly known. The dimensions of the radio sources are typically 10-100 kpc, but many galaxies contain components as small as 1 parsec or less, usually coincident with the galactic nucleus.

It is generally accepted that the radio emission, and possibly some of the observed optical, infrared or x-ray continuum as well, is due to synchrotron radiation from relativistic electrons spiraling in weak magnetic fields. Although the source of energy and the manner in which energy is converted to relativistic particles is not understood, observations of the angular structure of the radiating regions, the radio frequency spectra and polarization, and their time variations, allow estimates to be made of the electron energy distribution, the total energy contained in the form of relativistic electrons and the magnetic field, the rate of production and loss of the electrons, and the orientation of the magnetic field.

Radio Structure

Many of the extragalactic sources extend over 100 kpc or more and have complex brightness distributions, with most of the emission occurring from regions well removed from the galaxy. In these extended sources, the relativistic electron cloud is usually optically thin, and the radio spectrum depends on the distribution of electron energies, and the magnetic field strength. High resolution studies of these extended radio clouds often show considerable structure with one or more highly condensed regions existing many kiloparsecs from what is presumed to be the parent galaxy or quasi-stellar object (e.g. BASH 1968).

In the more compact sources, however, the density of relativistic electrons is so great that the source is optically thick over a large part of the observed radio spectrum. At frequencies where the source is optically thick, the spectrum is independent of the electron energy distribution, and the flux density increases as $(\text{frequency})^{5/2}$. The frequency at which a source becomes optically thick depends only on the magnetic field strength and the peak brightness temperature. The magnetic field is therefore completely determind by the observable parameters: peak flux density, S, cutoff frequency ν_c, and angular size, θ, and is given by the relation

$$[1] \qquad B \sim 2.4 \times 10^{-5} (S/\theta^2)^{-2} \nu_c^5 \text{ Gauss.}$$

Equation [1] assumes only that the radio emission is due to incoherent synchrotron emission from relativistic electrons. There are no additional assumptions about equipartition, nor is it necessary to know the distance to the source.

Often the radio emission is concentrated to a very small region near the galactic nucleus with dimensions ranging from a few hundred parsecs to less than 0.1 parsec. In some cases a single galaxy or quasi-stellar object has both compact and extended components.

Typically the compact radio sources are found in quasi-stellar objects or in galaxies that have nuclei which are bright at optical wavelengths and which often show strong emission lines such as Seyfert, N, or compact type galaxies. Some compact sources are, however, found in what otherwise appear to be normal elliptical or spiral galaxies. Table 1 lists a number of galaxies which have small radio components. The symbol "V" indicates that the radio emission is variable.

TABLE 1 — *Galaxies with Radio Nuclei.*

Elliptical Galaxies		
P0048 — 09 (V)	NGC 4278	NGC 5077
M 87	NGC 2911	NGC 3078
NGC 1052	NGC 4552	NGC 5444
Spiral Galaxies		
NGC 253	P1345 + 12	
M 81	3C 305	
Seyfert Galaxies		
NGC 1275	NGC 4151	NGC 7469
3C 120	NGC 3227	NGC 5548
NGC 1068	NGC 4051	
Compact Galaxies		
BL Lac	ZW 1727 + 50	III ZW2
N Galaxies		
CTD 93	P1514 — 24	P0521 — 36
P1934 — 63	3C 371	3C 171
Irregular Galaxy		
M 82		

Of the nearby galaxies, about half of the spirals (e.g. WADE 1968) and about 15 percent of the ellipticals (HEESCHEN 1970a, ROGSTADT and EKERS 1968) show detectable radio emission at centimeter or decimeter wavelengths. In about half of these nearby galaxies, the radio emission is confined to the nuclear regions of the galaxy (WADE 1968, HEESCHEN 1970b).

Among the extragalactic sources in general, about 15 percent have small structure of the order of 0.″001 arc seconds or less. In every case these very compact radio sources are coincident with the galactic nucleus or a quasi-stellar object to within the accuracy of measurement which is typically a few seconds of arc.

The smallest individual component which has been observed is the radio source in the nucleus of M 87 which has an angular size of about 0.″001 arc seconds or less corresponding to linear dimensions of only a few light months (COHEN, *et al.* 1969). A second small component about 150 parsec across, is located 1 kiloparsec away along the jet. In addition, there is the diffuse radio emission from the jet which is about 2 by 5 kpc plus an extended low surface brightness halo nearly 100 kpc in size. At centimeter wavelengths, the nuclear component contributes only about 1 percent of the total flux density.

The observations of BASH (1968), WADE (1968) and HEESCHEN (1970b) made with a resolution of about 2 arc seconds indicate that many galaxies have weak, small radio nuclei. It is likely that this may very well be a common property of radio galaxies. In general these very compact sources show considerable structure when examined with very high resolution. There is evidence in some cases that the compact sources may have multiple spatially separated components similar to, but on a much smaller scale than, the extended sources (CLARKE, *et al.* 1969). Often, however, the individual components of a source which may differ in size by more than two orders of magnitude appear to be essentially coincident. The form of this multiple core-halo structure appears identical in galaxies and in quasi-stellar sources. In those cases where the structure has been measured at several wavelengths, the smallest components appear strongest at the shorter wavelengths, probably due to synchrotron self-absorption at long wavelengths. The maximum brightness temperature observed in the compact sources is always of the order of 10^{11} to 10^{12} °K which, because of inverse Compton cooling, is the limit for any source of synchrotron emission. The good agreement between theory and observations of the self absorption cutoff frequency, the angular size of individual components, and the observed peak brightness temperatures is perhaps the best indication that the radio emission from these very compact sources is indeed ordinary incoherent synchrotron emission.

Time Variations

Many of the compact radio sources found in the nuclei of galaxies or in quasi-stellar objects show pronounced variations in intensity on time scales ranging from a few weeks in the case of the unusual object BL Lac (ANDREW, *et al.* 1969, OLSEN 1969), to a few years. Considering that observations are rarely made more often than once per month, and that accurate data exists for only about five years, the possibility of significant variations on much shorter or longer time scales cannot be excluded.

A number of the variable radio galaxies and quasi-stellar sources also show significant optical variations as well. Although there appears to be no simple relation between the intensity variations seen at radio and at optical wavelengths, those sources which are most active at radio frequencies such as 3C 279, 3C 345, 3C 446, 3C 454.3, 3C 84 (NGC 1275) are also outstanding optical variables. There are exceptions, however; 3C 273, which is one of the most active radio sources has not shown significant optical variations in recent years

On the other hand, there is no radio counterpart to the large variations seen in NGC 4151 at optical and infrared wavelengths.

There is no significant evidence in the radio data for any periodic phenomena. Rather, the variations appear to be in the form of random outbursts, which often appear first at short wavelengths and then at longer wavelengths at later times and with reduced amplitude. The typical time scale for an event to propagate from centimeter to decimeter wavelengths is of the order of one to several years.

These variations might be caused by changes in the rate of production or acceleration of relativistic particles; the loss of energy of the particles due to synchrotron radiation, inverse Compton scattering, or adiabatic expansion; the decrease in the magnetic field strength; and in the opaque region of the spectrum, the change in the angular size as a result of the expansion. Probably all of these contribute to a varying degree among the different sources, and at different epochs within individual sources.

The observed variations are often interpreted in terms of the simple model, initially suggested by SHKLOVSKY (1965), where the radio emission comes from a cloud of relativistic particles which is initially optically thick out to some wavelength, but which, due to expansion, becomes optically thin at successively longer wavelengths. In at least one galaxy, 3C 120, there have been three distinct radio bursts during a four year period. Each of these has followed, quite closely, the quantitative form expected from isolated bursts of particles (PAULINY-TOTH and KELLERMANN 1968).

The intensity variations which have been observed at 1.9 cm wavelength over the past 5 years are shown in Figure 1 for 3C 120 and three other radio sources. Somewhat surprisingly there is no discernable difference in the form of the outburst observed in the nuclei of radio galaxies and in quasi-stellar sources. Observationally, the intensity variations seen in quasi-

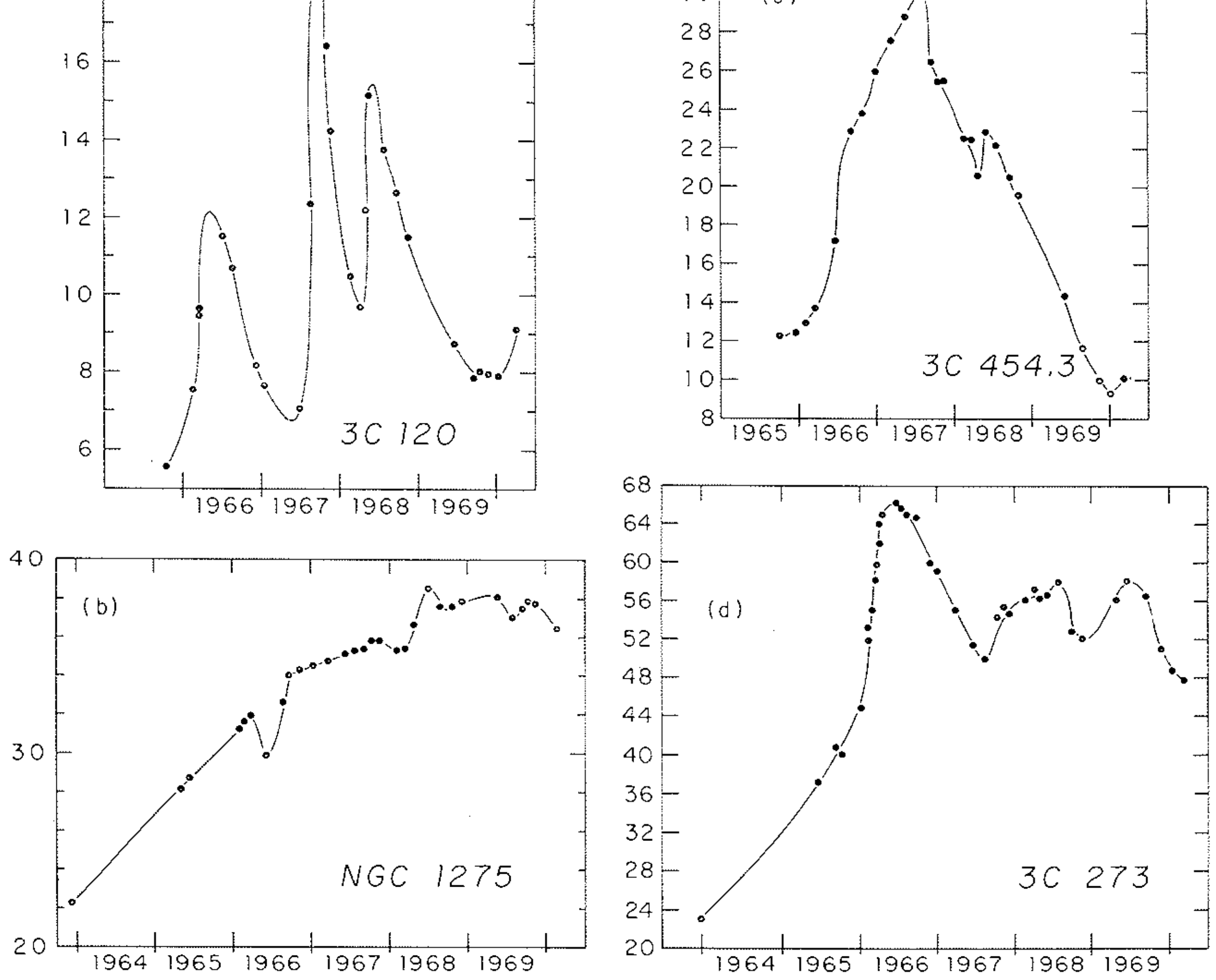

FIG. 1 — Flux density variations observed in the radio galaxies 3C 120 (a) and NGC 1275 (b), and the quasars 3C 454.3 (c) and 3C 273 (d). The data are taken from unpublished measurements at NRAO by PAULINY-TOTH and the author.

stellar sources have similar time scales, a similar form of light curve, and a similar change in apparent luminosity. On the cosmological interpretation of the quasi-stellar red shifts, however, the change in intrinsic luminosity in the quasi-stellar radio sources is up to 10^4 times greater than observed in the galaxies, and in some cases is greater than the total luminosity of the strongest radio galaxies such as Cygnus A.

In general, although the individual events are not sufficiently isolated in frequency or in time to allow a detailed analysis (e.g. figure 2d), the observed variations appear at least qualitatively to follow the form expected from the expanding cloud model. The limited data available at millimeter wavelengths indicates that the large and rapid variations expected at short wavelengths do not occur, so that the sources must be initially optically thin at wavelengths shorter than about one centimeter. This is not surprising, since the generation of particles must occur over a finite volume of space and last a finite period of time, and so the radio cloud must be initially optically thin at very short wavelengths.

In some sources the outbursts occur simultaneously and with nearly equal amplitude even at centimeter wavelengths (KELLERMANN and PAULINY-TOTH 1968, LOCKE, et al. 1969). In these sources, the electron cloud is clearly initially optically thin over the wavelength range where the event is observed, and the spectral index is close to zero. It is difficult to understand, however, how such rapid variations can occur in a source whose dimensions are sufficiently large so that it is not optically thick (LOCKE, et al. 1969).

Often it is not possible to separate individual outbursts and the generation of relativistic particles in some sources appears to be more or less continuous, although not necessarily constant. This type of activity has been observed in the nucleus of NGC 1275 where (as shown in figure 1b) the centimeter wavelength emission has been steadily rising. It appears that in the nucleus of NGC 1275 a number of minor outbursts have occurred at the rate of one every year or two (KELLERMANN and PAULINY-TOTH, 1968; HOBBS, CORBETT, and SANTINI 1969). Since the duration of a single radio event at centimeter wavelengths is typically of the order of one year, individual events are only barely resolved. In order to determine more accurately the rate of production of relativistic particles, more data is needed at millimeter wavelengths, where the individual radio events are short lived.

For several sources where there is adequate data during the initial expansion phase to compare with the expanding source model, the magnetic flux appears to be conserved so that $B_2 \sim B_1\ (t_1/t_2)^2$. The measurements of angular size and self absorption cutoff frequency indicate that B is never less than about 10^{-5} Gauss, which is also the typical value of the magnetic field strength deduced for the more extended radio sources from minimum energy arguments (e.g. MACDONALD *et al.* 1968). It therefore appears that after the field reaches 10^{-4} or 10^{-5} Gauss, it no longer decreases with time and the relativistic particles probably diffuse in a fixed magnetic field or escape from the source.

The rapid rise and fall of flux density with time typically requires that relativistic electrons be produced over a time span less than a few months and in regions less than a few light months across. The spectrum is initially flat above the cutoff frequency so that the number of electrons is approximately inversely proportional to energy. In some sources, at least for one year, this distribution is not significantly modified by synchrotron radiation losses or by inverse Compton scattering, so the electrons apparently lose energy mostly by expansion of the cloud (PAULINY-TOTH and KELLERMANN 1968, DENT 1968, LOCKE, *et al.* 1969). In particular, since in at least some sources there is no sign of a synchrotron loss or inverse Compton loss cutoff below 100 GHz, the initial value of the magnetic field cannot be much greater than about one gauss, or the initial brightness temperature greater than about 10^{12} °K.

Whether or not the repeated outbursts all occur in the same volume of space or are separated by some distance is not clear. This, and the detailed structure of the very young electron clouds, remains to be determined by future high resolution radio observations. Such observations, when made with sufficient resolution, can also measure directly the rate of change of angular size and thus the manner in which the magnetic field strength changes with time. Detailed observations of the intensity variations, particularly at short wavelengths corresponding to the early epoch following the generation of relativistic particles, are also necessary to determine the rate at which the particles are generated, the initial magnetic field strength and electron energy distribution, and the way the electrons lose energy.

Energy Requirements

If the distance of an optically thick radio source is known in addition to its angular size, θ, and self absorption cutoff frequency, ν_c, then it is possible to estimate the energy contained in the relativistic electrons and in the magnetic field without making any further assumptions (KELLERMANN and PAULINY-TOTH 1969). The energies calculated in this way depend strongly on the measured quantities, θ, ν_c, so the uncertainty in the calculated value is large unless the cutoff frequency and angular size can be measured with very high accuracy. Nevertheless, energies derived for the compact radio sources are 10^{52} to 10^{56} ergs. This is clearly very much less than the minimum energy of 10^{58} to 10^{61} ergs required for the extended sources. It should be emphasized that although the energy content of the compact radio sources is small compared with the extended sources, the compact quasi-stellar sources are among the most luminous extragalactic sources so that the reservoir of electrons is often only sufficient to last for about 100 years. This may be contrasted to the less luminous extended sources where the supply of electrons is adequate to radiate for 10^9 or more years.

The energy required in the individual bursts observed in galaxies is not excessive; the quasi-stellar sources, however, present somewhat of a problem. Since none of the variable radio components have been unambiguously resolved in the quasi-stellar sources, it is not possible to determine accurately the value of the magnetic field and the electron energy content. A rough limit to the size of the variable components may be made from consideration of the light travel time across the source. Assuming that the sources are at the distance indicated by the red shift, this leads in some cases to extremely small angular sizes, small magnetic fields, and relativistic electron energy content of 10^{58} ergs or more. This apparently excessive energy, which is required to be repeatedly released in a period of a few months or less and sometimes as often as once every year or two, is, however, significantly reduced if the quasi-stellar sources are closer than indicated by their redshifts, or if the electron energy cloud is expanding at a highly relativistic rate so that the apparent size is less than the true dimensions (REES 1967, REES and SIMON 1968). This is discussed in more detail in the following paper by VAN DER LAAN.

The only variable source which has been unambiguously resolved is the central component in the radio galaxy NGC 1275 (3C 84), which has two distinct opaque components, one of which is variable. In addition there is a more extended halo with a power law spectrum. Figure 2 shows the radio frequency spectrum of NGC 1275 and the spectra of the three individual components.

The spectrum of the high frequency variable component below the cutoff frequency near 8 GHz, is close to that expected from an optically thick synchrotron source. The present size

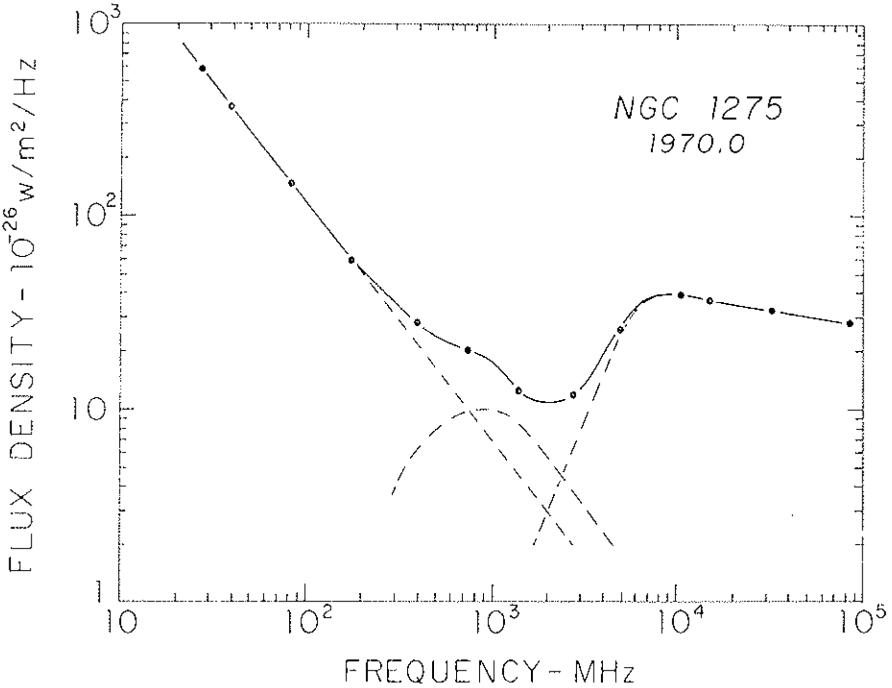

FIG. 2 — Radio spectrum of NGC 1275 (3C 84). The separation of the components is based on interferometer measurements made over a wide range of wavelengths and resolution (RYLE and WINDRAM 1968, KELLERMANN, *et al.* 1968, CLARKE, *et al.* 1969).

of the variable component is about 0."001 or one light year. Analysis of the rate of increase of flux density suggests that this component is approximately 10 years old, so that the average expansion velocity is about 5 percent that of light. The magnetic field strength is estimated from equation (1) to be about 0.1 Gauss, and the energy of relativistic electrons released over the past 10 years about 10^{52} ergs. The larger, compact component, which is either non-variable, or varies only slightly over a time scale of several years and contains 10 to 100 times as much energy, may be a remnant of one or more older outbursts. The extended component, which contains about 10^6 times the energy of the smaller compact source is thought to be the superposition of many outbursts of the type now being observed.

TABLE 2 — *NGC 1275 (3C 84)*.

	Halo	Core	Nucleus
Angular Size (arc seconds)	300	0.02	0.001
Linear Size (parsecs) . .	80×10^3	5	0.3
Luminosity (ergs/sec) . .	2×10^{41}	10^{41}	10^{43}
Total Energy (ergs) . . .	10^{58}	10^{53}	10^{52}
Lifetime (years)	10^9	3×10^4	30

Table 2 summarizes the angular size, θ; the linear dimension, ℓ; radio luminosity, L; the magnetic field strength, B, computed from equation 1; and an estimate of the energy contained in the relativistic electrons, E_e, in each of the three components of NGC 1275.

In addition there is a very large low surface brightness radio source extending over about 30 minutes of arc (500 kpc) plus two smaller sources associated with the galaxies NGC 1265 and IC 310 which, like NGC 1275, are members of the Perseus cluster (RYLE and WINDRAM 1968). In both NGC 1265 and IC 310 the radio source is elongated along the line joining the galaxy with NGC 1275 and it has been suggested that the relativistic particles in these sources originated in NGC 1275 located hundreds of kpc away (RYLE and WINDRAM 1968).

In the Seyfert galaxy, 3C 120, the luminosity of each of the three outbursts illustrated in Figure 1 was comparable to the outburst in the nucleus of NGC 1275 described above. The energy required in relativistic particles is about 10^{52} ergs for each of the three outbursts which is again comparable to NGC 1275. Like NGC 1275, 3C 120 also has an extended halo with a minimum energy content of about 10^{58} ergs.

The small radio source in the nucleus of M 87 is interesting because of its very small dimensions. As there are no measurements of the spectrum or of time variations in this source, detailed calculations are not possible. A rough estimate of the luminosity of the nuclear source is about 10^{40} ergs/sec if the flux density remains constant out to 100 GHz. This may be compared with 10^{41} ergs/sec for the halo, and 4×10^{41} ergs/sec for the extended jet component. It is not possible to calculate the energy contained in the nuclear component since neither the spectral cutoff frequency nor the angular size is accurately known. It is unlikely, however, to be in excess of 10^{52} or 10^{53} ergs, compared with the minimum energy content of 10^{54} ergs for the jet and 10^{59} ergs for the halo. The small sources found in the nuclei of NGC 1052 and NGC 4278, and in other elliptical galaxies (HEESCHEN 1970a) are very similar to the small source in the M 87 nucleus, except that there is no extensive halo component associated with these galaxies.

Summary

The relation between the compact and extended radio sources is not clear. It is not energetically possible for a single compact source to evolve into an extended source since the energy content of the latter is typically $10^{7\pm2}$ times greater. If the relativistic particles are generated in the compact radio sources, either the original particles must be continuously accelerated or some 10^5 to 10^7 separate events are required over a time scale of 10^6 to 10^8 years.

The direct observation of repeated outbursts in both galactic nuclei and quasars suggests that energy is released in repeated violent events. Each event generates 10^{52} ergs or more of relativistic particles in the nuclei of some galaxies, and possibly considerably more in quasars, in time scales of a few months or less and in volumes of space a few light months across. The superposition of many of these outbursts may provide a sufficient number of relativistic electrons to produce the extended sources of emission.

The ultimate source of energy and the manner in which it is converted to relativistic particles is still a mystery. Curiously, the phenomena appear to be surprisingly similar in the radio galaxies and the quasi-stellar objects. Both have a comparable range of radio properties including absolute luminosity, linear dimensions, structure polarization, spectra, and intensity variations. In spite of their very different appearance optically, the radio astronomer is unable to distinguish, from the radio data alone, a radio galaxy from a quasar.

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DISCUSSION

Chairman: M. SCHMIDT

SPITZER

In your model for 3C 120 which I believe is perhaps one of the best fits, can you estimate what the total mass ejected will be if one assumes that the total number of protons ejected is equal to the number of electrons?

KELLERMANN

The energy involved in relativistic particles is something of the order of 10^{52} ergs. This is made up of electrons with energies near 1 Gev. So the total mass is only about 1% of the solar mass.

HOYLE

I notice you included BL Lac among the galaxies. Would you like to say why you put this here?

KELLERMANN

No, it is probably either a compact galaxy or a quasi-stellar object, I had to put it somewhere.

HOYLE

What I meant is, are you convinced that the evidence does not indicate that it is a galactic object?

KELLERMANN

If it is, it is unique. I see no evidence that it is galactic.

SARGENT

With reference to the last question. I notice that two out of the three objects that you put in the compact galaxy group show no lines. I Zwicky 1727 + 50 has no spectral lines and it has been observed over several years, so there are two out of three which may, in fact, be galactic objects.

KELLERMANN

You think that that is galactic too?

SARGENT

Yes, why not? There is no evidence of their extra-galactic nature.

KELLERMANN

There is no evidence of their galactic nature.

LOW

Can you extrapolate with your model back in time to t_0?

KELLERMANN

Yes, you can do this.

LOW

Putting it from an observational point of view, if you had been able to observe at short enough wavelengths, presumably you would have seen that for each of these events there is a shortest wavelength or high frequency cut-off. Is your model still valid near t_0?

KELLERMANN

We can only extrapolate so far to where the assumption that the production of particles occurred in a point volume of space, or in zero time, is no longer true. The observations indicate that the model breaks down at millimeter wavelengths. You expect, as you go to shorter wavelengths, the flux density variation to be greater. The variations observed at millimeter wavelengths (and the observations are very sketchy) indicate with one or two exceptions that the millimeter variations are not as great as you would expect, which means that at millimeter wavelengths the source was always optically thin, that it never got optically thick.

MORGAN

Just to clarify a question, are there galactic objects known which are radio sources and which vary in the sense of the objects that you were discussing a moment ago?

KELLERMANN

There are many galactic radio sources. The non-thermal ones appear to be largely supernova remnants. These vary slowly, say one or two percent a year at the most. At the time of the supernova outburst, the radio variations may be similar to what we observe for the extragalactic sources, but this has never been directly observed. The phenomena are presumably similar, only the energies involved are very much greater in the extragalactic sources.

SPITZER

Can you state again, please, the energy corresponding to a single radio burst from 3C 273?

KELLERMANN

It would have to be of the order of 10^{58} ergs if you accept the redshift as indicating the distance, and if the expansion velocity is non-relativistic.

SPITZER

And does one of these bursts occur about once a year?

KELLERMANN

There were two or three peaks over a four year period. Whether or not these represent separate outbursts isn't completely clear.

SPITZER

That would correspond then, to a luminosity of 10^{50} ergs per second.

KELLERMANN

Yes, a single outburst is 10^{58} ergs in less than a year, or about 10^{50} ergs per second.

SPITZER

Of this total luminosity something like 10^{46} ergs per second is the energy radiated at radio frequencies?

KELLERMANN

About 10^{45} ergs per second at radio frequencies.

SPITZER

The total energy rate of 10^{50} ergs per second appears to be even greater than that required for the infrared luminosity.

KELLERMANN

A total energy generation of something like 10^{50} ergs per second seems not too surprising if you accept the 10^{48} ergs per second radiated in the infrared.

MORGAN

When you break down the radio spectrum of 3C 273 into three components, do you have any spatial evidence for their separation?

KELLERMANN

In 3C 273 for example, the radio spectrum and the high resolution interferometry show three distinct components, but it is not clear how these components are related to the components that you get from decomposing the variation curve. There's no simple relation — at least I couldn't find any. Also it is not clear if the components are spatially separated or concentric.

McCREA

About this estimate of energy, 10^{58} ergs, is that the integrated energy that is observed? Or is it the total energy inferred; if so, is it the energy in the electrons, or is an allowance made for heavy particles?

KELLERMANN

No, it's the energy that you need in the form of relativistic particles, to account for the observed radio luminosity, using the most conservative assumption that there are only electrons.

McCREA

Just electrons?

KELLERMANN

That's right, just electrons. But the number 10^{58} is uncertain by several orders of magnitude, just because of experimental uncertainties.

OORT

What is the separation of these three small outburst components in 3C 273?

KELLERMANN

We cannot see the difference from them being concentric. Exactly what this means isn't certain. I think they are not separated by more than the size of the biggest, that is by more than a few hundredths of a second of arc.

SPINRAD

Do the compact sources of WADE and HEESCHEN all have flat spectra, and if so, can the extrapolation to very high frequencies be of any use here in providing an excitation source for the optical emission lines which have been a bit of a problem in these nuclei?

KELLERMANN

All the very compact sources with dimensions of order of hundredths or thousandths of seconds of arc have to have flat spectra because they are optically thick. It appears that the flat spectra that you see in the extragalactic sources are not necessarily due to a flat electron energy spectra but just the fact that they have several optically thick components, which are peaking up at different wavelengths. What happens at wavelengths short of a few millimeters isn't clear. The few observations that exist indicate that at short millimeter wavelengths there are very few optically thick sources. That is they are all beginning to turn over, and becoming optically thin. This had to happen somewhere, because otherwise the sizes must be very small.

SCHMIDT

Has a correlation been looked for between the appearance of emission lines in radio galaxies and the occurence of a small component at the center?

KELLERMANN

Most or all of the galaxies or QSOs associated with small radio components have emission lines.

SANDAGE

Could you say something further about the halo radiation in M 82?

KELLERMANN

90% of the radio emission is from the small source that is near the nucleus and the other 10% is more or less comparable to the size of five minutes of arc or so of the galaxy.

SANDAGE

And is there any indication of what the spectral index of the halo is?

KELLERMANN

It is difficult to say, but it appears to be flat.

HOYLE

You mentioned the upper limit of brightness temperature as being around 10^{12} degrees. Could you say how firm this number is?

KELLERMANN

Well, as it turns out it's not possible to measure from the surface of the earth much higher brightness temperatures than this. Since the resolution of an interferometer is proportional to the base line and inversely proportional to the wavelength, and since as you go to sborter wavelengths you also see smaller sources and these two effects cancel each other. At any given physical baseline there is a limit to the brightness temperature that can be measured. For earth dimensions this is about 10^{12}. Thus, although you don't expect anything greater than 10^{11} to 10^{12} degrees, it is also true that from the surface of the earth it is not possible to resolve the brighter sources. But I think there are very few, if any, sources in which a significant fraction of the flux density is still unresolved. You could have something like ten percent of the flux in a higher brightness temperature component. The major part of the flux from most sources certainly doesn't have a brightness temperature greater than some 10^{12}.

HOYLE

The point is a very interesting one. I know you have an explanation of this upper limit in terms of the inverse Compton effect. There is another possible explanation in terms of proton and antiproton annhilation leading to electrons of about a hundred million volts, which also gives an upper limit to the brightness temperature at 10^{12} degrees. It would be good if one could separate in some way these two possible ways of explaining the upper limit.

KELLERMANN

That would require magnetic fields of 10^{-2} Gauss, or more, and the measurements indicate something like 10^{-4} Gauss.

MORGAN

You said you do not have a residuum of apparently bright unresolved sources, is that correct?

KELLERMANN

Yes, that's right. There may, however, be a small fraction of flux which is left unresolved.

FOWLER

You commented earlier in your talk that there was no evidence for periodicity, yet when you showed 3C 120 one might argue that there was some evidence for a periodic phenomenon there with one of the pulses missing.

KELLERMANN

It seems a bit hard to do on the basis of three events (hearty laughter).

FOWLER

Well that's only because you haven't looked long enough.

KELLERMANN

Yes, I've said that. The sampling of data is from a few weeks to a few months over a few years. There aren't many periodic phenomena that you can see with that kind of data. I believe my statement that "there is no evidence for periodic variations", still stands.

FOWLER

Well, let me ask what was the separation between those three?

KELLERMANN

Of the order of a year.

OORT

I'm surprised about your statement that there are practically no unresolved sources. If you consider the results obtained in Messier 87 one would think that all the more distant quasi-stellar sources might have very much stronger unresolved sources inside.

KELLERMANN

I said that the major fraction of the flux is resolved. In M 87 there is one percent in the small component. It is only because M 87 is so strong and so close that we can see that small component. In almost any other source such a low luminosity small component would not be detected. So it is certainly consistent to say that any or all sources may have such a small fraction of the flux in a very small component, of the order of light months in size. This, in fact, is an attractive hypothesis if we want to speculate that these small components are the origin of energy for the entire radio flux.

FRIEDMAN

Is there any evidence yet for variability in the small component of M 87?

KELLERMANN

There is no evidence for variation in the total flux of M 87. Since the small component is only one percent of the total flux it would be difficult to see when you look only at the total flux. There are two observations made a week apart of this small component alone.

EXPANSION MODELS OF ERUPTIONS
IN QUASARS AND RADIO GALAXIES

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1. *Introduction.*

Since the fundamental problems of energy generation and its distribution over several modes form the chief concern of several preceding and following speakers, I will limit myself in this introduction chiefly to the curious phenomenon of intensity and polarization variations in the radio frequency domain. Of all the amazing features of compact systems these variations are perhaps the only evidence of *systematic* violence. Violence because the common interpretation of the phenomenon implies an energy release rate equivalent to ∾ one S.N. (type II)/sec for several months to a year.

Radio observations of compact sources provide, in principle, as a function of frequency and time, the flux density, the degrees of polarization, the polarization angle and the angular diameter, denoted respectively by $S(\nu, t)$, $p(\nu, t)$, $\chi(\nu, t)$ and $\varphi(\nu, t)$.

The first of these functions is best known, for it is most easily measured. In 1965 SHKLOVSKY suggested that compact extragalactic sources might vary measurably. In 1966 KELLERMANN and PAULINY-TOTH, and MOFFET noted that early variability data, the first of which came from Michigan (DENT, 1965, 1966), were suggestive of an expanding optically thick source (IAU symposium 29, Byurakan, May 1966).

At the same time this suggestion was worked out quantitatively in a form directly comparable to observations (VAN DER LAAN, 1966). At that time the data were fragmentary and only the qualitative features of the model could be checked. However, it was clear that there were a number of instruments capable of acquiring the data necessary for quantitative tests and the simple model was published in the hope of stimulating many observers to start variable source monitoring programmes, rather than with the expectation that it would remain a viable model in the face of a greatly enlarged and refined body of data.

A number of variable source observing programmes were begun and the results were compared with the quantitative predictions of the model. Surprisingly, the variable source behaviour conforms, in the main, to the model far better than one had any reason to anticipate.

2. *Qualitative features of the variability data and of the adiabatic expansion model.*

The first detection of variability in the radio domain occurred at 8 GHz (λ 3.75 cm). Systematic monitoring at wavelengths from 2 to 40 cm revealed the following features:

(i) the variability first occurs at short wavelengths and propagates towards longer wavelengths.

(ii) the amplitude of the variation decreases steadily with increasing wavelength.

(iii) the rate of increase generally exceeds the rate of decrease.

(iv) the duration of a pulse as measured at half-power points increases with increasing wavelengths.

The figures in Dr. KELLERMANN's paper show these features.

The model which has served observers for the past thirty months as the standard of comparison is the following: take a sphere filled *instantaneously* and *uniformly* with a relativistic electron gas and a regular magnetic field and assume it expands *isotropically* and *nonrelativistically* without letting any particle escape or gain occur, retaining homogeneity.

In that case the electron gas cools adiabatically, the magnetic flux is conserved and its synchrotron radiation is easily computed as a function of the radius. If the expansion rate is constant the observations give the age of the source directly.

As shown in the paper which deals with this question in detail (VAN DER LAAN, 1966), the spectral evolution of such a source can be described as the migration of the spectral curve in the log S_ν — log ν plane, along a straight line of slope $\frac{7\gamma + 3}{4\gamma + 6} \simeq 1.2$ where γ is the usual exponent of the electron differential energy spectrum. This is shown in figure 1. Since a radio telescope observes at a single frequency, the flux density is seen to rise first, while $\tau_\nu \gg 1$. A maximum is reached as $\tau_\nu \sim 1$, followed by a decrease at $\tau_\nu < 1$. Figure 2 contains the same information as the preceding one, but now successive frequency curves are shown. These two diagrams illustrate that the four features mentioned above are characteristics of the simple model; (i) the variability proceeds from short to long wavelength; (ii) amplitnde decreases with increasing wavelength; (iii) the rate of increase exceeds the rate of decrease; (iv) the pulse widens with increasing wavelength.

Qualitatively the model accounts well for the early data's features.

3. *Quantitative predictions of the simple model and observational results.*

From the qualitative description of the spectral evolution just given it is clear that the measurement of a single observable and its rate of change, in principle, leads to predictions of the values and rates of change of other variables.

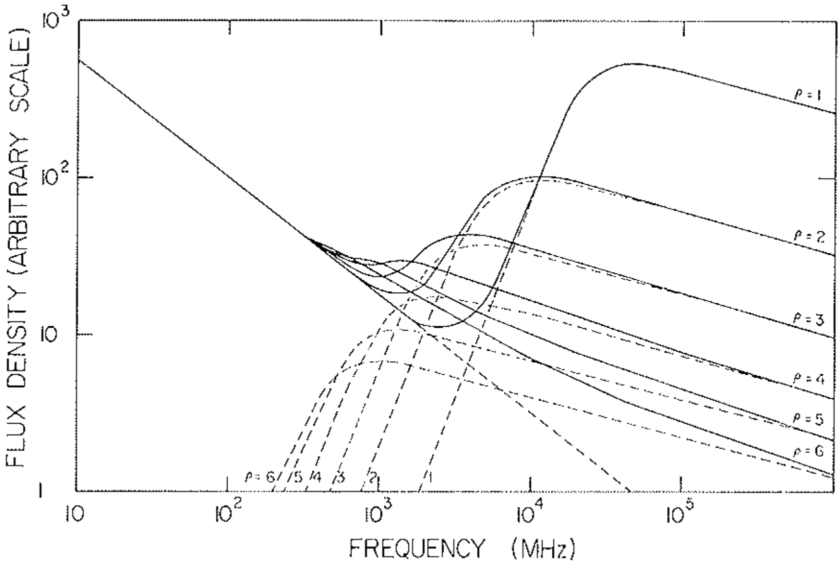

FIG. 1 — The migration of the spectral curve of an expanding, homogeneous, spherical synchrotron radiation source in the log S_ν — log ν plane. This spectrum is shown superimposed on that of the usual large transparent source.

One additional restriction must be made: in order to relate *temporal* variations of several parameters one to another, the expansion rate, that is the time dependence of the radius, must

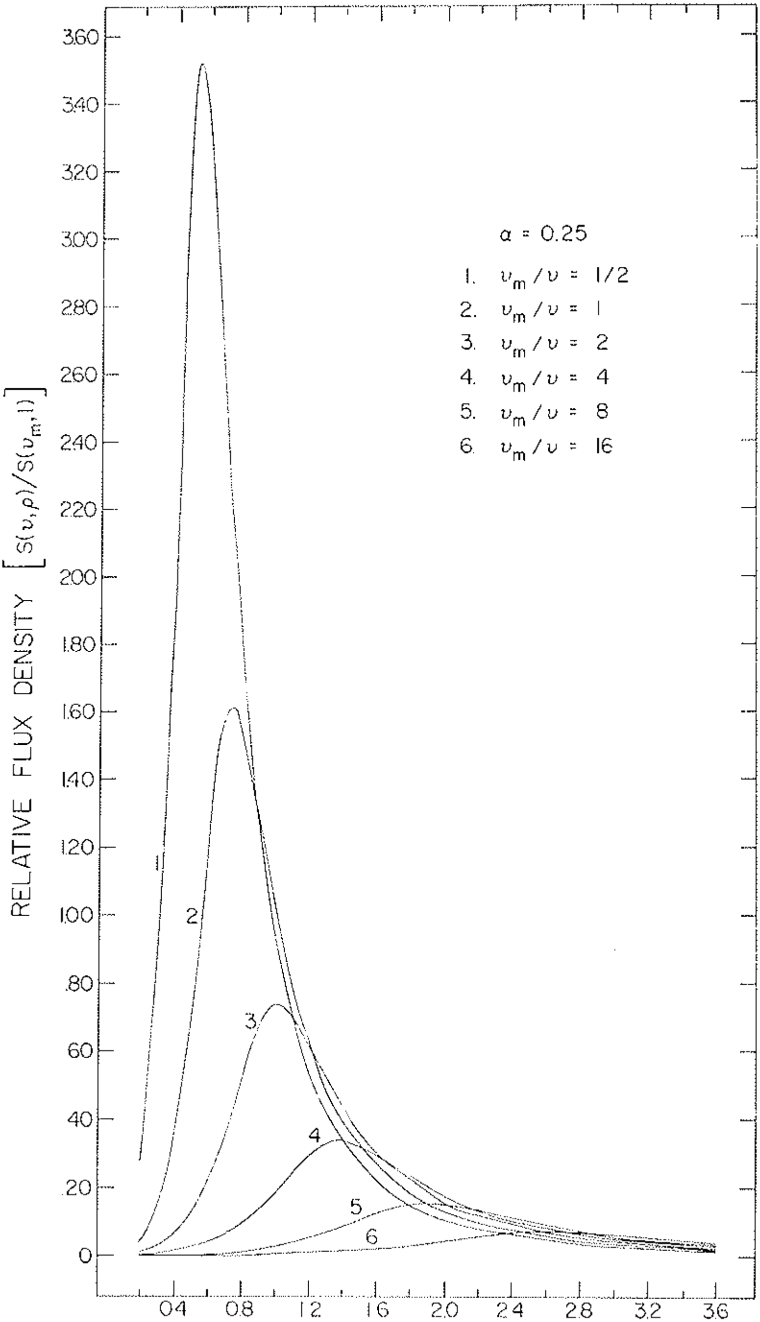

FIG. 2 — The flux density as a function of source radius, at frequencies which successively differ by a factor two.

be specified. Assuming the expansion rate to be constant it is easily shown that the apparent age of the expanding component can be specified in several ways:

$$
\begin{aligned}
T = t - t_0 &= \frac{3\,S}{\dot{S}} \quad \text{(in the opaque part of the spectrum)} \\
&= -2\,\gamma \frac{S}{\dot{S}} \quad \text{(in the transparent part of the spectrum)} \\
&= -\left(\frac{4\,\gamma + 6}{\gamma + 4}\right) \frac{\nu_{\max}}{\dot{\nu}_{\max}} \quad (\nu_{\max} \text{ is the frequency of maximum intensity}) \\
&= -\left(\frac{7\,\gamma + 3}{\gamma + 4}\right) \frac{S_{\max}}{\dot{S}_{\max}} \quad (S_{\max} \text{ is the maximum flux density})
\end{aligned}
$$

where t is the epoch of measurement and t_0 the epoch of the event.

In practice the flux densities are measured at particular frequencies. The epoch of birth deduced from them is then used to relate the maximum flux density, the frequency at which this occurs and the time as measured from that starting epoch.

Figures in the review by KELLERMANN and PAULINY-TOTH (1968) show that for 3C 120 (= II Zw — 14, an enormously powerful infrared source) the model predictions, calibrated by the epoch determinations from $S/\dot{S}$ represent the observations of the flux density maximum's displacement in the (ν, t) plane satisfactorily.

Quantitative deductions are complicated by the fact that most variable sources have several varying components. Since generally the magnitude, the rate of change and the starting epoch of each is different from the others, quite a lot of data are required, well spaced in ν and t, to unravel the spectrum and trace the behaviour of each component, made the more difficult by the presence of a quiescent component whose spectrum needs to be known to establish the variables' zero level.

The explosive events are observed to have starting epochs ∾ 1 year apart. Their spatial separation is therefore likely to be small. There are, however, sources with only a single known variable component. The observing period of five years since DENT's discovery is too short to judge whether the distribution of intervals between succeeding bursts has a maximum shorter than this timespan.

4. *Polarization data and variability interpretation.*

The extreme simplicity of the model just discussed and our ignorance about the initial conditions, as well as several difficulties implicit in this straight forward interpretation, leads one to wonder whether the radiation observed is synchrotron radiation at all.

Measurements at several observatories, but particularly at Michigan by ALLER (1970a), have established some of the sources' polarization characteristics and the polarization's change with ν and t.

These results and their interpretation are here briefly summarized. They show that the basic notion of the simple model, viz. that the variability is caused by the temporal change of the optical depth of an expanding electron-synchrotron radiation source, is correct.

ALLER (1970a) has monitored the linear polarization of several variable radio sources at 8 GHz. Five of the best-known variables, viz. 3C 120, 273, 279, 345 and 454.3, were definitely found to be polarization variables. Three others were probable polarization variables. Thus all sources stronger than 3 f.u. at 8 GHz that vary significantly in total flux density also show polarization variability.

Figure 3 shows ALLER's results for 3C 120 and 3C 273.

The variation of the polarized flux density S_p does not follow that of S. The polarization variability is generally much more rapid than the total flux variability. The large rapid variations of S_p are observed only when S in increasing or near its maximum.

The polarization angle sometimes changes greatly with changes in polarized flux, but appears always to return to a stable position. In addition this angle seems to go through a similar cycle during repeating bursts.

The interpretation of these results is straightforward in the framework of the adiabatically expanding synchrotron radiation source and it is given by ALLER (1970b) as follows. Take the volume emissivities and absorption coefficients of the synchrotron radiation of a homogeneous isotropic flux of relativistic electrons in a unidirectional magnetic field for a direction $\perp$ and // to the projected magnetic field respectively.

Then for $\tau \ll 1 \quad p = \dfrac{3\gamma + 3}{3\gamma + 7}$ and the position angle perpendicular to **B**.

$\tau \gg 1 \quad p = \dfrac{3}{6\gamma + 13}$ and the position angle parallel to **B**.

Figure 4 shows how the degree of polarization varies with opacity. If we now recall how this entire curve moves as the source expands, then it is easily visualized not only how the total intensity varies at a single frequency, but also how the polarized flux changes. Particularly it is clear that the polarization variability and the polarization angle changes are more rapid than the changes in S and occur as S increases.

Of course, since the degree of polarization will be much less for a real source in which a variety of projected directions of **B** are present, this idealization is good for a qualitative comparison only. Moreover one expects the real difference

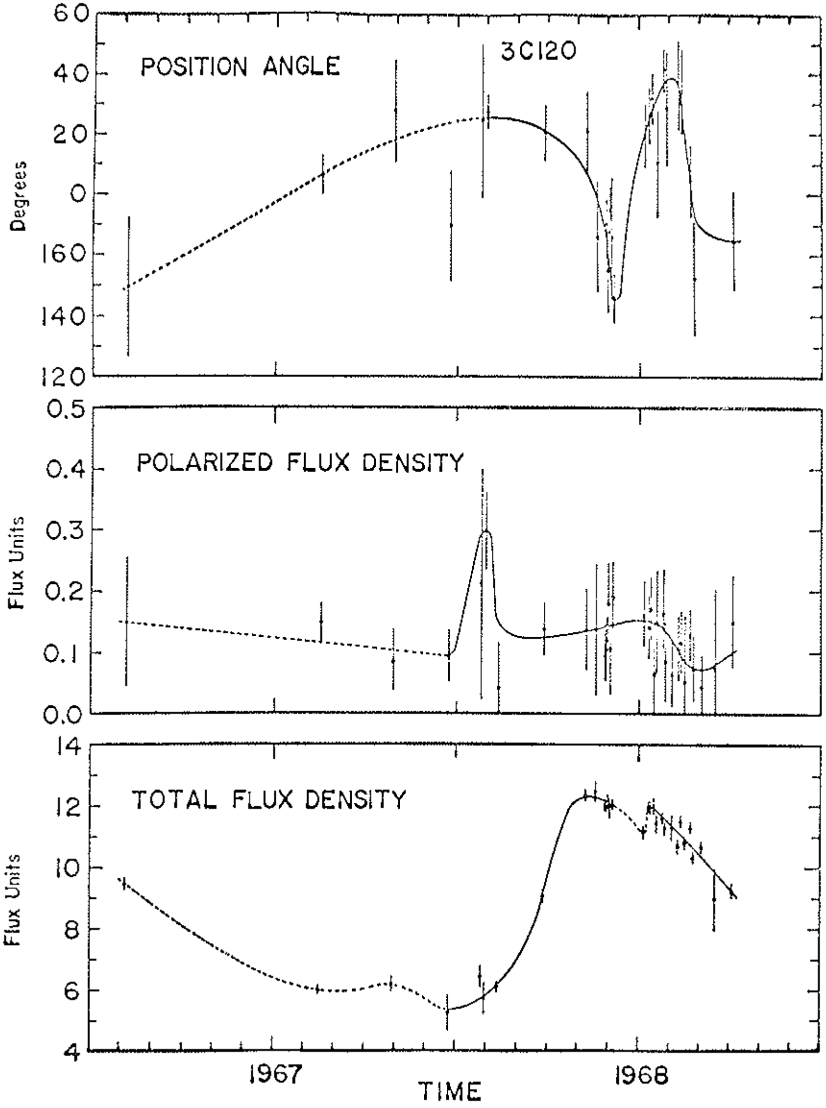

FIG. 3a — The polarization variability of 3C 120 at 8 GHz (ALLER 1970a).

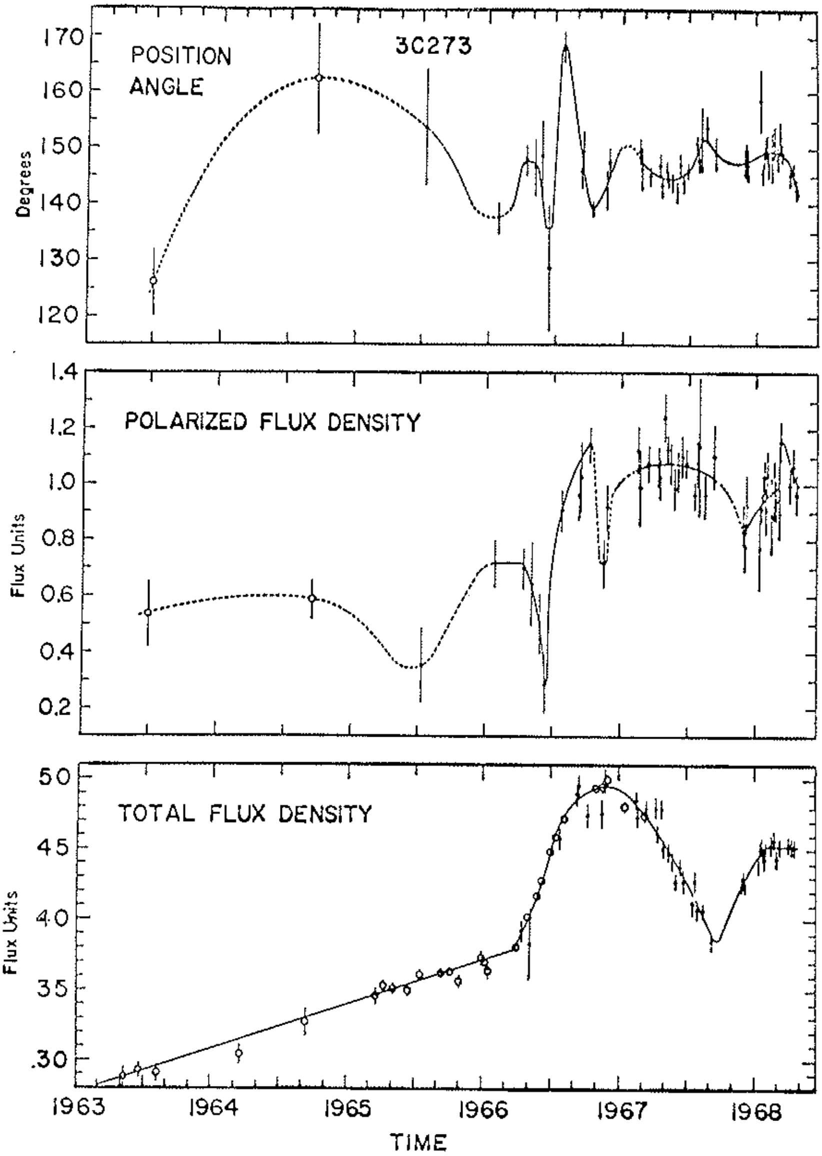

FIG. 3b — The polarization variability of 3C 273 at 8 GHz (ALLER 1970a).

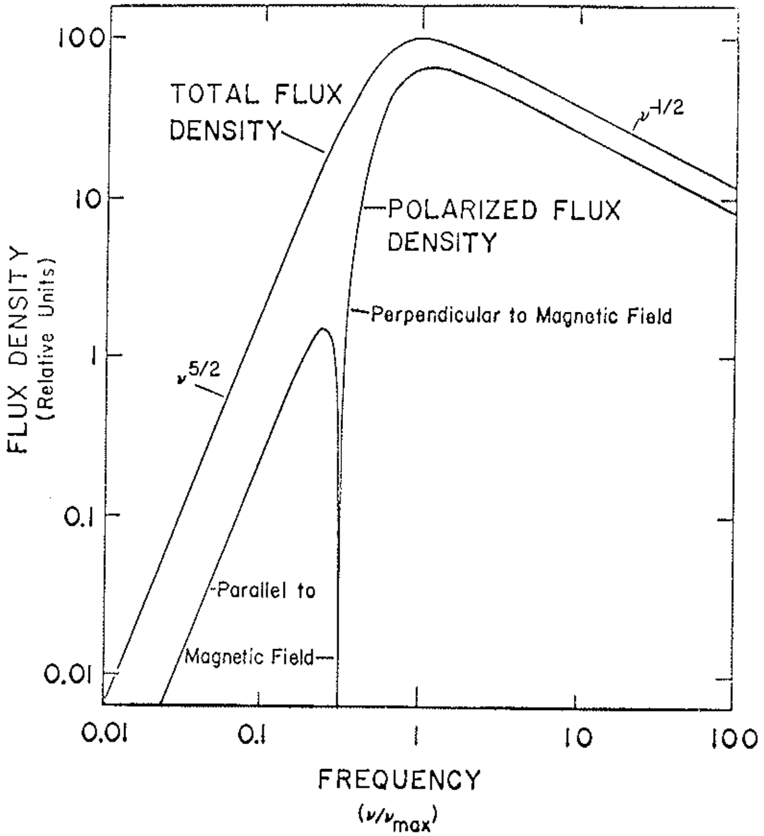

FIG. 4 — The intensity and degree of linear polarization of a homogeneous spherical source (from ALLER, 1970b).

in degree of polarization between the opaque and transparent cases to be much less than for the unidirectional source, because in the opaque source only the surface layers are seen so that the superposition depolarization is much less severe than in the transparent case.

Since large rapid variations in S_p are observed when $\tau \gtrsim 1$, it seems that the more striking features of the data meet the expectations based on the expanding source model. In other words, the behaviour of both S and S_p seems explicable in terms of the temporal change of optical depth at a given frequency in the manner expected for an expanding sphere.

5. *Departures from the simple model.*

The model discussed thus far is (i) instantaneous, (ii) isotropic, (iii) homogeneous and (iv) nonrelativistic. In this section *models* which differ from this simplest one and *data* indicative of departures from these idealized conditions are briefly considered.

(a) *Ryle and Longair* (1966). - Many sources, both radio galaxies and quasars, have a characteristic double structure. The authors mentioned have developed an attractive idea which unequivocally interprets the ratios of two observable quantities, namely the component flux density ratio S_1/S_2 and the ratio of the components' angular distances from the object with which the radio sources is identified optically, θ_1/θ_2. The fundamental assumption is that the two components are in every way identical, i.e. both initially and in their evolution. The fact that these ratios generally differ from unity is tben attributed to special relativistic and light travel time effects. This enables source ages and component speeds to be calculated. The weakness of the suggestion is that the basic assumption of component identity has no physical ground and that when the model is applied to existing data the results conflict with the model's premisses. Thus, *assuming* a constant component velocity, the theory operates on the data and *produces* a monotonically decreasing velocity.

(b) *Ozernoy and Sazonov* (1969). - As is clear from the data shown in Dr. KELLERMANN's paper, many of the variable sources show quite a complex spectral behaviour, which has been commonly interpreted by applying the simple model separately to several temporally-overlapping components whose radiative spectra are superimposed. OZERNOY and SAZONOV suggest an alternative interpretation which is a combination of RYLE and LONGAIR's relativistic component ejection with the simple model's nonrelativistic expansion. Clearly, several additional free parameters become available, e.g. the initial flux ratio, the ejection speed, the ejection angle with respect to the line of sight. This enables one to reproduce virtually any two-component spectrum and its time variations. Unique solutions are not easily obtained this way, so the model is difficult to check. It would seem at present that the model has more parameters than are needed.

(c) *Rees* (1967). - A model closely related to the simple one but then in a relativistically invariant form, was proposed by REES, who worked out the flux density variations of a relativistically expanding sphere. REES' work is analytic and confined to the cases of complete transparency ($\tau \ll 1$) or complete opacity ($\tau \gg 1$). Motive for this work was especially the elimination of several difficulties the simple model encounters when applied to some of the well-known variable sources. Thus the observed rapidity of some variations, when interpreted nonrelativistically, leads to such compactness and to such high ratios of particle energy to magnetic energy that inverse Compton losses become very severe. This leads to particle lifetimes inconsistent with the simple model in which radiative losses are ignored relative to expansion losses (cf. REES and SIMON (1969)). Relativistic expansion leads to a smaller ratio of particle to magnetic energy and a greater proper volume for the source. This relieves both the energy requirements and the inverse Compton loss problem.

An important feature of the relativistically expanding sphere is that its rate of change of linear diameter, seen as a change in angular diameter for a source at known distance, may exceed $2c$ by a large factor. Recent observations of 3C 273 (GUBBAY *et al.*, 1969) and 3C 279 (MOFFET, 1970) suggest this to be the case for variable components in these quasars, if they are presumed to be at the Hubble distance. This problem therefore relates the variability to the difficult question of quasistellar objects' redshift interpretation.

It becomes then all the more important to try and distinguish relativistic and nonrelativistic expansion without reference to distance and thus to check whether or not the spectral behaviour excludes the cosmological interpretation of redshift.

As shown in the next section it is necessary not only to calculate the spectral changes for $\tau \gg 1$ and $\tau \ll 1$, but also the behaviour in the transition region where $\tau \sim 1$. The analytic computation of REES was therefore complemented by this author with a numerical procedure applicable for all values of τ. This results in some observable differences between the spectral behaviour of the two alternative models.

(d) *Nonconforming data.* - The timescales for well known variables, as deduced by the formulae of section 3, are very short, from a few months to a decade. The model's assumption that the event is instantaneous, i.e. that the injection time is much less than the lifetime may therefore not be justified. There are data for a number of sources where this appears to be the case (cf. the discussion of 3C 84 by KELLERMANN and PAULINY-TOTH, 1968).

Canadian astronomers have monitored variable sources at 2.8 and 4.6 cm for several years with the Algonquin Radio Observatory 150 foot paraboloid. They have discovered some sources with intensity variations that do not conform to the model predictions. In particular it appears that there the injection time is comparable to the decay time. Fig. 5 is taken from

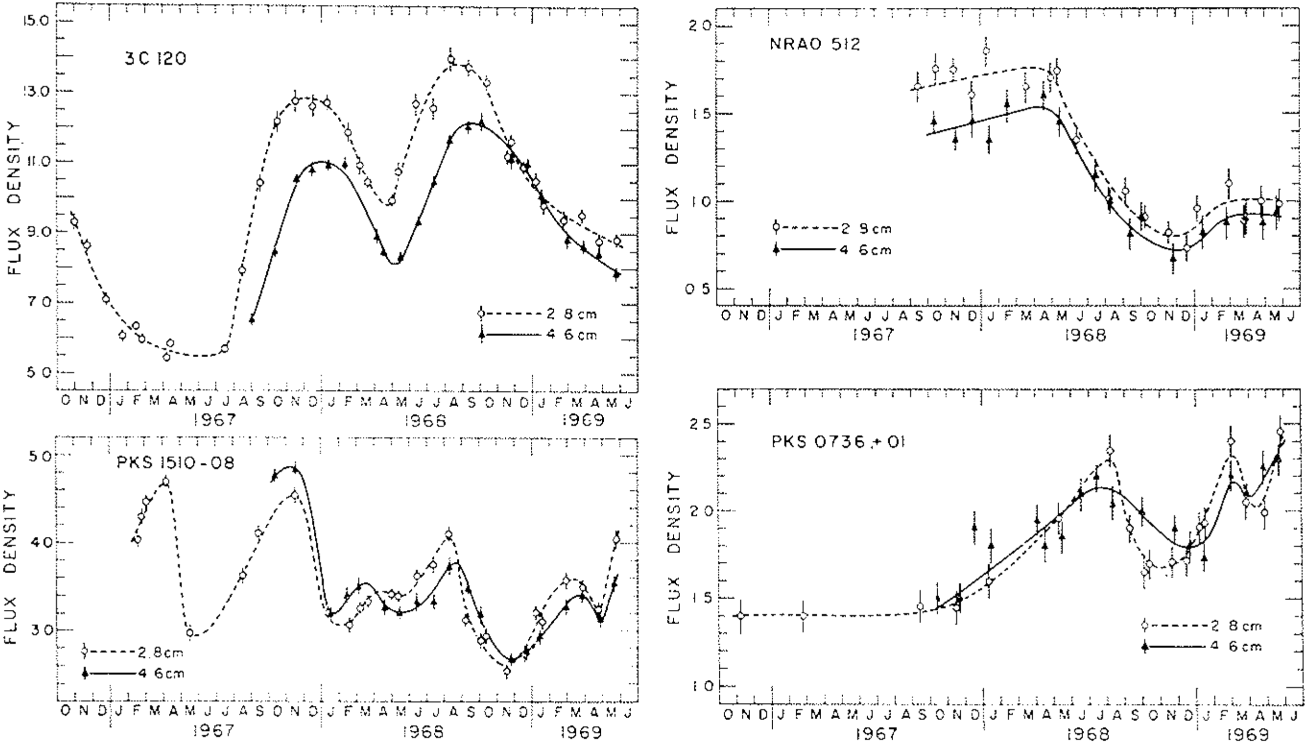

Fig. 5 — Three sources whose variability does not conform to the adiabatic expansion model (Locke, Andrew and Medd, 1969). 3C 120 is included for comparison.

a paper by Locke, Andrew and Medd (1969) and shows three sources of the type just mentioned, with 3C 120, which does behave as the model, for comparison. As the authors mentioned, these three sources vary rapidly and their dimensions are of the order of a few lightmonths. It is for such rapidly varying objects that the approximation of instantaneous injection is least likely to hold. Continued monitoring, also in polarization, of such sources is clearly promising, for such observations yield information about the *particle* source, an aspect of the problem the simple model does not include.

6. *Relativistic expansion rates.*

Let a surface expand spherically about a point C; what is the simultaneously visible surface for a distant observer O? If θ is the angle between the position vector of a surface element drawn from C and the position vector of O, then the simultaneous surface is the prolate spheroid

$$r(\theta) = \frac{r}{1 - \beta \cos \theta}$$

where $\beta = v/c$ and v is the expansion speed of the surface in the reference frame of C; r is the distance from C of the surface element travelling in the direction $\theta = \pi/2$.

The semi-major axis of this spheroid, on the line CO, is $r/(1 - \beta^2)$; the semi-minor axis is

$$y_{\max} = r/\sqrt{1 - \beta^2}$$

and this is the maximum extent of the surface perpendicular to the line CO, i.e. it determines the angular diameter of the object. As β approaches unity the apparent rate of expansion seen at O can therefore exceed the light velocity by a large factor.

If we now assume, as in the simple nonrelativistic model earlier, that the source remains homogeneous (in C's frame of reference), then one can calculate the time and frequency dependence of the synchrotron emission for various values of β. It means specifying for each volume element in the prolate spheroid seen at O, the field strength, the particle number density, the Doppler shift and the emission and absorption coefficients. The ratio $S(\beta, r, \nu)/S(\beta, r_o, \nu_o)$ is obtained by computing for each volume element the optical depth in the direction of O and then integrating over the whole volume to add each volume element's net spectral contribution.

The numerical integration meshes must be fine enough to give convergence to the nonrelativistic result for $\beta \ll 1$ and to the analytically calculated values for the asymptotic cases of $\tau \ll 1$ and $\tau \gg 1$ for the relativistic expansion rates (cf. REES, 1967).

If $\nu_{\max}$ is the frequency where the spectral curve has a maximum, then

$$S(\beta, r, \nu) \propto r^3 \nu^{2.5} \qquad \text{for } \nu \ll \nu_{\max}$$

and

$$S(\beta, r, \nu) \propto r^{-2\gamma} \nu^{-\left(\frac{\gamma-1}{2}\right)} \qquad \text{for } \nu \gg \nu_{\max}$$

just as in the nonrelativistic case. Moreover, the migration of the spectral curve in the $\log S_\nu$ — $\log \nu$ plane is independent of β: the slope of the curve in these coordinates is constant and the flux density maximum moves along a straight line with slope $+\dfrac{7\gamma+3}{4\gamma+6}$ (cf. figure 1).

The relations between observables and age of the source, given in section 3, are therefore equally applicable to observations of relativistically expanding variable sources. Even very different expansion rates can therefore not be distinguished simply from measurements of flux density and their rates of change.

The theoretically clearest distinction between the slow and highly relativistic expansion is the width of the transition from the transparent to the opaque domain of the spectrum. This is certainly to be expected, since a source which is homogeneous in the rest frame of its expansion centre is very inhomogeneous for an observer monitoring the source during relativistic expansion. The prolate spheroid seen, represents a combination of very different phases of the sphere's development, seen at different effective blueshifts. Figure 6 shows the

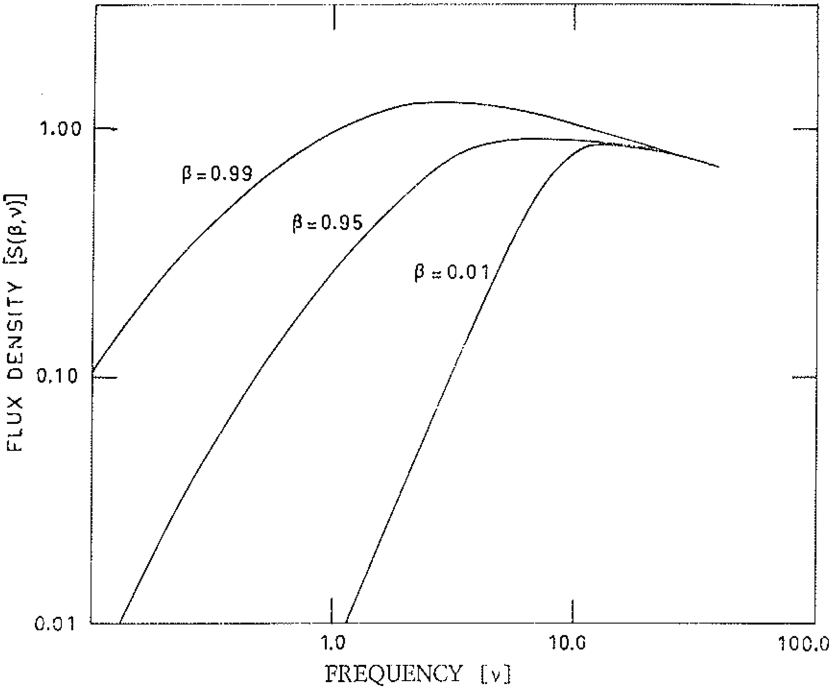

FIG. 6 — The spectrum for different expansion velocities.

calculated curve for three values of β. The frequency span required to get from the opaque to the transparent part of the spectrum naturally increases with increasing expansion speed. Alternatively, with reference to single frequency observations, the time span required to go from the maximum rate of increase to the maximum rate of decrease, relative to the age estimate made by means of the first equation of section 3, is greater for greater speeds of expansion. This is illustrated by the curve in figure 7, provided the expansion speed is constant during the observing period.

There is then, in theory, a manner of distinguishing slow and fast expansions in terms of observables (*). In practice there are complications. Firstly, the theoretically homogeneous relativistic expansion mimics an inhomogeneous slow expansion. Therefore, if a variable source exhibits the spectral behaviour similar to the $\beta \simeq 0.99$ curves of figures 6 and 7, then this can be equally well attributed to inhomogeneity or to relativistic expansion rates. On the other hand, a spectral behaviour conforming to the relations in section 3 and much narrower in frequency and time than the widest curves in the

---

(1) While the observable differences between slow and fast expansions have been shown to be small, the astrophysical difference is great.

Thus, taking a particular variable source and interpreting its variations in the opaque part of the spectrum for two very different values of β, say 0.10 and 0.95, leads to completely different evaluations of the energy balance between the relativistic particle and the magnetic field contributions.

The conventional interpretation, using the flux density in the opaque spectral region and angular diameter determined by VLB interferometry, generally results in a dominance of particle over magnetic energy by factors of 10^3 to 10^6. Because the total energy content can be expressed in the form $E_t = V(C_1B^{-3/2} + C_2B^2)$ where V is the source volume and C_1, C_2 are constants, the most economic source is one where the energy ratio is near unity. The large factors by which the particle energy exceeds the magnetic energy therefore leads to energy estimates up to 10^6 times greater than the already large minimum values. A relativistic interpretation of the same data yields a much greater magnetic field strength estimate and consequently a balance which can be much closer to the most economic one (Rees, 1967). This and the difference in the calculated effective volumes also alleviate the inverse-Compton loss problems (Rees and Simon, 1969).

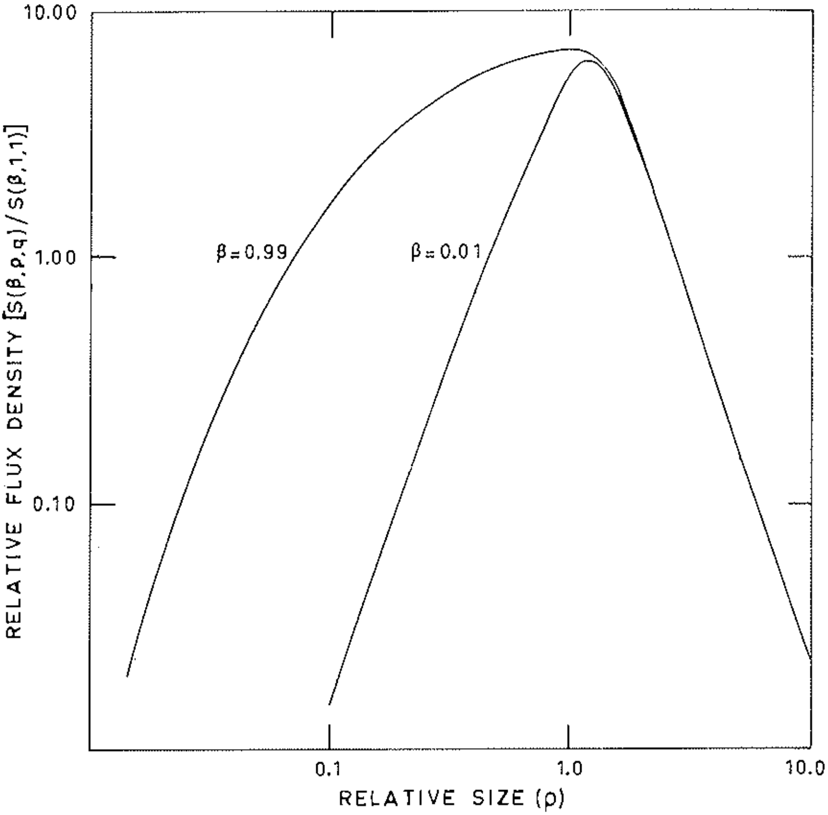

FIG. 7 — The single frequency intensity change for a slow and a fast expansion.

last two figures *excludes* relativistic expansion rates. While there are ways to narrow the instantaneous apparent spectrum of a relativistically expanding source, e.g. by means of a foreground region whose optical depth exceeds unity at the frequencies of observation, such a source would not show the same variations.

Another practical difficulty is the complex composite nature of most variable source spectra. The figures in KELLERMANN's contribution show that often several variable components occur simultaneously and are superimposed on the spectra of several constant features which may be transparent or partially opaque.

The clean burst in 3C 120 has been shown by long baseline interferometry not to require relativistic expansion (PAULINY-TOTH and KELLERMANN, 1968). This is confirmed by applying our criterion of spectral width in frequency and time to that event: a highly relativistic expansion is excluded. For 3C 273 and 3C 279 I have mentioned the interferometry data suggestive of relativistic expansion. There the spectra are so complex that the data are not yet sufficiently detailed to isolate the contribution of one burst with enough accuracy to apply this criterion.

Continued monitoring of a few of the strongest variable quasars must be combined with VLB interferometry which provides both an angular diameter and flux density of that component to the exclusion of the contributions from the remainder of the source. Such data can show whether or not a cosmological distance for these sources still allows a physically consistent interpretation of the radio variability.

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DISCUSSION

Chairman: M. SCHMIDT

MORRISON

Does the relativistic interpretation modify the limits, say, that KELLERMANN gave us for the minimum equipartition energy for a single burst? Have you looked at this at all?

VAN DER LAAN

The minimum or equipartition energy calculation assumes that the thing is non-relativistic. If you then interpret the same expansion relativistically, the magnetic energy density goes up a great deal and the particle energy density decreases, but you can get into difficulty because you then find the life expectancy of the particles is much too short. Then for the particular expansion, one gets an additional parameter, namely the injection and its rate.

KELLERMANN

I wasn't discussing equipartition energies. The values I quoted are calculated from the observed brightness temperature, or brightness temperature estimated from the time scales of the variations, and do not assume equipartition.

HOYLE

You mention that there is no evidence for relativistic expansion speeds except in the case of one component of 3C 273. My question is in relation to that component of 273. Are the data derived from angular diameters, or are they derived from the kind of analysis you have been speaking about?

VAN DER LAAN

From the angular diameters. Dr. KELLERMANN knows the details of this work.

HOYLE

Could I follow that by saying: do you have any evidence from the spectrum?

VAN DER LAAN

3C 273 is so difficult because you have so many components superposed that you don't know what the zero level is of any single component.

KELLERMANN

What actually happened was that the total flux-density at 13 cm varied by something like four flux units over a time-scale of about one year. High resolution interferometry during this time showed no change in the fringe amplitude and so over this time the variable component must have been completely resolved, which meant that it was bigger than about 10 light years. The age of the source was probably considerably less than that, about 3 years. So the Lorentz factor must be something like 3; but the situation in 3C 273 is very confused and it is difficult to be certain of the interpretation. In particular the variable component at 13 cm may have been much older than 3 years.

HOYLE

Isn't the point that you have to assume a distance if you are using angular diameter measures, whereas with your method you do not have to assume a distance?

VAN DER LAAN

Three years ago when we first published the model we thought that this was the way to get at the quasar distances because we could measure the time scale *and* the angular diameter. This becomes so elusive now because we can still say two things: 3C 273 is relativistic if it is at the Hubble distance, but if it is like, say, 3C 120, it is very much closer and non-relativistic. So we still cannot get at it; the angular diameters can be consistently interpreted either way. For very clean single bursts the spectral method I mentioned may be applied to check whether or not relativistic expansion is excluded.

REES

I would like to make a comment about the quoted total energy of 10^{58} ergs. It seems to me this should not be taken very seriously: it can in any case be reduced if the expansion is relativistic, but in all these models it is based on the assumption that the magnetic field decreases adiabatically. This is probably not a reasonable assumption and, if it is dropped, it seems to be quite possible even to reduce the energy below 10^{54} ergs, which of course means the energy of an outburst could come from a single star. In particular, if a pulsar formed from a collapsing star its electromagnetic radiation could produce a magnetic field which did not decrease like $1/R^2$. It might then be consistent to attribute each outburst to a single supernova.

VAN DER LAAN

Yes, except I believe that, at least with 3C 120, if you make the magnetic field behave rather differently than in a $1/R^2$ way, the variability in fact would not conform so well to the model.

KELLERMANN

The same can be said for 3C 273.

WOLTJER

In your relativistic model you take the distribution of the electrons to be isotropic in a co-moving frame. Now, one could of course consider the alternative case where you have the cloud of electrons expanding relativistically along a pre-existing magnetic field so that at all times the angles between the momentum vectors of the particles and the field are small. This may have certain stability problems, but it certainly would solve the problem of the short particle life time and still reduce the energy requirements per burst.

KELLERMANN

There appears to be some confusion on where the number 10^{58} ergs came from. It has nothing to do with assumption of conservation of flux. It is just that either from the time scale of the variations or from the limits on the measured angular size of the variable component we can put a limit on the magnetic field strength. Then you can calculate how much energy in relativistic particles is necessary to account for the flux density that you observe at that time, over a reasonable range of frequencies. This gives you something like 10^{58} ergs, with the uncertainty of several orders of magnitude. It doesn't assume equipartition, nor does it assume conservation of flux. It does assume a non-relativistic expansion and cosmological distances.

OPTICAL PROPERTIES OF NUCLEI

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This report deals with partial observational data on the nuclei of normal galaxies, Seyfert galaxies, N-type systems, and QSS. Data discussed are (a) colors, (b) optical variability, (c) absolute magnitude distributions derived from the Hubble diagram, (d) a computational example for the ratio of underlying galaxy starlight to the nonthermal component for N and QSS, and (e) the nature of ejecta from M 82 and NGC 1275.

I. Colors and Stellar Densities of the Nucleus of M 31

Many normal giant galaxies of type Sa, Sb, and Sc have a small, high surface brightness condensation at their center. M 31 is the best example among galaxies in the local group, although NGC 205, M 32, and M 33 also posses such nuclei. Visual inspection with a large telescope shows that the center of M 31 stands out *sharply* against the fainter background, and appears as a nearly unresolved spike of magnitude $V \simeq 12$. On short exposure photographs such as in Figure 1, the spike is slightly fuzzy (superficially resembling the globular clusters in M 31 but ~ 3 magnitudes brighter) and is elongated along the major axis of the main body. Its dimensions are 1.6 arc seconds by 2.8 arc seconds (diameter), corresponding to 5.4 and 9.4 pc at a distance of 690,000 pc [i.e., $(m - M)_0 = 24.2$].

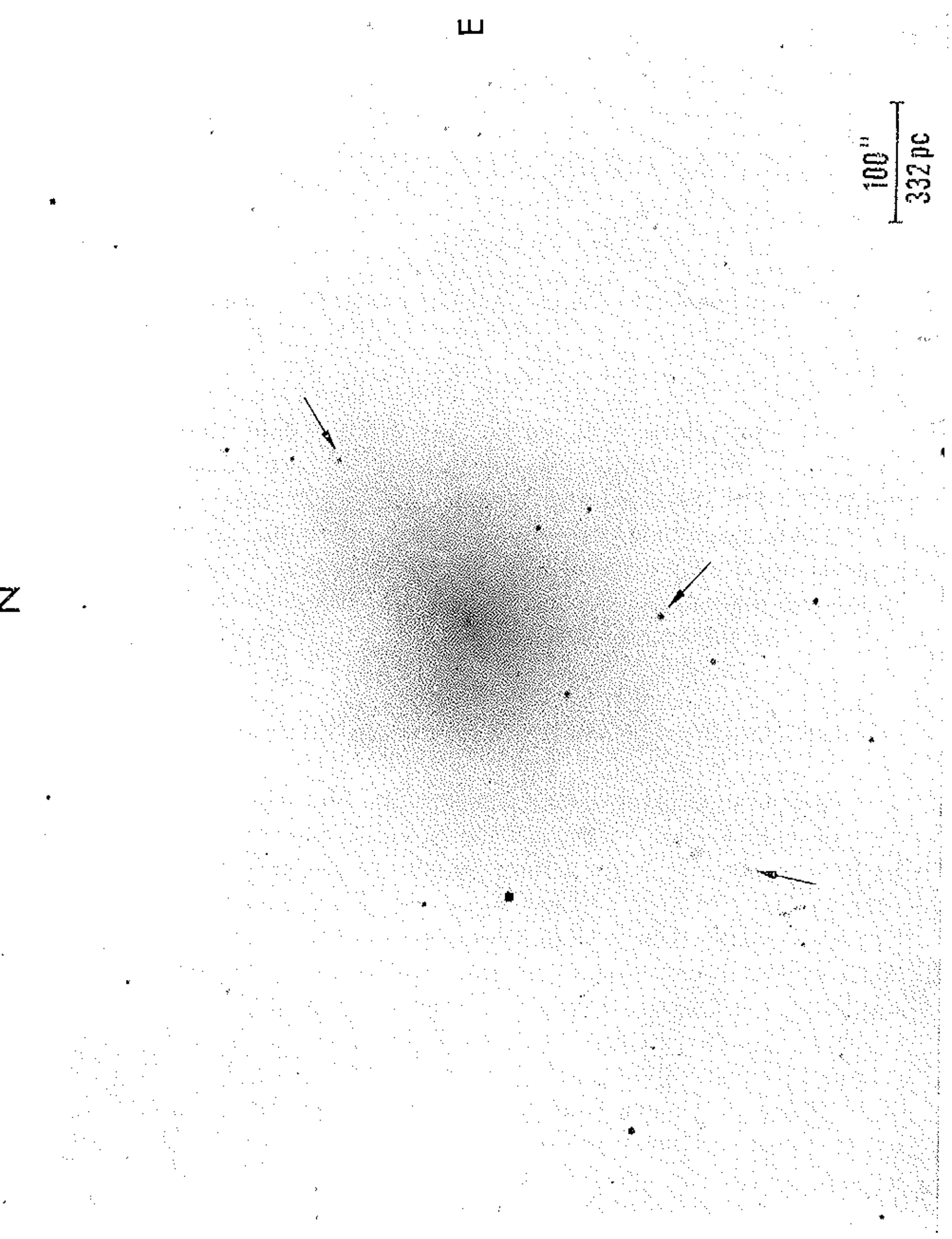

FIG. 1 — Short-exposure plate taken with the Mount Wilson 100-inch reflector of the nuclear region of M 31 showing the central spike embedded in fainter background luminosity. Several suspected globular clusters are indicated by arrows.

Some gas is present as shown by λ3727 [OII] in emission. Evidence by MÜNCH (1962) shows that the gas is moving outward from the center at about 50 km/sec with a flux of $\sim 10^{-2}$ solar masses per year. The *UBV* colors of the central region of M 31 and the nearby giant Sb M 81 are similar to each other and to many normal giant E, Sa, and Sb galaxies. Data on M 31, M 81, and M 33 are given in Table 1, where the diameter of the photometric measuring aperture (in arc seconds) is listed in column 2, the true modulus in 3, the size of the region measured in parsecs in 4, the surface brightness in magnitude per square second in 8, and the difference in magnitude between the smallest measuring aperture and the total galaxy in 9.

TABLE 1 — *Colors and Surface Brightness of the Centers of M 31, M 81, and M 33.*

Galaxy (1)	Measuring Aperture (Diameter) (2)	$(m-M)_0$ (3)	r pc (4)	V (5)	$B-V$ (6)	$U-B$ (7)	$B/\square''$ (8)	ΔV (9)
M 31	4.′9		17	12.03	1.10	0.79	16.3	
	7.″6	24.2	26	11.34	1.04	0.78	16.5	∽8.5
	1″ (KINMAN)		3.5	∽14	∽1.2	. . .	∽15.0	
M 81	4.9	27.6	79	12.29	1.13	0.70	16.6	5.3
M 33	6.4	24.6	26	13.8	0.65	0.07	18.2	8.0

Measurements of M 31 in the near infrared (SANDAGE, BECKLIN, and NEUGEBAUER 1969) fail to reveal a detectible (< 10% of the star light) infrared non-thermal component. These data, together with spectrographic evidence (see e.g., LALLEMAND, DUCHESNE, and WALKER 1960) give every reason to believe that the principal radiation from the nucleus is starlight.

It is of interest to estimate the stellar density in the M 31 central spike. Dynamical estimates from high dispersion, high spatial resolution spectrograms have been made by LALLEMAND *et al.* (1960) and by KINMAN (1965), and these depend on knowledge of the nature of the stellar orbits. With reasonable assumptions, there is a second, very simple but crude method based on the measured surface brightness alone which, although not precise, may give numbers that are correct in order of magnitude.

Suppose all stars in the nucleus of M 31 have the same surface brightness as the sun. The ratio of the M 31 surface brightness to that of the sun gives the fraction of the sky covered by stellar disks. From this follows the number of stars per unit volume.

Direct measurement with high spatial resolution gives the V surface brightness to be $V \simeq 14$ mag/□″ over the central second of arc radius (KINMAN 1965, and Table 1). The average surface brightness of the sun is $V = -10.63/\square''$ obtained by adopting $V = -26.78$ from STEBBINS and KRON (1957) and MARTYNOV (1959). The ratio of surface brightness is then M 31/sun = 24.6 mag. Hence, stellar disks in the center of M 31 cover only 1.4×10^{-10} of the available surface area. Let n be the number of stars in the nucleus contained within a spherical volumn of radius r. If each has an area A_s, the total area of stellar disks projected on the plane of the sky is nA_s. Hence

$$nA_s = 1.4 \times 10^{-10} \pi r^2 \,. \tag{1}$$

Taking A_s to be the area of the sun (1.6×10^{-15} ps^2) and r as 1 parsec gives $n = 3 \times 10^5$ stars/pc^3. Because most stars in M 31 probably have a smaller surface brightness than the sun, this is a lower limit.

Three other methods are available to check the estimate. (1) We can compare the center of M 31 with the parameters of a typical globular cluster, with suitable modifications. Consider M 3. The effective radius of the cluster is about 5 pc, containing of the order of 10^6 stars, giving a mean density of $\sim 2 \times 10^3$ stars/pc^3. The surface brightness of M 3, averaged over the central 5 pc radius, is about $V = 18$ mag/□″, which is 4 mag fainter than for M 31. If the stars in M 3 and M 31 were the same type, the density in M 31 would then be 40 times higher. But we believe the mass-to-light ratio is ~ 1 in M 3 and ~ 10 in M 31, giving $n_{M31}/n_{M3} \simeq 400$, or $\langle n \rangle \simeq 8 \times 10^5$. This can be directly tested in M 31 itself from plates taken of the central central region where the M 31 nucleus is seen together with its central globular clusters. The nucleus is indeed much brighter than the globular clusters, although it has about the same angular diameter.

(2) If the central nucleus is dynamically stable and the stars do not mix with those further out, as the observed $U - B$ color gradient (SANDAGE, BECKLIN, and NEUGEBAUER 1969) requires (since any instability or radial orbit mixing with the outer regions would destroy the gradient) then the virial theorem can be applied to the nucleus alone. If MINKOWSKI'S (1962) measurement of the velocity dispersion as $\sigma \simeq 225$ km/sec applies only to the central nucleus which was on the slit of the spectrograph (radius ~ 1.5 sec or $d \simeq 4$), we can take this to be the value of the mean random motion in the nucleus to within factors of the order of $\sqrt{3}$. For equilibrium

$$2\,T + \Omega = 0, \text{ or } \langle m \rangle\, N\, \sigma^2 \simeq \frac{G\, \langle m \rangle^2\, N^2}{r} \tag{2}$$

where $\langle m \rangle$ is the mean mass of the stars, and N is the total number within radius r. Taking $r = 2$ pc corresponding to a seeing disk of 1.″5 at the spectrograph, $\langle m \rangle = 10^{33}$ gm or half a solar mass, and $\sigma = 225$ km/sec gives $N = 4 \times 10^7$ stars in a volume of radius 2 pc, or $n = 10^5$ stars/pc^3 in order of magnitude, which is of the same order as the other two methods.

(3) Still another method exists from KINMAN'S (1965) estimate that the luminosity denisty of M 31 within the central 1 pc is $\sim 10^4 L_{pg\odot}$ per pc^3. If the mass to light ratio is ~ 10, this gives a mass density of $\sim 10^5$ M$_\odot$/pc^3, or $\langle n \rangle \simeq 2 \times 10^5$ stars/pc^3 for $\langle m \rangle$ of half a solar mass.

These methods are, then, reasonably consistent and we adopt $\langle n \rangle \simeq 2 \times 10^5$ stars/pc^3 over the central several parsecs of M 31. Because there is undoubtedly a density gradient toward the center, it is not unreasonable to assign $n \simeq 10^6$ stars/pc^3 for the central value. Although high by globular cluster standards, this density is still below that where appreciable collisions occur. The distance $\langle r_0 \rangle$ to the nearest neighbor follows from

$$\frac{4}{3} \pi r_0^3 n \simeq \text{total volume} = \frac{4}{3} \pi (1 \text{ pc})^3 \,, \tag{3}$$

$$\text{or } r_0 \simeq n^{-1/3} \simeq 10^{-2} \text{ pc} \simeq 2000 \text{AU}.$$

That collisions are relatively rare can be seen by noting that from a typical star in the nucleus, the nearest star will subtend a solid angle of only 2.5×10^{-11} steradians if r_0 is as equation 3, which is very small compared with 4π.

In more detail, the number of collisions that a single star suffers in time t is $nAvt$, where A is the collision cross section, v the velocity, and n the number of stars per pc^3. The total number of collisions per pc^3 is n^2Avt, and the collision rate is (n^2Av) per year per pc^3. Again adopting the idealized model that the average star is like the sun (which gives an upper limit for the rate because A is too high) gives 3×10^{-7} collisions/year pc^3 at the center, if $v \simeq 200$ km/sec. Because the density is such a steep function of distance from the nucleus (see Figure 1 which shows the nucleus "stops" at a radius of about 5 pc) we can take the effective volume of the region to be $\sim 10^{2.5}$ pc^3, and $\langle n \rangle = 10^5$, giving an average of $\sim 10^{-6}$ collisions per year over the entire volume. Therefore, in the age of the system, some 10^4 collisions or less may have occurred. The total energy released in such collisions is small. Even if the stars were entirely annihilated and $10^4 \langle m \rangle c^2$ ergs is available in the lifetime of the nucleus, the total energy released is $\sim 10^{58}$ ergs if each star has 10^{33} gm, and there are 10^4 such collisions. Averaged over the lifetime of 10^{10} years gives only 3×10^{40} erg/sec as an absolute upper limit, which is the same order as is now radiated in star-light by the nucleus [ie. $V \simeq 12$, $(m - M)_{AV} = 24.8$, or $M_V = -12.8$, or $L_V \simeq 3 \times 10^{40}$ erg/sec]. But collisions will not produce mc^2 per event, so we can safely conclude that the collision energy is negligible compared with thermal energy from the nuclear stars. But if the density is increased by several orders of magnitude, interesting effects will occur, as discussed in this conference and before by SPITZER, by GOLD, AXFORD, and RAY (1964), and especially by VON HOERNER. More detailed calculations of the collision rates in M 32 and giant galaxies by VAN DEN BERGH (1965) use more realistic models of the stellar content, but the conclusions are essentially the same.

II. COLORS OF SEYFERT GALAXIES, N SYSTEMS, AND QSOs

The colors of M 33 (Table 1) are significantly bluer than those of M 31, M 81, and giant ellipticals. Spectra of the nucleus show, however, that the light here is also caused by stars, but of an earlier spectral type. But this is not the case for Seyferts, N's and QSOs. Table 2 lists representative color measurements for six Seyfert and three N galaxies. More complete data are given elsewhere (SANDAGE 1967a, b). As the aperture size increases, the $B - V$ color generally becomes redder. The same is expected to hold for $U - B$ although not enough data are available in Table 2 to prove the case. That this must be true, however, is seen by inspection of direct photographs, showing that the blue nonthermal emission in Seyferts is confined to the small brilliant nucleus, and that most of the area of the galaxies is covered by the underlying normal galactic (redder) stars. In general, the Seyfert nuclei are between 1 and 4 magnitudes fainter than the light from the total galaxy in V, and do not, therefore, dominate the bulk of the total radiated energy between $0.35\ \mu > \lambda > 0.9\ \mu$ rest wavelength.

Observations show that the Seyfert nuclei by themselves have $U - B$, $B - V$ colors that resemble quasars (Figure 2), but that as the measuring aperture is increased to include more of the background galaxy, the colors of the composite system move redward in the two-color diagram. Most of the galaxies classified as Seyferts have small redshift, and hence are relatively close. Nevertheless, the area covered by even the smallest aperture listed in Table 2 is hundreds of parsecs and generally increases with increasing redshift. For the N galaxies in the second part of Table 2, the measured area in square parsecs is even greater, and for quasars where the smallest redshift is larger than any in Table 2, the usual measuring aperture of 7.″6 is greater than 10,000 pc. This increased contamination by outlying parts of the underlying galaxy must be taken into account as one variable in interpreting the colors. The other factor is the intrinsic strength of the nonthermal nuclear component.

It is clear that this second factor increases in the order Seyferts, N, and quasars. A clue to the ratio of nonthermal

TABLE 2 — *Colors of Typical Seyfert and N Galaxies.*

Object	Measuring Aperture (Diameter)	km/sec		V	$B-V$	$U-B$	ΔV Nu−Tot
N 1068	4″.9		390	11.90	0.85	— 0.11	3.0
	6″.4	1085		11.61	0.88	— 0.01	
	Total			8.91	0.82	. . . . .	
N 4051	7″.6	679	370	13.72	0.57	— 0.36	3.5
	Total			10.20	0.71	. . . . .	
N 4151	7′.6	978	540	11.74	0.37	— 0.71	1.2
	Total			10.5	0.7	. . . . .	
N 7469	4″.9	4944	1600	13.77	0.42	— .61	1.8
	Total			12.0	0.7	. . . . .	
3C 120	7″.6	10,000	5000	14.21	0.46	— 0.79	0.4
(It this a nearby N?)	Total			13.8	∾ 0.6	∾ — 0.6	
N 1275	4″.9	5433	1800	13.78	0.64	— 0.35	1.5
	7″.6			13.50	0.66	— 0.24	
	Total			12.24	0.78	. . . . .	
3C 371	7″.6	15,240	7700	14.8	0.68	— 0.38	. . .
3C 390.3	7″.6	17,070	8600	15.4	0.70	— 0.65	. . .
3C 445	7.6	17,040	8600	15.8	1.16	— 0.17	. . .

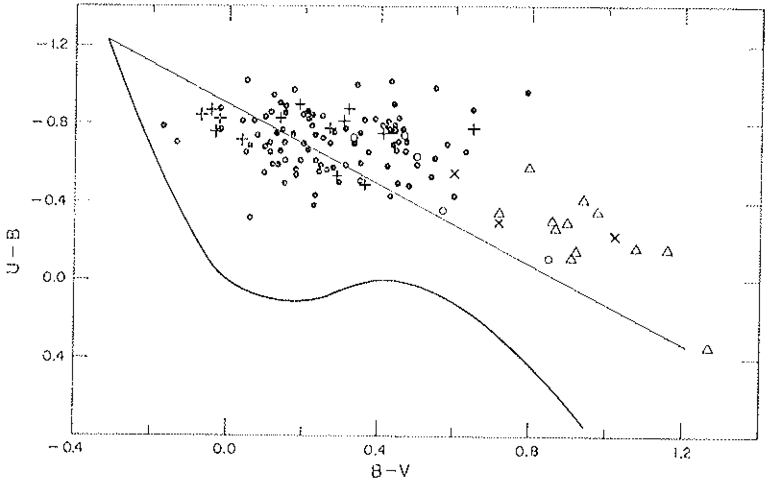

FIG. 2 — Two-color diagram for radio QSS (black dots), Seyfert nuclei (with some contamination from the underlying galaxy) as open circles, radio-quiet QSO (vertical crosses), N galaxies (triangles), and three blue compact galaxies (X). The separation of N from QSO's is evident, and is confirmed by data of Westerlund and Wall on southern-hemisphere N systems.

radiation to underlying galaxy light is given by the separation of the N systems from quasars in Figure 2. Additional data by WESTERLUND and WALL (1969) confirm the separation (they claim otherwise, but their correction for galactic reddening is spurious, and, if not applied, their data conform with Figure 2). This separation, if interpreted as in § V, suggests that N galaxies have less nonthermal radiation than quasars, relative to stars in the underlying galaxy. The physical processes in the nuclei leading to the nonthermal flux may well be the same in all three classes, but it differs principally in its relative strength. The separation of N's and quasars into separate classes is therefore probably itself only a matter of taste and telescope focal length. Cases where the classification is clear represent the two extremes of the distribution. Indeed, in the overlap region it has proved difficult to distinguish weak quasars and strong N galaxies. Because the ratio of star to nonthermal radiation is a function of proper wavelength (§ V), it is probably significant that objects now placed in the three classes differ significantly in mean redshift: Seyferts are predominantly of low velocity ($z < 0.03$), N's are intermediate, while quasars have high z values. The problem of definition is seen by asking how we would class 3C 120 if it were very near (a Seyfert?), at intermediate redshift (i.e., $cz \simeq 20{,}000$ km/sec) (an N?), or very distant (a quasar?). Other examples where confusion has arisen in the past are 3C 48 which has a fuzzy envelope, B 264, Ton 256, 3C 371, 3C 445, and 3C 459, all of which have been classed as both N and QSO according to the telescope focal length, its *f* ratio, and the exposure time. To be sure, a serious problem with this interpretation is that many N's have sharper emission lines than either Seyfert or quasars, which may betray an actual physical difference in the details of the radiation process, but the line width progression is not without exception. We may be dealing with various mixed cases of the explosion kinematics where either (1) the explosion has a well defined axis or narrow cone (like M 82) and the line widths depend on the observer's angle to the axis of the cone, or (2) a roughly isotropic explosion where the lines should always be broad.

A connection between Seyferts, N's, and quasars has been suspected for a number of years (e.g., BURBIDGE, BURBIDGE, and SANDAGE 1963; SANDAGE 1968), and has been recently discussed by a number of authors (e.g., proceedings of the Seyfert Galaxy Conference, *A. J.* 73, 836, 1968). The similarity in the physics is even more evident with the discovery that similar optical variations exist in all of the three classes of nuclei.

III. Optical Variations

(a) *Types of Variation*: One of the first properties to be discovered for QSS was that many vary in optical brightness. As observations accumulated, especially by Kinman at Lick, Penston and Cannon at Herstmonceux, and by several observers at Palomar, it became clear that in nearly every well-studied case, variability is the rule rather than the exception. Most quasars have small amplitudes and long time scales such that $\Delta V \simeq 0.3$ mag, with characteristic times of several years. 3C 48 and 3C 273 are of this type. However, about 1 in 5 quasars show much more violent activity, with light amplitudes greater than 1 magnitude and rapid variations over periods of days. 3C 446 is the best example where variations of 3 magnitudes occur in a period of several months.

In an excellent summary article with complete literature references, Penston and Cannon (1970) [see also Cannon, Penston, and Brett 1971] divide the types of variations into four classes. The grouping is for convenience and does not imply sharp divisions; some QSO have several of the four types superposed. Class 1 has small variations, typically of ∼ 0.5 mag amplitude over a period of ∼ 10 years. 3C 273 is a type example. Class 2 show variations up to a magnitude over periods of ∼ 1 years. 3C 345 has such an underlying variation. Class 3, containing about 20% of the sample, are optically violent variables (OVV) with amplitudes greater than one magnitude and time scales of the order of one month. Type examples are 3C 345, 446, and 279. Class 4 contains objects which vary rapidly (∼ 3 days) with amplitudes of ∼ 1 magnitude. Many OVV objects of class 3 also show class 4 characteristics part of the time. The maximum fluctuation rate observed so far is ∼ 0.5 mag/day for 3C 446 and 3C 454.3. Even greater rates are present in BL Lac (VRO 42.2201), but it is not yet certain that this object is extragalactic. Light curves for may of the interesting cases are given by KINMAN (1968) in an important review article.

One of the crucial developments in connecting up N's with quasars and in the discussion of distances has been the discovery that the nuclei of N galaxies and of Seyferts also vary, and can, in general, *be divided into the same four classes.* Class OVV variations have been found amongst N's and Seyferts as well. Table 3 lists representative objects of the OVV class, with absolute magnitudes of the nonthermal parts (the nuclei) at the bottom. It is clear that the total amount of energy involved, both in the average over long times and in the energy per outburst event, varies greatly between the classes, but again with the weak QSS and the strong N overlapping (see § IV).

TABLE 3 — *Representative Optically Violent Variables* (*i.e.* $\Delta V > 1$ mag).

QSS	Seyfert	N
3C 279	N 1275	3C 309·3
345	3C 120	PKS 0521 — 36
446	N 4151	3C 371
454·3	.....	3C 109
PHL 638	.....	....
PKS 0403 — 13	.....	....
PKS 1510 — 08	.....	....
$\langle M_V \rangle$ —22 to —28	—15 to —18	—22

(b) *Constraints on Causes*: Characteristics of the variation permit tentative conclusions to be drawn as to causes. The broad classes of models are (1) separate events, superposed randomly produce the fluctuations, and the average of all events gives the total luminosity L; (2) a single coherent object is involved which either has hot spots or outbursts on the surface; or (3) conditions near black holes release energy by infalling material, but at a nonsteady rate.

The observations seem to rule out the simplist type of the multiple-event model where the energy per event is nearly constant, such as would be the case if all events were caused by single "supernovae". One would then expect that when the absolute luminosity of the entire object is high (meaning more events per unit time), the fluctuation amplitude must decrease by something like $\sqrt{n}$, and there should be a correlation between the fluctuation amplitude and M_V. The observations are contrary to this expectation. Two of the most violent OVV's are 3C 345 and 3C 446, and these are intrinsically bright even at minimum light. Using $H = 75$ km/sec Mpc gives absolute magnitudes of $M_V = -24.4$ for 3C 345 at minimum ($V_{\min} \simeq 17.5$), and $M_V = -25.7$ for 3C 446 ($V_{\min} \simeq 18.0$). These are considerably brighter than $\langle M_V \rangle = -21.5$ ($\sigma = 0.311$ mag) for the brightest E galaxies, and are brighter than the faintest quasar ($M_V \simeq -22$). Similar results hold for the other OVV, many of which are much brighter (factor of $\gtrsim 10$) than quiescent quasars of the PENSTON and CANNON class 1.

Occultations of bright objects by dark bodies also seem to fail as an explanation because the shape of the light curves look much more random than can be produced by superposed square pulses.

Rotation with hot spots has been suggested (MORRISON 1969), but here the evidence for periodicities, which once seemed possible for 3C 345 (KINMAN *et al.* 1968) has become less clear. The general subject of periodicity is complicated and no clear decision exists. Fourier analysis of 3C 273 by several groups have given conflicting results, and there is no case where the evidence of periodic phenomenon is yet convincing.

(c) *Change of Color and Spectral Line Intensities*: Using OVV objects, the opportunity exists to decide if the emission lines and optical continuum vary together, or are uncoupled. The best case to date has been 3C 446 during its 3.3 mag outburst in June 1966. Spectral scans taken by OKE 18 months earlier in October 1964 showed an intense broad emission line of C IV (1550) with 230 Å equivalent width, and the weaker (10 Å EW) line of C III at λ1909. The magnitude and colors at this phase were $V = 18.42$, $B - V = 0.45$, $U - B = -0.93$. Spectra taken during the outburst in June 1966 when $V = 15.14$, $B - V = 0.57$, $U - B = -0.51$ showed the 1550 line very weakly (10 Å, EW), and the λ1909 line had disappeared. Analysis of the data (SANDAGE, WESTPHAL, and STRITTMATTER 1966), showed that both the change in equivalent width and the pronounced color change could be understood if the absolute intensity of the lines remained constant even though the continuum level rose by a factor of 20. A similar conclusion was reached from different observations by OKE. (Because most quasars vary, and spectra of many candidates appear lineless on certain spectrograms, it may only be necessary to wait until the continuum is faint to obtain a redshift). The implication of the observation of 3C 446 is that the emission lines are not coupled with the continuum variations, and are likely to be formed in different regions. Data leading to the same conclusion follows from the optical polarization.

(d) *Polarization*: Both KINMAN and VISVANATHAN have studied polarization from quasars. VISVANATHAN has extended the work to include the Seyfert nucleus of NGC 1068. Most quasars show small ($\lesssim 10\%$) linear polarization. VISVANATHAN'S data on 3C 345 show that the percentage polarization and the angle remain constant over long periods of time, but do occasionally change by large factors suddenly, thereafter returning to the original value in times of less than a month. In his study of 3C 345 over three years from 1966 to 1969, VISVANATHAN showed that 3C 345 remained quiescent in polarization changes for most of the time (contrary to observations by KINMAN over part of the same period). However, during one well-documented interval, the polarization angle rotated by 140°, and the percentage polarization decreased by a factor of two *in one day,* thereafter returning to the original value when observations were secured one month later. The change of magnitude when this occurred was only $\Delta V \simeq 0.2$ mag. For at least this case the earlier belief (SANDAGE 1968) is violated; namely, that at times of rapid intensity change, the % polarization is high, and is highly variable in angle — the rate of change $d\theta/dt$ being related to ΔV. This does not appear to be the case for 3C 345 from VISVANATHAN'S results where ΔV is very small but $d\theta/dt$ is large. However, because of the disagreement with KINMAN'S earlier data, more data are badly needed on this crucial point (see paper by VAN DER LAAN in this volume).

Of high significance is VISVANATHAN'S result that the emission lines are *not* polarized, even in those quasars which have appreciable continuum polarization. This again shows that the lines and continuum are produced in different ways, and in particular that the lines suffer no electron scattering within the plasma of the source. This may be the most direct evidence for a "layered" quasar model.

The nucleus of NGC 1068 is polarized, with the % polarization changing with wavelength, as discovered by M. F. WALKER (1968). VISVANATHAN and OKE (1968) interpret the result as due to varying amounts of thermal contamination (underlying, unpolarized galaxy starlight) with changing wavelength.

(e) *Are the Optical and Radio Variations Coupled?* It may be significant that many objects in Table 3 are also radio variables, and this raises the possibility that they are connected in some fashion, either directly through the same radiation mechanism or indirectly by secondary processes.

That this might be so is further suggested by KELLERMANN'S (1966) discussion that a correlation exists between the flatness of radio spectra and the OVV behavior. One cause of spectral flatness is the presence of multiple components with different low frequency cutoffs. The radio spectrum of each component changes with time, and the net effect of adding several components is to flatten the composite spectrum. Each component seems to be a separate radio explosion of small dimensions. The correlation between radio flatness and optical variation may only be that the spectral slope is the signal of multiple explosive activity (one explosion every several years), and the generation process leading to the optical flux, although not connected through the *same* electron reservoir, is nevertheless affected by the explosion.

That no *direct* connection exists is shown by the physical separation of the regions of radio and optical activity. Two good cases from Table 3 are the N galaxies 3C 390.3 and 3C 109 where high-resolution radio data (RYLE and LONGAIR 1967) show the radio regions to be double, widely separated, and nearly symmetrically placed on either side of the optical blue nucleus (the seat of the optical variation). In 3C 390.3, the radio components are 101 arc seconds and 167 seconds on either side of the optical object (i.e., separations of 1.1×10^5 pc and 1.8×10^5 pc) and are themselves of small size relative to their separation (one is 20″ in diameter and the other $< 10''$, or $d_1 \simeq 22$ kpc and $d_2 < 11$ kpc) with no detectable radio radiation along the ridge between the components, and especially none at the optical object (the optical center is "radio quiet"). 3C 109 is a similar case where the components are separated by 44″ and 38″ (i.e., 2.6×10^5 pc and 2.2×10^5 pc) with component sizes of 22″ and 20″ (i.e., $d_1 \simeq d_2 \simeq 1.2 \times 10^5$ pc), and the optically variable nucleus sits between. Another excellent case is the widely separated radio double connected with the quasar MSH 14-121 (VÉRON 1965).

These examples lead one to expect that no correlation should exist between radio and optical light curves.

However, it is difficult to test the expectation observationally because phase shifts between the radio and optical flux would be expected (due to dispersion) even if a connection does exist. The shifts could be large and we have only meager simultaneous radio and optical data at present. Figure 3 shows some of the available data on 3C 273. DENT (1968) observed a large radio flare in 1967. A corresponding trend in the optical *V* data is not convincing, since (random?) optical fluctuations of ∾ ± 0.1 mag are common in this quasar.

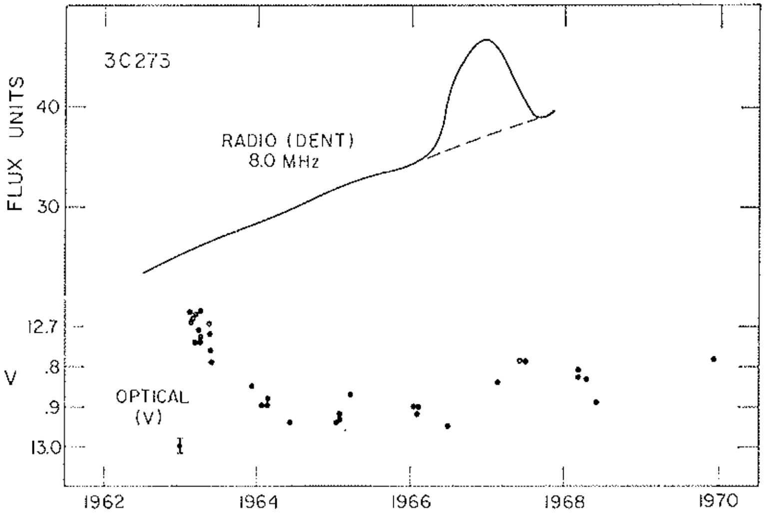

FIG. 3 — Radio and optical flux for 3C 273 as a function of time.

The cause of the optical radiation is still obscure, and a convincing case for optical synchrotron emission has not been made.

IV. ABSOLUTE MAGNITUDE DISTRIBUTIONS

Figures 4 and 5 show the observational data now available on the Hubble diagram for Seyferts, radio galaxies, radio

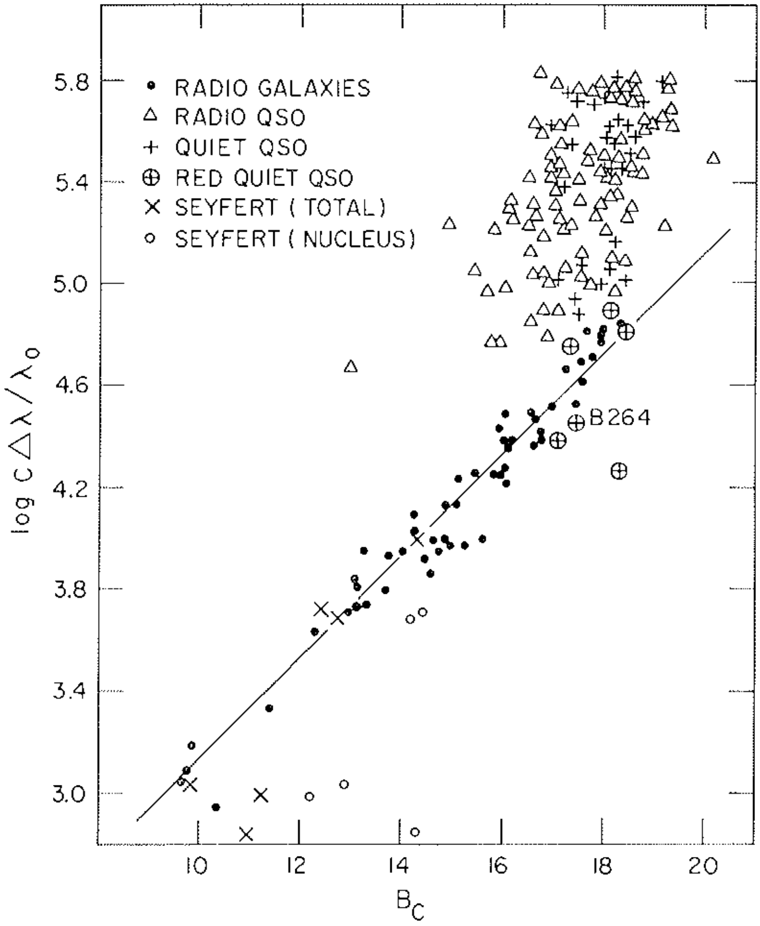

FIG. 4 — Hubble diagram for radio galaxies, quasars, and Seyferts in blue light. All magnitudes are photoelectric. Normal K corrections have been applied to the galaxies. No K corrections are applied to quasars because such corrections are small, and would be zero if $F(\lambda) \propto \lambda^{-1}$, which is nearly the case for QSS in the mean.

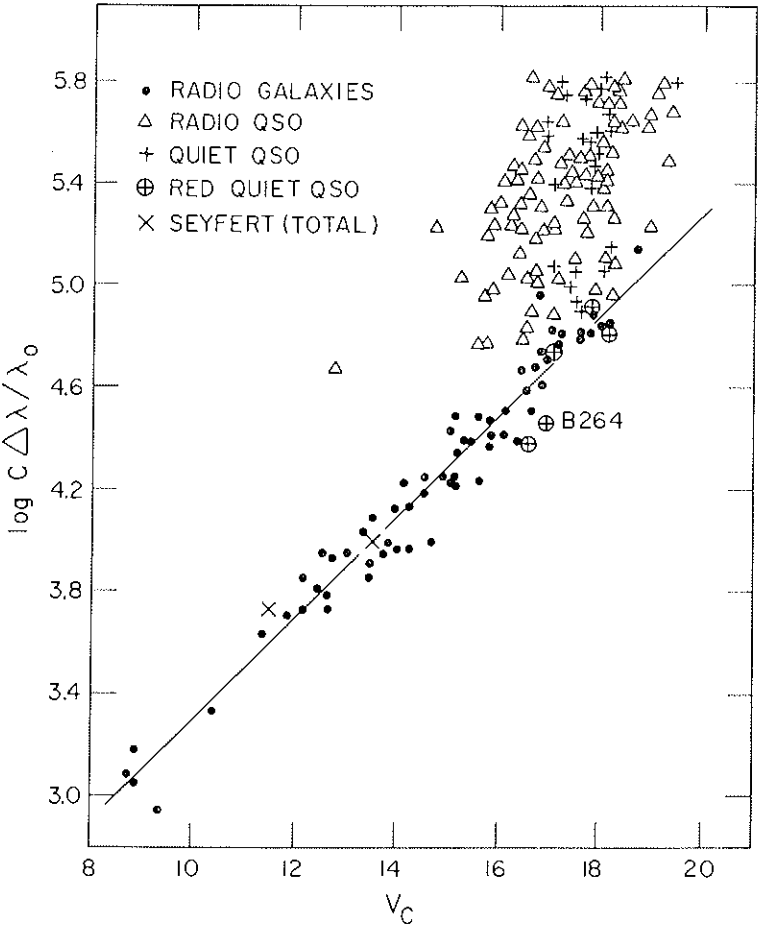

FIG. 5 — Same as Figure 4 for V.

QSS, and radio quiet QSO's. (Details are to be published in the *Astrophysical Journal*). All magnitudes have been determined photoelectrically, and the redshifts are generally from the literature, except for about half of the radio-quiet quasars. These are from MAARTEN SCHMIDT'S special study of the BSO survey fields (SANDAGE and LUYTEN 1969).

It is now crucial to emphasize an elementary and obvious point concerning the use and misuse of Hubble diagrams. The diagram can be interpreted only if one has some *a priori* knowledge that the objects which are compared to a line of slope 5 are of the same class. The closer one wishes to make the comparison, the smaller the dispersion must be in intrinsic absolute luminosity. It would be unreasonable to connect the open circles in Figure 4 (Seyfert nuclei alone), the radio galaxies with $\log cz > 4$ (dots), and the quasars (triangles) by a line of very steep slope, and to conclude therefrom that no evidence exists that the Hubble law applies for quasars, or that a new redshift effect is operating. The analysis is more subtle.

(1) Hubble's linear law $cz = HD$ is the theoretical predicion for all world models in the limit $z \rightarrow 0$. Observational verification can be established only from objects of known small dispersion in M.

(2) In the low redshift regime, $cz = HD$ transforms to

$$m_c = 5 \log z + M - 5 \log H + 5 \tag{4}$$

where m_c is the apparent magnitude corrected for redshift effects (K term), aperture effect, and galactic absorption, H is the Hubble constant, and $z = \Delta\lambda/\lambda_0$.

For constant M, $m = 5 \log z + C$. A distribution in M causes the same distribution in m if z has no dispersion at a given distance. [This is known to be the case by the form of the distribution function $f(m)$, because it is independent of z].

(3) Observations of first-ranked cluster galaxies show equation (4) to hold within the observed dispersion of $\sigma(m)_z = 0.30$ mag, which is taken to be $\sigma(M)$.

(4) Because there is no reason to suspect a breakdown of Hubble's law for N galaxies (SANDAGE 1967a, Fig. 2), and because N galaxies and faint quasars overlap in many properties, there is every reason to believe that Figures 4 and 5 can be read to give M of quasars by the horizontal deviation of each object from the line of slope 5. Absolute magnitudes were determined by this method (i.e., solving equation 4 for M using $H = 75$ km/sec 10^6 pc).

Before discussing the distributions, several features of Figures 4 and 5 are of interest. Solid dots represent radio galaxies. Figure 6 shows the diagram for these objects alone. The line has a slope of 5 as in equation (4) and the dispersion in magnitude is $\sigma \simeq 0.45$. Most of the galaxies are normal ellipticals with *no* optical evidence for abnormality. A few are indeed abnormal, such as NGC 1275 where the products of the explosion can be seen: M 87 with its jet, NGC 1316 (Fornax Cluster) with a few inconspicious dust patches, Cygnus A with a central dust lane, and a few others, but most are normal. However, the N galaxies are also plotted (but not isolated by symbols as shown elsewhere) (*Ap. J. 150*, L 9, 1967), and there is no significant deviation of the N's from the others. This requires an explanation in view of the bright nonthermal center as discussed in § V.

These data for radio galaxies are replotted in Figures 4 and 5 together with the line through them. The points to note are:

(a) Seyfert nuclei (open circles in Figure 4) are fainter than the radio galaxies by amounts up to 3.5 mag (consistent with the final column of Table 2).

(b) The magnitude of the total Seyfert galaxy (crosses) is about the same as the line.

(c) The small scatter of radio galaxies ($\sigma \simeq 0.45$) and the closeness of the line to that of the brightest galaxies (first-ranked cluster members) show that to form a radio galaxy

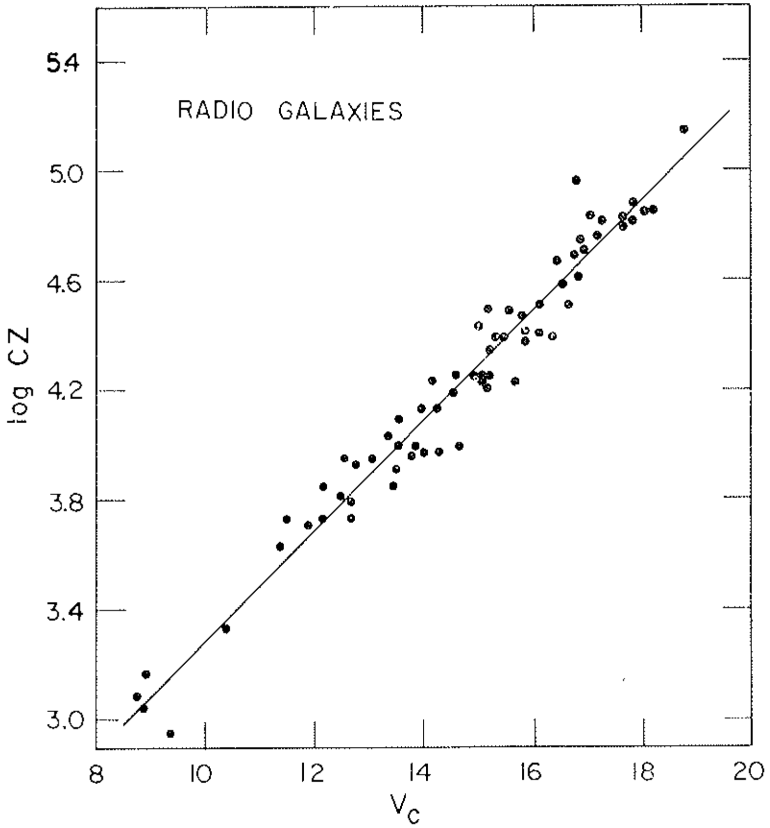

FIG. 6 — Hubble diagram for radio galaxies alone. Abscissa is the photoelectric V magnitude corrected for K term, aperture effect, and a galactic absorption of $\Delta V = 0.18$ (csc b-1). The line has the expected slope of 5.

brighter than $L_{\mathrm{rad}} \geq 10^{40}$ ergs/sec (between 10^{11} hz $\geq \nu \geq 10^{7}$ hz) requires that the underlying parent must be amongst the optically brightest (most massive) known.

(d) Radio quasars (triangles) are invariably to the left of the line. This is consistent with the view that giant galaxies underlie quasars (as they do N's and Seyfert nuclei). The optical (thermal) radiation from such galaxies will set the faint limit to the distribution of m at a given redshift, that limit being $\sim 3\,\sigma$ fainter than the line through the galaxies. *The fact that no quasars are known to the right of the galaxy line (to within* $\pm 3\,\sigma$*) is taken as strong evidence that bright galaxies do in fact exist "under" quasars.* No such limit should exist according to any of the "local" hypotheses, but is expected if quasars are essentially bright N's with their nonthermal rheostats turned up (§ V).

(e) Radio-quiet quasars (vertical crosses) become as bright in M as radio QSS and are indistinguishable from QSS, either in color (Figure 2) or in their distribution of redshifts.

(f) There appears to be a "wall" to the distribution of redshifts for QSO's at $z \simeq 2.5$ (although a few are known to exist with larger redshifts, such as LYNDS' recent discovery, and a second radioquiet quasar by SCHMIDT at $z \simeq 2.7$). Analysis of the statistical significance of the wall (TAMMANN and SANDAGE, unpublished) suggests that it is real (especially for the radio-quiet objects where selection effects are different and easier). If so, the density of QSO may be dropping rapidly at times in the past when $1 + z \simeq 3.5$, which is 90% of the way in time to the Friedmann singularity. The easiest speculation for the existence of such a density decline is that quasars were not turned on during the first 10% of the expansion (10^9 years), but started forming only $\sim 9 \times 10^9$ years ago when $z \simeq 3$.

(g) If the wall is real, and if no quasars are to the right of the line, then one expects few quasars to exist fainter than $V \simeq 23.5$ (the intersection of the line of slope 5 with the horizontal line representing the wall drawn at $z \simeq 2.7$), but there should be many brighter than this limit. The possibility of reaching back in time to the beginning of galaxies at magnitudes within observational limits is challenging to observers, because our present equipment may already be sufficient to see the "edge of matter", or rather the "beginning of time". Number counts of quasars should give high dividends on these problems during the next few years.

Some of the above points are summarized in Figures 7 and 8, which show the apparent distribution of absolute magnitudes of the sample. For the quasars, the apparent distribution differs from the luminosity function because of the selection effects. The diagrams are primarily useful in showing (a) the small dispersion of first-ranked cluster mem-

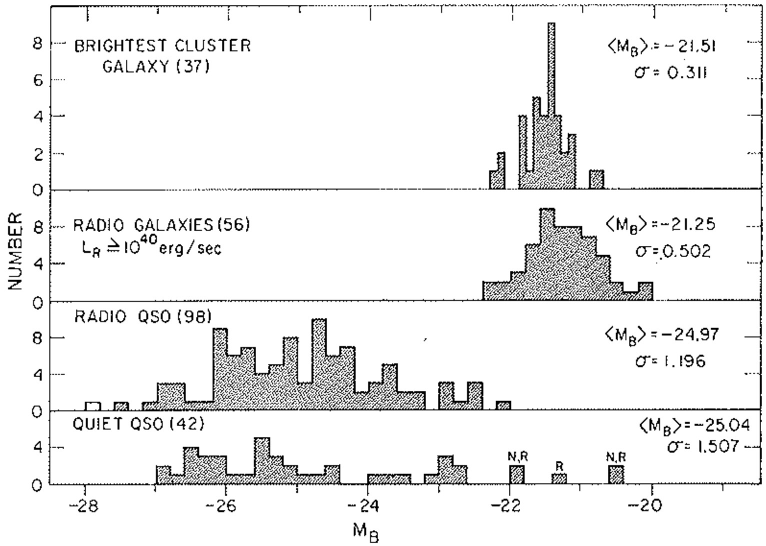

FIG. 7 — Histograms of the apparent distribution of absolute B magnitudes for objects in Figure 4. Symbols N and R on the bottom histogram denote objects with N characteristics (fuzzy appearance or redder B-V color than the statistical B-V = $f(z)$ relation predicts). The $\langle M \rangle$ and σ are for the *apparent* distribution; and have no significance concerning the true luminosity function. The distance scale of H = 75 km/sec/Mpc is used.

bers; (b) the larger dispersion in *M* for radio galaxies (but the distribution tails toward fainter magnitudes, the upper limit near $M_V \simeq -22.5$, $M_B \simeq -23.2$ is the same as for firts-ranked cluster members); (c) the near lack of overlap in *M* between QSO and radio galaxies; (d) those radio-quiet

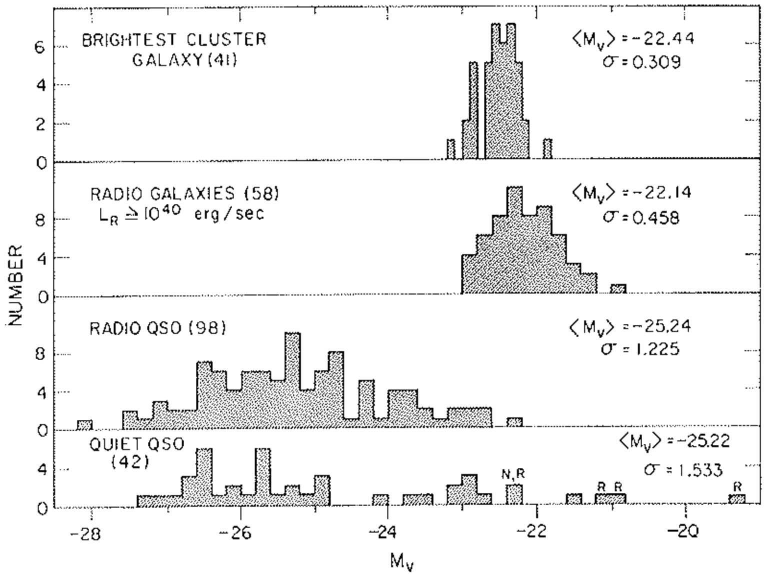

FIG. 8 — Same as Figure 7 for *V* magnitudes.

objects (bottom panel) which are fainter than $M_B \simeq -22$, $M_V \simeq -22.5$ and which therefore overlap the radio galaxy distribution have many characteristics of N galaxies, and some have been so classified (B 264). They are either fuzzy at large-telescope scale, or are redder than QSS at their redshifts (see Figure 7 of SANDAGE 1968). These are labeled either N, R or NR in Figures 7 and 8.

The case that galaxies may underlie QSO's is consistent with these data, and is developed further in the next section.

V. ARE THERE GALAXIES UNDER QSO AND N'S? CONTAMINATION CALCULATIONS

Two coupled questions raised by the preceding sections require explanation. (a) In the presence of such obvious nonthermal nuclei as in N galaxies, why do these objects lie within the dispersion of normal radio galaxies in Figures 4-8? (b) Why are the N's statistically separated from the QSO's in the $U - B$, $B - V$ diagram (Figure 2)?

To gain feeling for the problem, calculations were made of optical contamination in a composite model composed of a galaxy plus varying amounts of nonthermal (quasarlike) radiation. The purpose was to see how much nonthermal light must be added to a typical E-galaxy spectral-energy distribution to produce the trend in Figure 2, and thereby to calculate the contamination ΔV to N galaxies as a whole.

The energy distribution of the central regions of M 31 (OKE and SANDAGE 1968) was adopted for the typical galaxy spectrum. Four forms for the "average" QSS component were initially carried so as to test the sensitivity of the results to variations in the shape of $I\ (\lambda)_{QSS}$, which is known to vary amongst the quasars. It should be recognized that these calculations are illustrative only, and are not precise in any given case due to variations in emission line strength and the slope of $I\ (\lambda)_{QSS}$. We consider the model to be satisfactory if the general trend of Figure 2 can be explained, consistent with N galaxies following the relation of Figure 6.

The four QSS forms were: (A) $F\ (\lambda) \propto \lambda^{-0.5}$, or $F\ (\nu) \propto \nu^{-1.5}$ as given by 3C 48 between $3200\text{Å} < \lambda < 7000\text{Å}$ (MATTHEWS and SANDAGE 1963; OKE 1966); (B) the mean compromise function given elsewhere (SANDAGE 1966, Table 2) whose broad bumps statistically take into account the emission lines, (C) $F\ (\lambda) \propto \lambda^{-2}$, or $F\ (\nu) =$ constant as obtained by VISVANATHAN and OKE (1968) for the nonthermal component in NGC 1068, and (D) $F(\lambda) \propto \lambda^{-3}$, or $F(\nu) \propto \nu^{-1}$, which represents the steepest spectrum toward the blue for any observed QSS in the relevant optical region (3C 277.1 with $B - V = -0.17$ and $\alpha_1 = +1$, SANDAGE 1966, Table 1). These distributions bracket the known range of $F(\lambda)$ for nonthermal sources in rest-frame optical wavelengths.

A first goal was to simulate the energy distribution of the central 10 arc seconds of 3C 371 for which accurate spectrum-scan data exist (OKE 1967). Here the H and K Ca II lines and the G band were observed in absorption. The model must be able to produce the appropriate absorption-depth of the lines, at the same time explaining the large ultraviolet excess in the continuum color ($U - B \simeq -0.35$) and the moderately red $B - V$ of $\sim +0.70$.

Figure 9 shows the result of adding various amounts of QSS model B light (the mean compromise function) to M 31 in amounts given by a parameter a such that I (total) $=$ I (M 31) $+$ $a\,I$ (QSS), defined at λ (proper) $= 5500$Å. Note that an excellent fit to the observed 3C 371 spectrum (heavy line) is obtained with adding only 24% contamination to M 31 (at $\lambda_0 = 5500$Å). The H, K, and G-band dip is reproduced, and the continuum spectrum is reproduced to within 10% at all wavelengths. The QSS component provides more than half of the total flux for all wavelengths shortward of $\lambda_0 = 4200$Å, but its contribution is only 24% at $\lambda = 5500$Å, and less than 15% of the combined light at $\lambda_0 = 6000$Å. The calculated colors of the model are $B - V = 0.69$, $U - B = -0.36$, which agree remarkably well with observed colors of the inner 7.6 seconds of 3C 371 which vary between $0.55 < B - V < 0.72$ and $-0.48 < U - B < -0.35$ (SANDAGE 1967b, Table 2).

The general conclusion is that, because the nonthermal spectrum rises so steeply toward the blue and ultraviolet, only a small amount of QSO energy need be added to a galaxy

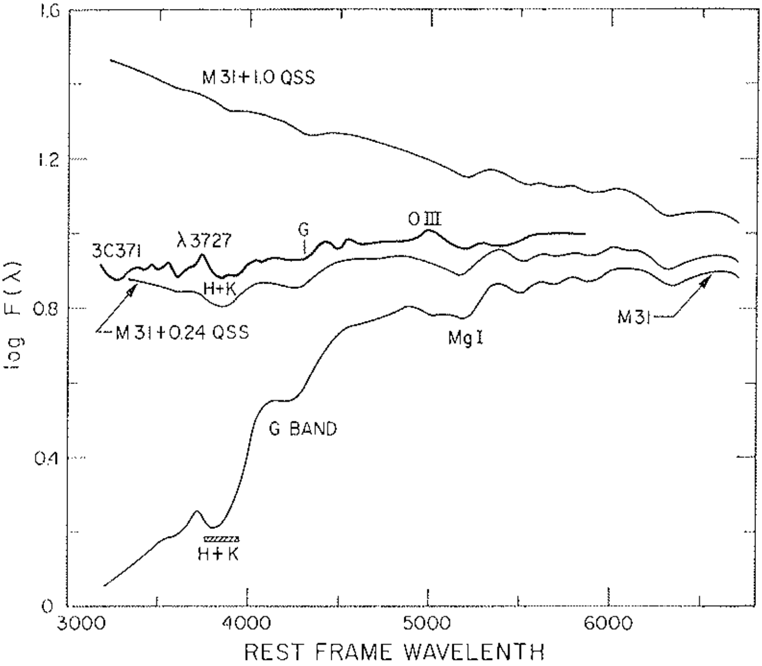

FIG. 9 — Eenergy distribution (per unit wavelength interval) of M 31 plus varying amounts of QSS component (of type B according to text). Heavy line is the observed distribution of 3C 371 measured by OKE when its nuclear light was relatively faint.

under the *V* band (i.e., $\Delta V \simeq 0.3$ mag) to produce highly negative $U - B$ colors, at the same time retaining moderately red B — V values. Equally good fits to 3C 371 were obtained with energy distributions C and D where the parameter *a* was 0.38 for type C quasars, and 0.20 for type D.

It is of considerable interest to follow the change of color of the composite system as more QSO light is added (i.e., as *a* is varied from O to ∞). Table 4 shows the result, calculated in every case at rest wavelengths (i.e., zero redshift), using precepts given elsewhere (Matthews and Sandage 1963, appendix A). The energy distribution of model B (the mean compromise function) was used.

Table 4 — *Change of Contamination and Colors For Various Mixes (Zero Redshift).*

Mix	$B-V$	$U-B$	ΔV	ΔB
M 31 alone	1.05	0.62	0.00	0.00
M 31 + 0.1 QSS	0.86	— 0.03	0.10	0.28
M 31 + 0.2 QSS	0.74	— 0.30	0.19	0.50
M 31 + 0.3 QSS	0.63	— 0.44	0.28	0.69
M 31 + 0.5 QSS	0.48	— 0.61	0.43	0.98
M 31 + 1.0 QSS	0.28	— 0.77	0.73	1.50
QSS alone	— 0.19	— 1.00	∞	∞

Note how rapidly $U - B$ becomes negative even for very small contamination in V magnitudes. These results offer a possible solution to the two questions posed at the beginning of this section.

An important additional consideration can be seen by inspection of Figure 9. The model-colors and contamination will be a strong function of redshift. If the detector is kept at a fixed wavelength, the galaxy intensity decreases relative to the QSO component as the redshift increases, giving larger Δ mag contamination corrections and bluer colors. Approximate calculations of the effect (using effective wavelengths instead of detailed integrations as was done for Table 4) are listed in Table 5 and 6.

TABLE 5 — *Effect of Redshifts on Colors for Given Mixes.*

Mix	$z = 0.0$		$z = 0.1$		$z = 0.2$	
	$B-V$	$U-B$	$B-V$	$U-B$	$B-V$	$U-B$
M 31 alone	1.05	0.62	1.40	0.51	1.65	....
M 31 + 0.1 QSS	0.86	—0.03	0.99	—0.23	1.18	—0.52
M 31 + 0.2 QSS	0.74	—0.30	0.78	—0.48	0.88	—0.64
M 31 + 0.3 QSS	0.63	—0.44	0.64	—0.58	0.71	—0.70
M 31 + 0.5 QSS	0.48	—0.61	0.47	—0.70	0.52	—0.76
M 31 + 1.0 QSS	0.28	—0.77	0.26	—0.79	0.31	—0.79
QSS alone	—0.19	—1.00	—0.11	—0.92	—0.10	—0.85

TABLE 6 — *Effect of Redshifts on Contamination Corrections For Given Mixes.*

z	M 31 + 0.3 QSS		M 31 + 1.0 QSS	
	ΔV	ΔB	ΔV	ΔB
0.00	0.28	0.69	0.75	1.49
0.05	0.35	0.95	0.90	1.88
0.10	0.41	1.15	1.04	2.15
0.15	0.47	1.65	1.11	2.72
0.20	0.53	1.82	1.26	2.90
0.30	0.90	2.08	1.84	3.28
0.40	1.47	2.36	2.56	3.57

The color effects are shown in Figure 10, and illustrate again that the separation of the N galaxies and QSO's in Figure 2 is easily and reasonably explained by the presence of a normal underlying galaxy which contributes most of the light to the *V* band; the nonthermal component dominating only in the ultraviolet.

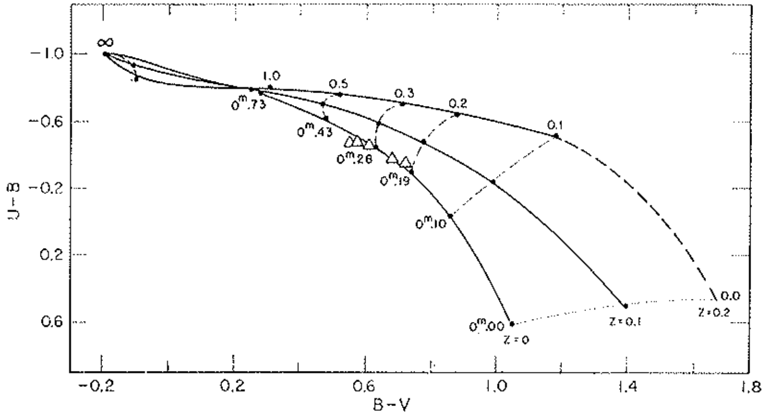

FIG. 10 — Theoretical two-color diagram for a composite model composed of a standard E galaxy plus varying amounts of QSS for redshifts of $z = 0$, 0.1, 0.2, The parameter a (λ5500) is shown along the top curve. The contamination in *V* magnitudes is shown along the bottom curve. Triangles are observations of 3C 371 at various times. Hypothesis in the text is that quasars have underlying galaxies, but that a is larger than 0.5. N systems are also composites, but with $a \lesssim 0.3$. Compare with Fig. 2.

Table 6 shows why N galaxies at large redshift will appear as quasars. The proper wavelength that is sampled by fixed detector-bands is moved far enough blueward so that the QSS component dominates, and the object will resemble a QSS in appearance and color (although not in emission line widths, a point which does make the present precepts less attractive).

The crucial question now comes not for N's but for QSS. Can bright elliptical galaxies be present under the objects we now call quasars (triangles and vertical crosses in Figures 4 and 5), and if so, should they betray themselves in the colors of the faintest QSO which lie closest to the galaxy line? The problem is complicated because the effect of the redshifts must be considered. The contamination must be read at the *proper* wavelength in Figure 9. Table 6 shows how rapidly ΔV increases with z. The *observed* ΔV values listed in the final column of Table 7 refer to values *from the already K corrected line for galaxies in Figures 4 and 5,* i.e., that which applies if the observations of the QSO were to be made at $\lambda_0\ (V) = (1 + z)\ (5500)$Å. These proper wavelengths are listed in column 7 of Table 7. The contamination at the *observed* wavelengths of *UBV* is much greater (Table 6), and no effect on these colors is expected from the underlying galaxy. It would be most important to observe and to photograph the objects in Table 7 at wavelengths at or redder than the listed $\lambda_0\ (V)$, where any underlying galaxy is expected to show maximum contrast. It seems to me to be most significant that the faintest objects in Table 7 (i.e., PHL 1070, LB 8891, B 234, and B 264) are redder in $B - V$ than is expected at their redshift (i.e., they violate Figures 1, 2, and 5 of *Ap. J.*, *146*, p. 13, 1966), and that this betrays the underlying galaxy. Direct photographs at $\lambda > \lambda_0\ (V)$ may be expected to show some fuzz around the image for redshifts less than $z \simeq 0.2$ (ellipticals of 10 Kpc diameter will have 3 arc seconds diameter), but detection of fuzz around quasars observed at $\lambda_0\ (V)$ for larger redshifts will be difficult.

The conclusion is, then, that lack of present evidence for underlying galaxies in classical QSO is consistent with the expectations of Tables 5 and 6, and the question is still open. The most positive evidence for such underlying galaxies is (1) *the lack of quasars to the right of the galaxy line* in Figures 4 and 5, and (2) the definite N characteristics for those few objects which are to the right of the line.

TABLE 7 *QSO's Closest To Hubble Line* (Δ mag = 1.5 mag).

QSS (1)	z (2)	V (3)	B (4)	$B-V$ (5)	$U-B$ (6)	$\lambda_o (V)$ (7)	M_V (8)	M_B (9)	ΔV (10)
3C 2	1.037	19.35	20.14	.79	—.96	11,200Å	—23.73	—22.94	1.59
3C 47	0.425	18.1	18.2	.05	—.65	7,800	—23.0	—22.9	0.86
3C 215	0.411	18.27	18.48	.21	—.66	7,700	—22.80	—22.59	0.66
3C 275.1	0.557	19.00	19.23	.23	—.43	8,500	—22.73	—22.50	0.59
3C 277.1	0.320	17.93	17.76	—.17	—.78	7,250	—22.60	—22.77	0.46
3C 323.1	0.264	16.69	16.80	.11	—.85	6,950	—23.42	—23.31	1.28
PHL 1078 (4c)	0.308	18.25	18.29	.04	—.81	7,200	—22.20	—22.16	.06
PHL 1093 (4c)	0.261	17.07	17.12	.05	—1.02	6,900	—23.02	—22.97	.88
0736 + 01	0.191	16.47	16.90	.43	—.77	6,550	—22.94	—22.51	.80
1217 + 02	0.240	16.53	16.51	—.02	—.87	6,800	—23.38	—23.40	1.24
Radio Quiet.									
QSO									
Ton 256	0.231	15.41	16.06	.65	—.78	6,200	—23.18	—22.53	1.04
PHL 964	0.47	18.18	18.20	.02	—.63	8,100	—23.19	—23.17	1.05
PHL 1070	0.08	16.6	17.0	.32	—.5	5.950	—20.82	—20.50	—1.33
PHL 1194	0.30	17.5	17.4	—.07	—.85	7,100	—22.9	—23.0	0.76
PHL 1226	0.40	17.5	17.5	.04	—.72	7,700	—23.5	—23.5	1.36
LB 8948	0.33	17.4	17.6	.23	—.86	7,300	—23.18	—22.95	1.04
LB 8891	0.22	18.2	18.5	.26	—.71	6,700	—21.52	—21.26	—.62
LB 9308	0.40	18.05	18.10	.05	—.67	7,700	—22.46	—22.91	0.82
PHL 3375	0.390	18.02	18.31	.29	—.51	7,650	—22.94	—22.65	0.80
PHL 1186	0.270	17.4	17.4	—.02	—.83	7,000	—22.66	—22.68	0.52
B 46 Fuzzy	0.271	17.8	18.2	.36	—.87	7,000	—22.34	—21.98	0.20
B 234 Sharp lines	0.060	17.5	18.4	.86	—.43	5,850	—19.38	—18.52	—2.76
B 264 in cluster	0.095	16.9	17.5	.58	—.65	6,000	—21.0	—20.42	—1.14
B 340	0.184	17.0	17.4	.41	—.74	6,500	—22.36	—21.95	0.22

VI. COMMENT ON THE EJECTA IN M 82 AND NGC 1275

M 82 and NGC 1275 are the two best objects for studying the nature of the optical ejecta of explosions from nuclei. The interpretation of M 82, using data on spectra, polarization, and continuum energy distributions has, to date, suggested that $\sim 10^6$ solar masses of gas, mostly hydrogen, is moving outward in a cone along the major axis at speeds of $\sim$ 1000 km/sec, and that recombination of hydrogen, and de-excitation of Si, oxygen, nitrogen, and other gases at distances of $\sim$ 4000 pc gives rise to the spectral lines. Synchrotron radiation in the halo was suspected by the high degree of optical linear polarization. However, very recent observations by VISVANATHAN and SANDAGE in March 1970 with the Hale reflector showed that in a region of the halo ($d \simeq 3000$ pc from the main body) the Hα emission line is linearly polarized by the same amount and at the same angle as the radiation in the blue filaments. This new result shows that our previous model for M 82 needs modification. One possibility is that the emission lines and the blue filamentary radiation in the halo are caused by scattering from electrons high in the halo; the scattered radiation would then be from a Seyfertlike nucleus embedded in the main body. This has some elements of SOLINGER'S model (1969a, b), with the exception that little or no recombination can be taking place in the halo because the % polarization of Hα is *not smaller* than that of the neighboring continuum radiation. The kinematics of the explosion would then differ by a factor of two from the model proposed by LYNDS and myself because the electrons act as a moving mirror giving twice the Doppler shift to the scattered light. Also our original estimate of the mass in the exploded gas would be incorrect. Aside from these obvious points, many of the consequences of the new data have not yet been worked out.

For NGC 1275, improved knowledge of the explosion is available from the spectacular Hα photograph of the outer filaments obtained by LYNDS (1970). To test for similarities with M 82, I have searched for blue continuum filaments in the outer regions of the system. Figure 11 shows the result of superposed, sequential printing of four blue plates (103aO + GG 13), automasked to avoid high contrast. Some filamentary structure is present which differs from the Hα photograph. Preliminary linear polarization measurements of these exceedingly faint features by VISVANATHAN and SANDAGE showed no detectable polarization. The six blue knots shown by arrows in Figure 11 are themselves exceedingly interesting. They do not show in LYNDS' Hα photograph. They are each of apparent magnitude $V \simeq 20$, are slightly fuzzy, and, with $m - M \simeq 34.3$, have $M_V \simeq -14$. The nature of these very bright knots is entirely unknown.

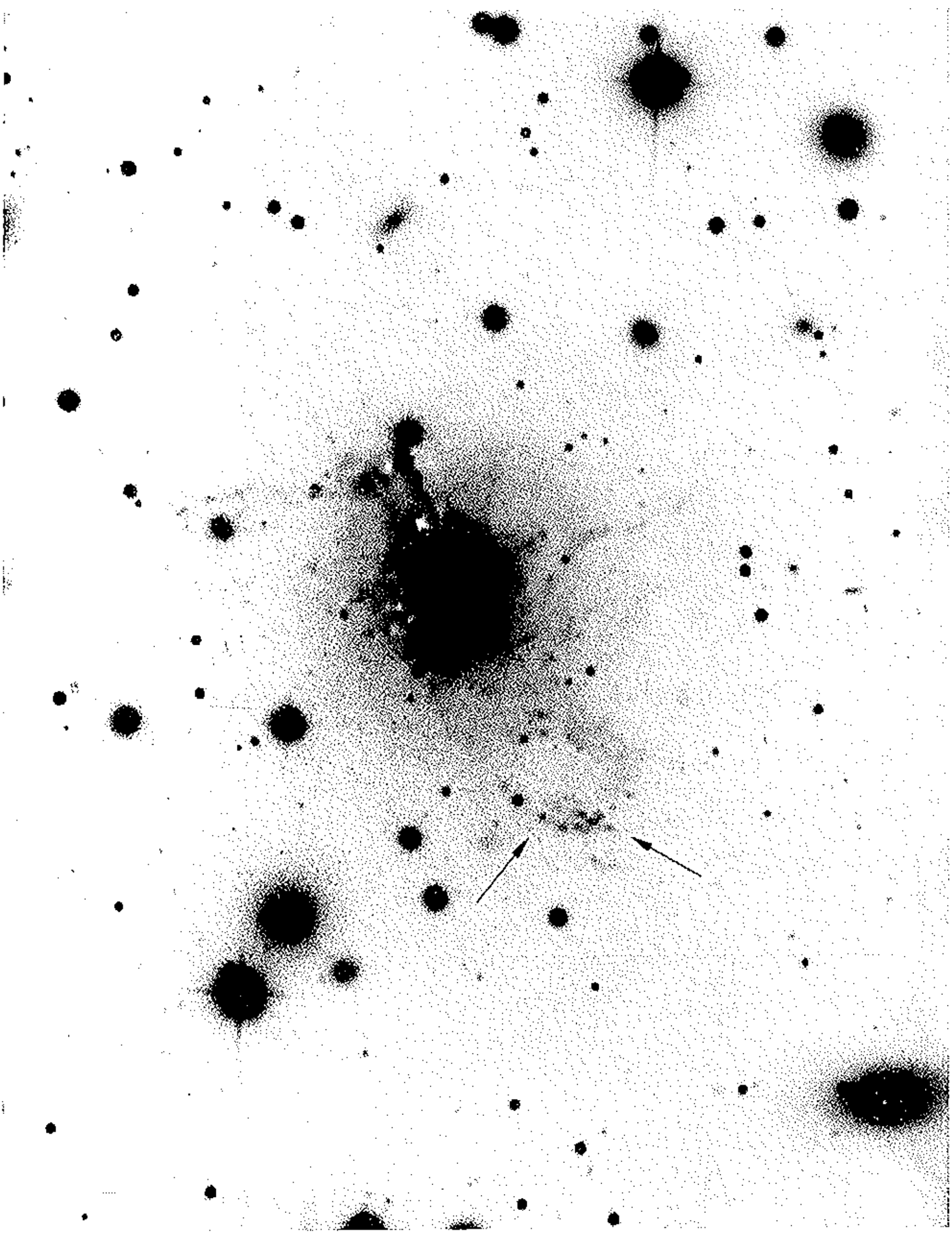

FIG. 11 — Sequentially printed composite of four blue plates (103aO + GG13) of NGC 1275 taken with the Hale 200-inch reflector. The printing positive film was automasked to decrease the contrast of the final paper print.

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DISCUSSION

Chairman: D.E. OSTERBROCK

E. M. BURBIDGE

I wanted to ask about 3C 48. Some years ago you worked on some wisps around this, and 3C 48 belongs in the QSO region from the *UBV* colors. Can you say anything about the color of that faint wispy structure?

SANDAGE

It is somewhat red.

E. M. BURBIDGE

Then why doesn't it contribute to the color like the background of an N-type galaxy?

SANDAGE

The wisps are three magnitudes fainter than the star-like object.

G. R. BURBIDGE

There are two components, a thermal and a non-thermal one. Were these both taken into account?

SANDAGE

The continuum that was used for the contamination calculations was that derived from the colors themselves. It is surely an approximation, because the emission lines vary from object to object.

I should emphasise that the calculation is an attempt to find the sensitivity of various parameters, but cannot be strictly valid in any individual case, because of deviations from the adopted mean continuum.

G. R. BURBIDGE

The basic point is that it is not strictly a non-thermal component which you add, but a component which includes both a synchroton-type spectrum and a component from hot gas.

E. M. BURBIDGE

With regard to the lines in 3C 446 not having varied when the continuum varied, I think an object that will be very interesting to look at is the object I mentioned yesterday, 5C 2.56. I hope people will look at its continuum and lines because it varied quite a lot in the last year or two, one magnitude or so, and now that it is bright and easily observable again, the lines are really pretty strong, so I would very much like to know the intrinsic line strengths and check whether they do vary or are constant.

HOYLE

I would like to ask how sure the conclusion is that the lines have not varied in objects like 3C 446 when the brightening occurred. Suppose we made the hypothesis that the lines brightened but widened enormously, could one exclude this possibility?

SANDAGE

Yes, because the λ1550 line in 3C 446 was still visible at maximum light with the same width (shape) but reduced intensity relative to the continuum.

FOWLER

Whenever I look at your diagrams in regard to the question of periodicity, it always looks to me as though there could be some periodicity, given quite a large variability in the amplitude. Has anyone really made a careful enough study of this matter on which rather dogmatic statements have been made twice today?

SANDAGE

Fourier analysis of the data of 3C 273 has been performed by others, using SMITH's values, with no convincing results.

FOWLER

Yes, but two groups have done that and there was a difference of opinion.

MORRISON

I think we periodicists will get equal time! Tomorrow I shall show you a picture. I do not want to claim the object *is* periodic, but I want to show you the data, so that we can talk about it.

VAN DER LAAN

Dr. SANDAGE, you mentioned some variability in polarization and, one night, a change of position angle of 140°. Did that correspond to violent activity in the total intensity as well, and did the polarization intensity also change or just the polarization angle?

SANDAGE

VISVANATHAN's result is that the visual magnitude changed only by $0^m.2$, while the position angle changed by 140°. The percentage polarization decreased by a factor of two, from 10% to 5%.

HOYLE

Is NGC 4151 unusually blue?

SANDAGE

NGC 4151 is not unusually blue for the nucleus of a Seyfert galaxy, but is bluer than the N's. The difference between N galaxy and Seyfert *nuclei* colors can be explained by difference in the percentage of the total galaxy included in the photometer measuring diaphragm.

AMBARTSUMIAN

You have given the distribution of the absolute magnitude of optical QSOs, but, of course, the distribution of the values observed. This means that it is the distribution of absolute magnitudes of objects observed in some interval of the apparent magnitudes, but of course it is quite different from the real luminosity function, and therefore I think that the number of the weaker QSOs must be much larger than it appears.

SANDAGE

If you restrict the radio power to greater than 10^{40} ergs per second, I think nature is restricting the mass of the system to something betwen 5×10^{11} and 10^{12} masses.

AMBARTSUMIAN

I am now speaking about the optical QSOs, radio quiet. I think that there is every indication that amongst them are also many fainter objects.

SANDAGE

Yes, if you now do not demand that the radio power be greater than 10^{40}, then the optical power can be anything. So amongst those objects which are not radio sources, I also believe with you, that the things like the Markarian objects and the other blue things can be to the right of the optical Hubble line for bright radio galaxies.

SCHMIDT

I would like to further respond to Dr. AMBARTSUMIAN'S question. I will speak tomorrow about the luminosity functions of optical quasars. The numbers do increase steeply towards fainter QSOs with no clear end to the distribution.

AMBARTSUMIAN

You speak only about radio-quiet objects?

SCHMIDT

This applies to both radio-quiet and radio non-quiet objects.

MORGAN

How does the upper limit of optical luminosity of N type galaxies and the QSSs compare?

SANDAGE

The N types are intermingled with the radio galaxies which means that they are $\langle M_V \rangle = -22.4$. All of the QSOs are brighter. The difference probably lies only in the observer's definition of the objects.

MORGAN

And the radio luminosity at the upper end, how do they compare for the two groups?

SANDAGE

The range is from 10^{40} to 10^{45} ergs per second in the observed sample.

MORGAN

I mean the radio sources as compared to the Ns and the QSSs, what is the upper limit?

SANDAGE

Amongst the 11 Ns that we had identifications for, I don't think any got up to 10^{45} ergs per second like 3C 295, but the sample is small.

KELLERMANN

I would like to go back to the variations. It is unfortunate that we did not get together a little bit to combine some of the radio and optical data so that they could be compared a little better, but I would like to make some general comparisons. You presented a table of optically violent variable QSS, Seyferts and N galaxies. If we use the same kind of definition of radio violent variables for the optically violent variables, the four objects listed under the quasi-stellar sources are all what we could call radio violent variables, and there is only one other object which would be included in this group and that is 3C 273. These are the five most variable quasi-stellar radio sources. In the second column, NGC 1275 and 3C 120 are the two most variable Seyfert galaxies as radio sources. NGC 4151 is an extremely inconspicuous radio source as it is very weak. It is optically thin and one has to look very hard even to find it, and there is absolutely nothing unusual about it. In the third column, none of these are violently variable. 3C 371 has varied by some 20-25%, the other three, as far as I remember, have not varied significantly.

AMBARTSUMIAN

Have I understood you correctly? You say that almost all these objects, quasars and other things, if they are checked for variability, they as a rule show variability?

SANDAGE

Yes.

SALPETER

If you take, not quasars, but ordinary galaxies, let us say Sb or some other particular type, and then divide them into two groups, ones that have bright nuclei and those that do not, is there any difference in the luminosity of the non-nucleus part?

SANDAGE

I don't know the answer to that completely, but I would believe not. The galaxy which SEYFERT originally called the Seyfert galaxy 4258, looks quite the same as M 31 for example, so these are two cases where, I think, there is no difference.

MORRISON

What was the σ for the quiet QSOs, do you remember that from your slide?

SANDAGE

This is an artificial σ in the sense that if one includes Markarian objects and everything else, it is surely going to get larger, so this is a small value. The mean M_V is -25.2 with a σ of 1.53 mag.

SCHMIDT

May I say that is the σ for an apparent-magnitude limited sample. Per unit volume there is no clear limit to the distribution, so no σ can be specified.

OSTERBROCK

The radial polarization of Hα is very convincing evidence that it is electron-scattered, but I should think that the line profile should be quite wide, of the order of several thousand km/sec.
I wonder if it is observed to be this wide?

SANDAGE

No, it is in the order of 300 km/sec wide.

E. M. BURBIDGE

Could I ask what mass of electrons did SOLINGER's model require?

SANDAGE

A month ago, before the measurement of the Hα polarization, we were so convinced that SOLINGER's model was not right that I did not read his paper with enough care to remember that answer. To compute it, you have to know, of course, the intensity of the source in the nucleus to find the optical depth of the electrons in the halo which are doing the scattering. One can put limits on that, but I do not know what it is.

SPITZER

Since the Hβ profile is really so narrow, shouldn't one perhaps, consider an alternative model in which the polarization is produced by aligned dust grains?

SANDAGE

Well, the problem with that is that the polarization is constant with wavelength. VISVANATHAN has measured the polarization from 3,500 to 10,000Å and it is constant to within the measuring errors of a few percent.

OORT

I haven't made any computation about the mass which would be required if this would be electron-scattering, but I remember when SOLINGER gave his colloquium in Leiden, I was very much worried about the enormous mass that would be needed. I have forgotten the numbers now, but it would have to be tremendous and something quite difficult to understand.

FOWLER

Could someone for my benefit just outline the SOLINGER suggestion briefly, because I am not familiar with it.

OORT

It is quite simple, I think. He just says that all the polarization that you see in these outer filaments of M 82 comes from electron scattering. Then he tries to compute an optical absolute magnitude for the nucleus which would be sufficient to give these intensities. But with any reasonable value for the optical radiation of the nucleus the mass needed would be fantastic for the electrons to be able to scatter that much radiation. His idea at the time, I think, was that this would not have been mass ejected from the initial galaxy, but mass already present in the universe around it.

COMPOSITION AND ACTIVITY OF THE NUCLEUS OF OUR GALAXY, AND COMPARISON WITH M 31

J.H. OORT
Leiden Observatory

For a study of the nuclear region of our own Galaxy we are at a considerable disadvantage compared to the study of other galaxies because we are situated within an absorbing layer which absorbs about 25 magnitudes over the distance to the galactic centre. As a consequence, no very important observations of the central region can be made at optical wavelengths. This great disadvantage is offset by the possibilities for observations at other wavelengths, of a kind which cannot be made in other galaxies, due to their larger distances.

Let us first review briefly the different phenomena that have been observed.

The bulk of the mass in the central region consists of stars. For the Galaxy as a whole the interstellar gas forms only a few percent of the mass. In the central region the gas is relatively still less important, since the density of what in the 1957 Semaine d'Etude have been termed disk population II stars, which are the principal constituents, increases strongly towards the centre, while the gas density remains almost constant over the main part of the entire galactic disk.

The mass density in the nuclear region can be computed from the rotation velocities measured in the so-called nuclear disk (cf. ROUGOOR and OORT, 1960), which can be roughly measured from the edge of the disk of 750 pc radius down to about 100 pc from the centre (cf. also ROUGOOR, 1964). ROUGOOR and OORT showed that the rotation velocities found for the nuclear disk agreed well with the circular velocities computed from the light-distribution in the nucleus of M 31 on the assumption that the mass-to-luminosity ratio in the nuclear part is the same as for the bulk of the system. Although there is evidently some absorption in M 31 the circumstance that we observe it under an angle of some 12° with its equatorial plane makes it possible to get a fair determination of the light-distribution, also in its central part. ROUGOOR and OORT used the apparent similarity between the central regions of the two systems to derive provisional values for the mass density in the Galaxy close to its centre.

The supposed resemblance between the mass-and light-distribution of the two central regions has since been beautifully demonstrated by measurements in the infrared. At a wavelength of 2.2μ, at which BECKLIN and NEUGEBAUER (1968) made extensive observations, the interstellar absorption is so much less than in the optical region that they could make reliable measurements of the distribution of the surface intensity in our own Galaxy. They found that within 50 pc of the centre this distribution is practically identical with that in M 31 (cf. their Fig. 10). Furthermore, SANDAGE, BECKLIN and NEUGEBAUER (1969) have shown that also the *absolute* intensities of the 2.2 μ radiation are very nearly the same. These authors showed, furthermore, that in the nucleus of the Andromeda nebula the distribution of the 2.2 μ radiation is identical with that at optical wavelengths. From the spectra we know that the latter comes from *stars*, so that in M 31 the 2.2 μ radiation is proportional to the star density (the authors further confirm this by showing that the spectral intensity distribution, including the infra-red, is identical with that of late-type dwarfs). On these grounds it is plausible to suppose that the same holds for our Galaxy, and that the 2.2 μ radiation as measured in its nucleus can be used as a measure for the density distribution of the stars. An independent support for this assumption is given by the rotation velocities in the nuclear disk which, as was mentioned above, agree with the star densities obtained if a reasonable M/L ratio is assumed (¹).

The detailed comparison with M 31 is limited to distances beyond about 5 pc (or 1″.5). Within this distance the M 31 nucleus cannot be adequately resolved. In our Galaxy, however, the 2.2 μ observations, made with a half-power beam of 5″ (corresponding with 0.24 pc), permit a resolution of 0.2 pc, so that the star density can be estimated down to much smaller distances from the centre than in any other galaxy. This involves, however, a new assumption, viz. that the proportionality of star density and 2.2 μ radiation continues to hold for this innermost part. It is not at once evident that this would be so. For there is convincing evidence that the nucleus emits non-thermal radiation at somewhat longer wavelengths (cf. pp. 324 and 333). There are, however, two arguments which seem to support our assumption: In the first place the distribution of the 2.2 μ radiation from the nucleus is different from that of the undoubtedly non-thermal radiation at wavelengths of 10μ and longer, indicating that the former has a different origin. The difference may be seen by comparing the upper and lower parts of Fig. 1. In the second place the hypothesis that the 2.2 μ radiation close to the nucleus is due to the same mechanism as further out receives some support from the fact that its surface density shows the same exponential variation with distance from the centre (R) over the entire range from $R = 0'.05$ to $R = 5'$ (0.15 to 15 pc). Over this whole range it is proportional with $R^{-0.8}$ (cf. BECKLIN and NEUGEBAUER, Paper I, 1968, Fig. 8). The variation of this surface bright-

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(¹) The argument may also be turned around, and be used as an indication that the velocities measured in the nuclear disk *are* rotational motions governed by the gravitational field.

ness close to the centre is illustrated in the upper half of Fig. 1, taken from BECKLIN and NEUGEBAUER's Paper II (1969). The scan shown passed through the centre of what the authors called the "dominant source", avoiding the "point source" situated about 5″ North of this centre. The figure shows that the density increases steeply down to at least R ∾ 0.1 pc. The nucleus within this distance is unresolved.

Table 1 shows the mass densities calculated with the aid of the above data. They are based on the density of 7.1 ×

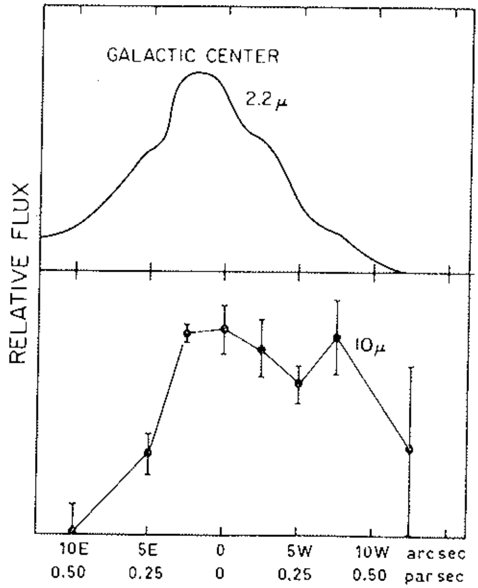

FIG. 1 — Right-ascension scans across the galactic-centre (BECKLIN and NEUGEBAUER, 1969). The scan passed 5″ South of the point-like source found in a previous investigation (BECKLIN and NEUGEBAUER, 1968); the zero point of the right-ascension scale coincides with this point source. Observations on the 200-inch telescope, with a 5″ aperture.

The upper half shows the distribution of the radiation at 2.2μ wavelength, which is assumed to be proportional to the star density. The 10μ radiation, shown in the lower half, is non-stellar, and apparently has a different distribution.

10^{-21}g cm^{-3}, or 105 M$_\odot$pc^{-3}, at R = 100 pc estimated by ROUGOOR and OORT (1960) from the rotation of the nuclear disk, and on a variation proportional with R$^{-1.8}$ corresponding with the R$^{-0.8}$ variation of the surface density found by BECKLIN and NEUGEBAUER. The star density at R = 0.1 pc estimated in this manner is roughly 10^8 times the density near the Sun.

TABLE 1 — *Star density, ρ(R), and mass within R, M(R), in the nuclear region of our Galaxy.*

R (pc)	ρ (R) (M$_\odot$ pc^{-3})	M (R) (M$_\odot$)
0.1	2.6×10^7	0.3×10^6
1.0	4.2×10^5	4.4×10^6
10.	6.6×10^3	$70. \times 10^6$
20.	1.9×10^3	$160. \times 10^6$

The mass of 1.6×10^8 M$_\odot$ within R = 20 pc may be compared with the value of 2.3×10^8 M$_\odot$ given by BECKLIN and NEUGEBAUER in their Paper I for a cylinder of radius 20 pc. This was derived from the 2.2μ radiation assuming an absorption of $2^{\mathrm{m}}.7$, an intrinsic spectral distribution identical with that in the nucleus of M 31, and a mass-to-light ratio of 10. The agreement between the two masses is rather better than might have been expected in view of the various uncertain factors involved.

The density distribution in the galactic nucleus differs radically from that observed in globular clusters, where the distribution follows an exponential law rather than a power law, and is quite flat within 1 pc from the centre. The total mass in the galactic nucleus is about 10^3 times higher than in an equal volume of the cluster M 3.

Let us now turn to a survey of the further phenomena presented by the *gas*, and in the first place by the atomic hydrogen. As already mentioned, the 21-cm line observations indicate the existence of a disk-like structure which extends from the nucleus out to a radius of 750 pc. There it stops abruptly, at least in the galactic plane. The thickness of this "nuclear disk" between half-density surfaces is about 100 pc within 300 pc from the centre, and about 250 pc in the outer parts. It appears to rotate with a velocity wbich runs up to about 230 km/s near the outer edge (ROUGOOR, 1964). The density in the central plane is approximately constant over the entire disk, and averages about 0.3 H-atoms per cm^3. The total H I mass is roughly 4×10^6 $M_\odot$. Recent observations at 100μ wavelength (HOFFMANN and FREDERICK, 1969) showed an unexpectedly intense radiation coming from a source which may have the same extent as the nuclear disk. This has been interpreted as thermal radiation of dust particles (cf. LEQUEUX, 1970). On the supposition that the dust has the same extent as the H I nuclear disk (viz. to $R = 750$ pc) LEQUEUX estimated the total mass of the dust as about 2×10^6 $M_\odot$. The total hydrogen mass must be at least 10^2 times that of the dust, or 2×10^8 $M_\odot$. This is almost two orders of magnitude larger than the H I mass found from the 21-cm line observations. If the proposed dust mass is correct the hydrogen should therefore be almost entirely in molecular form. (2) This would not

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(2) Since this report was prepared another estimate of the amount of dust required to explain the 100μ observations was published by OKUDA and WICKRAMASINGHE (1970). They obtained a rather lower mass, viz. 10^3 M within $R = 100$ pc, which would correspond with about 10^5 $M_\odot$ when extended to 750 pc. With such an estimate of the dust mass there would be no convincing evidence for a large proportion of molecular hydrogen. The true mass of the gas in the nuclear disk is therefore still unknown. An attractive feature of the model proposed by OKUDA and WICKRAMASINGHE is that it provides an explanation for the large difference between the radius of the radiation at 100μ and that at 10μ wavelength.

It should be noted that recent observations by LOW and collaborators suggest that the 100μ radiation might possibly come from a few discrete small sources instead of from a more or less homogeneous medium as considered above (cf. this volume, paper by LOW).

be so surprising, because observations of OH and CH_2O had already shown that in the nuclear region the relative abundance of molecules must be of a higher order than elsewhere in the Galaxy.

Extensive observations have been made of these molecular lines, which are observed in absorption against the bright continuous radio-frequency radiation emitted by the nuclear region. The observations are therefore mostly restricted to within 1° from the centre. They indicate a complicated structure (Fig. 2). The strongest features are at v = – 130 km/s and at v = + 40 km/s. The former extends over a broad interval

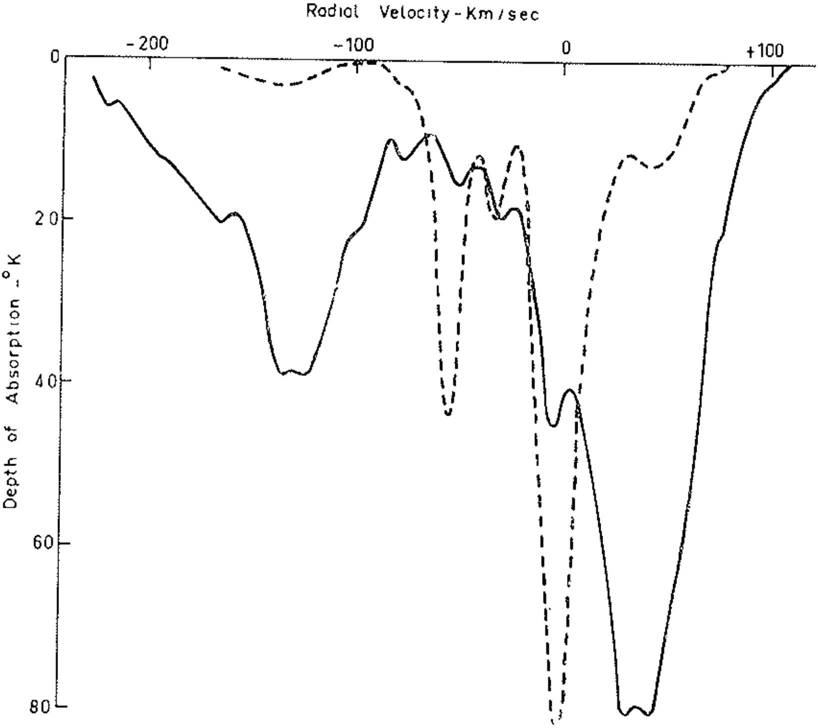


FIG. 2 — Absorption spectrum of Sagittarius A (BOLTON, GARDNER, McGEE and ROBINSON, 1964). Full-drawn curve OH-absorption, dashed curve H I-absorption.

in longitude. It may be connected with an expanding arm outside the disk to which I shall return later. The broad component at + 40 km/s appears to be connected with the concentrated radio source Sgr A. A second inward stream at this velocity is found near a second bright radio source close to the nucleus at $\ell = +0^\circ.6$. A full discussion has been given by ROBINSON and MCGEE (1967 and 1970).

Rather remarkably the observations give no clear evidence of OH absorption in the fast-rotating disk itself. If there were OH present in the nuclear disk one would have expected to see it clearly in OH absorption in the region between -1° and $+1^\circ$ longitude where the central source is sufficiently strong, and where fairly strong H I emission is seen up to velocities of at least ± 200 km/s. Maybe all molecules other than H_2 have condensed on to solid particles in this inner region of the disk.

In connection with the nuclear disk attention should be drawn to the fact that Mrs. RUBIN and FORD (1970) have found, from observations of a faint N II line, that on the North-Eastern part of the major axis of the Andromeda nebula there appears to be gas near the nucleus rotating at roughly the same velocity as the nuclear disk in the Galactic System, and extending also to about 800 pc from the centre, with a sudden drop beyond (Fig. 3). While these observations suggested the existence of a nuclear disk in M 31, later observations on the opposite side of the nucleus have indicated that conditions are more confused. The ionized gas in the nuclear region according to these observations as well as to earlier observations by MÜNCH (1960) shows complicated motions, often with large radial components.

In our Galaxy, however, the evidence for a rotating disk appears rather strong (Figs. 4 and 5). As mentioned, it breaks off quite abruptly at 800 pc. Beyond this one finds gas moving in a totally different way; part of this gas has apparently large radial motions, and only small velocities in the direction of the rotation.

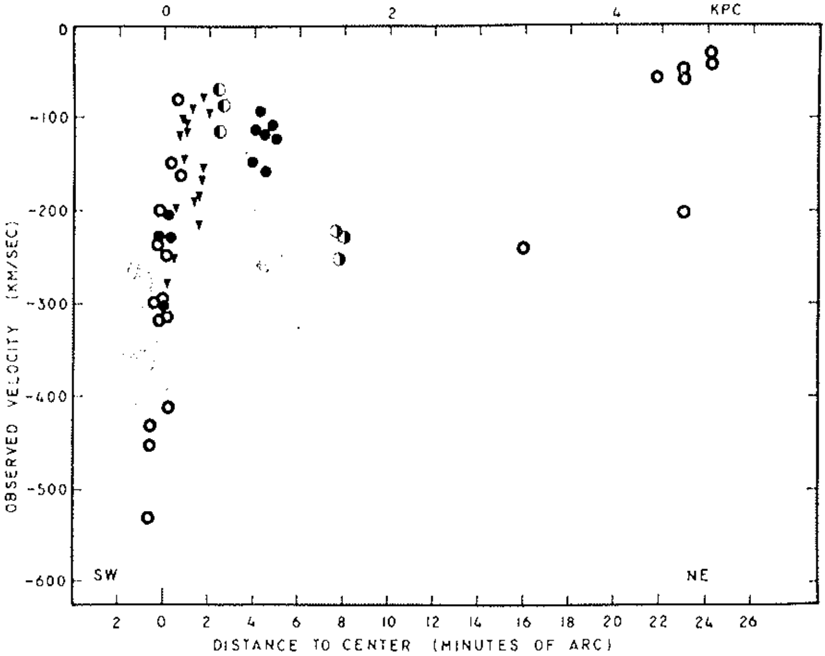
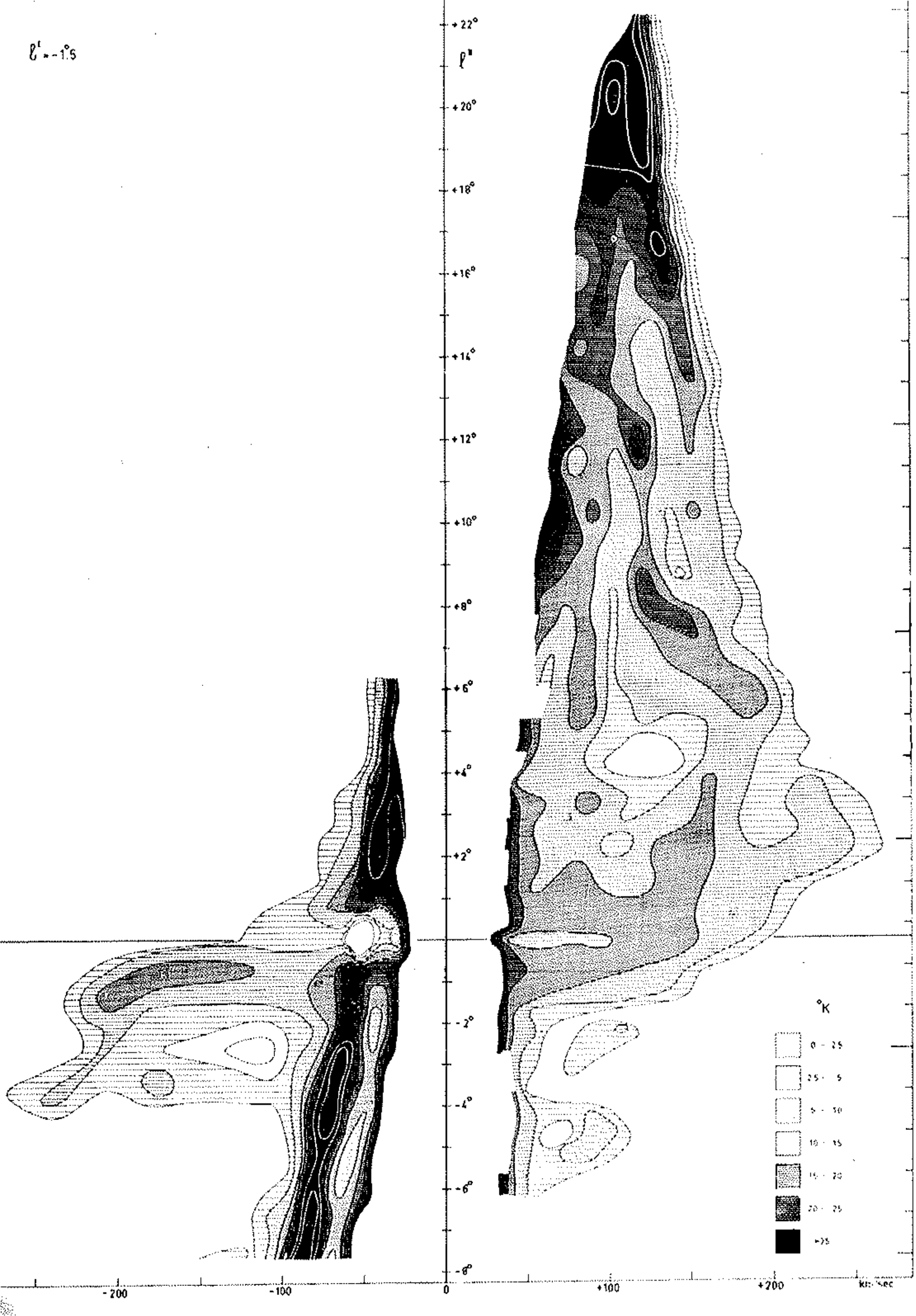


FIG. 3 — Velocities along the NE major axis of M 31. For R $\leq$ 8′, different symbols represent different plates. For R $>$ 15′ open circles indicate velocities of innermost emission regions.

The most striking structure that one meets when going still further out from the centre is the so-called 3-kpc arm. This arm has a systematic outward radial velocity component of 53 km/s. It is situated between us and the centre, at a distance R of several kpc. Outward motions have similarly been found in arm-like features on the far side of the centre, the principal one having a radial component of 135 km/s. A sketch of the possible arrangement of these arms in the central region is given in Fig. 6 (ROUGOOR, 1964).

Recently, SHANE (1970; cf. also BURTON and SHANE, 1970) has found evidence for considerable radial motion away from the centre in the so-called Scutum spiral arm up to distances of about 4 kpc from the centre.



4 — Velocity-longitude contours of neutral hydrogen in the galactic plane for the area around the centre.

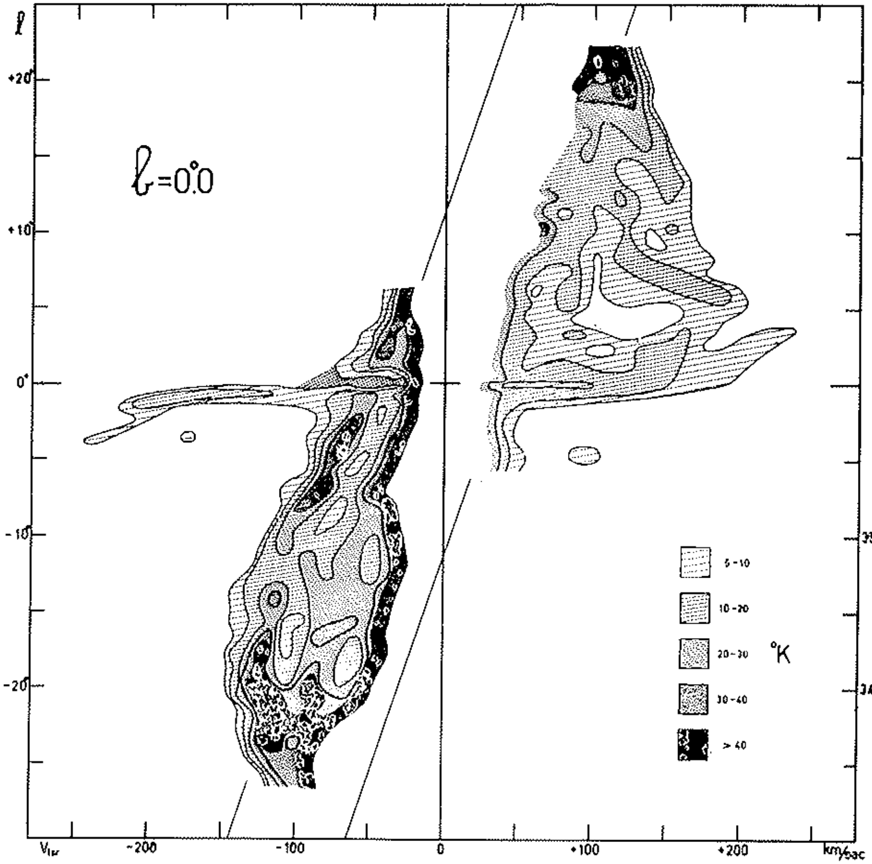


FIG. 5 — Extension of Fig. 4 to lower longitudes, indicating the uniqueness of the wing ascribed to the negative-longitude half of the nuclear disk (ROUGOOR, 1964).

So far, no satisfactory explanations have been found for the expansion of these arms. In view of the evidence that has accumulated on explosive events in the nuclei of galaxies, and in particular the fact that such violent events must be quite common: at least two of the twenty or so nearest large galaxies,

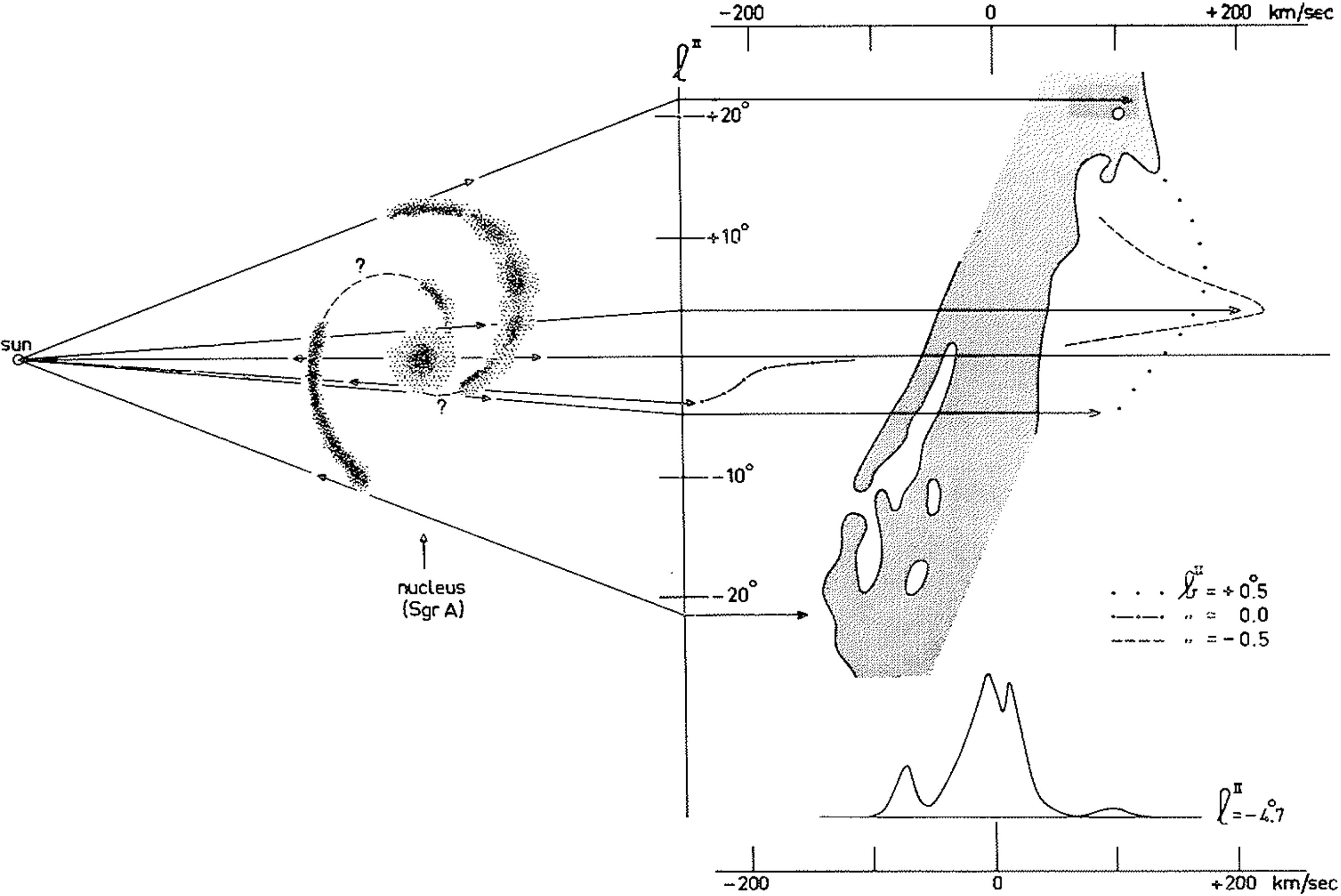


FIG. 6 — Sketch of expanding "arms" in the central region (ROUGOOR, 1964).

M 82 and NGC 5128, must recently have experienced bursts of enormous compass, it is perhaps not too implausible to think that the expanding motions in the galactic disk might be due to explosive activity in the nucleus.

That some activity is going on in the galactic nucleus is made probable by two sorts of observations.

In and around the nucleus there is a non-thermal radio source, with half-power diameters of about 9 × 6 pc. It has a central core, with a diameter of about 1 pc, or less. As non-thermal radio sources are always connected with explosive events this forms a direct confirmation of the occurrence of such activity at the present time. This is further supported by recent observations by BECKLIN and NEUGEBAUER (1969) and by LOW, KLEINMANN, FORBES and AUMANN (1969) showing that there is a nuclear source of about 1 pc diameter, the far-infrared spectrum spectrum of which is exactly like that of a Seyfert nucleus (Fig. 7). (³) The intensity of the radiation is, however, a factor of approximately 3×10^4 less than that emitted by the nucleus of NGC 1068. The distribution of the $4 - 20\mu$ radiation is markedly different from that at 2.2μ which is supposed to come from the concentration of *stars* near the centre (cf. Fig. 1).

The second kind of evidence comes from motions of gas outside the nuclear disk. Here the Galactic System has a great advantage over other galaxies in which large internal gas motions have been observed, viz. that it is seen exactly edge-on. Because of this, one can distinguish clearly between motions in the plane of the disk and motions at an angle with the plane.

In recent years a considerable effort has been made in Leiden to observe neutral hydrogen outside the plane of the nuclear disk. The presence of such gas, with velocities deviating strongly from the rotational motions in the disk, was discovered by SHANE in 1965 (cf. OORT, 1966). Extensive observa-

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(³) For the most recent data cf. Fig. 1 and Table 4 of the article by LOW in this volume.

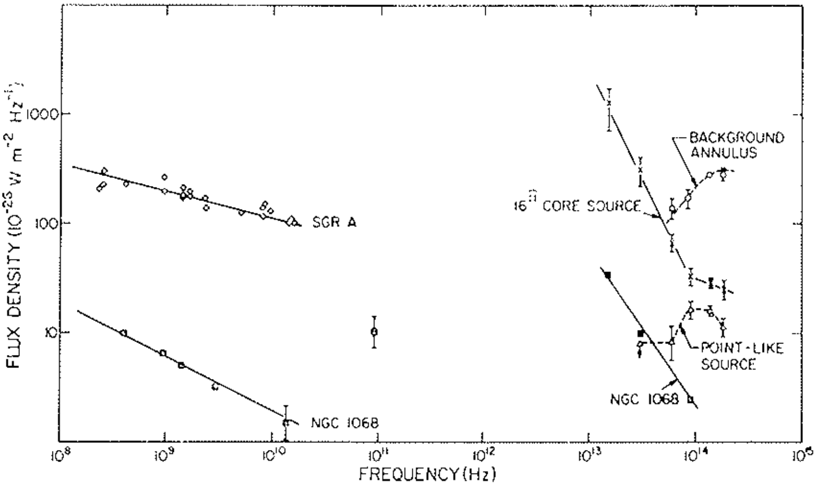

FIG. 7 — Energy distributions of three infrared sources of radiation within 3′ of the galactic centre and of the 2′.5 radio source Sgr A are shown. All the infrared data have been corrected for 27 mag of visual absorption. Flux density in background annulus corresponds to the radiation of the extended source within a 110″-diameter area less the energy in the 16″ core source. Curve drawn through background data represents radiation expected from M- and K-type stars. Flux density in the 16″ core source has the radiation from the pointlike source subtracted. For comparison, infrared and radio energy distributions of NGC 1068 are shown. Infrared points are from LOW and KLEINMANN (1968). (BECKLIN and NEUGEBAUER, 1969).

tions have since been made by VAN DER KRUIT (1970). There appears to be a considerable mass of gas above and below the nuclear disk, and apparently well separated from it. The bulk of this gas moves in a direction opposite to what one would expect from the galactic rotation. It probably represents material expelled with rather high velocity from the nuclear region, at a considerable angle with the galactic plane in two roughly opposite directions (Figs. 8a and b, and 9). The total H I mass is at least 10^6 $M_\odot$. Of the two strongest features outside the plane the one at positive longitude and negative latitude (no. XII in VAN DER KRUIT's article) has a velocity of − 130 km/s near ℓ = 0°; its mean latitude is − 2.°5 (Fig.

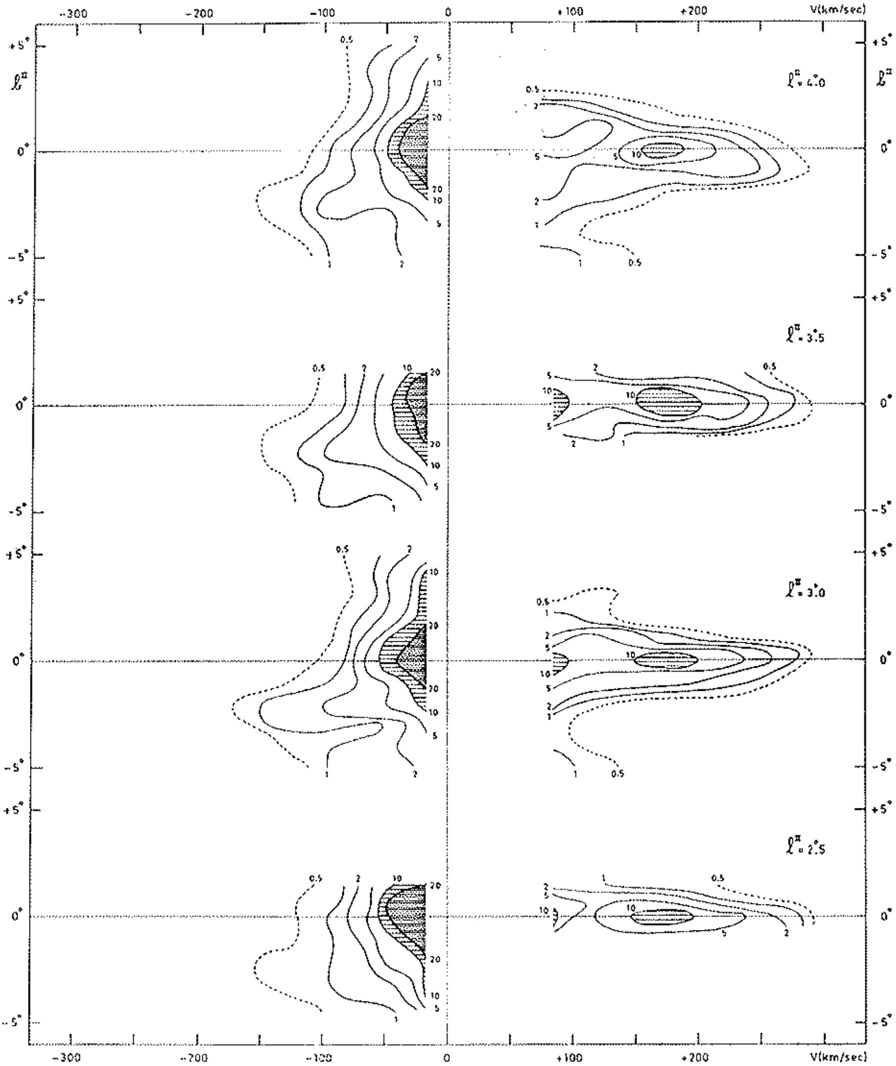

FIG. 8a — Velocity-latitude contours of neutral hydrogen for = 4.°0 to l^{II} = 2.°5 showing hydrogen with high negative velocities outside the galactic disk, at negative latitudes (VAN DER KRUIT, 1970).

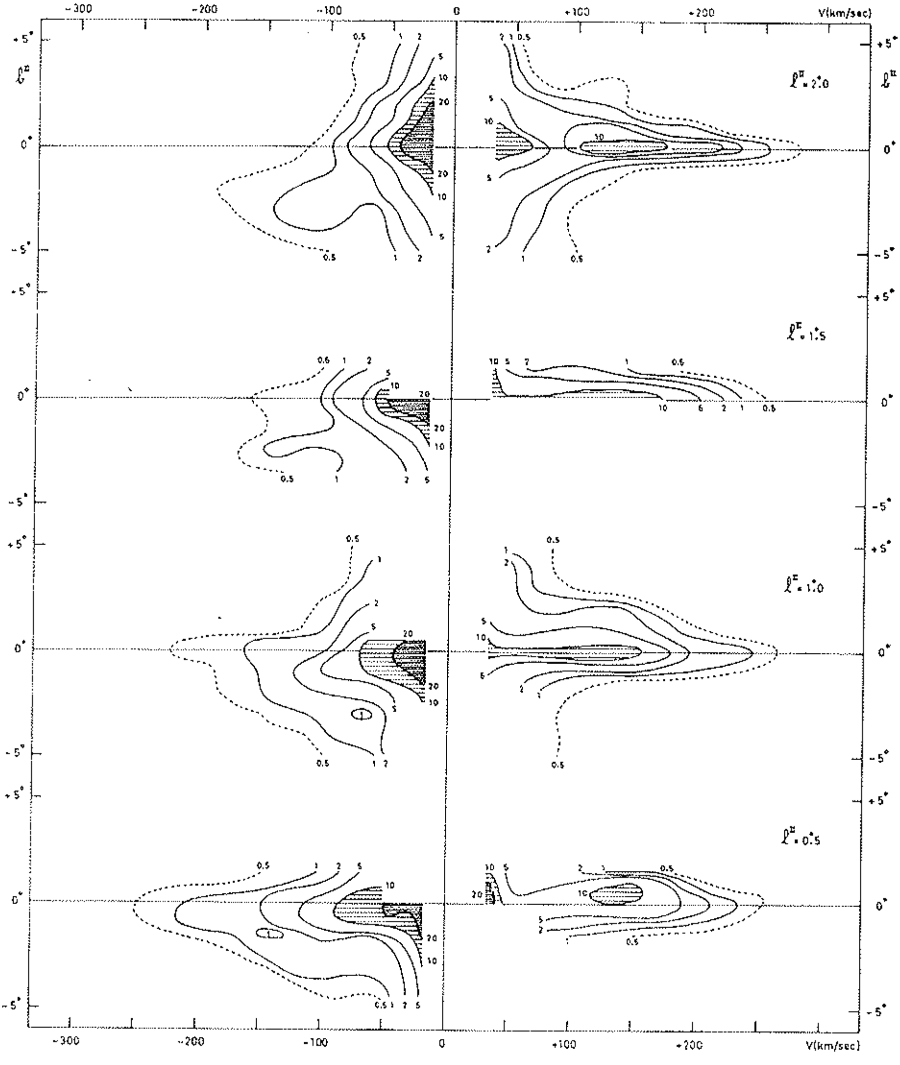

FIG. 8b — Velocity-latitude contours of neutral hydrogen for ℓ = 2.°0 to ℓ = 0.°5 showing hydrogen with high negative velocities outside the galactic disk, at negative latitudes (VAN DER KRUIT, 1970).

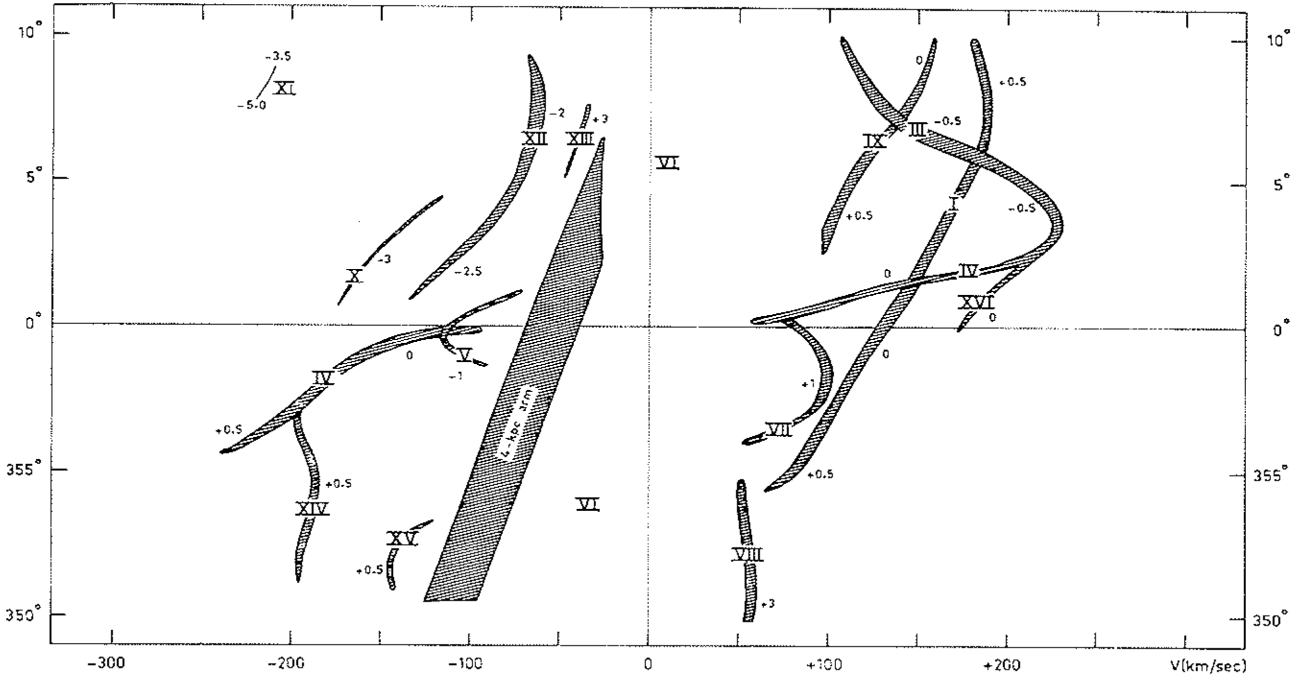

FIG. 9 — Survey of high-velocity features around the galactic centre. Arabic numbers indicate galactic latitudes, ordinates are galactic longitudes. (VAN DER KRUIT, 1970).

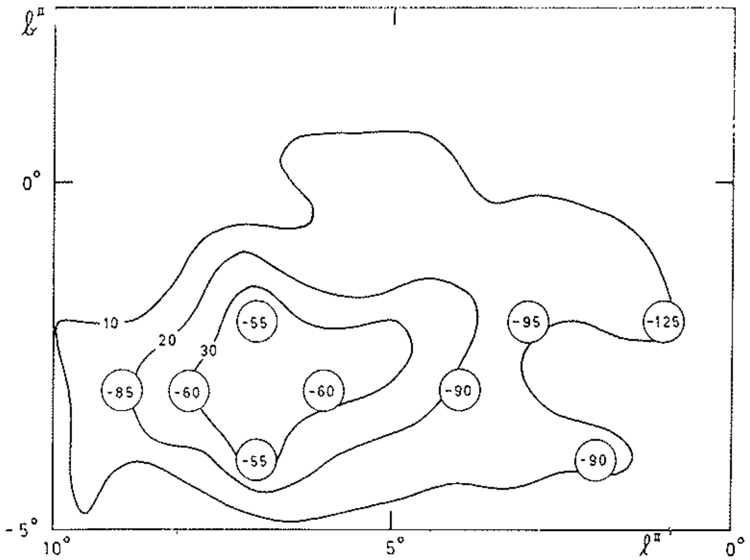

FIG. 10 — Equidensity contours of the high-velocity feature at negative latitude indicated in Figures 8a and 8b. Contours show surface densities of 10, 20 and 30 × 10^{19} atoms per cm^2. Velocities are indicated by encircled numbers (VAN DER KRUIT, unpublished).

10). The velocity coincides with that of a rather weak, but very wide, 21-cm absorption dip in the spectrum of Sgr A (cf. dashed curve in Fig. 2) which may well be due to a thin outskirt of XII. If this is so, the very strong OH absorption at — 130 km/s in Sgr A would in all probability likewise be caused by this same outskirt. That the OH feature lies South of the galactic plane is clearly shown by the absorption contours (cf. ROBINSON and MCGEE, 1967, Fig. 2; also ROBINSON and MCGEE, 1970). The feature even seems to end completely before it reaches the concentrated central source, as is indicated by the total absence of CH_2O absorption in Sgr A. As suggested by SANDQVIST (1970) the probable explanation of this is that the much narrower beam at the CH_2O frequency lies entirely outside the feature concerned. If the connection between VAN DER KRUIT'S feature XII and the OH absorption is real it would indicate that the gas in the expanding cloud is largely in molecular form, and that its total mass may therefore be much larger than the H I mass (which was estimated by VAN DER KRUIT as $2 \times 10^5 M_\odot$). It is extremely interesting that a feature can apparently have acquired a large radial motion, and yet contain a large fraction of molecules.

An intriguing detail is that in the same opposite quadrants of l, b where the abnormal-velocity hydrogen is observed KERR and SINCLAIR (1966) have found, at 20-cm wavelength, secondary ridges of emission seeming to make a similar angle with the galactic equator as the gas expulsion (Fig. 11a).

As I pointed out at the Byurakan symposium, it is conceivable that gas expelled from the nucleus under an angle with the galactic plane, and falling back into the galactic layer at larger R, might be responsible for the outward motions of the expanding arms in the plane. Such a mechanism would not greatly affect the gas in the nuclear disk, whose more permanent existence could thus be ensured.

It is of interest to find out what conditions would be required for the expanding arms to be explained in such a manner.

By the considerations given in the first part of my introduction we have sufficient knowledge about the gravitational field in the central part of the Galaxy to compute the orbits of clouds expelled from the nuclear region. Such computations have recently been made by VAN DER KRUIT. He finds that the location and motion of the 3-kpc arm could be explained if about 13 million years ago gas was expelled from the nucleus at angles between 25° and 30° with the galactic plane, with velocities which at R = 100 pc were about 500 km/s. A considerable part of this gas would at the present time have fallen back to the galactic plane between 3 and 4 kpc from the centre, and have been decelerated by the original quiescent

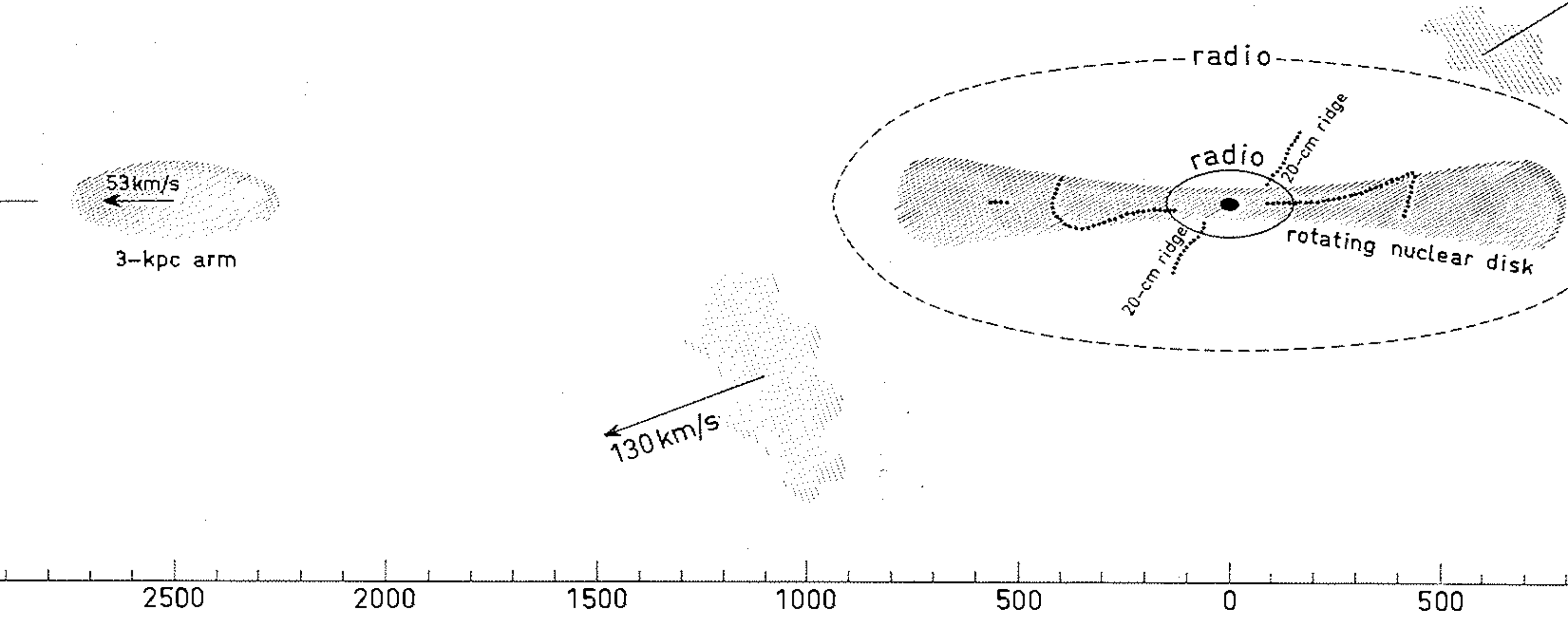

FIG. 11a — Schematic section perpendicular to the galactic plane showing the central region of the Galaxy; the hydrogen outside the plane as well as the 3-kpc arm are marked by arrows indicating the velocity components directed away from the centre.

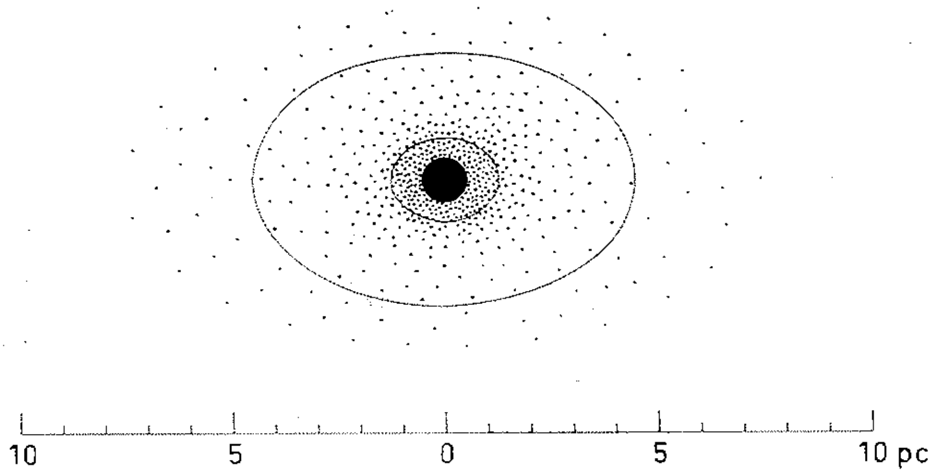

FIG. 11b — Schematic section through the nuclear part on an enlarged scale. The black disk shows the extent of the "Seyfert" core. The ellipses give a schematic indication of the contours of the central radio source Sagittarius A, and of the extent of the OH inflow at + 40 km/s.

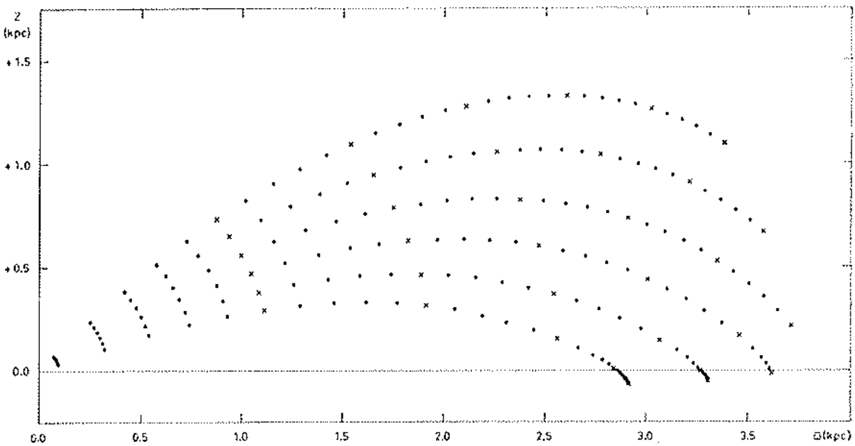

FIG. 12 — Possible orbits of gas clouds expelled from the nucleus under an angle with the galactic plane. Ordinates are distances from the plane, abscissae distances from the nucleus *in* the plane, both in kpc (VAN DER KRUIT, unpublished).

gas layer, so that the outward radial component has become about 50 km/s (Figs. 12 and 11a). In this very schematical model it was assumed that once they are outside the sphere of radius 100 pc the motions of the clouds would be governed solely by the gravitational field up to the time when they fall into the galactic layer. The clouds were supposed to expand laterally in proportion to the distance travelled from the nucleus.

The expulsion velocity required is of the order of the cloud velocities observed in the nuclei of Seyfert galaxies. The mass which would have had to be expelled in order to explain the present outward momentum of the 3-kpc arm is several million solar masses. As only a fraction of the expelled mass will have collected in the 3-kpc arm the total required mass should have been at least 10^7 $M_\odot$. This is of the same order as the present total quantity of gas in the nuclear disk, from which, presumably, it should ultimately have come. For comparison, the mass of the high-velocity ionized hydrogen within a sphere of 200 pc radius around the centre of NGC 1068 is of the order of

10^5 $M_\odot$. If the activity is continuous a mass of 10^6 $M_\odot$ would be expelled by this system in a time of the order of a few million years. The *total* quantity of gas thrown out of the nucleus of NGC 1068 is, however, likely to be considerably larger, as there is evidence that much neutral gas exists in addition to the observed ionized hydrogen.

The general conclusion is that the expanding arms can only be explained by the mechanism suggested if some 13 million years ago the nucleus of the Galaxy was similar to a Seyfert nucleus, and, therefore, enormously more active than at present. This stage should have lasted about a million years. The corresponding total kinetic energy produced by the nucleus should have been between 10^{55} and 10^{56} ergs.

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DISCUSSION

Chairman: D.E. OSTERBROCK

FOWLER

Why were the angles of the expulsions confined to the ones that you showed?

OORT

There are essentially two parameters of which you can dispose, viz. the initial velocity and the angle under which the gas is expelled. The range in angle indicated is that in which the clouds come down to the plane at the right place. The angles do not seem unreasonable.

FOWLER

What kind of an expulsive phenomenon would that have been?

OORT

Our vague ideas would be that it might have something to do with the magnetic field in the nucleus, but we don't know. The presumably non-thermal secondary ridges of radio frequency radiation near the centre found by KERR and SINCLAIR, and indicated in the picture, lie in the same quadrant as the direction in which the clouds are being expelled.

E. M. BURBIDGE

I have always been very interested in this work and I just thought I'd mention another galaxy where I think there is also pretty good evidence for ejection of matter in a cone not axially symmetrical in the central region. Of course one only sees one side of the galaxy, one only sees one direction of ejection, and it is ionised gas not neutral gas. The galaxy is NGC 253, which Mademoiselle DEMOULIN and I have studied.

OORT

Yes, and there you can also see that it goes at an angle to the equatorial plane.

E. M. BURBIDGE

Yes, there are large non-circular motions in the central region of that galaxy and the approach velocities extend in a bright column of gas which you see on the far side of the centre.

OORT

One of the advantages of the Galactic System over others is that you can distinguish so clearly between things in the plane of the disk and outside the plane, which is, of course, more difficult in galaxies which you see only projected on the sky.

HOYLE

I have the impression of a similar kind of rotating disc in M 31 where you can see the dust lanes are curved in the sense of a spiral structure — the dust lanes come right out of the central part with typical spiral curvature.

OORT

I am not implying at all that the nuclear disk in our galaxy would be a smooth feature. It may well have a structure like a spiral, or even more complicated. It would probably have that. In M 31, as I said before, RUBIN and FORD found a striking asymmetry indicating rotation on one side, while on the other side the motions are quite irregular.

HOYLE

The presence of the dust lanes does seem to suggest that there is dust in these central regions.

SALPETER

I wanted to comment on the possibility of there being a lot of molecular hydrogen in the 800 pc disk, even though the atomic hydrogen does not have a particularly high density. Purely theoretically, once you have efficient formation on dust grains of molecular hydrogen there is indeed rather little correlation between the atomic and the molecular density. For instance, take a particularly simple picture where you increase the density of bright stars in proportion to the density of the dust grains. You then find that the density expected of atomic hydrogen is completely independent of the density expected of molecular hydrogen which then makes up most of the gas. Unfortunately the 21cm studies alone then do not tell one very much about the total amount of hydrogen.

One other point: the efficiency of molecule formation on dust grains depends rather strongly on the temperature of the dust grains: if the grain temperature is below about 50 degrees, then we are fairly sure that molecule formation is efficient. We don't know yet what it is if the temperature is above 50 degrees.

OORT

But one wonders how a feature like the suggested arm at − 135 km/sec, which has obtained such a high velocity, and presumably had a still higher velocity when it started, could conserve its molecular constituents; maybe the molecules formed afterwards, but they would have had to be formed rather quickly in that case.

SALPETER

Yes, you would probably need a density of well over 100 atoms per cc for the recombination time to be as short as 10^7 years.

OORT

There would be no objection to that.

LOW

May I clarify the statement I made about the re-radiation from the dust. The argument against dust which I gave in my talk applied only to the nucleus. It was not meant to apply to the Hoffmann source which may be dust.

OORT

Then I didn't quite understand what you meant: As I understood this morning, your point was that, if you have a very large dust cloud like this having at two microns an optical depth of, say, 5 in front of the small nucleus, the fine structure which you see at two microns would be obliterated by the obscuring dust in front of it. Wasn't that your point?

LOW

No, the point was that dust inside the central 100 micron source of diameter 1 parsec would shield and/or redden the 2.2 micron light from the stars in the same volume. An additional point that should be considered follows from your suggestion that a large amount of H_2 may be present in the volume occupied by the Hoffmann source. HOFFMANN may have observed line emission from the H_2, rather than a continuum.

OORT

Would it emit radiation in the 100 micron range?

LOW

I am not sure which of several lines would be strongest.

SCHMIDT

I understood Dr. Low this morning to say that he could not confirm the Frederick-Hoffmann disk — could we have a clarification?

LOW

HOFFMANN and I looked carefully at the two conflicting experiments and have not been able to find an explanation. My results are in conflict with his by a factor 3 to 10 depending on assumptions about the size, shape and temperature of the source. If the H_2 line emission is what HOFFMANN has seen, it may be possible to understand why we do not see it. Our observations at 50,000 ft. are more affected by narrow H_2O absorptions than Hoffmann's at 100,000 ft.

AMBARTSUMIAN

Is this figure of 130 km/sec the radial velocity of the cloud? What is the velocity referred to the nucleus?

OORT

This is the velocity relative to the nucleus; at least in the radial direction at a point near zero longitude it would have this velocity.

AMBARTSUMIAN

Yes, but if there is an angle between the line of sight and the direction of ejection the two velocities must be different.

OORT

Yes, then the velocity would be a little higher, but not so very much; the angle cannot be large.

VELOCITY DISPERSIONS AND DISCREPANT REDSHIFTS IN GROUPS OF GALAXIES

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I. INTRODUCTION

The virial theorem was first applied to a cluster of galaxies — the Coma cluster — by ZWICKY (1933). If the cluster is in a stationary state, the kinetic energy, K.E., and the potential energy, Ω, satisfy the equation

$$2\ \mathrm{K.E.} + \Omega = 0, \tag{1}$$

and in principle the average masses of galaxies can be obtained by measuring the line-of-sight velocities and positions relative to the cluster center for a suitable sample of galaxies. Later, the same method was applied to other clusters and to small groups of galaxies. The kinetic energies have consistently been found to be so large that equation (1) could only be satisfied if the masses of the galaxies were much larger than masses found for individual galaxies by other means.

These results have been interpreted in two ways. Either the excessive kinetic energies have been assumed to be compensated by gravitational potential energy provided by matter having an unusually large mass-to-light ratio, or else it has been postulated that the clusters and groups are in fact not in a stationary state, and are perhaps even in a state of positive total energy. In the latter case, the configurations are not stable and will dissipate in time scales given by the ratio of the characteristic velocity of the cluster members to the dimension of a typical cluster or group. It has been the short time scales — from 10^8 years for some small groups to $\sim 10^9$ years for clusters — which have prevented general acceptance of the idea of positive energies, first put forward by AMBARTSUMIAN (1958).

The observational evidence which had been collected by 1961 was reviewed at the Santa Barbara conference on Stability of Groups and Clusters (NEYMAN, PAGE and SCOTT 1961), and at that time the general consensus was that rich clusters were probably stabilized by unseen matter. This should have a lumpy distribution since a smooth homogeneous distribution of matter would not provide the necessary potential energy. The small dimensions of the groups, however, made it difficult to postulate unseen matter as a stabilizing mechanism, because so much matter packed into the given volume would have to be at average galactic densities, and it was difficult to see why it should not condense into stars and become luminous, like the galaxies themselves. And the configurations of many of these small groups are similar to AMBARTSUMIAN'S trapezium configurations of hot young stars in short-lived stellar associations, as was pointed ont by AMBARTSUMIAN (1961). Yet there was not general acceptance of the idea that these configurations were actually groups in the process of dissolution and therefore only $10^8 - 10^9$ years old. The reasons for this were (*a*) the galaxies in the groups often looked like "ordinary" galaxies, for which it had become customary to accept ages $\sim 10^{10}$ years, i.e., the time scale for the expansion of the Universe, and (*b*) it was difficult to see how an unbound group could form in the first place, in an expanding Universe in which all galaxies were conventionally presumed to have formed from proto-galaxies of lower densities and larger volumes than present-day galaxies.

KARACHENTSEV (1966) summarized the situation for groups and clusters by pointing out that the mean value of $\langle f \rangle = M/L$ (in units of solar mass and solar (photographic) luminosity) required to bind gravitationally a group or cluster of galaxies is a steadily increasing function of the size of the system. Although the statistics are not yet good in some of the cases, the results, shown in Table 1, are interesting; the correlation with size of group is quite strong.

TABLE 1 — *Mean Mass-to-light ratios, in solar units, taken from Karachentsev* (1966).

Type of System	$\langle f \rangle$
11 triple systems	$(85 \pm 28)\, f_\odot$
29 small groups	$(331 \pm 96)\, f_\odot$
9 poor clusters	$(446 \pm 102)\, f_\odot$
6 rich clusters	$(841 \pm 168)\, f_\odot$

We turn now to the small groups, to recapitulate briefly the older data and to discuss new evidence. Then we briefly describe some work by ARP and HOLMBERG concerning distributions and discrepant velocities. Finally, we describe observations of large velocity differences in some single galaxies or in multiple-nuclei objects, which may be related to the problem.

II. GROUPS OF GALAXIES

VORONTSOV-VELYAMINOV (1959) collected many examples of close groups of galaxies in his Atlas of Interacting Galaxies. Several examples of groups, most of them not extremely close together but plainly physically connected, can be found in the redshift lists by HUMASON, MAYALL and SANDAGE (1956). Further examples of close groups have been published by ZWICKY (1957) and by ARP (1966) in his Atlas of Peculiar Galaxies.

1. *Application of Virial Equation*

When Eq. (1) is applied to groups containing only a few members, uncertainties arise because of the unknown projection factors in the separations and velocity vectors (LIMBER and MATHEWS 1960). Statistically, however, these can be taken into account and there are data now on a large enough number of groups for the average projection factors used by most workers to give valid average results.

The masses and mass-to-light ratios obtained for groups are to be compared with the results for single galaxies, obtained from rotation curves or, for ellipticals, from velocity dispersions of stars in the nuclei. Mass-to-light (photographic) ratios for these usually fall in the following ranges: spirals, 1 - 15; E and So, 10 - 50; Sc galaxies have lower values than the Sa and Sb types, and giant ellipticals have higher values than E and So galaxies of lower luminosity. In analyzing groups of galaxies that are near enough to be classified, some workers have assumed that mass-to-light ratios for the ellipticals are larger by some fixed factor than for the spirals; others have made no separation.

ZWICKY and HUMASON (1960, 1961, 1964) published their observations and analyses for several groups. BURBIDGE and BURBIDGE (1961a) gave their observations and analyses for various groups in the VORONTSOV-VELYAMINOV (1959) catalogue, and applied Equation (1) to further groups where the redshift data came from other sources. KARACHENTSEV (1966) made a comprehensive tabulation, including almost all of the results listed earlier by BURBIDGE and BURBIDGE (1961a) together with many more cases, in a compilation that includes doubles, triples, compact small groups, open small groups, and clusters of varying richness. New data recently obtained by SARGENT (1970) are shown in Table 2; we discuss some of these systems in Section II (2). Two groups not included in KARACHENTSEV'S tables or in Table 2 are the NGC 55 group (DE VAUCOULEURS 1959) and the NGC 6769 triple, with redshifts by EVANS and WAYMAN (1958) and analysis by BURBIDGE and BURBIDGE (1961a). The virial equation gives high mass-to-light ratios for both these groups, in line with the average results shown in Table 1.

What is remarkable is the small number of groups, particularly among those containing spiral galaxies, which have low mass-to-light ratios. One good example of such a group is VV 116 (BURBIDGE and BURBIDGE 1961b), for which the virial theorem gives masses of 5×10^{10} $M_\odot$ for the 3 spirals and 5×10^{11} $M_\odot$ for the 2 ellipticals, on the assumption that $M_{ell} = 10$ M_{sp}, whereas a direct mass from the spectral line inclination in one of the spirals gave 3×10^{10} $M_\odot$. This group thus appears to be bound with normal galactic masses. The NGC 3395 group (KARACHENTSEV 1966) and the NGC 833 group in Table 2 are further examples.

A particularly interesting form of group is the chain. The instability of such a configuration was discussed by BURBIDGE,

BURBIDGE and HOYLE (1963). VV 172 (SARGENT 1968) is an especially interesting case, which we discuss individually below. Other cases are the chain at $\alpha = 0^h\ 45^m$, $\delta = -20^0$, near NGC 247, MARKARIAN'S chain in the Virgo Cluster (MARKARIAN 1961), and there are several more in Table 2. All of these have proved to have large kinetic energies. The time scales for dissolution if the values of M/L are actually in the normally accepted range are only $\sim 10^8$ years.

TABLE 2 — *Groups and chains observed by Sargent.*

Name	Configuration(*)	V_R km. sec.$^{-1}$	Scale; pc. per second of arc	Mean 3-dim. separation (kpc)	Virial theorem	
					Mass (suns)	M/L_p
NGC 833 group	G	3885	248	89	4×10^{11}	10
VV 161	C	8447	546	—	—	—
VV 169	C	9087	626	37.5	4.0×10^{12}	90
VV 144	C	6365	402	—	1.2×10^{11}	(29)
VV 150	C	8080	525	34	1.3×10^{12}	38
VV 282	G	9074	582	141	9×10^{12}	74
VV 165	C	12742	812	70	2.4×10^{12}	42
VV 159	C	10475	674	—	—	—
Seyfert's Sextet	G	4282	278	17	5.2×10^{11}	49
Arp 330	C	8702	553	96	2.3×10^{13}	5560
VV 197	G	11861	755	66	5.8×10^{12}	211
VV 101	G	8165	510	104	1.2×10^{13}	87
VV 208	C	7932	504	61	2.5×10^{12}	36

(*) G = Group; C = Chain.

2. *Recent Observations*

SARGENT (1970) has recently applied the virial theorem to 13 groups and chains; most of them are illustrated in ARP's (1966) *Atlas*. These systems are listed in Table 2. The total mass and the mass-to-light ratios deduced from the virial theorem are shown in the last two columns of the table. Two of the systems have members with discrepant redshifts. One of these, SEYFERT's Sextet, is discussed in Section II (3). The other, VV 159, is illustrated schematically in Figure 1. It is No. 324 in ARP's *Atlas* where it is described as a chain of three elliptical galaxies which are elongated along the line joining them. The measured redshifts are 10402 km/sec for A, 13242 km/sec for B and 10548 km/sec for C. Galaxy B is clearly not bound to A and C. However, in this case the discrepant object may well be a background galaxy since the surrounding field is rich in nebulae.

Most of the remaining systems in Table 2 have deduced M/L ratios which comfortably exceed those of normal galaxies. An exception is the NGC 833 group (No. 318 in ARP's *Atlas*) which is composed of four spiral galaxies. The virial theorem mass-to-light ratio of 10 for this system is quite reasonable. Among the "unbound" systems, ARP 330, which is shown schematically in Figure 2, is particularly interesting. This is a chain of galaxies discovered by MARKARIAN (1963); redshifts and absolute magnitudes for the six brightest components are given in Table 3. ARP 330 is a well defined system in a field that is only sparsely populated by nebulae. Table 3 shows that the six galaxies have a range in redshift of 1200 km/sec. This is too large for the system to be gravitationally bound; however, there is no systematic trend of redshift with position along the chain and no reason to dismiss one or more of the galaxies as non-members. As is frequently the case with such systems, the luminous galaxy in the chain falls at its center

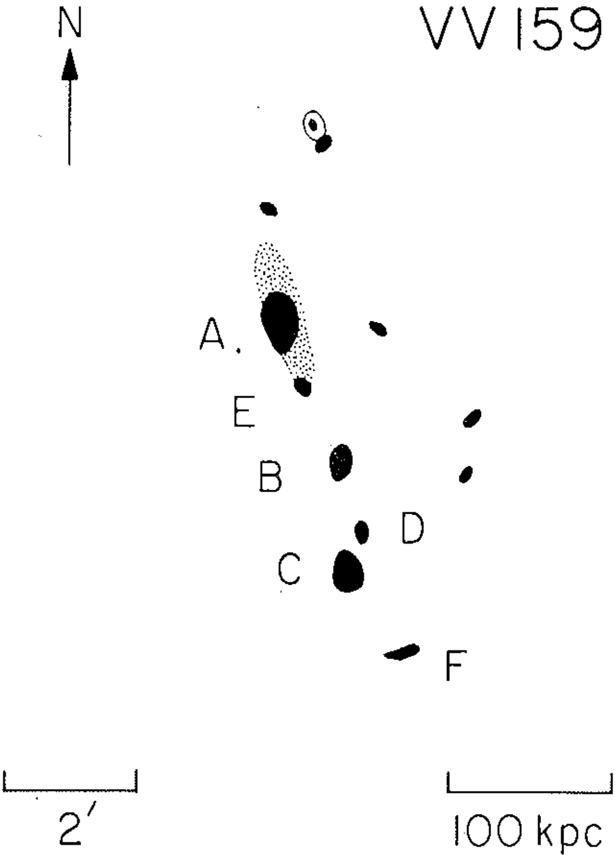

FIG. 1 — Sketch of VV 159 (Arp 324); see Arp (1966) for photograph.

(for other examples see the photographs of VV 172 (No. 329) and the NGC 833 chain (No. 331 in ARP'S *Atlas*). The virial theorem value of $f = 5560$ given in Table 2 has been calculated on the assumption that the position and velocity vectors of the member galaxies are randomly distributed in three dimensions. If it is supposed that they lie in a plane containing the line of

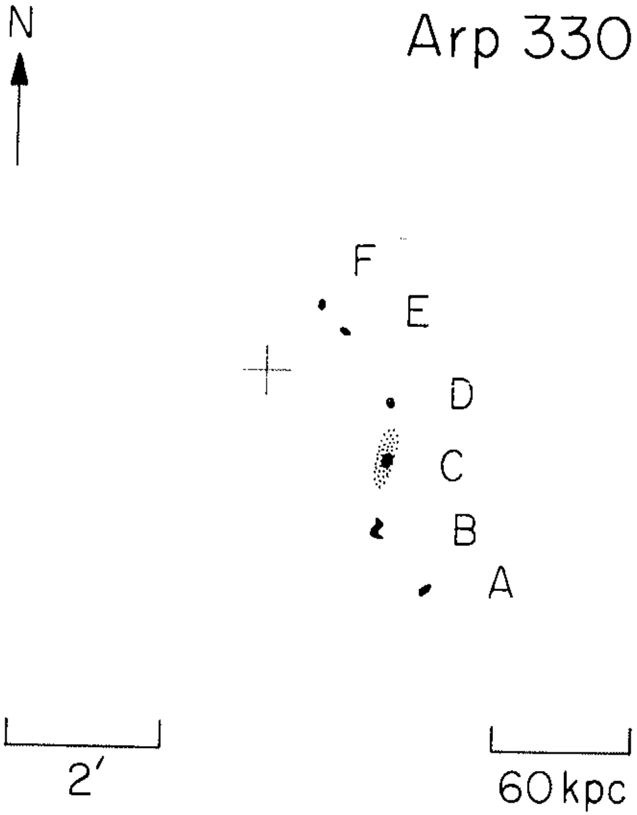

FIG. 2 — Sketch of Arp 330; see Arp (1966) for photograph.

sight, the value of *f* required for stability is about 2000. It is hard to escape the conclusion that this system is disrupting on a time scale of about 2×10^8 years. However, there is no indication from their spectra that the member galaxies are as young as this. Only one of them, B, has an emission line – [O II] λ3727, which is commonly found in the spectra of spiral nebulae in the field.

TABLE 3 — *Redshifts and magnitudes for Arp* 330.

Galaxy (*)	V_R (km. sec.$^{-1}$)	Type	m_p	M_p
A	9093	E	(16)	(-19½)
B	8237	Sba	(16)	(-19½)
C	8948	E	15.5	-20.0
D	9170	E?	(17)	(-18½)
E	8831	E?	(17)	(-18½)
F	7934	E?	(17½)	(-18)

(*) The galaxies are identified in Figure 2.

Finally, we mention the case of VV 282, shown schematically in Figure 3. This is object No. 320 in ARP'S *Atlas*. It is a particularly convincing case of an unbound system because it has a virial mass-to-light ratio of 74 despite the fact that all the bright members are spiral galaxies. As Figure 3 shows, the galaxies are in two main groups — in fact VV 282 as defined by VORONTSOV-VELYAMINOV consists only of E, F and G. However, the northern group A, B and C does not have a systematically different redshift from the southern group E, F and G so they evidently form a single system. The dissolution timescale of VV 282 is about 3×10^8 years. However, the galaxies' colours, given in the last two columns of Table 4, are again not unusual for their morphological types.

We now turn to a discussion of a few groups in which a single very discrepant velocity has been found.

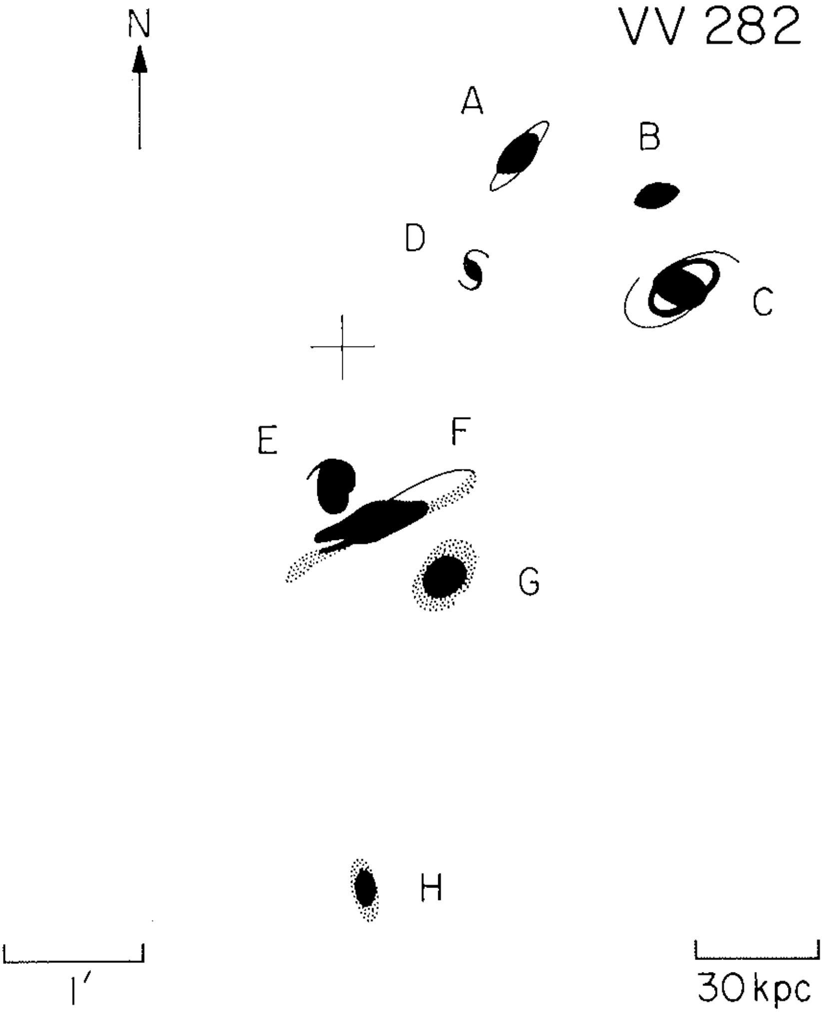

FIG. 3 — Sketch of VV 282 (Arp 320); see Arp (1966) for photograph.

TABLE 4 — *Redshifts and magnitudes for VV 282.*

Galaxy(*)	V_R (km. sec.$^{-1}$)	Type	m_p	M_p	$B - V$	$U - B$
A	8913	Sa	15.2	-20.4	1.01	0.49
B	9337	So?	15.5	-20.1	0.88	0.36
C	9161	SBb	15.3	-20.3	1.00	0.46
D	—	Sc	16.5	-19.1	—	—
E	9048	So?	15.4	-20.2	0.82	-0.10
F	8608	SBa?	15.1	-20.5	1.10	0.46
G	8935	E	15.2	-20.4	1.05	0.48
H	9515	E	15.9	-19.5	1.03	0.46

(*) The galaxies are identified in Figure 3.

3. *Single Discrepant Velocities*

VV 172 - This chain was discussed by BURBIDGE and BURBIDGE (1960) and BURBIDGE, BURBIDGE, and HOYLE (1963), on the basis of redshifts for two out of the total of five galaxies. A surprising discovery was made by SARGENT (1968) when he measured the remaining three objects and found that one of the galaxies has $v = 36{,}880$ km/sec whereas the mean velocity of the other four is near 16,000 km/sec. There are three possibilities for explaining this strongly discordant velocity: either this is a case of the chance coincidence of a background object with a higher intrinsic luminosity, fitting into a convenient gap between the neighboring galaxies in the chain, as seen projected on the celestial sphere, or there is a non-velocity component in the redshift of the discordant object, or, thirdly, this object is being ejected with explosive violence out of the group. The probability of the first was estimated by SARGENT to be 1 in 5000; its is not possible to assign probabilities to the latter two options.

Zwicky's Triple around IC 3481 - ZWICKY (1957) discussed this group, in which the discrepant velocity is *smaller* by some 7000 km/sec than the other two. IC 3481 and a fainter galaxy have velocities +7011 and +7229 km/sec, while IC 3483 has +33 km/sec. A luminous bridge connects the first two, and a long luminous structure extends from the fainter galaxy and appears to connect with IC 3483. The question of the probability of these luminous arms extending into free space and ending by chance near some foreground or background galaxy is obviously difficult to evaluate, since the production of such arms is not understood. They also figure in some of the evidence presented by ARP. A study of the frequency of luminous arms that end in clear space, with no nearby galaxy, should be undertaken.

Stephan's Quintet - When four velocities were known in this group, from the list of redshifts by HUMASON, MAYALL, and SANDAGE (1956), it was already apparent that a large value of *f* would be required to bind the group (AMBARTSUMIAN 1958; BURBIDGE and BURBIDGE 1959; LIMBER and MATHEWS 1960). The surprise here came with the measurement by BURBIDGE and BURBIDGE (1961c) of the fifth redshift, that of NGC 7320, which was found to be some 5000 km/sec smaller than the others. An estimate of the probability of chance coincidence of a foreground galaxy indicated that this was small but not impossibly so; again, the probability of the alternative explanation — explosive ejection of the fifth galaxy from the group — could not be evaluated.

However, examination of the location of Stephan's Quintet on the Palomar 48-inch Sky Survey Atlas reveals that it lies quite near NGC 7331, a large, well-studied Sb galaxy (RUBIN *et al.* 1965). The velocities of NGC 7320, the discrepant member of Stephan's Quintet, and NGC 7331 are so similar as to suggest that the two galaxies may be physically related. Corrected for a rotation of our Galaxy of 250 km/sec, the velocity of NGC 7320 is +1027 km/sec, and that of NGC 7331 is +1082 km/sec. Figure 4 shows this area of the sky on the Palomar Atlas. A stndy of the H II regions in the two objects has not been made but would be well worthwhile, because if the two galaxies are in fact at the same distance, this should be apparent from a study of the distribution of angular diameters of their H II regions.

Seyfert's Sextet - This group of galaxies around NGC 6027 is shown in Figure 5 which is copied from a 200-inch plate taken by W. BAADE. It was discovered by SEYFERT (1951) on a Harvard Schmidt plate. The individual galaxies are identified in Figure 6, using SEYFERT's notation. Recent measurements by SARGENT which are summarized in Table 5 show that galaxy "d" has a discrepant redshift, differing by 15,000 km/sec from the mean defined by the other four objects measured. Galaxy "d" is 16.0 mag. and appears to be an Sc. Before any redshifts had been measured, BAADE, in a letter to SEYFERT, expressed the view that "c" and "d" were not members of the group on the grounds that, unlike the other components, they were not tidally distorted. SEYFERT (1951) disagreed with BAADE. He stated "From a statistical view the probability of two members being field nebulae seems extremely remote since the entire group occupies a circular area of approximately three square minutes of arc, whereas the general field nebulae brighter than magnitude 17 on the rest of the

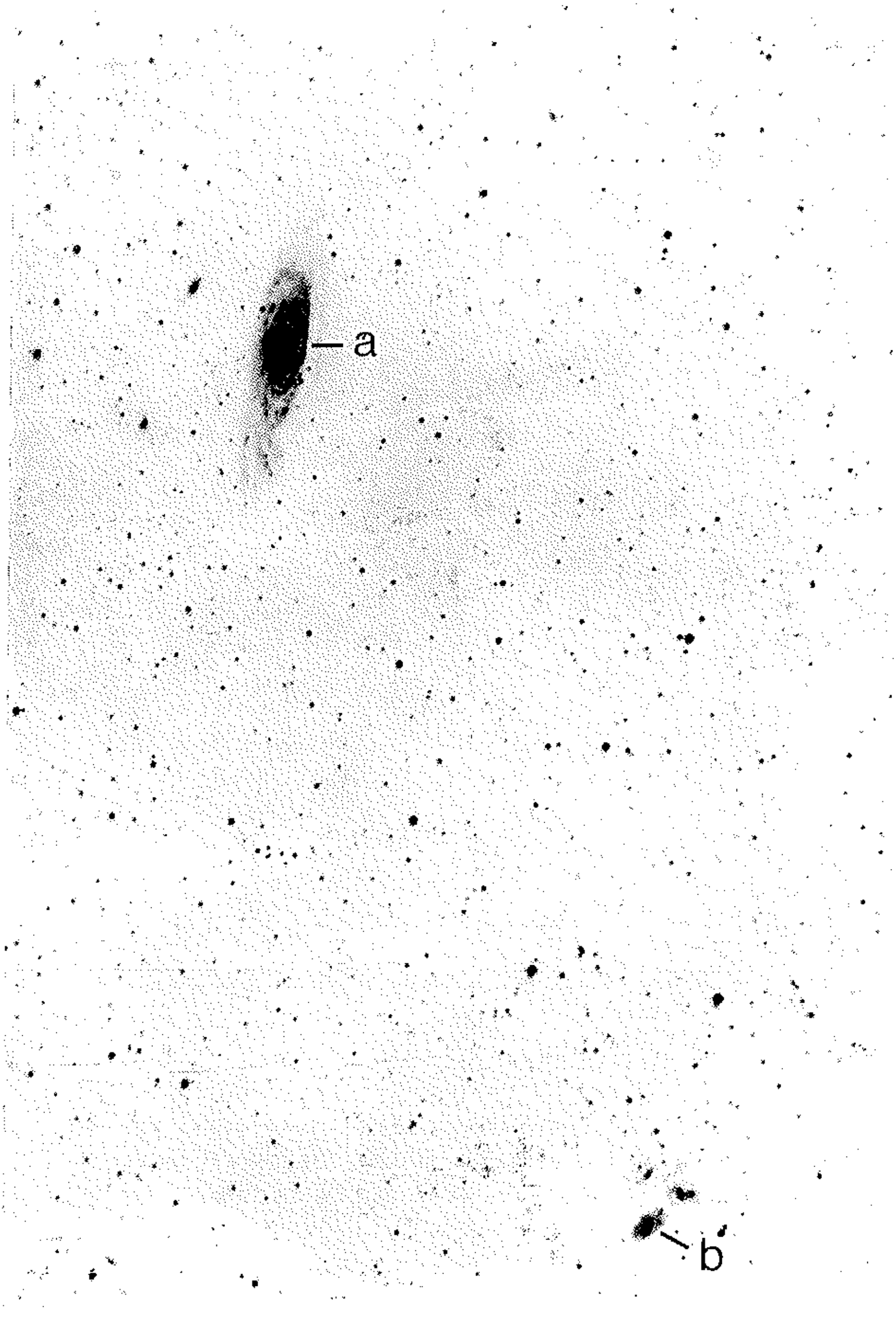

FIG. 4 — NGC 7331 (a), and NGC 7320 in Stephan's Quintet (b). Reproduced from National Geographic Society - Palomar Observatory Sky Survey, O print.

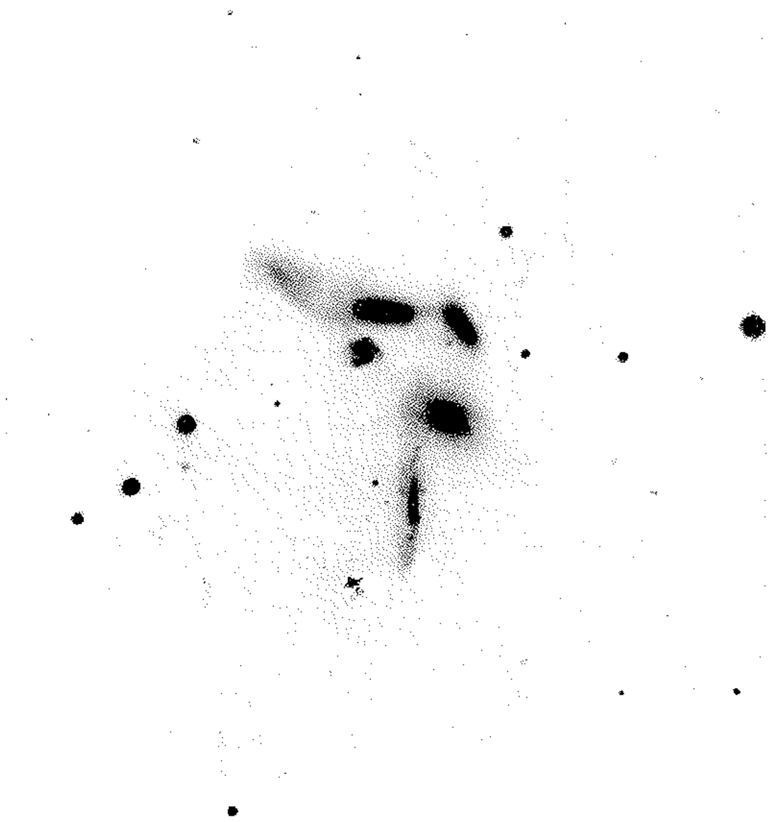

FIG. 5 — Seyfert's Sextet; photograph by W. BAADE with 200-inch Hale telescope.

Schmidt plate (25 square degrees) average one galaxy per 160 square minutes. As a matter of fact, the nearest galaxy to the group brighter than the 17.0 mag. is 18′ away. On the

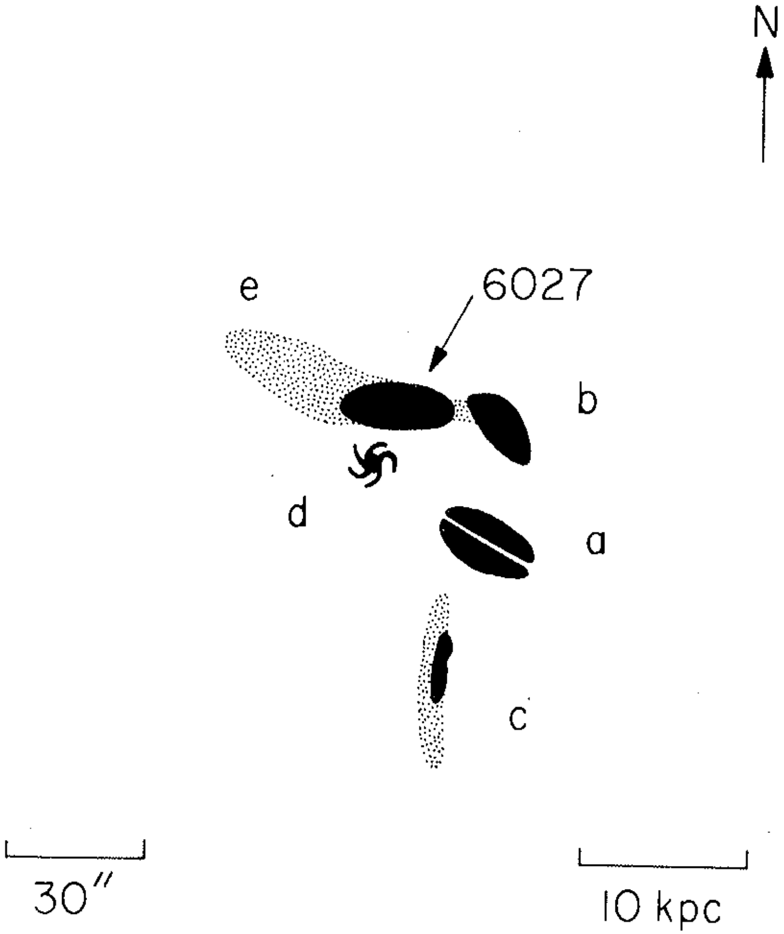

FIG. 6 — Sketch of Seyfert's Sextet, showing scale and identification of members.

other hand, if the Sc spirals are members of the group, they are statistically abnormal because of their extremely small size".

TABLE 5 — *Redshifts and magnitudes for Seyfert's Sextet.*

	V_R (km. sec.$^{-1}$)	Type	m_p	M_p
NGC 6027	4468	Sa or So	14.7	-19.4
a	4141	Sa	15.1	-19.0
b	4430	Sa or So	15.3	-18.8
c	4581	Sbc	15.6	-18.5
d	19930	Sc	16.0	(*) -21.3
e	—	(**) Irr.	16.5	-17.6

(*) Absolute magnitude calculated on the assumption that "d" has the distance corresponding to its redshift.

(**) Component "e" is probably not a separate galaxy but matter tidally displaced from NGC 6027.

If galaxy "d" is a member of SEYFERT'S Sextet its absolute magnitude is $M_p = -18.1$. If it is at the distance corresponding to its redshift, then $M_p = -21.3$. Such a luminosity is unusual but not unprecedented for an Sc galaxy. It lies near the upper limit of the range quoted by VAN DEN BERGH (1960). An independent way to estimate the distance of galaxy "d" is provided by VAN DEN BERGH'S (1960) system of luminosity classification for Sc's. Unfortunately, the image of galaxy "d" on BAADE'S plate does not resemble any of VAN DEN BERGH'S standards. This may be due to the fact that the image is small with too few information elements for convenient classification.

If we ignore galaxy "d", SEYFERT'S sextet is a remarkable system. The mean three-dimensional separation of the remaining members is only 17 kpc, even smaller than the mean separation of the components of STEPHAN'S Quintet. It is remarkable that such a high proportion of the groups with very small physical separations between the members — VV 172, STEPHAN'S Quintet and SEYFERT'S Sextet are all in this category — have discrepant redshifts associated with them.

III. COMPANIONS AROUND GALAXIES; CHAINS AND LINES OF GALAXIES OR RADIO SOURCES

The large velocity dispersions in small groups, and the few cases of single very discrepant velocities, might imply that the material out of which galaxies form could be ejected from existing galaxies, or that in some cases the measured wavelength shift might not be due to Doppler shift. It is therefore worthwhile to consider any other evidence which might have a bearing on this possibility. We first mention work on distributions of galaxies.

ARP (1967, 1968a) suggested that, in a statistically significant number of cases, radio sources occur in pairs lined up on either side of galaxies falling into a certain category in his Atlas of Peculiar Galaxies (ARP 1966). The radio sources can be either radio galaxies, QSOs, or optically unidentified sources. The type of central peculiar galaxy is that categorized by ARP as having very disturbed, "eruptive", forms. He suggested that the radio sources have been ejected in opposite directions by the central object and, since the radio sources often have much larger redshifts than the central object, he has concluded that redshifts can contain a component not due to Doppler shift. He also (ARP 1968b) drew attention to distributions of galaxies about certain bright radio galaxies, in chains or lines through them, looking as though they or their progenitors had been thrown out of the radio galaxy in preferential directions. MARKARIAN (1961, 1963) had earlier discussed some of these lines or chains.

There has been considerable criticism of the statistics involved in discussion of the pairs of radio sources, and the general consensus has been that the conclusions drawn by ARP are so far-reaching that firmer evidence is needed for their acceptance. The ball has therefore been returned to the observers.

Two further statistical studies have a bearing on the question. In a study of 174 physical groups of galaxies centered on prominent spiral galaxies, HOLMBERG (1969) has looked into the distribution of satellite galaxies about the primary. After careful estimation of the contribution to the numbers of satellites by background or foreground galaxies, he found some interesting effects. Spiral galaxies with an edgewise orientation (ratio of apparent diameters ≤ 0.53) have a majority of their satellites distributed around the elongation of the minor axis of the spiral, i.e., in high local latitudes with respect to the equatorial plane of the central galaxy. The predominantly face-on spiral galaxies, with ratios of apparent diameters < 0.53, showed a distribution nearly independent of local latitude. HOLMBERG'S diagrams illustrating this are shown in Figure 7. Further, the number of satellites around a spiral galaxy appears to be larger for spirals with exceptionally blue nuclei and for spirals with large hydrogen masses. HOLMBERG concluded that the results favor the hypothesis that the satellites are produced by matter ejected from the nuclear regions of the spirals, ejection being much easier out of the galactic plane, but that the statistical evidence was not conclusive.

ARP (1970a, b, c) has also considered the companions or satellites of galaxies. Compact satellites around the active variable N-type radio galaxy 3C 371, itself a very compact object, are connected to it by low-luminosity bridges. Redshifts of two of the companions have not been measured, but there is no discrepancy between the redshift of 3C 371 itself and those of the other two companions. In the case of NGC 772, however, where similar luminous arms or bridges appear to connect nearby small galaxies to it, there are considerable differences between the redshifts. Low-luminosity arms of this type were referred to in Section II; it is desiderable to investigate the

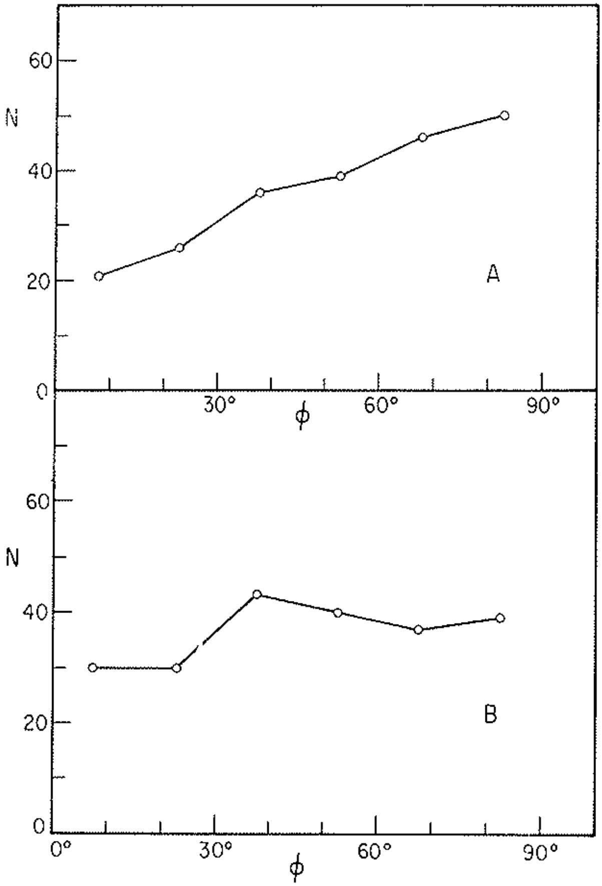

FIG. 7 — Distribution of position angles, φ, of satellite galaxies with respect to the major axis of the primary galaxy, from HOLMBERG (1969). N = number of galaxies with φ in 15° ranges about plotted value. A: edge-on primaries, ratio of minor to major axis ≤ 0.53; B: face-on primaries, ratio > 0.53.

frequency with which they occur without connecting to a nearby galaxy. Finally, ARP (1970b) looked into the distribution of redshifts among 19 companions or satellites of larger galaxies, and found that in 16 of the cases the redshift of the companion was larger than that of the primary galaxy, by amounts of order 100-200 km/sec, the average difference being +72 km/sec. This suggested to him the existence of a non-velocity component in the redshifts of the companions. Clearly, further observations of redshifts of galaxies with companions are desirable, and considerable care will be needed in evaluating the contributions from background galaxies. Perhaps the method of diameters of H II regions can be applied, as we suggested for the case of STEPHAN'S Quintet.

IV. LARGE VELOCITY DIFFERENCES IN SINGLE GALAXIES OR MULTIPLE-NUCLEI OBJECTS

The velocity dispersions in the groups are usually in the range of several hundred up to about 10^3 km/sec. It is worth noting that velocities in this range, exceeding the central escape velocity and reaching even a few thousand km/sec, have been found in some of the active single galaxies being discussed at this Study Week, and that multiple-nuclei objects, e.g. NGC 6166, a complex radio galaxy, can also exhibit large velocity differences. Since these observations may be related to the phenomenon of large velocity dispersions in groups, we briefly consider some cases. Fuller discussion and references have been given by BURBIDGE (1970).

NGC 1275 and other Seyfert Galaxies

The gas cloud in NGC 1275 has a velocity 3000 km/sec greater than the galaxy itself (MINKOWSKI 1957, BURBIDGE and BURBIDGE 1965, LYNDS 1970). This is very similar to the velocity difference in the group VV 159 (Table 2), in which the velocities are +10,402, +10,548, and +13,242 km/sec. The emission-line profiles of other Seyfert galaxies, e.g. NGC 1068 (WALKER 1966, 1968), show that there are gaseous cloud complexes moving at velocities of several hundred km/sec in the nuclear region, in addition to the larger velocity spread indicated by the outer wings of the lines. The absorbing clouds detected by ANDERSON and KRAFT (1969) in the nucleus of NGC 4151 have velocities up to 970 km/sec relative to the nucleus itself.

M 82 and M 87

The gaseous filaments extending along the minor axis of M 82 were deduced by LYNDS and SANDAGE (1963) to be moving outward from the nucleus at velocities of about 1000 km/sec. WALKER and HAYES (1967) found that the nucleus of M 87 contains gaseous clouds moving at discrete velocities of hundreds of km/sec, as in the Seyfert nuclei.

3C 390.3, a More Distant Radio Galaxy

LYNDS (1967) drew attention to the very great widths of the Balmer lines of hydrogen in 3C 390.3, an N-type radio galaxy. He estimated the total widths to correspond to a velocity spread of 17,000 km/sec, fully as great as the net redshift of the object. Figure 8 shows an image-tube spectrogram of this galaxy, obtained at the prime focus of the Lick 120-inch telescope. It may be seen that both Hα and Hβ are double; Hγ is also and its longward component is blended with [O III] λ4363. The forbidden lines are not double. The mean velocity of the longward components of Hα and Hβ is 16,800 km/sec, in agreement with the mean velocity of the forbidden lines; the mean velocity of the shortward components of Hα, Hβ, and Hγ is 12,250 km/sec. Thus there is a velocity difference of 4550 km/sec between the two components, quite apart from the great total width of the Hα wings. The absence of a shortward component in the forbidden lines may indicate that the gas producing this component has a high electron density.

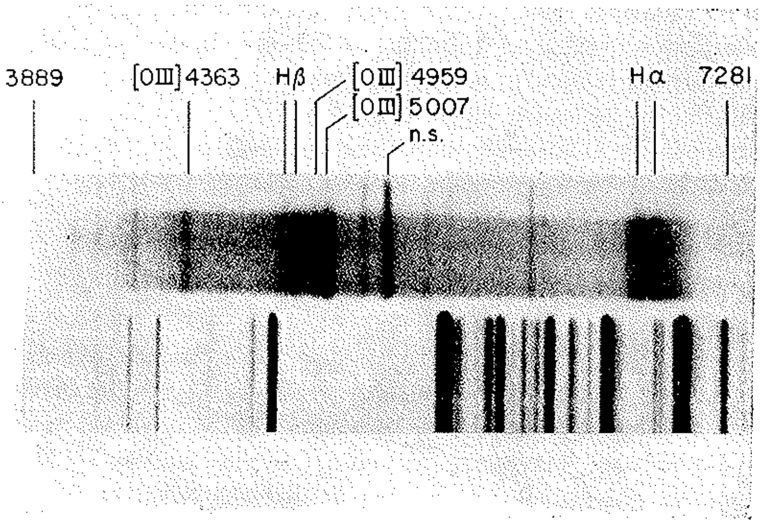

FIG. 8 — Spectrum of N-type radio galaxy 3C 390.3, photographed with Carnegie image-tube spectrograph at prime focus of Lick 120-inch telescope. Note very great width of Hα and Hβ, and double maxima.

Multiple-Nuclei Objects

The complex cD+E radio galaxy NGC 6166 is a quadruple object with a common envelope. MINKOWSKI (1961) measured redshifts of three of the four components and obtained velocities of +9480, +7960, and +10,050 km/sec, from stellar absorption lines and [O II] λ3727 in the cD component. Thus the total spread in velocity here exceeds 2000 km/sec, and there is no question but that these three components form a physical system. The mass of the system obtained by MINKOWSKI from the virial theorem was 1.4 × 10^{13} $M_{\odot}$; even with the extensive outer envelope of the cD and the great total luminosity of the system, this gave a large mass-to-light ratio of $f = 149$, and it seems likely that the system has positive total energy.

A very large spread in velocities was measured by SERSIC (1966) in NGC 6438, a peculiar galaxy near the S. pole. He found +6300 km/sec in the So component and +2680, +4300 km/sec in two parts of the irregular component, and suggested that the object was the aftermath of a galactic explosion.

Nuclei with Smaller Velocity Differences

The apparently normal spiral galaxy NGC 4939 was found by BURBIDGE and DEMOULIN (1969) to have in its nuclear region a gas cloud with a velocity 700 km/sec different from the galaxy as a whole. For a normal galactic mass, this is well in excess of the escape velocity. The cloud is quite small, and features like this might lurk undetected in the nuclear regions of many spiral galaxies. On the other hand, BURBIDGE and HODGE (1971) have found that the galaxy NGC 4569, suspected by WEEDMAN (1970) to have gas in its nuclear region with a velocity 1300 km/sec different from the galaxy as a whole, actually has very little velocity difference between the stars and gas. The discrepancy apparently arose because of a wrong tabulation of the redshift of NGC 4569 by HUMASON *et al.* (1956).

V. CONCLUSIONS

There is enough evidence now, assembled in the tables, to demonstrate that the majority of the small groups of galaxies which have been investigated have large velocity dispersions which lead to large virial masses and mass-to-light ratios if Equation (1) is assumed. Chance orientation effects can no longer be invoked to account for the large velocity dispersions. To explain the large mass-to-light ratios obtained from using Equation (1) by means of conventional stellar populations or the existence of much dark unseen matter no longer seems feasible. The conclusion appears inescapable that many groups are indeed systems of positive total energy, as originally suggested by AMBARTSUMIAN. The observers may now, therefore, return this ball to the theoreticians since a serious attempt to fit this into an overall cosmological and cosmogonical picture now seems warranted.

On the other hand, the cases of one single very discrepant velocity in groups are few in number, and explanations of them by the chance superposition of background or foreground galaxies upon the group may be possible. As long as such discrepant velocities are no more than about 3000-4000 km/sec, the objects may be part of the groups and the phenomenon may be connected with what is seen in NGC 1275 and 3C 390.3; also, in systems of positive total energy, one component may tend to acquire most of the excess kinetic energy. The cases where discrepancies of some 20,000 km/sec are involved would, however, be very difficult to account for, both theoretically and from the point of view of statistics. Such velocity differences would carry the discrepant object away from the group at the rate of 20 kpc per 10^6 years. Survey work on many more groups, and investigation of individual distances in objects with discrepant velocities, is needed.

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DISCUSSION

Chairman: Prof. OSTERBROCK

McCREA

I wish to refer to the recent work of ARP mentioned by Professor BURBIDGE. ARP considered several galaxies having "satellite" systems. ARP gave a histogram of Δz = satellite redshift minus galaxy redshift. He found a preponderance of positive values of Δz. However, if we suppose that the cosmological redshift of the galaxy is greater than the measured value by an amount corresponding to 50 to 100 km/s, then the histogram becomes symmetric. It then occurred to me that there there might be an uncertainty of this order in the velocity-shifts in clusters of galaxies generally. With the help of a colleague, J. JACKSON, I find that such an uncertainty could be of about the order needed to account for the so-called "missing mass" in clusters. That is, there may not be a problem of missing mass.

E. M. BURBIDGE

Well, it is not my impression that you can account for it in that way; maybe SARGENT can set some errors on his velocity measurements since he has the largest body of data now.

SARGENT

I think that you can get random errors of orders of 50 km/sec in this kind of work. What you are suggesting, I take it, is that the central galaxy is wrong systematically by, say, 100 km/sec. I would think that not impossible, but I would hope that with sufficient sources of data different observers should agree to better than 100 km/sec for a bright galaxy, although an individual image tube measurement might be wrong by 100 km/sec.

E. M. BURBIDGE

But what about your groups?

SARGENT

I estimated from the radial velocities of the night sky lines on many plates and also from the agreement of the repeated measurements of the same object that errors were about 50 km/sec and that was much smaller than the velocity dispersion I find, which is about 400 km/sec, typically in a group.

McCREA

I didn't mean, in answer to Dr. SARGENT, that this was an actual error, but that the measurements might be confused maybe by material coming out towards us in the larger objects.

E. M. BURBIDGE

I am sorry, I misunderstood. Well I think the velocities of the larger objects — the principal galaxies — are mostly absorption line measuments. Most of the velocities in the groups depend largely on absorption line measurements not on emission line measurements, and I think that we have to accept that they belong in the objects themselves.

McCREA

There could be material coming towards you in the large objects.

E. M. BURBIDGE

There again you are using absorption lines; you may be using emission lines as well but you will most probably be using some absorption lines.

McCrea

But wouldn't that tend to show this effect?

E. M. Burbidge

Not when you use the H and K lines or the G band etc.

Sandage

This is probably a detail concerning NGC 6638 where there is a large discrepancy according to Sersic between the velocity of the elliptical galaxy and that material which looks as if it is coming out. Ken Freeman at Mount Stromlo took a number of spectra and could not confirm Sersic's result. For this particular object there seems to be no difference of radial velocity between the outer blue material and the parent elliptical galaxy.

E. M. Burbidge

Has he been in touch with Sersic? Have they got together about their observations?

Sandage

I think so, and Freeman thinks he has an explanation why Sersic got his result in terms of night sky lines. The blue material is very faint, but with the measures of many spectograms there is no question at all that Freeman's negative result is correct.

Ambartsumian

My first remark is about NGC 1275. In my introductory speech I have given 10^8 solar masses as a rough estimate of the mass of the cloud ejected. I have used a formula which shows that the luminosity is proportional to the square of the mass and inversely proportional to volume. The estimate, is, of course, very rough. Everything depends on the distribution and thickness of the filaments. It is not easy to take these factors into account, but 10^8 solar masses is a conservative estimate. My second remark — apparently now the evidences show that there are many unstable systems. My third remark is that when you have a discrepancy of the order of 15,000 km — then it is impossible to explain this even under the assumption of ejection of the galaxy under consideration by one of other members.

SCHMIDT

I would like to make two remarks about that. If these large velocity differences were really due to ejection, one should see once in a while systems which when plotted in the Hubble diagram would be well above the line of the brightest galaxies. Also, in a few cases one should see galaxies with very large negative velocities. As long as these two phenomena are not seen there doesn't seem to be conclusive support for ejection.

Perhaps I might add to your objects with discrepant velocities 3C 386, a radio source at low galactic latitude which in our paper Dr. MORGAN identified as an E galaxy. It shows H and K in absorption at a radial velocity of 30 km per second. PSKOVSKY interpreted this as a supernova remnant, but the whole thing remains rather puzzling.

E. M. BURBIDGE

I have always had a suspicion that the bright centre of 3C 386 might be a foreground star. It is in a very rich star field.

SCHMIDT

I took another spectrum last summer and looked at the object very carefully this time and it is nebulous, extended and certainly not a star.

MORGAN

Does it have a composite spectrum?

LYNDEN-BELL

As far as I can see the three outstanding cases of a galaxy with a discrepant redshift where it might be a foreground or a background object, in every case where the redshift is greater the object is of smaller angular size, and where the redshift is smaller the object is of greater angular size. Now I feel this is significant even in 3 cases.

E. M. BURBIDGE

In the Zwicky triple the discrepant velocity is low and the object is smaller than the galaxy to which it appears to be connected.

HOYLE

I don't see the logic of rejecting data because they seem incredible. (Laughter)... We have something like 4 cases of large difference of velocity where I suppose the probability of a chance effect is something like 1% or less. The relevant question therefore is, how many chains and small groups Dr. SARGENT has looked at.

SARGENT

In answer to Professor HOYLE's question, I should think about half a dozen chains have been looked at among which VV 172 is the best example, that is, the objects are closer together on the plane of the sky. The thing that worries me is that such a high proportion of the very compact groups or chains show a discrepant velocity. It means that you cannot interpret this as being an ejection from the system because it turns out that the time scale required for an object to cross the system is of the order of 10^7 to 10^8 years, so only one in 1000 or so, or 1 in 100, should be seen doing it now and yet nearly one third of the very compact groups and chains seem to have a discrepant velocity. If I might make another point which is slightly related. It is rather difficult to calculate the probability of the chance association because it is hard to know in retrospect what questions to ask. It is well known in the theory of statistics that any given configuration of objects is highly improbable and the only way I can see of doing it is to ask two questions — first, "what is the probability of finding a galaxy of the observed apparent magnitude within some region of the sky around the group". And this turns out to give a probability of around 1 in 300 typically. Then you can be more specific and say "what is the probability of finding an Sc galaxy with an absolute magnitude of — 21 in the vicinity of the system" and that always gives a lower probability since you ask a more specific question. It is in that case that you get probabilities of the order of one in a few thousand.

VAN DER LAAN

I do not believe the second question is relevant; had you found something quite different, then you would have asked for the probability of finding that, and you still would have lowered your initial probability.

SARGENT

The question I did ask was not the probability of finding an Sc but the probability of finding a galaxy of — 21 since they are such rare objects.

REES

Have people considered whether you can interpret this in conventional ways by, for example, appealing to an anisotropy in absorbing matter around the galaxy or anisotropy in the gravitational field around the big galaxy which presumably is a disk galaxy?

E. M. BURBIDGE

HOLMBERG is always very careful to take account of absorbing matter in the plane of the galaxy in question. For example, he always corrects his diameters for absorbing matter. He seems pretty careful about that, and I think he has been careful here too.

MORGAN

Where does this leave the question of the reality of the chains? The reality, unreality or what?

SARGENT

That is for you to decide. There has been a statistical analysis of the reality of chains made by MARKARIAN which perhaps Prof AMBARTSUMIAN knows more about than I do. In this analysis, which is given in one of the Burakan Publications, MARKARIAN has analysed the probability of chains being real without knowing the redshifts because many of them do not have the redshifts measured yet. He arrives at a probability of something like one in several million that they are not physically associated.

AMBARTSUMIAN

I only wish to say there are two different things. One thing is the equation — whether the energy was positive or negative. Is the group stable or unstable? Another question concerns the sign of the energy — whether it is positive or negative.

SCHMIDT

I would like to state that I did not correct, object to or criticise the ejection hypothesis. I was only trying to say that in that case certain forbidden parts of the Hubble velocity — magnitude diagram might become occupied and then it would become really convincing.

SALPETER

I wanted to ask SARGENT more quantitatively about his argument against the probability of ejection. If I understood you right you said that the velocity of the peculiar galaxy is so high that it would only last 10^7 years and the universe has lasted 10^{10} and that is only a probability of 1 in a thousand. However, if the chain as a whole has positive energy (even though the other velocities are smaller) the whole chain will not last anywhere near as long as 10^{10} years, especially for a compact chain.

SARGENT

Yes, that is true. The time for dissolution of the group as a whole is typically of the order of 10^8 or 10^9 years, and the timescale required for the object with the peculiar velocity to cross is about 10^7 years.

AMBARTSUMIAN

I agree with your comments. However, I do not think the discrepancy will be such that it will not escape our attention. It is not so strong as it seems at first.

SARGENT

If you remember, one of the discrepant galaxies was an Sc galaxy in the Seyfert sextet, and in that case there were two possible absolute magnitudes according to whether or not the object was a member, which I think varied betwen — 18 if it were the member, and — 21 if it were at the distance suggested by the redshift. Now such a difference should be easily detectable from the form of the spiral structure. I have asked both VAN DER BERGH and SANDAGE to look at a direct photograph of this particular galaxy, and they both failed to classify it on the luminosity classification scheme.

MORGAN

Dr. SARGENT, have you indicted Dr. SANDAGE and Dr. VAN DER BERGH, or what is the conclusion to be reached from that statement?

SANDAGE

He has indicted the galaxy.

SPACE DISTRIBUTION AND LUMINOSITY FUNCTIONS OF QUASI-STELLAR OBJECTS

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Quasi-stellar objects (QSOs) are selected optically exclusively on the basis of color. Candidate objects are required to have ($U - B$, $B - V$) colors similar to those of known quasi-stellar radio sources (QSS). SANDAGE and LUYTEN (1969) have collected such blue stellar objects in a number of fields at intermediate and high galactic latitude. A most remarkable property of their list of candidate QSOs is that the number increases by a factor of around 6 per magnitude. Such a strong number-magnitude gradient requires an increase in density with distance in any relativistic-cosmological model with zero cosmological constant.

Extensive spectroscopic observations are being made of the SANDAGE-LUYTEN blue stellar objects. All objects in a generous range of colors are investigated and galactic stars eliminated. Tentative redshifts for a small but essentially complete sample of 23 confirmed QSOs have now been derived.

The redshift distribution of the twenty QSOs that have approximate optical magnitude $17\frac{1}{2} - 18\frac{1}{2}$ is given in Table 1. (We actually use the flux density f (2500) at 2500 Å rest wavelength, rather than the optical magnitude, see SCHMIDT 1968).

Also given in the table is the redshift distribution of 3CR quasi-stellar sources. There is no statistically significant difference between the two distributions. Although this finding is unexpected and requires an explanation to be discussed presently, we accept the identity of the two distributions and give in the last column the slightly smoothed adopted fractional distribution of redshifts at optical magnitude 18.

TABLE 1 — *Distribution of redshifts of 3CR QSS and* SANDAGE-LUYTEN *QSOs of approximate optical magnitude 18* $(-30.0 < \log f\,(2500) < -29.6)$.

log z	QSOs	3CR	Adopted Fractional
+ 0.2 — + 0.4	5	3	0.20
0.0 — + 0.2	7	6	0.35
— 0.2 — 0.0	2	6	0.20
— 0.4 — — 0.2	3	2	0.15
— 0.6 — — 0.4	0	1	0.05
— 0.8 — — 0.6	2	0	0.05
unknown	1	1	
	20	19	1.00

We present in Table 2 a *redshift-magnitude table,* which represents the distribution of points in a diagram of redshift z versus optical flux density. Each entry is the number of QSOs expected over the whole sky in a box with $\Delta \log z = 0.2$ and $\Delta \log f\,(2500) = 0.4$. Since in a cosmological model with deceleration parameter $q_0 = +1$ the flux density of a given source is proportional to z^{-2}, diagonals in the table correspond to sources of the same absolute luminosity. The entries under optical magnitude 18 follow from the last column of Table 1, and the total number estimate of QSOs by SANDAGE and LUYTEN.

The second column of Table 2 gives the total volume v in the Universe in each shell of thickness $\Delta \log z = 0.2$, in Gpc^3 ($1\ \mathrm{Gpc} = 10^9\ \mathrm{pc}$). Since each entry is the product of the volume and the space density of objects of relevant absolute luminosity, the ratio of entries along a diagonal of constant absolute luminosity simply reflects the ratio of volumes. If we were to predict the six entries under magnitude 17 from those under magnitude 18 through the given volumes v we would find a total number of 11,000 under magnitude 17. This is incompatible with the observed number ratio of 6 per magnitude.

In order to account for the steep number-gradient, we assume that the number of QSOs per co-moving volume element is proportional to $(1 + z)^n$, independent of luminosity. It turns out that $n = 6$ is required to account for a number ratio of 6 per magnitude. The volumes v' shown in Table 2 are given by $v' = v\ (1 + z)^6$ and hence correspond to the apparent or density-weighted volume. Division of the entries under magnitude 18 by v' then yields the local ($z = 0$) luminosity function given in Table 3. The total local density of QSOs is 686 Gpc^{-3} or around $0.7 \times 10^{-6}\ \mathrm{Mpc}^{-3}$. The luminosity function is rather steep, showing an increase by a factor of 3 or 4 per magnitude, with a steeper cut-off at the bright end. Inspection of the origin of the entries in Table 3 through those in Tables 1 and 2 shows that the faint end of the luminosity function is very poorly determined; the local volume density of QSOs intrinsically fainter than are observed in this sample may be much more than $10^{-6}\ \mathrm{Mpc}^{-3}$. However, the definition of QSOs of such low luminosity poses a problem.

With the luminosity function given we can now compute all entries in Table 2. If we limit ourselves to $z < 2.5$ then the total number of QSOs that can be observed down to optical

TABLE 2 — *Redshift-magnitude table for quasi-stellar objects with density* $\sim (1+z)^6$ *in a cosmological model* $q_0 = 1$.

		Approximate Optical Magnitude	13	14	15	16	17	18	19	20	21	22	23
		log f (2500)	—27.8	—28.2	—28.6	—29.0	—29.4	—29.8	—30.2	—30.6	—31.0	—31.4	—31.8
log z	v (Gpc³)	v′ (Gpc³)											
+0.5	24	(148000)							(35×10^3)	(480×10^3)	(1.9×10^6)	(8×10^6)	(15×10^6)
+0.3	21	17100						4×10^3	56×10^3	217×10^3	1.0×10^6	2×10^6	9×10^6
+0.1	14	2150					503	7×10^3	27×10^3	124×10^3	0.2×10^6	1×10^6	
—0.1	8.5	315				74	1026	4×10^3	18×10^3	32×10^3	0.2×10^6		
—0.3	4.2	52			12	169	660	3×10^3	5×10^3	27×10^3			
—0.5	1.75	9.7		2	32	123	560	1×10^3	5×10^3				
—0.7	0.63	1.96	0	6	25	113	202	1×10^3					
—0.9	0.21	0.43	1	6	25	44	219						
—1.1	0.061	0.098	1	6	10	50							
—1.3	0.017	0.023	1	2	12								
—1.5	0.0047	0.0056	1	3									
—1.7	0.0012	0.0014	1										
		n [f (2500)]	5	25	116	573	3170	20×10^3	111×10^3	400×10^3	1.4×10^6	3×10^6	9×10^6

magnitude $23\frac{1}{2}$ is 14 million. It is interesting to realize that at the present cosmic time there supposedly exist only 35,000 QSOs, the larger observable number being due to the enormously higher density at the earlier epochs surveyed at large redshifts.

TABLE 3 — *Optical luminosity function for quasi-stellar objects* with density $\sim (1+z)^6$ in model with $q_0 = 1$.

log F (2500)	Local Density (Gpc^{-3})	Approximate Optical Magnitude at $z = \frac{1}{2}$
+ 23.8	0.2	15
23.4	3	16
23.0	13	17
22.6	57	18
22.2	103	19
21.8	510	20

The distribution of the optical magnitudes of identified 3CR quasi-stellar sources is quite different from that of QSOs; the number of 3CR QSS increases by a factor of only 2 or so per magnitude, rather than the factor of 6 seen for QSOs. This does *not* mean that 3CR QSS can have a uniform distribution in space. In this case the number-gradient is affected by the radio selection, which requires that the object must be stronger than 9 flux units at 178 Mhz. This case of simultaneous optical and radio selection has been discussed by SCHMIDT (1968).

We noted in Table 1 that the redshift distribution of 18th magnitude QSOs and 3CR QSS seems to be essentially identical. This is not expected if the optical luminosity function of QSOs and QSS is the same and if the radio luminosity function is independent of the optical luminosity. The requirement of radio observability above 9 flux units introduces discrimination against sources of large redshift, the more so the larger the redshift. Hence, we would expect the 3CR source redshift distribution to be concentrated to the lower redshifts, compared to that of the QSOs.

Since the observations do not show this effect, there must be an increase of the mean radio luminosity either with redshift or with optical luminosity. If the mean radio luminosity increased with redshift, this would counterbalance exactly the radio discrimination against large redshift discussed above, and hence the distribution of QSS redshifts would be the same as that for QSOs. This would be so at all optical magnitudes and hence Table 2 would represent the distribution of 3CR QSS, except for a scale factor. This is in conflict with the large difference between the distribution of optical magnitudes of 3CR QSS and that of QSOs discussed above.

Instead, we assume that the radio luminosity function is displaced toward higher radio luminosity as a function of the optical luminosity. Specifically, we propose that the dependence is such that the relevant distribution function is that of the *ratio* of radio to optical luminosity. Since this ratio is independent of the distance of the source, the distribution function may be written as that of the ratio of the measured radio flux density to the optical flux density. This ratio is constant for radio sources of given flux density in a column of constant optical magnitude in Table 2. Hence the redshift distribution at given optical magnitude is independent of radio properties in this case.

The distribution function of the ratio of radio and optical luminosity may be determined from the optical magnitude distribution of QSOs and that of 3CR QSS. It shows an increase by a factor of about 3 per magnitude toward lower radio luminosity. It may be shown that the approximately exponential shape of this function essentially explains why identified QSS in the 3CR catalogue show little systematic change of redshift with radio flux density. With both optical and radio luminosity functions given, it is possible to determine the number-flux density relation for QSOs. For S (178 Mhz) $>$ 10 flux units the logarithmic slope is -1.8, as observed for extragalactic radio sources. For smaller flux densities the slope becomes smaller, roughly simulating the N (S) relation for extragalactic sources. The QSS according to this model constitute about 20 to 30 per cent of the extragalactic radio sources, the remainder presumably being radio galaxies. If this is correct, the radio galaxies also have a steep N (S) relation.

The scarcity of observed redshifts larger than 2.5 suggests that the density law $(1+z)^6$ determined above may not be applicable above that redshift. Since our 3CR QSS and QSO samples do not contain any sources that are sufficiently luminous to have a redshift larger than 2.5 for a magnitude less than 18½, we can only get evidence on the density beyond a redshift of 2.5 from fainter objects. Table 2 shows that 24 per cent of the QSOs of magntiude 19 would have redshifts larger than 2.5 if the $(1+z)^6$ law applies. QSOs supply insufficient evidence, since only seven fainter than 18½ mag. have redshifts. However, relying on our above discussion which suggested that the redshift distribution at a given optical magnitude is independent of radio properties, we can use redshift information from 13 QSS fainter than 18½ mag. None of the 20 objects has a redshift larger than 2.5. Hence the $(1+z)^6$ law is a considerable overestimate at z larger than 2.5. A single redshift larger than 2.5 is known (LYNDS and WILLS) for a source of optical magnitude 18, so the density cannot drop to zero. All we can say at present is that the density beyond a redsbift of 2 or 2.5 shows little or no increase, and may actually decrease.

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SPACE DENSITIES AND TIME SCALES OF SEYFERT GALAXIES, RADIO GALAXIES AND QUASI-STELLAR OBJECTS

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Space densities and time scales of classes of objects that are part of an evolutionary sequence are proportionally related. We list in Table 1 local space densities of several kinds of objects of interest.

Around one per cent of the spiral galaxies are Seyfert galaxies. Assuming an age of 10^{10} years for the spiral galaxies, they spend 10^8 years in the Seyfert stage. This derivation cannot differentiate between one or more periods of Seyfert activity; only the total time spent in the Seyfert stage is obtained.

Essentially all radio galaxies are giant elliptical galaxies. If we assign the latter an age of 10^{10} years, then the life times of the radio galaxies are: 10^4 years for radio power 10^{45} ergs/sec,

$10^{5\frac{1}{2}}$ 10^{44} ,
10^7 10^{43} ,
$10^{8\frac{1}{2}}$ 10^{42} .

TABLE 1

Galaxies	$M_B < -21$	10^{44} ergs/sec optical	$10^{-3\frac{1}{2}}$ Mpc^{-3}
	< -20		$10^{-2\frac{1}{2}}$ Mpc^{-3}
	< -19		$10^{-1\frac{1}{2}}$ Mpc^{-3}
	< -18	10^{43} ergs/sec optical	10^{-1} Mpc^{-3}

Irr and E galaxies each constitute about 10%, the remainder are spirals.

Seyfert Galaxies		$10^{-3\frac{1}{2}}$ Mpc^{-3}
Rich Clusters of Galaxies		10^{-5} Mpc^{-3}
Giant Elliptical Galaxies		10^{-4} Mpc^{-3}
Radio Galaxies	10^{45} ergs/sec radio	10^{-10} Mpc^{-3}
	10^{44}	$10^{-8\frac{1}{2}}$ Mpc^{-3}
	10^{43}	10^{-7} Mpc^{-3}
	10^{42}	$10^{-5\frac{1}{2}}$ Mpc^{-3}
Quasi-Stellar Objects	10^{46} ergs/sec optical	$10^{-8\frac{1}{2}}$ Mpc^{-3}
	10^{45}	10^{-7} Mpc^{-3}
	10^{44}	10^{-6} Mpc^{-3}

Most QSOs have $L_{\text{radio}} \simeq 0.001\ L_{\text{optical}}$ or less,
10 per cent have $L_{\text{rad}} = 0.01\ L_{\text{opt}}$ and
1 per cent have $L_{\text{rad}} = 0.1\ L_{\text{opt}}$.

The radio luminosity function is:

10^{45} ergs/sec radio	$10^{-10\frac{1}{2}}$ Mpc^{-3}
10^{44}	10^{-9} Mpc^{-3}
10^{43}	10^{-8} Mpc^{-3}
10^{42}	10^{-7} Mpc^{-3}

The evolutionary relation of quasi-stellar objects with other objects is speculative. If we assume a link with radio galaxies, then we get life times of

$10^{5\frac{1}{2}}$ years for optical power 10^{46} ergs/sec,
10^{7} 10^{45} ,
10^{8} 10^{44} ,

These life times are sufficiently small to allow a thousandfold decrease in the number of quasi-stellar objects over the last 8 billion years.

If the number of radio galaxies has undergone a similar secular decrease, then a peculiar problem arises since there are only 20 times as many parent objects (elliptical galaxies) at the present time as there are radio galaxies. This suggests either a life time of giant elliptical galaxies much less than 10^{10} years, or a luminosity-dependent density evolution of the radio galaxies.

QUASAR STATISTICS
FOR LEMAITRE COSMOLOGIES

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I want to outline what happens to an analysis of quasar statistics if one uses a cosmological model of the LEMAÎTRE kind rather than a FRIEDMANN model. Let me say straight away that the LEMAÎTRE models of interest of interest for quasars lead to a deceleration parameter $q_0 \sim - 1$, which is incompatible with optical data on bright galaxies, but let me discuss such models nevertheless. These models have a "coasting period", an epoch where there is little expansion, and depend on two disposable parameters. One of these parameters (related to density) determines the red-shift from the coasting-period to the present epoch; the other parameter λ, proportional to the cosmological constant, determines the length of the coasting period. In Fig. 1 a function F is plotted schematically which is essentially the product of apparent brightness of a standard source times the apparent space-density of sources (assuming the absence of any evolutionary effects or of selection effects). The curve labelled $\lambda = 1.02$ refers to a LEMAÎTRE model, the one labelled $\lambda = 0$ to the "standard model" with zero cosmological constant and $q_0 = + 1$. Note two features of the LEMAÎTRE curve: it has a "broad hump" in the vicinity

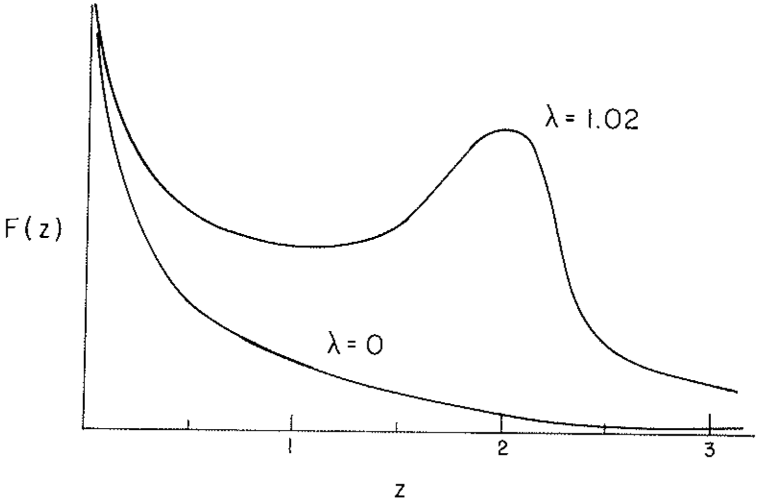

FIG. 1

of $z \sim 2$ and F decreases less rapidly with z than for the standard model also at smaller and larger values of z.

Fig. 2, taken from some unpublished work by V. PETROSIAN, corrects the function F for selection effects, i.e. multiplies it by the fraction φ of quasistellar radiosources of a given redshift which should have been observed. PETROSIAN calculated φ, separately for each cosmological model, by first deriving a crude luminosity function (from identified 3C-sources) and assuming *no* evolution. The solid curve is for a LEMAÎTRE model (without any further multiplying factor), the dashed curve is for the "standard model" but multiplied by an additional factor of $(1 + z)^6$. To fit the observations also at intermediate redshifts ($z \sim 1$) PETROSIAN finds that for the LEMAÎTRE models he needs a multiplying factor of about $(1 + z)^{1.5}$.

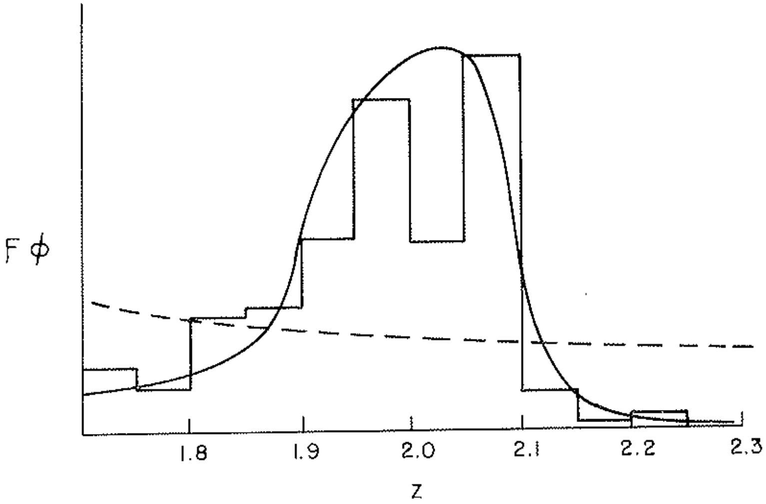

FIG. 2

DISCUSSION

Chairman: J.H. OORT

HOYLE

Can you say what change there is in the density function if q_0 is changed from $+1$ to zero?

SCHMIDT

The density law would become around $(1 + z)^7$, i.e. an exponent about 1 larger than for $q_0 = 1$.

SCHMIDT

I am showing here a slide of the redshift distributions of the two samples I reported on, in the form of histograms in blocks of 0.1 in z. I want to emphasize that there seems to be no concentration near a redshift around 2.0 at all.

So you may then ask why is there in the published redshifts a concentration of redshifts around 2. This is entirely due, I believe, to the ease of observation of redshifts around that value, because Lyman α becomes easily accessible at 3600Å, while C IV is always a strong line. These redshifts are immediately noticed by the observers even in the dark room. You see immediately that you have a redshift of 1.9 or 2.1, but the redshift of .8 or 1.3 requires a lot of work to detect two lines. This is specifically and exactly why I undertook this study to try and get for a number of QSOs complete redshift determinations. This is very time-consuming. but I think that it pays off in showing that selection effects in favour of observed redshifts around 2 have been, I think, misleading us badly.

The other point I wanted to make is that with the information I could extract from PETROSIAN's published paper of one or two years ago, about his LEMAÎTRE model, I did the same job, as reported above in the redshift magnitude table. Putting in no evolution, all I could obtain for the ratio of 17 to 18 magnitude QSOs was a factor of four rather than the observed factor of six. It looks to me as if, with the observed rather wide absolute luminosity distributed, one cannot get this factor of 6 that is required.

SALPETER

Your last remark about not obtaining the full factor of 6 without evolution even for a Lemaître model, is probably compatible with my last remarks: if you want to fit the data at all z (not just get a "hump" near $z \sim 2$) you need an evolution factor of about $(1 + z)^{1.5}$ on a Lemaître model.

E. M. BURBIDGE

I would just say that I do not agree that it is so much harder to get a redshift of .8 to 1.3, e.g. all image-tube spectra show the long wavelength region and you generally can find lines, even if you do not see them right away in the dark-room. Mg II is easily accessible up to $z = 1.4$, and C IV 1549 appears at about $z = 1.2$.

SCHMIDT

I am sorry to disagree, it is my own working experience that I have many that I have not published because I did not do enough work on the thing to get a second line, which is required in order to get the redshift. I am sure this really explains the difference between these complete samples and the overall, but not complete, list of published redshifts.

G. R. BURBIDGE

I am not going to argue with these two authorities. I want to raise another question entirely, namely to Dr. SALPETER. I am under the impression that even the discovery of one redshift as large as 2.88 makes trouble for the Lemaître model. Is this correct?

SALPETER

I do not know quantitatively how it will be. I remember that the apparent brightness for redshifts well beyond the "hump" comes out rather similar to what it does on the standard model, but the apparent density is higher for the Lemaître model than the standard model (although not by as large a factor as in the "hump").

The Lemaître models predict a sharp decrease of observed numbers beyond redshifts of $3 \sim 2$ or 2.5, but, if one assumes the *same* (or no) evolution effects on the Lemaître and the "standard" Friedmann model, the Lemaître model predicts numbers about ten times larger than the standard model. I'm not sure what fraction of one source for $z > 2.5$ the Lemaître model would predict.

OORT

I wonder whether one should worry so much about getting a model to explain things without evolution. For it is natural that there should be evolution in radio galaxies, and in galaxies in general. In an expanding universe without continuous creation there will necessarily be evolution effects; these will always be in the direction of increasing the population density in the past, and such increases as Dr. SCHMIDT has been pointing out are not at all unreasonable. They are just of the order of what one would expect if one considers the probable process of galaxy formation in an expanding universe.

To explain the maximum density of radio sources around $z = 2$ there is no need to introduce a cosmological constant. I believe that such a maximum follows naturally from the process of galaxy formation.

SANDAGE

May I make a point to what you just said? At a redshift of 2.3 on a model with $q_0 = 1$ you are looking back only 85 percent of the way in time. Here the radius via the redshift factor is only

3.3, which then means that the density increase at that time is less than a factor of 100. This is a somewhat smaller density factor than people talked about, at least in the past, for the density at which galaxies formed.

OORT

I have puzzled about this a long time. But now it puzzles me no longer. In the process of galaxy formation one should distinguish two stages. The first stage is when the protogalaxy separates itself from the surrounding universe. The formation of the stellar system itself can only take place when the protogalaxy which is expanding at first re-collapses again. For a galaxy with an amount of angular momentum such as contained in a large spiral the collapse period will be of the order of 10^9 years. This means that the actual formation of galaxies must have taken place rather late in the evolution of the universe, presumably around $z = 3$, or later. As there cannot be radio-galaxies before there are galaxies, it is to be expected a priori that there will be a strong increase in the population density of radio-galaxies, even at relatively small values of z. In particular, if one believes that a galaxy is likely to be a specially bright radio source at or near the time of its formation.

SANDAGE

May I ask Maarten and Margaret how many unpublished redshifts there are with only one line in their plate files?

E. M. BURBIDGE

Well, I published my one-line objects, giving the strong probability that the one line is Mg II, which is what LYNDS thought was the most likely case. I always do publish them, and since I recently prepared a list of redshifts for publication, I haven't any unpublished ones left.

SANDAGE

Well in Maarten's case how many unpublished out of the total number that he has?

SCHMIDT

I think probably I have one and a half dozen or so.

MORGAN

My question was identical with Dr. SANDAGE's later question. It is important to include statistics on those together with the ones that are published.

HOYLE

I think the question is what fractions of quasi-stellars are one-line or no-line objects, irrespective of whether they are published or not.

E. M. BURBIDGE

Well mine may be 10 percent of the total for the one line objects and probable but not certain redshifts, but there are also those which you usually assume are some kind of white dwarf, I mean you have no means of identification, if it is a lineless object, but if there is one line, then I assume it is correctly identified as a quasi-stellar object.

SCHMIDT

But I think one has to include the non-line cases too. Among the cases that I reported were several that initially seemed to give no lines at all and only hard work finally resulted in the certain detection of two lines.

MORRISON

I'd just like to ask judgement from your statistically small but complete study: would you say you can give limits to the cut-off — clearly it is not known to be a sharp cut-off? If it falls by a factor of five, I think, you'd be content; that is, compared with $(1 + z)^6$. Can you give me some correction factor? I would judge between 5 and 10 would be adequate to fit the data.

SCHMIDT

Yes, indeed. If you extrapolate the $(1 + z)^6$ law to a redshift of 3 you overestimate the number by a factor of the order of 5.

E. M. BURBIDGE

It just occurred to me, on this question of the proportion of one-line objects, I was counting up my *total* bag of one-line objects and I think this is what we have to compare with the total list of 200 redshifts that we now have. The figures I quoted refer to my total number of determinations, which are, I forget the exact figure, something like 80 or so.

III.

THEORY

THEORETICAL CONSIDERATIONS REGARDING NON-THERMAL EMISSION AND EJECTION OF MATTER FROM GALACTIC NUCLEI

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In the first part of this meeting we have heard an extensive description of the various forms of activity in galactic nuclei. In this paper I shall attempt to discuss some of this material and relate it to the requirements for a successful theory which can account for what we observe. Much of what I shall discuss has been published elsewhere in much greater detail (BURBIDGE 1970a).

I. STRONG SYNCHROTRON SOURCES

Radio Sources

The energetics of the powerful radio sources is a subject which has been under study for about fifteen years, and the deductions that can be drawn from the observations are well known. They are that

i) Very large energies in the form of relativistic particles and magnetic flux must be present in the extended radio sources associated with galaxies and QSOs. The *minimum* total energies in the most powerful radio sources are about 10^{61} ergs. The minimum energy condition is reached when $E_p = 4/3\ E_m$. For the extended radio sources this condition requires average magnetic fields of the order 3×10^{-5} gauss. Typical values have been given by BURBIDGE and BURBIDGE (1965).

It is important to stress the dependence of these minimum energy calculations on the size of the source. If the characteristic dimension is R, we find that

$$E_{\min} \propto R^{9/7}$$

$$B_{eq} \propto R^{-6/7}$$

$$t_{1/2} \propto R^{9/7}$$

where $E_{\min}$ is the minimum total energy required to explain a source with luminosity L, B_{eq} is the magnetic field strength corresponding to this minimum energy condition, and $t_{1/2}$ is an average half life of the source determined from the radiating electrons. It has frequently been pointed out that there is no reason to believe that rough equipartition has been achieved, and for this reason alone the total energies may be greater than the values calculated on this simple assunmption. A detailed discussion of the efficiency of the generating processes was given at the Solvay Conference in 1964 (BURBIDGE and BURBIDGE 1965).

There are now other important aspects of the radio source problems which are beginning to emerge. The first is connected with the fact that, as more high resolution studies have been carried out, it has become clear that often very small nuclear components are present in strong radio sources. Also, studies of a considerable number of weak radio galaxies — normal spirals and ellipticals — have now shown that most of the radio flux is coming from regions whose angular extents are frequently smaller than the optical galaxies, and often a very small nuclear component is present. At the same time, it also appears that halos around weak radio galaxies are rarely found. Thus, the evidence points even more strongly toward the view that the radio phenomenon is always associated with a very small nuclear region. In some radio sources the nuclear components are very active, since we see rapid time variations at high frequencies. This activity has been explained in terms of the ejection of bursts of relativistic particles. Since often only a fraction of the total power of the source is being emitted by the nuclear component, and also because it is very small, the energy content in particles and field, as calculated by the usual methods, may be very much less than the large values obtained for the extended components. For the nuclear sources it is frequently found that the characteristic lifetimes of the particles are very short, because the magnetic field strengths are likely to be very strong in the small sources, and for radiation at a given frequency, $t_{1/2} \propto B_{\perp}^{-3/2}$.

This shows clearly that the activity which gives rise to radio emission extends over a considerable period in the life of a galaxy, and indeed it may be that the nucleus is active over a large part of the life of a galaxy.

The methods of estimating lifetimes associated with the activity are:

1) To calculate the radiation lifetimes associated with electrons emitting at a range of critical frequency. This is the method just described, and it depends sensitively on the magnetic field strength which is assumed.

2) To obtain a time by dividing the size of a source by a characteristic velocity of ejection of relativistic plasma. In this way we can obtain only a lower limit ($t = R/c$) to the time over which activity has taken place.

3) To obtain a lifetime by calculating the frequency f, of radio emitters of a certain class of objects which have the same optical properties. If all of the objects of the same optical class have an equal probability of becoming active at the level observed over their total life, assumed to be 10^{10} years, then the harmonic mean lifetime in the active phase is $10^{10} f$ years. This method breaks down if the activity changes the optical appearance of the galaxy.

From (1) we obtain times which can be as short as about 1 year for very small nuclear sources and as long as 10^8 years for extended sources. From (2) we find, for extended sources, time scales for activity $\geqslant 10^6$ years. From (3), from the strong radio emitters, we obtain time scales for activity in the range $10^7 - 10^9$ years. On the other hand, a very large proportion of spiral galaxies appear to be weak radio emitters, while radio emission is less common among normal elliptical galaxies. But the frequency of weak radio sources suggests that activity at this level ($10^{38} - 10^{41}$ erg/sec) takes place over the major fraction of the lifetime of a galaxy ($\sim 10^{10}$ years).

A second aspect of the radio source problem is to understand the distribution of radio emission. In the case of the majority of galaxies, the weak sources, the distribution can be understood largely in terms of jets of relativistic particles ejected from the nuclei and streaming out of the galaxy in comparativcly short times $\sim 10^5 - 10^6$ years. Supernova remnants may make some contribution to the particle supply, but the concentration of the sources in the nuclear region leads one to suspect that they only make a minor contribution.

In the case of the strong sources, it is necessary to explain how particles can be generated in the nuclei and give rise to double sources which are often widely spaced and far from the centers. It is clear that the relativistic plasma does not move freely outward, but is controlled either by inertial forces or by a surrounding medium. At the same time it cannot be argued that a relativistic plasma cloud has simply expanded adiabatically from the nucleus, because in this case the energy requirements would be totally unreasonable. A number of proposals have been made in which it is suggested that the relativistic electrons and nucleons which are generated in the nucleus are confined by an intergalactic medium to the elongated double structures which are often seen. It is argued that confinement is achieved either by an intergalactic magnetic field, or by the ram pressure of intergalactic gas. The difficulties with these models are, in part, due to the fact that there is no independent and unambiguous evidence for an intergalactic gas at all, and certainly not one with the density or magnetic field required. The values are unreasonably large, $\rho_{ig} = 10^{-27}$ gm/cm^3 in the model of MILLS and STURROCK to explain the structure of Cygnus A by the ram pressure, and intergalactic magnetic field strengths $\sim 10^{-4} - 10^{-5}$ gauss in a realistic model of the Gold type. Nor does it appear that components with linear size, r, very small compared with the distance, R, from the nucleus ($r/R \simeq 10^{-2} - 10^{-3}$) can be explained by these schemes.

The alternative proposal which was made originally because of the difficulties with GOLD's model, and because very compact radio components ($< 0.''1$) had been found in large sources far from the centers from which they were ejected, is that the confinement is gravitational in origin, i.e., coherent objects are ejected and these are the secondary sources of particles. If this type of model is correct the double nature of many radio sources is probably due to the breakup of a massive object and the ejection of fragments. The lifetime of the source is determined first by the period in which ejection of fragments takes place, and the spectrum of ejection velocities, and secondarily, by the period over which these fragments eject particles. It is no longer a simple matter of estimating the lifetime from a size divided by some typical expansion velocity.

Optical Sources

We now know that the active nuclei of galaxies often emit optical synchrotron radiation. The evidence that a non-thermal optical component is present comes from evidence of optical variability, polarization measurements, and the spectral energy distribution. Since, in the raw observations, we are observing the radiation from three components, stars, hot gas, and non-thermal processes all together, the most certain observations of an optical non-thermal component have been obtained from nuclei where it clearly dominates in some part of the optical spectrum. This is the case for Seyfert nuclei, for N-galaxies, and QSOs. For the majority of the N-galaxies, and for QSOs, we have no evidence that there is any stellar component. The non-thermal component appears to originate in a very small region with a size no greater than a light year or so, with a more extended region around it containing gas which has been excited by the central source. The only extended optical synchroton sources known are the jets in M 87 and possibly 3C 273; in M 87 several small bright condensations extending up to distances ∾ 2000 pc from the nucleus are seen. As we have heard, there is now thought to be some question as to whether the continuous optical emission in the outer parts of M 82 is due to the synchrotron process. The energetics of the optical synchrotron sources in the nuclei of galaxies have been investigated by MARIE-HELENE DEMOULIN and myself (1968). Because the sources are so small, the equipartition calculations lead to the conclusion that the total energy in particles and field is rather small, with magnetic fields which are much stronger than those required to explain the extended radio sources. However, the high density of radiation which must be present in such sources means that we have to consider the possible importance of the Compton effect. If the Compton effect is not to be of importance, the magnetic field energy density in the region where the electrons are radiating must dominate over the local radiation density. This sets a lower limit to the permissible magnetic field B_c, which may sometimes be greater than the minimum magnetic field B_{eq} obtained in the usual synchrotron calculations when the equipartition condition is assumed. Results for some galactic nuclei taken from the calculation of DEMOULIN and BURBIDGE are shown in Table 1. If it is found that this situation is reached, there are several possible models that can be considered which overcome this apparent difficulty.

a) It can be argued that the synchrotron radiation is being emitted by a flux of protons, rather than an electron flux. At present we cannot disprove this hypothesis. However, if protons are involved, the source contains about 10^4 times as much energy in particles and magnetic fields than is the case if it is an electron synchrotron source. The magnetic fields in this case must be exceedingly strong.

b) It may be that the optical radiation is generated by Compton scattering involving lower energy (infrared and microwave) photons. As will be discussed later, very large fluxes of radiation of lower frequencies are often emitted by galactic nuclei. However, again it appears that generation of optical flux by this process is likely to be highly inefficient.

c) It can be argued that the magnetic fields are much stronger than the equipartition values. In this case the synchrotron process will dominate, but the electrons cannot all be generated by a single central source. Instead it is necessary that the source be made up of a number of discrete objects, each of which is able to generate particles which then radiate in the magnetosphere of that object.

Infrared Sources

It is now known that many galactic nuclei are very powerful sources of infrared radiation between 1μ and 20μ and there

TABLE 1 — *Typical energetic properties of optical synchrotron sources in the nuclei of galaxies and QSOs.*

Object	B_c (gauss)(¹)	Total Energy if $B = B_c$(²) (ergs)	B_{eq} (gauss) (³)	Total Energy if $B = B_{eq}$ (ergs)	Typical Electron Energy (GeV)	Distance Traveled by Electron (cm)
NGC 1068	5.4(−4)	1.4(54) 6.1(55)	5.0(−4)	5.0(53) 1.9(55) 4.6(54)	270($B = B_{eq}$)	9(19)
NGC 4151 (Seyfert)	2.6(−1)	2.8(49) 1.7(50)	1.1(−1)	1.6(49) 5.9(50) 1.4(50)	12($B = B_c$)	9(15)
3C 120 (Seyfert)	3.2(−1)	1.1(51) 2.7(51)	8.8(−2)	3.0(50) 1.1(52) 2.7(51)	11($B = B_c$)	7(15)
3C 390.3 (N)	1.6(−1)	1.0(52) 2.3(52)	4.3(−2)	2.5(51) 9.3(52) 2.2(52)	15($B = B_c$)	2(16)
3C 109 (N)	4.6(−2)	5.2(51) 2.6(52)	1.7(−2)	2.5(51) 9.3(52) 2.2(52)	30($B = B_c$)	1(17)
QSO (cosmological)	1.6(+1)	4.4(52) 4.5(52)	1.2(0)	9.0(50) 3.5(52) 8.4(51)	1.5($B = B_c$)	2(13)
QSO (local)	8.0(−1)	1.1(50) 2.7(50)	2.2(−1)	3.0(49) 1.1(51) 2.7(50)	7($B = B_c$)	2(15)
QSO (very local)	1.6(−2)	4.9(47) 2.3(49)	2.4(−2)	3.4(47) 1.3(49) 3.1(48)	40($B = B_{ec}$)	3(17)

Numbers in parentheses are powers of 10 by which value are to be multipled.

(¹) Minimum magnetic field if Compton effect is unimportant.

(²) Upper line, $\alpha = 1$; lower line, $\alpha = 100$.

(³) Equipartition magnetic field.

A detailed discussion is given by DEMOULIN and BURBIDGE (1968). This table is an adaptation of Table 2 in that paper.

is preliminary evidence that the spectra continue to rise steeply beyond 20μ and turn over somewhere in the range 100μ – 1000μ. Low has described the observations earlier in this meeting. The infrared luminosities detected so far range from about 10^{42} erg/sec in the case of our own galactic nucleus to values of about 10^{46} erg/sec for some Seyfert nuclei and an even larger value for 3C 273, if it lies at a cosmological distance. Thus, while only a small number of galaxies have so far been observed, it is clear that the flux emitted in the far infrared is considerably greater than that emitted by non-thermal processes in any other part of the spectrum so far observed in many of the sources studied.

There are several possible ways of explaining this flux. Low and his colleagues have considered this problem, and STEIN and I have also studied it in some detail. It is likely that the radiation has a synchrotron origin. However, there are then two possibilities. It may be incoherent synchrotron radiation directly emitted at infrared frequencies. If this is the case, the energy spectrum of the electrons must be very steep $\{N(E) \propto E^{-5}\}$. Rather strong magnetic fields are required, and to avoid the Compton effect mentioned in the discussion of the optical spectra, we must again consider a model containing a number of discrete objects with strong magnetic fields.

It has also been proposed that perhaps the strong infrared emission is thermal radiation of dust clouds which are heated by a central source which is emitting ultraviolet radiation, presumably of synchrotron origin, at power levels up to $10^{46} - 10^{47}$ erg/sec. The model to explain this (unseen) ultraviolet source must then be similar to that discussed for the optical synchrotron emission. The attractions of this type of model stem from the fact that we know that dust is present in the central parts of galaxies, and it has been proposed that it may be formed in such regions as a result of nuclear activity, and also because it could naturally explain the form of the energy curve in the infrared — a composite of black-body curves. However, it is easily shown that, to have temperatures in the correct range to explain the observed flux, the dust clouds must have sizes of from 10 – 100 pc. But flux variations on a time scale of years, and perhaps much less, have been seen in at least one infrared source, the nucleus of NGC 4151, and these set upper limits to the infrared source, unless we invoke highly relativistic motions, of light years or less. This is therefore a very powerful argument against the dust hypothesis.

Returning to the synchrotron explanation, the work by Low and his colleagues and by NEUGEBAUER and BECKLIN has shown that much can be learned from studies of the infrared nucleus of our Galaxy. Here the shape of the spectrum has been rather closely defined, and arguments given elsewhere (LOW *et. al.* 1969; BURBIDGE and STEIN 1970) have shown that the shape of the spectrum and the peak at about 300μ, with a decline to the long wavelength side, can only be explained as due to synchrotron self-absorption, if the source is composite and is made up of a number of small discrete objects. This conclusion has been reached for the galactic center only and is arrived at because the size and shape of the spectrum have been fairly well determined. Thus, as far as present data are concerned, we do not have to invoke a multiple model for other infrared sources. However, the arguments arising from the Compton effect discussed previously make such a model rather attractive.

At this meeting LOW has expressed the view that the steepness of the spectrum of the source at the galactic center, at wavelengths longward of the peak, makes it improbable that synchrotron self-absorption or any other absorption process is responsible. Instead, he has argued that the discrete sources are radiating in a coherent fashion so that the wavelength band over which the infrared energy is emitted is limited by the radiating process.

The picture which appears most attractive is that the radio, optical, and infrared emissions are all due to the synchrotron process. The most powerful sources are exceedingly small with total sizes of no more than 10^{15} - 10^{18} cm. They, in turn, may be made up of even smaller objects, and a possible prototype is the pulsar. These objects are able to transform rotational energy into relativistic particles with high efficiency, and the bulk of the energy is radiated in the vicinity of the objects. Surrounding these are more extended regions of radio emission. In my view the more extended radio sources are likely to be due to the ejection of collections of these coherent objects. The structure of objects such as the jet in M 87, and the radio source 3C 274 which may be connected with it (BURBIDGE 1970b; BURBIDGE and BURBIDGE 1969), 3C 33 (MOFFET 1966), and the sources associated with NGC 1275 (RYLE and WINDRAM 1968) are very suggestive of this.

Background Radiations

There are four separate components of background radiation that have been discovered. They are starlight, non-thermal radio background, x-ray and γ-ray background, and the microwave background. At least two of these, and perhaps three, would not be present if there were no activity in galactic nuclei.

The radio background is generally acknowledged to be due to the integrated effect of discrete non-thermal radio sources, and as we have just discussed, this can be traced back largely to the nuclei of galaxies.

One of the major new discoveries has been that of the x-ray and γ-ray background which is found to be fairly isotropic and must have an extragalactic origin. Some part of the very soft ($\gtrsim$ 0.5 kev) x-rays may be thermal bremsstrahlung from a hot intergalactic or intercluster plasma. We are rather unsure about this at present, but the remainder of the flux is either a composite of many different processes which give rise to x-rays in external galaxies, or else it is radiation generated between the galaxies by Compton collisions or bremsstrahlung involving high energy particles.

The only powerful discrete extragalactic x-ray sources so far identified are the radio galaxies M 87 and NGC 5128. In the case of M 87 it is likely that the x-ray sources are associated with the jet and the nucleus. While we cannot observe the nucleus of NGC 5128 optically, I suspect that the x-ray source will turn out to be a comparatively small compact region associated with the nucleus. If the x-ray and γ-ray background is made up of discrete sources, it is likely that powerful galaxies of this type, and perhaps a new class of x-ray galaxies, are responsible. In any case, it appears likely that much of this radiation is likely to have been generated directly in galactic nuclei.

If, on the other hand, the background arises in the intergalactic medium, in all theories it is supposed that the high-energy particles have their origins in radio galaxies and the like, so that, in these theories also, the background is due ultimately to activity in galactic nuclei.

The most important component of background radiation is the flux of microwave radiation which has an energy density at least 100 times that of starlight and 10^4 to 10^5 times the energy density in the x-ray or radio background. Following the prediction that such radiation would be present as a result of a primeval fireball, the discovery of flux in the range 20 cm - 1 cm, which fits very well the Rayleigh-Jeans part of the black-body curve at a temperature close to 3°K, led to a very strong belief that this radiation had been discovered. However, the critical measurements close to the peak of this black-body curve — between about 1 mm and 0.1 mm — have led to conflicting results which do not confirm the black-body form. The indirect measurement of the temperature of the background radiation in which the interstellar molecules CN, CH, CH^+ are bathed gives upper limits or results consistent with a temperature of 2.7°K. However, there is some preliminary evidence suggesting that higher temperatures are indicated for formaldehyde and carbon monoxide, though these temperatures ($T \sim 6\text{-}7^\circ K$) could result from the fact that some of the regions studied are close to discrete galactic sources of microwave radiation. The direct measurements of the microwave flux in this critical wavelength region made above the earth's atmosphere, first by rockets, and more recently by a balloon flight, indicate that the flux is much larger than that expected from a 2.7°K black-body radiation field. If the radiation is of black-body form, the temperature is 7° or 8°K, so that the energy density of the radiation is some 30 times that from a 2.7°K black body. The possible ways of resolving the conflict are:

(*a*) to argue that the measurements made from above the atmosphere are wrong, and that data from some interstellar molecules which give high temperatures are due to their proximity to local galactic sources. In this case the black-body form of the curve can still be maintained.

(*b*) to argue that the rocket and balloon observations are correct but that the radiation is concentrated in one or two sharp lines, so that we are seeing a black-body curve with some line radiations superposed on it.

(*c*) to accept that the rocket and balloon observations are correct and that they indicate broad band intensities much higher than those expected from a 2.7°K black body, and that the limits obtained from CN, CH, and CH^+ are, in some way, not meaningful.

It is not possible at present to determine which is the most likely possibility. However, if either (*b*) or (*c*) is correct, it appears likely that some part, if not all, of the background radiation is due to extra-galactic discrete sources and not to a primeval fireball. If this is correct, the small-scale isotropy of the radiation requires that there be a large population of sources, equal to or greater than the space density of bright galaxies. Since these sources must show peak intensity in the microwave and infrared parts of the spectrum, they are likely to be nonthermal sources rather similar, but not identical, to the infrared nuclei discussed earlier. Since they must be very plentiful, they will not be very luminous. Objects like BL Lacerta, if it is only at a distance of a few hundred kiloparsecs, are possible prototypes of the sources required. There is, therefore, a finite possibility that the microwave background, or part of it, arises, not from a big bang, but in the nuclei of galaxies.

II. MASS EJECTION FROM NUCLEI

A considerable body of evidence is now available which shows that galactic nuclei eject large amounts of matter. The evidence comes from several directions.

Ejection of Neutral or Ionized Gas

Spectroscopic observations using radio and optical lines have shown that:

a) Much mass ($\gtrsim 10^7 M_\odot$) of neutral atomic hydrogen has been ejected from the nuclear region of our Galaxy (see the paper by J. H. Oort in this volume).

b) Optical studies of the ionized gas in the nuclear regions of nearby normal galaxies such as M 31, M 51, NGC 253, NGC 4939 show velocity fields indicating that large amounts of gas have non-circular motions with velocity fields $\sim$ 100 km/sec or more. In all cases the most reasonable interpretation is that gas is being ejected from the nucleus, and in some cases, e.g. NGC 4939, the velocity (700 km/sec) is greater than the escape velocity from the center.

c) Optical studies of Seyfert nuclei give direct evidence that gas is being ejected at a high rate. If the broad wings of the hydrogen lines are due to Doppler motions and not due to electron scattering, the random motions in the nuclear regions are $\sim$ 3000 km/sec, far in excess of the escape velocities. The direct evidence of the outward motions from the narrow absorption lines in the spectrum of NGC 4151 suggests that very large amounts of matter are flowing out at velocities of $\sim$ 500 km/sec.

d) In some very active galaxies evidence has been obtained which shows that large masses of gas have been ejected and are found at great distances from their place of origin. In the case of M 82, it was shown some years ago that mass of the order of 10^6 $M_\odot$ is moving out below and above the plane of the galaxy as a result of an outburst that occurred about 2×10^6 years ago. In the case of NGC 1275, about 10^8 $M_\odot$ of gas moving from the center at velocities of at least 3000 km/sec is seen at distances up to 30 kpc from the nuclear region.

e) There has been considerable discussion about the nature of the absorption lines found in the spectra of QSOs. It appears that in most if not all cases the absorbing gas is associated with the QSOs and not with any intervening medium. Since in many cases $z_{em} > z_{abs}$ this interpretation means that, if $(z_{em} - z_{abs})$ is due to relative motion of absorbing gas with respect to the emission, large amounts of gas are being ejected from the nuclei of these objects. However, no detailed estimates of the mass loss rates have been made, and the problem is complicated by the fact that in a number of cases z_{abs} is found to be slightly greater than z_{em} (see the papers of REES and McCREA and the discussion following them).

Gravitational Radiation

This topic has not previously been discussed at this meeting. WEBER has recently announced that he has detected gravitational waves at a frequency of 1660 H*z*, and if the observations are correct, there is a strong presumption that they are radiated by the nucleus of our Galaxy. The rate at which he is detecting pulses suggests that, if this interpretation is correct, the nucleus is radiating mass at a rate $\sim 10 - 10^3$ $M_\odot$/year.

Objects of Galactic Mass Ejected from Nuclei

The evidence that gas is being ejected from galactic nuclei is incontrovertible. However, in addition to this, various kinds of evidence have been presented in recent years which suggest that perhaps massive coherent objects — galaxies, or objects which evolve into galaxies — are ejected from galactic nuclei. The evidence concerning this possibility, the existence of systems of positive energy and their possible interpretation, the results of ARP, and other material, have been described by E. M. BURBIDGE in paper No. II, 12. Thus it will not be discussed further here.

III. THEORETICAL CONSIDERATIONS

In Table 2 I have attempted to summarize all of the information we have on the mass-energy loss rates from the nuclei of galaxies and QSOs, using data summarized in the previous section, that given by previous speakers, and that given in my detailed compilation (BURBIDGE 1970a). For comparison I have included the corresponding energy loss rates for a normal range of galaxies as far as thermonuclear processes

TABLE 2 — *Estimates of the masses ejected or radiated from galactic nuclei.*

Source	Estimated Mass Loss Rate ($M_\odot$/year)	Estimated Time Scale (years)
Galactic Center		
Neutral Hydrogen	1 — 10	10^7
Gravitational Radiation	10 — 10^3 (?)	?
Non-Thermal Radiation	10^{-5}	?
M 31 (outflow of gas: optical data)	1	?
Seyfert Nuclei		
Non-Thermal Radiation	0.1	10^8
NGC 4151 (outflow of gas assumed steady)	10 — 1000	10^8
NGC 4151 (outflow of gas assumed sporadic)	0.6 — 0.006	10^8
NGC 1275 (outflow of gas)	1 — 10	10^8
M 82 (outflow of gas)	1	10^6
Strong Radio Galaxies		
Ejection of Relativistic Particles and Magnetic Energy, $\geq 10^{59}$ — 10^{61} ergs	$> 10^{-1}$ — 10	(10^6 — 10^9) (?)
QSOs		
Non-Thermal Optical Radiation	0.1 — 0.001	10^7 (?)
Non-Thermal Infrared Radiation	(10 — 0.1)(?)	10^7 (?)
Ejected Gas	?	?
Microwave Background ?		
(if assumed to come from discrete sources - normal galaxies; contribution per galaxy)	1 — 0.1	10^{10}
(if assumed to come from 10^5 times as many fainter objects - contribution per object)	10^{-5}	10^{10}
Cosmic Rays ?		
(assumed universal; contribution per normal galaxy)	1 — 0.1	10^{10}
Systems of Positive Energy	10^2	10^8
Young Galaxies (data of Sargent Paper No II. 3)	1 — 10	10^8
Energy in Starlight		
(per normal galaxy, assuming a range of luminosities)	10^{-4} — 10^{-2}	10^{10}
Hydrogen-Helium Conversion ($\backsim 10^{10}$ $M_\odot$ He made in a 10^{11} $M_\odot$ galaxy)	10^2 — 1	10^6 — 10^8

are concerned. Thus I include the normal losses based on their luminosities, and also the total energy radiated if, as seems likely, the bulk of the helium were synthesized from hydrogen in "little big bangs" at some stages during their evolution. Many of the numbers, both the rates of mass loss and the time scales, are very uncertain. In addition, some of the entries are only appropriate if one accepts a particular theory for the origin of the effect. This is particularly the case for the microwave background where the numbers quoted only apply if it arises from discrete sources and not a primeval fireball. Also, if the bulk of the cosmic rays do not have an extragalactic origin, the numbers given for cosmic rays are gross overestimates.

Despite all of the uncertainties the table shows that activity in galactic nuclei is much more important than had been thought until fairly recently.

The theoretical problem that we face is to understand how such very large masses and energies are emitted from the very small volumes that are indicated from direct measurement and from time variations in the emission. Sizes as small as 10^{17} - 10^{15} cms are indicated. To tackle the problem of understanding the evolution of a galactic nucleus to a state in which these processes can be understood, it is essential to understand the processes of galaxy formation, and this is where the trouble begins.

Most of the attempts at understanding the formation of galaxies have been made within the framework of an evolving universe, the idea being that the galaxies were largely or completely formed in the distant past when the universe was in a much more condensed state. Added impetus to these ideas has been given by the discovery of the microwave background radiation which many have taken as proof of the existence of a primeval fireball in a big bang universe. Investigations have been made in which the effect of the radiation on the condensation process is taken into account but the net result has been that no satisfactory theory giving results in accord with observations on the gross properties of galaxies, their masses, angular momenta, and their clustering tendencies has been found.

A basic problem recently stressed again by HARRISON is that in all of the theories it has been necessary to *postulate* the existence of initial density fluctuations which are large enough so that, in an expanding medium, condensation can occur. These fluctuations in an initial fluid have not been justified on the basis of known theory (though they might be a result of highly non-linear phenomena), and HARRISON has pointed out that they also have to be treated as cosmological in origin. HOYLE has stressed that in the big bang cosmologies it is necessary to suppose that initial conditions were responsible for the state of the universe as we now find it. This means that all the phenomena that we have described so far must be assumed to have been initiated by an early formation process, with evolution of the systems leading to conditions as they are seen at the present epoch.

Not all astronomers have taken this view. Forty years ago, baffled by the problem of the origin of spiral structure, JEANS stated "The type of conjecture which presents itself, somewhat insistently, is that the centers of the nebulae are of the nature of 'singular points' at which matter is poured into our universe from some other, and entirely extraneous dimension, so that, to a denizen of our universe, they appear as points at which matter is being continuously created".

This is essentially the view of AMBARTSUMIAN, who arrived at it following his early appreciation of the very active role that nuclei of galaxies appear to play.

In a steady-state universe the problem of galaxy formation is an exceedingly difficult one. Originally attempts were made to argue that galaxies must be formed out of diffuse clouds of newly created matter by the development of gravitational or thermal instabilities, perhaps in the wakes of other galaxies.

However, this point of view has now been abandoned. More recently it has been proposed by HOYLE and NARLIKAR and by McCREA that matter is created in the regions where the density is high, and that consequently creation and the formation of new galaxies must be closely associated with galactic nuclei. These ideas are again closely akin to the original suggestion of JEANS.

What do the observations described in the first part of this meeting have to say about these two very different approaches?

The observations indicate that activity in galactic nuclei is a widespread and probably quite a general phenomenon taking place in many, if not all, types of galaxy. There is a wide range of power levels, and the activity seen is always in the form of generation of non-thermal radiation, relativistic particles, hot gas, outward moving gas clouds, possibly gravitational waves and the ejection of dense objects with large masses. The activity is going on over the full range of times spanned by observations of nearby nuclei like that of our Galaxy, to the most distant radio galaxies. If the redshifts of the QSOs are cosmological, then the activity extends back to epochs many billions of years ago. In all cases what is observed is the outflow of mass and energy. Inflow, if it is taking place, is rarely, if ever, seen.

The theories are of two different types. In one case it is argued that following the condensation of galaxies from low-density matter, with inhomogenities of cosmological origin, the nuclei gradually evolve by shrinking to higher densities, until they reach such large densities that there is large and violent release of gravitational energy leading to outflow and ejection of matter and energy.

In the other picture it is argued, both in evolutionary cosmology and in steady-state cosmology, that galaxy formation and the activity in nuclei are a direct result of outflow from very dense initial states.

In neither approach has there yet been any satisfactory explanation of why the energy is released in the form in which we see it. There have been no convincing explanations why high-energy particles are generated in such profusion, why infrared and radio fluxes can be so large, how coherent objects can be ejected, if indeed they are, and so on. The question of whether this outflow of energy can be understood without invoking "new physics" is a matter of great debate at present.

In a sense the second approach appears to be the more natural one. The delayed core model is attractive since it may be able to explain the wide range of evolutionary times involved, continuous activity, the possible existence of young galaxies, systems of positive energy, etc.

Repeated activity, or even continuous activity, may be understood by repeated violent relaxation phenomena in the first scheme. The steady-state model has also the attraction that one would expect continuous activity, formation of new galaxies, etc. The objections to it are largely based on cosmological observational evidence which has not been discussed in detail here. I would only say here that, in my opinion, none of it is very secure.

From the numbers given in Table 1 we see that in a few cases the product of the estimated mass ejected times the time scale for activity appears to give a mass which is comparable with, or greater than, the mass of a normal bright galaxy. These are frequently the most uncertain cases! However, everyone is aware that in such a situation, it would then be necessary to argue:

a) that there is a high rate of accretion from intergalactic space, and we really have very little direct evidence that there is any appreciable amount of mass available for that purpose; or

b) that in an evolving universe galaxies did have very much higher average masses in the past; or *c*) that nuclei are objects of the type envisaged by JEANS, and that matter is either being created or it is expanding from delayed cores.

I do not anticipate that we are going to reach any very profound conclusions about these fundamental questions in the remainder of this meeting. Most of us are only beginning to realize the full importance of the activity that is now being found in so many circumstances in galactic nuclei.

The physics of the radiation processes and the ejection of matter is still a considerable mystery. Some years ago HOYLE, FOWLER, BURBIDGE, and BURBIDGE (1964), in trying to understand the energy release in a massive object which is collapsing gravitationally, realized that rotation might be very important. We thought that such an object might break up and that the ejected fragments might account for some of the phenomena which are seen. There is now considerable interest in the idea that, in the nucleus of a galaxy, a coherent rotating object is responsible for much of the activity. This idea has come by analogy with pulsars, and it will be discussed in the papers by MORRISON and WOLTJER. I tend to believe that rotation is of great importance, but that both numbers of small rotating objects and single massive rotating objects are present in nuclei at different stages. The fundamental question, however, still is how did these dense massive configurations arise in the first place and how can activity be maintained by them through much of the life of a galaxy?

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as long as 10^9 years it may be necessary to argue that continuous injection of electrons is required, so that the total energy may be considerably higher than the total values in the left hand column.

SCHMIDT

There is some freedom in assigning these lifetimes over the whole of radio galaxies, and I've tended to think that those with higher radio luminosity should be given the smallest lifetime. Perhaps those with the highest total energy contents should be given the lower lifetimes.

G. R. BURBIDGE

I have no disagreement with that; I think that it is possible. I started off by saying that I believe that equipartition is reasonable in some cases. However, if the ejection takes place in the way I discussed earlier, there is no reason to believe in overall equipartition. In this case continuous injection of electrons from sub-sources is indicated and the total energy content is very difficult to estimate.

HOYLE

I have several comments. The first concerns the table which is on the board there. The item which involves the greatest total amount of energy, the greatest product of the two columns, is the case of systems of positive energy. I would have thought the table gives a rather conservative estimate for this case. The next comment I have relates to the table for compact infrared emitters, the table where you worked out minimum energies. It seemed to me that if you took your minimum energies and divided by the light travel time across the system the resulting emission rates were less than the observed values by a factor of about a hundred.

G. R. BURBIDGE

That is in part due to the fact that I used early data, and did not include some of the highest fluxes discussed by LOW.

HOYLE

So one could say that minimum energies are not right in this case, which is interesting in relation to minimum energy calculations generally.

G. R. BURBIDGE

Yes, in some cases the numbers are underestimated.

MORRISON

Let me fling down a number. Can you give me an example of an object, whatever it may be (barring the universe as a whole) where more than 10^{62} ergs has been put out anyhow? If so, which one?

G. R. BURBIDGE

My view is that the strong radio galaxies may indicate the ejection of energy equal to, or possibly greater than, 10^{62} ergs.

MORRISON

But you assume a hundred times as much proton energy as electron energy, which is not demonstrated.

G. R. BURBIDGE

I think that 10^{62} ergs is about right for the best cases of strong radio sources. The other possible class of objects where the energy release may be $\geqslant 10^{62}$ ergs is the class of systems of positive total energy.

WHEELER

The energy has been discussed so far. Could you say something about the concentration of energy? Is there anyone of these roughly 15 cases on the board where one can say in a convincing way that the energy coming out is of the same order of magnitude (expressed in terms of mass) as the mass of the system from which that energy comes? In other words is there any convincing evidence that one must call on anything more than ordinary hydrodynamics or ordinary gravitation, or ordinary nuclear reactions? Is there any evidence for complete conversion of mass into energy?

G. R. BURBIDGE

Well, in the simple case, if you consider a nucleus with a very small size, you rapidly use up all the mass originally present there. If you argue that mass can evolve inwards fairly rapidly there is no reason to believe that you run into problems of mass conservation. In very few cases can we argue that more mass is being radiated than there is in a galaxy as a whole, and in such cases the evidence is very uncertain.

I think these questions come up not only for the radio sources but, for example, as someone just mentioned, this question of coherence. This apparently increases the efficiency of the machine, but some energy is required to organise the machine so that it becomes that efficient and I don't know how to take that into account.

VAN DER LAAN

Early in your paper you talked about strong radio sources and showed a slide of 3C 33 which has very compact components remote from the optical galaxy. I think that even in a magnitude-limited sample this is not a common system so that in unit volume of space this is extremely rare. My impression from the Cambridge results is that for most of the radio sources the components are not stable and that you can get away with having an expansion of the components themselves. The expansion speed must be somewhat less than the ejection speed, but components need not be confined or self-confining.

G. R. BURBIDGE

I partially agree with that and I partially disagree. I mean I think there is quite a lot of structure in extended sources. You find comparatively small features in large components, and it was this result which first interested me in the problem two or three years ago. As far as confinement is concerned, if you look carefully at the kind of models that have been worked out, even for sources like Cygnus A which are much more extended than objects like 3C 33, you find that the intergalactic magnetic field or gas density required is enormous.

OORT

I wonder whether the possibility of confinement by an intergalactic medium which you mentioned should be rejected altogether. If the overall density is 10^{-29}, it is easily conceivable that in the regions where the galaxies or clusters of galaxies are, the densities are several powers of 10 higher. This brings me to another point that you mentioned; you more or less said that it was a hypothesis that there are density fluctuations in the universe. I think that one should not call this a hypothesis. If one looks at the nearby part of the universe you see that there are enormous density fluctuations in the distribution of galaxies, and these must have come from density fluctuations in the universe. So, from an experimental point of view, one knows that there have been density fluctuations in the universe, though on a much bigger scale than what you need here. But it seems logical then to assume that there have been smaller-scale fluctuations as well.

G. R. BURBIDGE

Well, I'm not sure about this. I think that Professor WHEELER and Professor HOYLE might discuss this more, but it does seem to me that there are really two components in the universe, in the normal evolving cosmologies, that you have to worry about. On the one hand, as you say, there are these density fluctuations in the mass, on the other there is an extremely smooth distribution of the background radiation, which really implies that things were very smooth at one time, and if you look at attempts to understand the condensation of galaxies at an earlier epoch you find that you must *assume* that comparatively large density fluctuations are present.

OORT

The isotropy of the 3°K black-body radiation is certainly very perfect, but it refers to a very early stage of the universe where all these tremendous fluctuations which you see now must have been only of the order of perhaps 0.1 or 0.01%. So the three-degree radiation doesn't teach us anything about this.

G. R. BURBIDGE

But the point is that it's these small fluctuations which are so hard to understand in any known physical theory at the early stages. All I'm saying is that in this kind of theory you basically say that they are there, without understanding why.

OORT

One more remark about the table you wrote on the blackboard. You everywhere get numbers of the order of one solar mass per year. It is, perhaps, worth mentioning that the amount of gas we think is streaming into the Galaxy from the surrounding universe is similar to this: also of the order of one solar mass per year. It is true that this figure applies to the entire Galactic System. However, it may very well be that in these systems with very high nuclear masses there is much bigger flow near the centres.

G. R. BURBIDGE

In answer to Dr. WHEELER, what this really says in a way is that the galaxy is not a conservative system, that matter can flow in as well as flow out, and, if you can undestand the way in which energy is released as matter flows in, it may be possible to explain some of the outflow which we see.

KELLERMANN

I would like to go back to the question of small scale structure and the production of particles outside the galaxy. It is certainly true that a large fraction of the extended sources have small scale structure. I have also thought for some time that the particles might be actually produced out there. There are two pieces of information which I would like to add, one which supports this idea and one which worries me a bit. The one which supports it is some recent observation of Cygnus A made at NRAO by MILEY and WADE. You are familiar with the published maps which show that the flux from Cygnus A comes from two large components, well separated from the galaxy. Each of these components has about 10% of its flux concentrated in a very small component. One of these is in fact elongated or double itself, with a separation of about 5 seconds of arc, and has component dimensions of 1 sec of arc. The position angle of the separation is not along the line joining the bigger components. This certainly suggests that some new event has happened out there and that this is a source where the particles were not produced in the galaxy. The thing that worries me is that all the very compact sources, with dimensions of 10^{-3} of 10^{-2} arc seconds, and all of the variable sources appear to be coincident with the optical object, that is the quasi-stellar object or the nucleus of the galaxy. We never see these removed from the optical object and if particles are actually being produced, away from the galaxy or the quasi-stellar object, I think you can expect to see these very compact sources or variable sources removed from the optical image.

G. R. BURBIDGE

Yes, I understand this. I don't have an answer. It's possible that several quite different basic scales are involved.

HOYLE

I think that if one drives out clouds which are expanding, then during the expansion one loses internal random motions which either become used up in pushing against a piston of intergalactic matter, or which go into increased radial motion. In either case the energy is not available to draw on for the emission of radio waves in the synchroton mechanism. So you have very big losses here. You are bound to have very big losses if you have expanding systems, but this can be avoided if compact machines are expelled.

McCrea

My question is a very brief one. If you think that these components of primary sources are self-gravitating, is there any need to suppose that they are ever driven out of the central galaxy?

G. R. Burbidge

Well, the radio sources are often beautifully symmetrically placed around optical objects. If you say that there is a whole cloud of objects always around an optical source, and for some reason two of them pop off, communicating by ESP or something, you might explain what we observe; but it is really quite hard to believe that this is what is going on. There is so much evidence that matter is ejected from nuclei, that I, for one, find this a very difficult concept.

DYNAMICAL EVOLUTION OF DENSE SPHERICAL STAR SYSTEMS

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ABSTRACT

Three physical processes that must affect the evolutionary history of a galactic nucleus are considered briefly. First, the ejection of mass from newly formed massive stars throughout a galaxy is discussed, together with the infall of gas towards the center and the formation of the next generation of stars. Second, a brief analysis is given of the exchange of kinetic energy between stars as a result of their mutual gravitational encounters; if the relative number of massive stars is sufficiently great, these heavy stars will form a secularly unstable system at the center which will contract rapidly. Third, direct physical collisions between individual stars are considered; these can lead to ejection of mass (disruption) or to coalescence of the two colliding stars, leading in turn either to formation of new stars at the center or to the building up of massive stars, respectively. A possible evolutionary sequence for a galactic nucleus is described, embodying these three processes. In particular, results are presented from a Monte Carlo calculation by SANDERS which indicates the relative importance of collisional mass ejection and coalescense in systems of different total mass.

The observational evidence presented in the previous papers indicates that many complex phenomena must be taking place in galactic nuclei. Clearly the unravelling of these processes, or even the dominant ones only, presents theoretical astrophysics with a challenging task, one that may require many years for its completion.

The present paper does not attempt to explain any of the types of activity observed in galactic nuclei. Instead, we adopt a more deductive approach, and investigate what properties can be expected for an evolving spherical system of stars. Whatever else may be happening in a galactic nucleus, such a system is generally assumed to contain many stars within a relatively small volume. An understanding of the properties to be expected of a dense aggregation of stars sets the stage, so to speak, for an analysis of the complex activity that we observe in galactic nuclei.

In the evolution of a spherical system of stars three effects must clearly be present. The first of these, which is treated in the following Section I, is the loss of mass from individual stars, either gradually or by supernova explosions; if much of the ejected gas is retained in the system, as seems not unlikely for a galactic nucleus, this material may form new stars near the center. Section II considers a quite different effect, the changes of each star's kinetic energy and angular momentum because of the graininess of the total gravitational field. This process, which is usually analyzed in terms of two-body encounters between mass points, leads to virtual expulsion or evaporation of some stars from the core of the system, the contraction of the remaining system as a whole, and under some conditions to the development of a central core of relatively high star density. The third process that must be considered is the direct physical collision of two or more stars. Such catastrophic events, which are considered in Section III, can produce loss of mass from the colliding stars, a process called disruption, and also coalescence of the two stars, with the formation of a more massive object.

The evolution to be anticipated for a galactic nucleus, under the influence of these three effects — mass loss from single stars, distant gravitational encounters and direct impacts between stars — is treated in Section IV. This final section is somewhat hypothetical, partly because the effects of individual collisions cannot be accurately predicted, and especially because the fate of gas ejected from the stars is unclear; in particular one does not know to what extent this gas forms new stars of familiar types.

I. Mass Loss from Stars

The death of individual stars naturally affects the evolution of any stellar system. For a star with a mass no greater than the Sun's, death produces a contraction of the star to the white dwarf phase, and a large decrease in luminosity. Since little if any mass loss is believed to be involved in the death of such low-mass objects, the dynamical behaviour of a stellar system will be unaffected.

The death of a star much more massive than the Sun leads to quite different results. It is generally believed that such objects, when they run out of nuclear fuel, lose much of their mass, either by gradual ejection in the red giant phase, or by a catastrophic supernova explosion. For a system of stars all formed at about the same time, the total mass of gas lost by the stars since they were formed may be determined from the initial luminosity function, as measured from stars forming recently in the solar neighbourhood. If we take the form of this function as determined by Limber [1] and assume that every star when it dies leaves a remnant (white dwarf or neutron star) of one $M_\odot$, ejecting the rest into space, we obtain the results in Table 1. Evidently between 10^7 and 10^8 years about a fifth of the total mass present initially in stars is ejected into space, with a rapidly falling ejection rate in subsequent years.

TABLE 1 — *Fraction of Mass Ejected as a Function of Age.*

Age (years)	3×10^{6}	10^{7}	3.6×10^{7}	1.4×10^{8}	1.6×10^{9}	1.2×10^{10}
Fraction ejected	.0012	.068	.134	.20	.27	.29
Greatest Remaining Mass ($M_\odot$)	200	16	6.3	3.2	1.58	1.00

The assumption that the initial process of star formation produced the same distribution as we observe for stars formed recently in the solar neighborhood is, of course, entirely arbitrary. TRURAN and CAMERON [2] have recently pointed out that the chemical composition of early-type stars is better explained if the more massive stars predominated in the early days of the Galaxy, a conclusion pointed out many years ago by SPITZER and SCHWARZSCHILD [3]. However, even on the rather conservative assumption underlying Table 1 the fraction of mass ejected is already large.

The fate of the gas ejected is uncertain. In a globular cluster, where the escape velocity is only a very few kilometers per second, it seems unlikely that the gas can be contained. If the ejected gas does not stream out of the system immediately, it is likely to evaporate from the cluster at the expected temperatures. In a galaxy, however, where the escape velocities exceed a hundred kilometers per second, containment of an appreciable fraction of this gas seems very probable. For example, in a galaxy with a mass of 10^{11} $M_\odot$, there will be an appreciable number of supernovae each year during the first 10^{8} years, and collisions between the expanding envelopes will dissipate much of the directed momentum, heating the gas to very high temperatures. Even in the absence of heavy elements, the gas would cool by free-free collisions of electrons with protons in less than 10^7 years if T is less than 10^8 degrees and the proton density exceeds 10 cm^{-3}, corresponding to a mass of 10^8 suns within a sphere of radius 300 pc. While a more detailed theory is required to indicate what fraction of the ejected gas escapes the galaxy entirely and what fraction is retained, we shall assume here that a substantial fraction of the gas is in fact retained.

Ultimately any gas retained must cool and fall towards the center of the system. During the phase of violent mass ejection, the gas may conceivably be kept sufficiently hot to extend throughout much of the galaxy; the r.m.s. velocities required are an appreciable fraction of the stellar velocities and the kinetic temperature, correspondingly high. When the period of activity ends, however, and possibly well before this, the gas will cool and start to contract.

If the galaxy in question has no angular momentum, the gas will tend to collect at the center. As pointed out some 30 years ago [4], if the mass of the gas is a minute fraction of the stellar mass, the gas can be in stable equilibrium in the stellar gravitational field. However, if the mass of the gas exceeds a certain critical fraction of the total mass, equal to about 4×10^{-4} if the ratio of root mean square velocities for atoms and gas is about 0.1, then the self-attraction of the gas is so large that no equilibrium is possible if isothermal conditions are assumed; the gas will presumably collapse gravitationally. We assume that stars will form from such a gas cloud. Before the critical amount of mass is passed, the ratio of gas cloud radius to the radius of the stellar system is somewhat less than the ratio of root mean square velocities, or several percent. The system of new stars that form at the center will presumably have about the same radius. While the details of the process are obscure, it would seem that gas ejection and star formation can produce a subsystem of relatively high density at the center of a galaxy. Thus if ten percent of the mass collapses to the center and forms new stars with a radius of 5 percent of the original system radius, an increase of density by about 10^3 occurs.

This process can presumably occur again; the new stars again evolve, eject 20 percent of their mass in 10^8 years, and a subsystem of still larger density, but less total mass, forms at the center. Thus with three successive stages of contraction a spherical galaxy with 10^{11} $M_\odot$ in a radius of 10,000 pc might form first a subsystem of 10^{10} $M_\odot$ with a radius of 500 pc, next a tighter subsystem of 10^9 $M_\odot$ with a radius of 25 pc, followed by a core of 10^8 $M_\odot$ with a radius of about 1 pc. This process of gas ejection, infall and star formation could be nearly continuous, though star formation may well occur in a great many separate spurts as gas collects at the center, exceeds the critical mass and condenses into new stars. As the number of new stars formed at the center increases, the radius of a gas cloud of small mass in equilibrium decreases, and successive generations of new stars are formed closer and closer to the center.

The assumption that the infalling gas forms new stars is, of course, arbitrary, and the mass distribution is particularly uncertain. We shall assume throughout that the gas reaching the center condenses into new stars with the same distribution of masses observed in the solar neighborhood [1] and discussed above. It is equally conceivable that a single supermassive object could form directly, a possibility to which we return again below.

If the stellar system possesses angular momentum, these phenomena are altered. The gas in this case will presumably contract to a disc, and star formation may require more mass than in the case considered above. Discussion of the angular momentum problem and of the general manner in which these processes may have entered into the history of our Galaxy and similar systems is postponed to Section IV.

II. DYNAMICS OF SPHERICAL SYSTEM OF POINT MASSES

We consider now the dynamical evolution of a spherical system of stars under the assumption that each star can be treated as a point of constant mass. It is well known that such a spherical system of self-gravitating constant masses cannot be in a state of long-term equilibrium. From the virial theorem it is easily shown that in a system that is changing only slowly, the r.m.s. velocity of the individual masses is about one half the r.m.s. escape velocity of an individual mass from the system. The irregularities in the gravitational field, resulting from the particulate nature of the gravitating masses, lead to an exchange of kinetic energy between stars, tending to produce a Maxwellian velocity distribution. Evidently any particle in the Maxwellian tail, with a velocity more than twice the r.m.s. value, will escape from the system.

The rate at which particles escape will be determined, of course, by the time required for the exchange of energy between the stars to be comparable with the stellar kinetic energy. In an actual cluster this time will depend markedly on the orbit of the star, since deviations from a smooth potential function are much greater near the center of the system where the density is greater and encounters between stars are more frequent. To obtain a first approximation, it is frequently useful to consider an idealized cluster of constant density, situated in a potential well with a flat bottom and steep sides. Then conditions are essentially uniform through the cluster and the relaxation time may be set equal to a reference time t_R, defined by SPITZER and HÄRM [5] as

$$t_R = \frac{(3/2)^{3/2}\, v^3}{2\pi\, G^2\, m^2\, n\, \ell n N} \tag{1}$$

where m and n are the mass and particle density of the stars, v is the r.m.s. velocity and N is the total number of stars in the system. If the virial theorem is used to evaluate v, and the cluster radius, R, is expressed in parsecs, equation (1) gives

$$t_R \approx \frac{8 \times 10^5 N^{\frac{1}{2}} \; [R\,(pc)]^{3/2}}{[m/m_\odot]^{\frac{1}{2}} \; \log_{10} N} \text{ years} \tag{2}$$

A more detailed discussion of relaxation times has been given earlier by CHANDRASEKHAR [6]. Since in a Maxwellian velocity distribution about one percent of all the stars have a velocity exceeding the r.m.s. value, one may then infer that one percent of the stars escape during the time t_R, a conclusion first pointed out by AMBARTSUMIAN [7] and SPITZER [8].

If the escaping stars are assumed to escape with no appreciable kinetic energy, the total energy of the remaining system must be constant, and N^2/R is unchanged; R decreases with time and the density increases sharply as $1/N^5$. According to equation (2), t_R decrease as $N^{7/2}$, and evaporation accelerates. On the basis of these assumptions, the cluster contracts to a point in about 40 t_R, as shown by KING [9].

Evidently it is most unrealistic to assume that n, the particle density of stars, is uniform throughout the system. HÉNON [10, 11] has shown that a consideration of the radial density gradient significantly alters the conclusions based on the approximate constant-density model. Exchange of energy between stars takes place mostly in very small amounts, and many orbits of a star are required before its energy or angular momentum are significantly changed. Stars are likely to gain appreciable energy only if their orbit passes through the dense core of the system, where the rate of encounters and of energy interchange is greatest. As such stars gain more and more energy, they will move in more and more elongated orbits passing through the central core more and more rarely. Thus as a star approaches the zero total energy needed for escape, its effective relaxation time increases steadily. The actual rate of escape is in consequence much reduced below the result obtained on the simplified constant-density model.

However, during a time of 100 t_R a substantial fraction of the stars in the central core will gain sufficient energy so that their orbits become markedly elongated, and the stars become essentially part of an extended "halo" surrounding the system. While these stars have not escaped, in the sense that their orbits continue to pass through the dense central nucleus, such central passages occupy a small fraction of their time. Thus the simple theory may be used to give the rate not of actual escape but of accumulation in the outer regions. This ejection of stars must give rise to a contraction of the central core. In place of the uniform radial contraction given by the constant density theory it is clear that the rate of loss of energy and the resultant rate of contraction will be greatest where the density is greatest, at the center of the cluster. This tendency may produce a relatively dense core at the center of the system, a possibility discussed by LYNDEN-BELL and WOOD [12]. The time scale for this development is relatively long, much greater than t_R.

The presence of relatively more massive stars is probably a much more important factor in producing a central high-density core in a galactic nucleus. As shown recently elsewhere [13], a sufficiently massive core of such stars should contract at a relatively rapid rate. In the simple case of a system with two types of stars present, lighter ones with mass m_1, and heavier ones of mass m_2, the condition for the development of a contracting core can be stated very simply, provided m_2 is much greater than m_1. It is evident physically that encounters will tend to establish equipartition of kinetic energy so that

$$m_1 v_1^2 = m_2 v_2^2 . \tag{3}$$

where v_1 and v_2 are the r.m.s. velocities of the two types of stars. As the heavier stars lose energy, they will fall towards the center.

If the total mass of the heavier stars is only a small fraction of the total mass of the system, these stars can form a low-velocity subsystem at the very center. The situation is similar to the distribution of low-temperature gas at the center of a stellar system, which was discussed above. In either case, equilibrium is possible with predetermined low velocities if the density of the low-velocity stars or atoms is negligible, and the gravitational field is essentially that of the high-velocity stars. If the density of the more massive stars much exceeds the density of the lighter stars at the center of the system, then the self-gravitational energy of the heavier stars is great and the random velocities of these stars must become large and cannot satisfy equation (3). Thus v_2^2 will be above its equipartition value, and as a result of energy exchange in collisions the subsystem of heavy stars will continually lose kinetic energy to the lighter stars in the vicinity. This loss of energy by the self-gravitating system leads to a contraction of the system and a continual increase of v_2^2, which is essentially a form of secular instability. This collapse of the heavy star subsystem will occur [13] if M_2/M_1 exceeds $\beta\,(m_1/m_2)^{3/2}$ where β is a constant of order unity; if m_1 is much less than m_2, an approximate theory indicates that β equals 0.16.

The time scale for this resultant contraction is ronghly the equipartition time, t_{eq}, about equal to $t_R\, m_1/m_2$, where t_R is computed for stars of mass m_1. Thus the rate of contraction of the central subsystem is between one and two orders of magnitude more rapid than the rate of contraction computed from the evaporation of stars. As the central subsystem contracts, the relaxation time for the heavier stars will decrease in accordance with equation (2), and will ultimately become less than t_{eq}. Evidently a dense core at the center of the system will develop with a time scale about equal to t_{eq}; this conclusion has been confirmed by detailed dynamical calculations, which will be published elsewhere.

The finite lifetime of the more massive stars will clearly modify any results involving the concentration of massive stars. These stars will eject matter on a time scale discussed in the preceding section. If the system is sufficiently compact so that t_R is comparable to the stellar life time, relaxation effects will be important for these new stars. As a result of the tendency towards equipartition, stars of average mass will tend to acquire the same velocity as the average stars in the cluster, and will consequently diffuse out from the center. Stars of high mass will tend to be concentrated near the center, and as these accumulate they will tend to form a contracting subsystem exactly as before. Thus the rebirth of massive stars may lead to a continuing process of contraction until a very dense core is reached. This process is discussed again in Section IV.

III. Collisions between Stars

As the density increases in an evolving stellar system, direct collisions between stars become inevitable. The number of such collisions can be computed approximately if the stars are assumed to remain spherical before collision. On this assumption, the value of the impact parameter, p (defined as the distance of closest approach of the centers of the two stars in the absence of gravitational forces) for a just grazing collision may be computed from the conservation of energy and momentum, and becomes

$$\pi p^2 = \pi (r_1 + r_2)^2 \left\{ 1 + \frac{2G(m_1 + m_2)}{(R_1 + R_2) V^2} \right\} \tag{4}$$

where V is the initial relative velocity, while r_1, r_2, m_1 and m_2 are the radii and masses of the two stars. For slow collisions, in which the initial kinetic energy is much less than the potential energy at closest approach, tidal deformation may be significant and equation (4) is not very precise.

For any one star the mean time, t_c, between collisions is roughly given by

$$t_c = 2^{1/2}/n\pi p^2 v \tag{5}$$

where n is the number of stars per unit volume and v is the r.m.s. velocity, equal on the average to $2^{\frac{1}{2}}$ times the r.m.s. value of the relative velocity V. If we evaluate v from the virial theorem and substitute from equation (4) for πp^2, equation (5) gives

$$t_c \approx \frac{10^{22}\ \mathrm{R}^{7/2}}{\mathrm{N}^{3/2}\,(m^{1/2}\,r^2/m_\odot^{1/2}\,r_\odot^2)\,(1 + 8.8 \times 10^7\,\mathrm{R}r_\odot/\mathrm{N}r)}\ \text{years} \tag{6}$$

where m and r are again the mass and radius of the stars and R is the radius of the cluster in parsecs. Table 2, taken from Ref. [16], compares values of t_c for different values of N and R.

The detailed processes that occur during a direct impact of two stars are obviously very complex and difficult to predict. To trace the effect of such collisions on the evolution of the stellar system there are two questions of particular importance that need to be answered. First, how much gas is ejected from the two stars? Second, will the two stars separate or will they coalesce to form a single star, as proposed by COLGATE [15]? To answer these two questions, at least on an approximate basis, a very simplified theory has been developed [16]. In this theory the two stars are assumed to move in straight lines, as in Figure 1. The assumption is then made that the collision is strictly one-dimensional, and that the mass elements in one star interact only with the mass elements towards which

TABLE 2 — *Relaxation and Collision Times.*

No. of Stars	Radius, R (pc)	0.1	1	10	100
$N = 10^6$	Stellar velocity, v (km/sec)	147	47	14.7	4.7
	Relaxation time, t_R (years)	4.6×10^6	1.46×10^8	4.6×10^9	1.46×10^{11}
	Collision time, t_c (years)	3.2×10^8	1.09×10^{11}	3.5×10^{13}	1.09×10^{16}
$N = 10^8$	Stellar velocity, v	1470	470	147	47
	Relaxation time, t_R	3.4×10^7	1.08×10^9	3.4×10^{10}	1.08×10^{12}
	Collision time, t_c	2.8×10^6	5.2×10^9	3.1×10^{12}	1.09×10^{15}
$N = 10^{10}$	Stellar velocity, v	14700	4700	1470	470
	Relaxation time, t_R	2.7×10^8	8.6×10^9	2.7×10^{11}	8.6×10^{12}
	Collision time, t_c	3.1×10^3	9.7×10^6	2.8×10^{10}	8.5×10^{13}

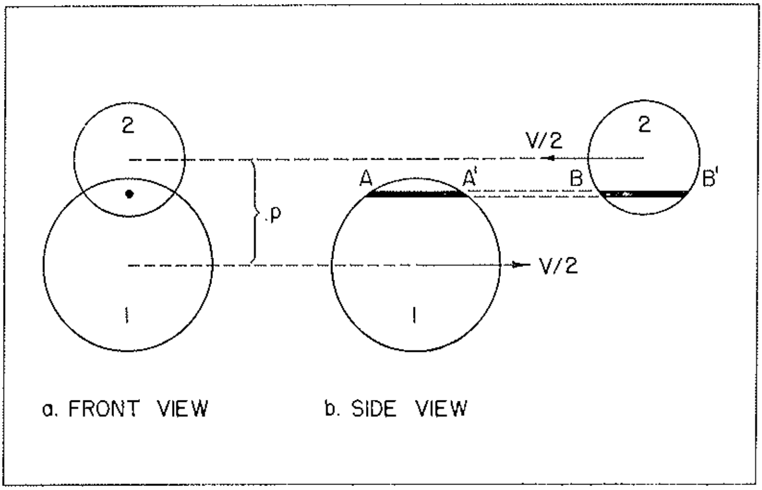

FIG. 1 — Front and side view of two colliding stars, showing colliding mass elements in each star.

they are moving; all lateral effects are entirely ignored. Thus the mass elements in the cylinder A - A′, extending through star 1, in a direction parallel to the relative velocity, V, are assumed to collide only with the mass-elements in the coaxial cylinder B - B′ extending through star 2. The collision of these mass elements is assumed to be completely inelastic.

To determine the mass of gas ejected, escape of the mass element A - A′ is assumed if the thermal energy which it gains during the collision exceeds the total binding energy of these mass elements in star 1, or the corresponding binding energy of the mass elements B - B′ in star 2, whichever is the greater. The answer to the second question, on the possible coalescence of the two stars, is determined from the total loss of kinetic energy in the collision, summed over all colliding mass elements. If this loss of kinetic energy exceeds the initial kinetic energy of relative motion, when the stars are far away from each other, then it is assumed that the two stars do not have sufficient energy to escape from each other's gravitational field; if they do not coalesce immediately, they will form a binary which, after repeated collisions at each periastron passage, will ultimately coalesce to form a single star.

Evidently these assumptions represent a very crude approach to a complex physical problem. They probably yield an upper limit on the number of collisions leading to coalescence; this application of the principle of momentum conservation would seem to give a reliable upper limit on the amount of kinetic energy transformed into heat. If this upper limit is less than the kinetic energy associated with the relative velocity, V, at infinity, it is difficult to see how coalescence is possible. On the other hand, the amount of gas escaping from the two stars, in this process which we may call "disruption", is not well determined; the thermal energy in a gas element is not likely to be converted entirely into the potential energy of the same element in the gravitational field of one of the two stars.. Some of the thermal energy will certainly be transferred elsewhere by shocks, adiabatic expansion, etc., and may lead to expulsion of a small amount of gas at large energy, or to heating of a gas that is securely bound gravitationally. On the other hand, in the time-dependent gravitational field of the two colliding stars the amount of energy required for a mass element to escape from both stars may be much less than assumed.

This simple model should give correctly the dominant feature of grazing collisions, in which the dense central cores do not collide directly. These cores presumably move past each other without much change, while the parts of the envelopes that collide will be violently heated, with some gas escaping completely.

For direct central collisions, on the other hand, this model does not give anything very useful if the two stars have the same mass. In this situation all the kinetic energy of relative motion is converted into heat, and all mass elements receive the same kinetic energy per unit mass. On the approximations made here, none of the mass escapes unless most of it does. The exact computations for central collisions between identical stars, carried through by SEIDL and CAMERON [17], show that even when V, the relative velocity at infinity, is zero, shock waves accelerate a small amount of gas to rather high kinetic energies, so that 4 percent of the mass of each star is ejected. This fraction rises to 17 percent at 1000 km/sec. At 2000 km/sec, when the total energy is positive and complete disruption of both stars would result according to the simple model, only 60 percent of the mass is found to escape. Such central collisions are relatively improbable and for the more important grazing collisions the model described here gives the best results presently available.

Detailed calculations of mass loss and coalescence probability have been made by SANDERS [18], on the basis of the simple model, for a wide variety of stellar mass ratios and velocities. The results have been used in an investigation of how a galactic nucleus is likely to evolve in time. We return to this topic again in the next section.

IV. EVOLUTIONARY HISTORY

We attempt now to reconstruct the evolution of a galactic nucleus, taking into account the physical processes discussed in the preceding sections. Primary emphasis will be placed on systems without angular momentum, though we treat briefly the possible extensions of the theory required to explain spiral systems like our own.

a) *Formation of the nucleus*

The first stage may be called the formation of the nucleus; this stage may be regarded as part of the formation of the galaxy out of intergalactic gas. One may visualize a relatively homogeneous but turbulent cloud which condenses into stars as it is collapsing towards the center. Numerical computations by HÉNON [19, 20] and others show that even if appreciable turbulence is present, the resultant system shows strong central condensation; for example, the ratio of the radii containing 90 percent and 10 percent, respectively, of the mass is 8 in a typical case, as compared with about 4 for an $n = 3$ polytrope and 2.2 for a uniform sphere. However, the central concentration in a galactic nucleus is enormously greater, with an appreciable fraction of the mass in less than one percent of the radius. To explain so great a concentration it appears necessary to invoke the mass ejection from stars discussed in Section I.

This strong central condensation could also be achieved by the infall of gas that had not yet condensed into new stars. Some uncondensed gas is certainly likely to be present. The time taken for such gas to fall some 10,000 pc in the gravitational field of a galaxy is about 10^8 years, about equal to the time for significant mass loss by the heavy stars - see Table 1. Thus the infall of uncondensed gas and of gas ejected from stars are dynamically rather similar in the early stages of contraction; the ratio of these two sources of gas in the inner regions will determine the ratio of heavy elements to hydrogen in these regions. If a sequence of mass ejection from stars, formation of new stars and subsequent mass ejection again is the dominant process in the formation of a galactic nucleus, the relative abundance of heavy elements might be expected to increase systematically with decreasing distance from the galactic center.

There is little evidence on how the chemical composition of elliptical galaxies varies with distance from the center. For spiral systems, on the other hand, there is substantial evidence on chemical composition as a function of position. The paper by SPINRAD, presented earlier during this Study Week, indicates that the stars in the nuclei of spirals have systematically higher metal abundances than the Sun. Similarly, PEIMBERT [21] has concluded that the tenfold increase of N II emission lines relative to Hα, observed within about a hundred parsecs of the center of spiral nuclei, must be explained by a higher ratio of nitrogen to hydrogen than is observed in the solar neighborhood. If gas in the galactic nucleus represents material ejected from evolved stars, progressively less and less diluted with primordial hydrogen at decreasing distances from the center, these observations find a ready explanation.

One naturally enquires how gas can concentrate towards the center of a spiral system, in which so much angular momentum is present. Let us consider what happens to gas ejected from a spheroidal distribution of stars, such as the halo of our Galaxy. Stars at some 10,000 pc from the axis of rotation possess an average angular momentum corresponding to equilibrium circular orbits at about 5000 pc from the center. Stars much closer to the axis will have a mean angular momentum varying about as the square of their distance from the axis if we make the plausible assumption that in such a spheroidal system, where the random velocities much exceed the circular velocity, the mean rotational velocity varies linearly with distance from the axis. If the circular velocity is assumed constant with distance, as is nearly the case in our Galaxy at present [22], the radius of the equilibrium orbit into which any ejected gas must fall as it cools will vary as the square of the initial distance from the axis. In consequence, gas ejected from within 2000 pc of the axis of rotation, containing about 6 percent of the mass, can condense to within about 200 pc of the center. One can visualize gas ejected by the stars in the galactic halo condensing into a disc at radii between 1000 and 5000 pc, but forming in addition a relatively dense spheroidal system at the center. A repetition of this same process will produce an even smaller system of stars in the galactic center. As compared with a spherical system, where all the gas ejected presumably condenses into an inner spheroidal system, the amount of gas in a spiral system which reaches the inner regions of a nucleus may be reduced by several orders of magnitude. In any case these arguments would indicate that relatively dense nuclei, with some 10^5 to 10^8 stars within a radius of a few parsecs, may be expected to form early in the life of most galaxies.

b) *Relaxation and stratification.*

We consider next the development of a nucleus when it has reached a sufficiently compact stage so that the relaxation effects discussed in Section II become important. From equation (2) and Table 2 we see that for a system of 10^8 stars, R must be less than about 5 pc if t_R is to be less than 10^{10} years. For dynamical relaxation to have a large effect, t_R must not exceed 10^9 years, requiring a system either with a smaller radius or a lower mass. While such small radii cannot be measured directly, Stratoscope observations [23] have set an upper limit of 5 pc on the radius of the nucleus in the Seyfert galaxy NGC 4151, with preliminary analysis of new data [24] suggesting an even lower limit of 2 pc. As we have seen above, there is some theoretical reason to expect such compact structures to arise naturally, early in the history of a galaxy.

As relaxation effects become important, the more massive stars will tend to fall towards the central regions of the nucleus. If t_R exceeds 10^9 years, then after one time of relaxation there will be no stars heavier than 1.5 $M_\odot$. Whether the remaining distribution of mass is secularly unstable cannot be determined without more detailed information; it is possible that a relatively dense central core of the more massive stars may form, become secularly unstable and contract further. In accordance with the discussion in Section II such a core will initially contract through loss of energy to the lighter stars, but as the central density increases, evaporation of some of the heavy stars from the central core might provide an additional effect in decreasing the energy per unit mass. In any case, the contraction will accelerate, and the collisions discussed in the next section will soon become important.

If the relative number of massive stars is insufficient to produce secular instability, the evolution of the nucleus during the relaxation phase will be significantly slower. In this case the stratification of stars of different mass will be secularly stable, and the nucleus as a whole will lose mass by evaporation into the halo. The total energy of the remaining nucleus will not be much altered, and hence M^2/R will remain constant. As pointed out above, the density, n, will vary as $1/M^5$ and will rise relatively rapidly as evaporation decreases M. This process is relatively slow, since the time scale for evaporation is about 100 t_R, while for the concentration of massive stars the time scale is more nearly equal to t_R.

c) *Collisions, disruption and coalescence*

As collisions become important, the nucleus enters its active phase, in which the stars themselves are profoundly altered and vast energies are released. In the absence of angular momentum it appears inevitable that this activity must escalate without limit, with the core of the nucleus contracting at an accelerated rate until at least the core itself disappears into the Schwarzschild singularity, possibly followed by many of the remaining stars outside the core. We shall not attempt to follow the nucleus very far in this apocalyptic course to self-destruction, but shall consider only the beginning of this final collisional stage, treating such matters as time scale, changes in the stars involved, and the energy released.

The time scale given by equation (5) is best expressed as a function of v, the r.m.s. stellar velocity, since the nature of the collisions is strongly a function of v. If we express n in terms of M and v^2, eliminating R through the dependence of v^2 on M/R, equations (4) and (5) yield

$$t_c \propto \frac{M^2}{v^7 \left(1 + \beta \dfrac{v_\infty{}^2}{v^2} \right)} \tag{7}$$

where β is a coefficient of order unity and v_∞^2 is the mean square velocity of escape from the stellar surface. Evidently the collision rate accelerates enormously as v increases. The rate of energy released goes up even more rapidly. Comparing two systems of different mass, the time scale for evolution evidently varies as M^2. The rate of energy release is proportional to the number of stars and hence varies as M/t_c or as $1/M$. The total energy released from the system, during a fixed number of collisions per star, must evidently vary as M.

We consider next the changes produced by collisions. As we have seen in Section III, either partial disruption or coalescence or some combination of both is to be expected. The calculations carried through by SANDERS [18] indicate that for V much less than 1000 km/sec, coalescence occurs with relatively high probability, but for V much in excess of 1000 km/sec, disruption is the more likely. Thus if v is less than 700 km/sec, we may say that the system is in the "coalescence regime", while greater V corresponds to the "disruptive regime". The fate of the coalesced stars depends on the competition between their own evolution, which accelerates with increasing mass, and collisions with other stars, which in the coalescence regime tend to increase the mass still further. The time scale for evolution of a massive star is less than 10^8 years. For comparison, the collision time, t_c, for a system with 10^8 stars of solar mass, is 5×10^9 years when v is 500 km/sec, well within the coalescence regime - see Table 2 or equation (6). Even at 700 km/sec t_c is 5×10^8 years, still less than the lifetime of the more massive stars. Evidently in such a system any relatively massive star formed by coalescence will tend to burn its fuel and become a supernova before it increases its mass much further by more coalescence. In a system with 10^7 solar masses, however, the collision times for the same values of v are less by two orders of magnitude, and become less than the evolution times. As such a system evolves, stars of rather large mass should be possible.

These expectations are confirmed by detailed Monte Carlo computations by SANDERS [18], tracing the history of a galactic nucleus. He considered an initial population of several thousand stars, regarded as a sample from a much larger system, and followed the fate of each star with a computer, determining by random choices the types of collisions which it undergoes with the other stars of the sample. The cluster was assumed uniform and homogeneous, with no consideration of stratification effects; dynamical effects between collisions, such as evaporation and equipartition of kinetic energy, were introduced analytically rather than through the Monte Carlo approach. Figure 2 shows his results on the mass distribution in a system with 10^8 $M_\odot$, with all stars assumed to have one half a solar mass initially. The mean stellar velocity is expressed in terms of the escape velocity from the solar surface, equal to 620 km/sec; thus v ranges from 500 km/sec initially to 1860 km/sec at the end, after an evolution time of 1.4×10^{10} years. The initial and final radii of the nucleus were 0.88 and 0.048 pc, respectively. This Figure shows that in the coalescence regime (v_∞ less than 1.6 times the escape velocity for the Sun) the mean mass increases slightly and the maximum mass reached does not become very great. For larger velocities the mean mass declines, as coalescence becomes less probable, but collisions become so rapid that a very few stars can build up to a large

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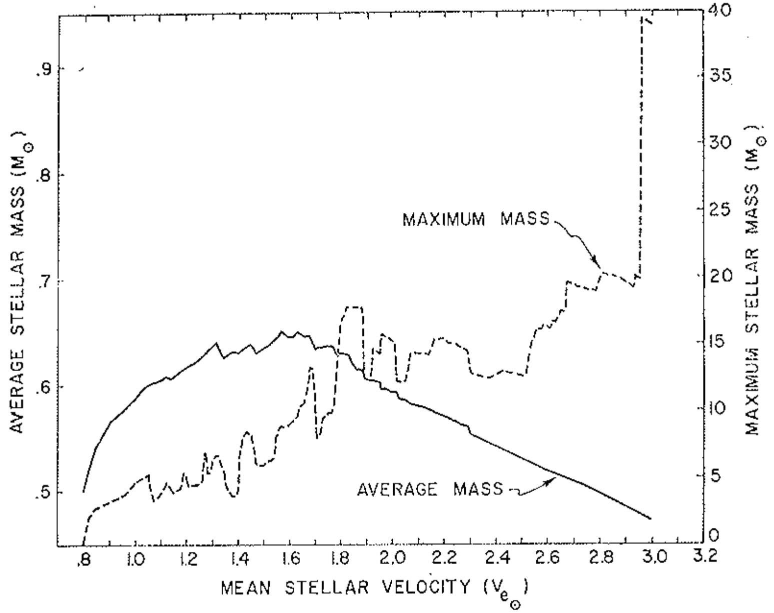

FIG. 2 — Average stellar mass and maximum stellar mass in a system with a mass of 10^8 $M_\odot$, shown as a function of ratio of r.m.s. stellar velocity to the velocity of escape from the solar surface. (Courtesy of the *Astrophysical Journal*).

mass by successive coalescence before they run out of fuel and explode.

The energy radiated by this model is shown in Figure 3 during the final 3.5×10^8 years covered by the integration. The value of v during this period increases up to 1860 km/sec, at which point the calculation ceased. The supernova luminosity does not increase significantly with time during this period; while the rate of collisions increases dramatically, the percentage of collisions producing coalescence declines correspondingly. The "collision luminosity" is the energy released by the gas ejected from the colliding stars; this gas is assumed to cool and fall to the center. In the computer simulations it was

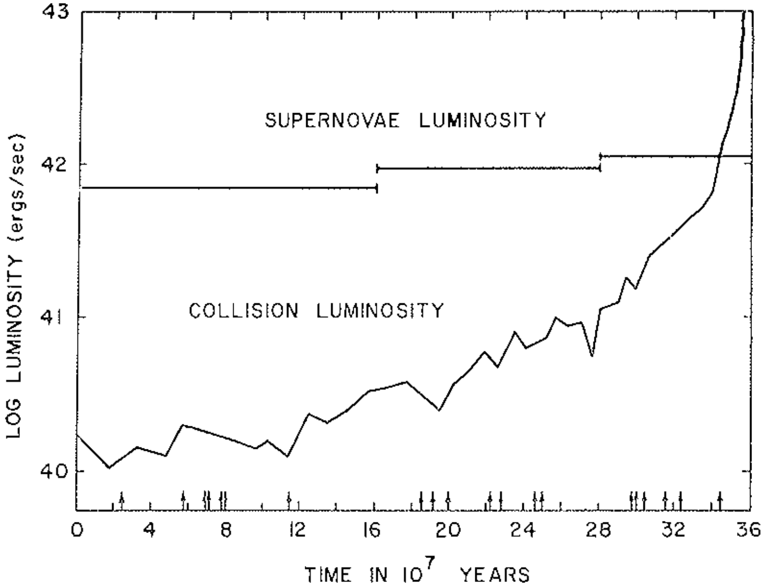

FIG. 3 — The luminosity resulting from stellar collisions and from coalesced stars exploding as supernovae in the late evolution of a 10^8 $M_\odot$ system. The small arrows on the time axis represent individual supernovae in the sample group of 4000 stars. (Courtesy of the *Astrophysical Journal*).

assumed that this gas promptly formed new stars all of mass $M_\odot/2$, which shared kinetic energy with the old stars. Since this energy release varies somewhat more rapidly than v^9, a continuation of this process to velocities as great as 3700 km/sec would increase the computed luminosity to 10^{46} ergs/sec. The assumptions underlying the theory certainly break down well before so high a luminosity can be reached; for example, the time required for new stars to exchange kinetic energy with the old stars becomes so long [25] that the process visualized in these computations would clearly be altered.

Computations for a system with 10^7 stars were also carried out by SANDERS, extending over a period of 1.4×10^8 years, during which the r.m.s. velocity increased from 500 to 900 km/sec. At the end of this period, a star of several hundred solar masses was formed; when it was arbitrarily removed, a similar massive star began to form as shown in Figure 4. Evidently the growth of massive stars is a stable characteristic of this type of model. No supernova explosions occur, since the interval between successive collisions is small compared to the evolution time, and each coalescence is assumed to mix up the stars, prolonging their lives before a burnt out core leads to a supernova explosion. In the actual nucleus there would be many such stars of several hundred solar masses, and they would tend to coalesce, forming even more massive stars. Stratification of the more massive objects near the center would

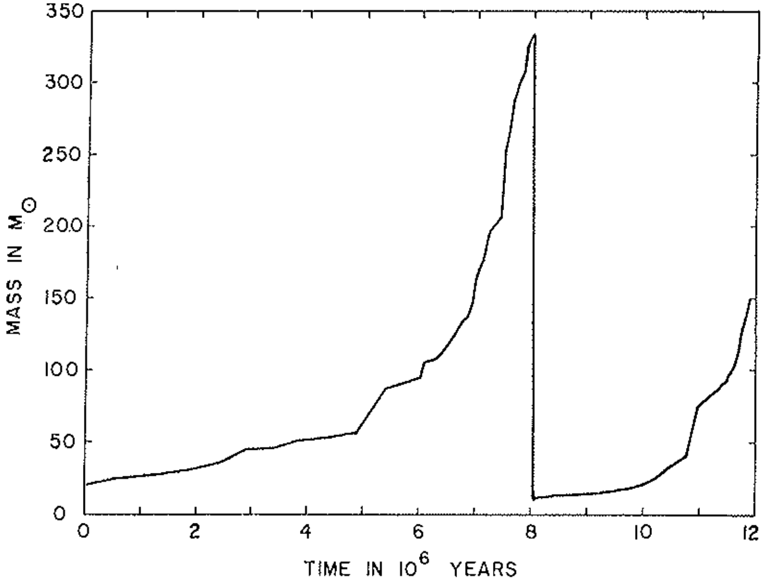

FIG. 4 — Growth of the maximum stellar mass in a sample group of 2500 stars in the late evolution of a system whose mass is 10^7 M$_\odot$. At 8 × 10^6 years the star of maximum mass is arbitrarily destroyed. (Courtesy of the *Astrophysical Journal*).

enhance this tendency. It is quite possible that such very massive stars would be unstable; SCHWARZSCHILD and HÄRM [26] have found that main sequence stars are pulsationally unstable if their mass exceeds 60 $M_\odot$. Conceivably, however, this process may provide a method for concentrating appreciable mass in a few massive stars, possibly in one single very massive object, of the sort discussed by HOYLE and FOWLER [27] and others.

Obviously if the system possess no angular momentum, no steady state appears possible, and there seems no escape from the conclusion that at least the inner core and probably, in time, most of the entire system as well must inevitably contract so much that it disappears from the visible universe, approaching the Schwarzschild singularity. Problems associated with this singularity will be discussed by WHEELER in a later paper of this series. The later stages of this catastrophe are difficult to follow analytically. The stars will collide at such high velocities that nuclear detonations may aid in the complete disruption of the stars; the presence of normal stars becomes improbable when v is as great as 10,000 km/sec, though white dwarfs, with their small cross-sections, might survive to even later stages, and neutron stars might well persist until they approached the Schwarzschild singularity.

In the more likely situation, some angular momentum will be present, and as with the galaxy as a whole the material ejected from stars will tend to collect in a disc, with a small amount of material contracting further in a nearly spherical configuration. The amount of material that could disappear down the Schwarzschild singularity would presumably be much reduced. It is not clear what would happen to the material in the disc, or even whether such a disc could be stable. The total amount of energy that could be released from gravitational contraction of a system with a mass of 10^8 $M_\odot$ is presumably limited by the angular momentum present, if the limiting disc is stable; if stability is not possible, presumably oscillatory phenomena could eject some mass outwards, carrying away the bulk of the angular momentum, leaving the rest of the system free to contract.

Evidently these last few paragraphs are entirely speculative. The tentative theory outlined here, based on work by many different astronomers and physicists, seems to account for the development at the galactic center of a compact core of many millions of stars, in which collisions are rapidly changing the nature of the system and where further developments are bound to be fascinating and important.

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DISCUSSION

Chairman: J.H. OORT

HOYLE

I agree with the technical details of a great deal of what SPITZER has said, in particular we have found the result that the massive component in a cluster with mixed masses settles to the centre more quickly than one might have guessed. I do have a difficulty, however, with the general overall picture. If you start with a cloud which falls together, the velocity distribution of stars becomes statistical fairly early. This means that the gravitational potential near the centre has the form (constant) ($1 - \alpha r^2$ plus...) where α depends on the magnitude of the velocities. Because there is no linear item in r the potential is flat near the centre. In a case where the speeds of the stars were a few hundred kilometers per sec the potential would be substantially constant to about 1 kpc, and would be exceedingly flat near the centre. Then I do not see why a deep central pip develops in the potential at the very centre.

SPITZER

I think that to get the initial density peak at the galactic centre one has to rely on gas, which falls into the centre of the system. If the amount of gas is sufficiently small, the gas will reach equilibrium in the parabolic potential field produced by the stars. If there is no angular momentum present, the radius of the gas will then be much less than that of the stars.

SALPETER

Can you answer roughly what happens, if some fixed percentage of massive stars did not go through the usual evolution of losing most of their mass, but became black holes without any mass-loss? What would happen if, for instance, one third of all heavy stars did this?

SPITZER

As long as roughly half of the mass comes off in the way I have assumed, the results would be unchanged. Actually my table assumed that of the mass available only half would fall to the centre and condense into stars. If you wish to assume that half of this mass never comes out in the first place, as long as you do not lose the other half, you still get an appreciable amount of gas condensing into new stars.

SALPETER

Will these heavy "black hole" mass points speed up the dynamic evolution very greatly or not?

SPITZER

These mass points would be mostly in the region where the time of relaxation is very long, so I would be rather doubtful whether they would be brought into the centre by ordinary collisions. Hence, I would not expect such black holes, formed early in the history of a galaxy, to affect the subsequent dynamic evolution appreciably.

G. R. BURBIDGE

Just one question concerning the time scale or the stage of evolution at which these processes will occur. I get the impression that with this picture you would expect nuclei to form, and violence to take place, early in the life of the galaxy.

SPITZER

The formation of the nuclei, resulting from early mass ejection and gas inflow, should be complete in a few times 10^8 years.

G. R. BURBIDGE

Can you see any way in which the rather continuous activity, or at least the repetitive activity, can be maintained? Galaxies are doing this now, very long after they have formed in an evolving universe. Would you expect them to do it at this stage, or do you feel that the processes you describe are all confined to the first few hundred million years?

SPITZER

For our galaxy, the activity seems to be relatively weak, and may last quite a little while. More generally, the rate of dynamical evolution will depend on how compact is the stellar system resulting from initial gas inflow. If this rate of evolution is slow, activity will not begin for a long time. In fact, in some systems there might be a wait of 10^{12} years before the fireworks begin. If you want to have one system that goes on being active for 10^{10} years, that is more difficult; I do not quite see how to do that.

MASSIVE ROTATORS IN GALACTIC NUCLEI

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ABSTRACT

Phenomenological similarities between the Crab Nebula and Quasi Stellar Objects are considered, and an attempt is made to account for both by the same general type of mechanism. The evolution of massive rotating objects with magnetic fields is studied and it is concluded that the most powerful Q S O may be related to rotators with masses of 10^8 — 10^9 solar masses and rotation time scales of no more than 10^4 — 10^5 seconds.

Several striking similarities exist between Quasi-Stellar Objects and active Radio and Seyfert galaxies on the one hand and the Crab Nebula on the other. In both relativistic particles and magnetic fields are generated with great efficiency, in both eruptive phenomena are seen to occur frequently (the wisps in the Crab) and in both the magnetic fields interact with gaseous filaments which are observed by their emission lines. In the case of the Crab Nebula a minimum of 2×10^{38} ergs/sec in relativistic electrons must be provided at the present time while the rotational energy of the rotating neutron star decreases by about 5×10^{38} ergs/sec with an uncertainty of a factor of 3 on account of the uncertainty in mass and model. Consequently the efficiency factor for electron acceleration is better than 10%. In both the energy spectra of the injected relativistic electrons are flat ($\gamma \approx 1.5$) and even the characteristic double structure of the radio galaxies may be rudimentarily present in the Crab Nebula, where the wisp activity has a strong directionality and where the highest optical isophotes suggest two concentrations of emission on opposite sides of the pulsar.

The dynamics of the shell of the Crab Nebula (WOLTJER 1970) indicate that the magnetic field is not very different from the equipartition value; the field geometry results in a net polarization of 8 per cent for the whole object and about 20 per cent for the inner parts, values very similar to those observed in the extragalactic objects.

The available studies make it seem doubtful that a 10% efficiency for electron acceleration can be achieved by a Fermi mechanism, a neutral line acceleration process, the (relativistic) hydrodynamic expansion of a supernova shell or stellar collisions. In the latter two typically only a few per cent of the total energy goes into relativistic particles and, because electrons and protons are basically accelerated to the same velocity, the electron energy is low. In the former two mechanisms much depends on the particular physical circumstances, but despite much effort no very satisfactory results appear to have been obtained.

However, acceleration by electromagnetic waves (OSTRIKER and GUNN 1969) can be rather efficient; in case of an electron — proton mixture about 8 per cent of the energy could go into electrons. The electromagnetic waves could be produced by a rotating non-axisymmetric magnetic field configuration (PACINI 1967). Even higher efficiency electron acceleration seems possible in the electrostatic fields generated by a rotating magnetized sphere (GOLDREICH and JULIAN 1969). In an electrostatic acceleration process electrons and protons can attain the same energy and the electrons could have 50% of the total particle energy. GOLDREICH and JULIAN also show that electrons and protons will follow different trajectories and that the resulting currents may account for the magnetic field in the Crab Nebula.

As a consequence of these and other considerations we and other investigators have independently speculated that a massive rotating object with a magnetic field could under suitable circumstances account for the acceleration of the relativistic electrons observed in the Quasi-Stellar Objects (MORRISON 1969, CAVALIERE, PACINI and SETTI, 1969). We wish to discuss here the way in which this general type of model may help in understanding the evolution of Seyfert galaxies and QSOs and to suggest some simple observations that could be, but have not been, made. We do not pretend to discuss a theory, but only to derive some order of magnitude estimates so as to see if such a model deserves closer study.

When rotating masses of galactic magnitude are involved we should expect that the objects ultimately are differentially rotating and mainly centrifugally supported. The objects would be flattened and the magnetic field structure can be expected to be complex and non steady. For our exploratory purposes we shall neglect all of these effects and consider a uniform spherical mass M with radius R, with a dipolar field of strength B and rotating with angular velocity Ω. Neglecting relativistic effects we have from the virial theorem

$$\Omega^2 R^3 = \frac{3}{5} GM \tag{1}$$

if the object is mainly in centrifugal equilibrium. From GOLDREICH and JULIAN (1969, eq 27*a*) we have for the angular momentum loss rate in case of an aligned dipole (field strength at pole B)

$$\frac{dJ}{dt} = \frac{2}{5} M \frac{d R^2 \Omega}{dt} = - \frac{1}{8c^3} \Omega^3 R^6 B^2 \tag{2}$$

If we consider instead the angular momentum loss from an inclined dipole rotating in a vacuum, only the numerical coefficient would be slightly changed. Integrating eqs (1) and (2) under the assumption that flux is conserved during the evolution of the object ($B = B_0 R_0^2/R^2$) we have

$$\Omega = \frac{\Omega_0}{(1 - t/\tau_0)^{\frac{1}{2}}} \tag{3}$$

with

$$\tau_0 = \frac{8c^3}{15} \frac{M}{B_0^2 R_0^4 \Omega_0^2}$$

with $t = 0$ corresponding to $R = R_0$ and $\Omega = \Omega_0$. Apart from the neglect of various important factors like differential rotation, non-sphericity and inhomogeneity, the most serious deficiency of equation (3) will arise from relativistic effects which become dominant when $\Omega R \rightarrow c$.

Assuming that the electromagnetic torque is associated with the acceleration of particles and that these particles radiate, the net efficiency factor being s, the luminosity becomes

$$L = \frac{1}{8c^3} s B_0^2 R_0^4 R^2 \Omega^4 , \tag{4}$$

or with L_0 corresponding to $t = 0$

$$L = \frac{L_0}{(1 - t/\tau_0)} \tag{5}$$

As the object contracts its luminosity increases until relativistic effects intervene. When that happens the object is close to the Schwarzschild radius and some further contraction will lead to collapse and rapid dimming. To obtain an order of magnitude estimate of the parameters we therefore take the most powerful QSOs to be objects with $R \backsimeq 2GM/c^2$. Setting $t = 0$ and adopting $L_0 = 10^{47}$ ergs/sec, $s = 0.25$ and $\tau_0 = 3 \times 10^5$ years we obtain

$$\begin{aligned} M &= 1 \times 10^8 \odot \\ R &= 3 \times 10^{13}\ \mathrm{cm} \\ B &= 1 \times 10^6\ \mathrm{G} \end{aligned}$$

While if we have to consider $L = 10^{49}$ ergs/sec in combination wth $s = 1$ and $\tau = 10^5$ years we have

$$\begin{aligned} M &= 1 \times 10^9 \odot \\ R &= 3 \times 10^{14}\ \mathrm{cm} \\ B &= 5 \times 10^5\ \mathrm{G} \end{aligned}$$

Changing the parameters, it is easily seen that $M \propto L\,\tau_0 s^{-1}$. Expanding the configuration from its present density to a density of 5×10^{-23} g cm^{-3} would lead to a field of 1×10^{-9} gauss in the first case and 1×10^{-8} gauss in the second; hence only a weak seed field need have been present in the galaxy in which the object formed. It should be emphasized, however, that these values refer to the large scale magnetic field component only. The value of Ω is 5×10^{-4} sec^{-1} corresponding to a period of 10^4 seconds in the first case, while for the $10^9 \odot$ object $\Omega = 5 \times 10^{-5}$ and the period is 10^5 seconds. It would be very interesting to search for optical variability on such a time scale. Because the real objects would rotate differentially no strictly periodic variations are expected and the amplitudes are likely to be small. The estimated periods are much shorter than those discussed by MORRISON (1969) and CAVALIERE, PACINI and SETTI (1969). MORRISON (1969) in particular has attempted to interpret KINMAN'S data on 3C 345 as indicative of a rotation period of the order of a year. In our view the data are still quite ambiguous. If again a comparison with the Crab Nebula is made we would rather compare the wisps with the outbursts on 3C 345.

Each massive rotating object will during its evolution increase its rotation rate and the total power emitted. With the luminosity law (5) we would expect for a steady state population of QSOs a luminosity fuction $n(L)$ which is proportional to $L^{-7/4}$. Qualitatively this increase towards lower luminosities is similiar to what was reported here by Dr. SCHMIDT. However his luminosity function is even steeper and this seems to imply — not unexpectedly — that a distribution of objects with different masses and magnetic fluxes is involved.

It is not clear how the typical — optically not particularly over luminous — Seyfert galaxies relate to our considerations. These objects are too numerous to connect them in an evolutionary fashion with the brighter QSOs. The frequency of the Seyfert galaxies indicates lifetimes of 10^8 years or more and the integrated luminosities may well exceed those of the brightest QSO. The long time scale and large total output could be obtained from a rotating object of rather large mass and comparatively low magnetic flux. In the case of NGC 1068, BURBIDGE, BURBIDGE and PRENDERGAST (1959) established an upper limit of $3 \times 10^9\ M_{\odot}$ on the mass of the central region; this might be just barely sufficient. However in the case of these long lived objects it is not at all obvious that the rotating object evolves at constant mass; accretion might be quite important, while if a "black hole" has developed near the center the process discussed here by Dr. LYNDEN-BELL could also contribute importantly to the energy generation. The main motivation for considering massive rotators with magnetic fields is the high efficiency of acceleration for electrons. There is, however, not much evidence for a large producton of relativistic electrons in objects like NGC 1068 and other processes may well contribute significantly to the energetics.

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SPINARS: A PROGRESS REPORT

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1. *Introduction*

We list patterns which recur in active galactic nuclei and in quasi-stellar objects:

a) Emission of highly non-thermal e.m. radiation was historically the first recognized. The energetic limits: 10^{47} erg/s and 10^{62} erg, still hold up after long scrutiny. The complete sounding of the infrared band may bring the limits up, in a few instances, to 10^{48} erg/s (3C 273), possibly to 10^{63} erg (Seyferts with 10^{47} erg/s and a guessed 10^9 yrs. lifetime) (KLEINMANN and LOW 1970).

b) Ejection of matter in various forms is increasingly recognized. The *IR* and optical radiation, and the recent x-ray observations (BOWYER *et al.* 1970, FRIEDMAN 1970) require matter at high $\frac{E}{Mc^2}$. Discontinuous radio-cloud activity in QSS (typically $\lesssim$ 1 $M_\odot$/year) and the outflow of mass from Seyfert nuclei (NGC 4151, even if revised) seem to involve comparable or higher masses, though at lower $\frac{E}{Mc^2}$. Jets (two striking examples are M 87 and 3C 273) and the double radio structures (two opposite extremes: Centaurus A, and 3C 33, suggestive of the baffling examples singled out by ARP (1966)) entail increasingly massive yet well-confined release of matter, ejected with low velocity spread.

c) Coherence: such directional structures hint strongly at some form of coherence. On the other hand, the quasi-periodic optical behavior of 3C 345 (both in intensity and in polarization plane, KINMAN *et al.* 1968, VISVANATHAN 1970, KINMAN 1970) points directly toward coherent rotation, and if accepted yields at least the magnitude of the period.

d) Concentration of activity centers (sometimes multiple as perhaps in the Cygnus A radio clouds) with dimensions down to 10^{17} cm is directly observed more and more often in the radio band. Similar or even smaller dimensions can surely be inferred from time variability.

Our working hypothesis, aimed at unifying the observations of the compact sources, is a picture of the basic phenomenon as highly coherent in both coordinate and momentum space. The first requirement is almost the defining property; a less evident corollary is a genetic relationship with the multiple and the clearly extended great sources. The second is, instead, a thermodynamic requirement, as long as one attempts to keep the overall energetics within the limits of conventional physics. From these premises, the spinar model for the dynamical cores of these sources follows. In essence, the model is a means to a delayed, not necessarily complete, collapse, bound to give off coherent energy and mass both continuously and in random bursts.

2. *The Spinar model*

By spinars we mean a class of bodies storing a considerable fraction of their total energy in a single, continuous degree of freedom - rotation; their luminosity is directly drawn from this ordered motion by way of a magnetic field (MORRISON 1969; CAVALIERE, PACINI, SETTI 1969; CAVALIERE 1970; WOLTJER 1970*). As gravitational machines, their principle is (deceptively) simple: unsupported masses collapse; conservation of angular momentum J increases the rotational energy as $W \sim 1/R^2$ and, as we shall see, any slow loss of J increases W as $1/R$, at the expense of the gravitational energy V; while conservation of magnetic flux increases the surface poloidal field, $B_s \sim 1/R^2$. This large field eventually provides the e.m. link to couple the rotational energy into the external world. Their overall efficiency as non-thermal radiators can be defined as $\eta \equiv$ non-thermal e.m. emission/Mc^2, to be conveniently factorized into $\eta = \eta_1 \eta_2 \eta_3$, with $\eta_1 \equiv |V|/Mc^2$, $\eta_2 \equiv W/|V|$ and $\eta_3 =$ e.m. *em.*/W. The presente of a Schwarzschild radius at R_s would limit $\eta_1 = R_s/2R$ to $1/2$ at most; however, post-Newtonian instability could set a lower limit. A purely rotational equilibrium $\alpha W + V = 0$ maximizes $\eta_2 \leq \alpha^{-1}$ ($\alpha \geq 2$). The last step, from rotational into e.m. energy, is expected to be very efficient for a near rigid rotation, since the reservoir has so high an "effective temperature". This is indeed confirmed in one case, the pulsars.

Pulsars are a very special subclass of spinars. They are in mechanical equilibrium, in that for $M < M_{\mathrm{Ch}}$, the Fermi pressure of particles (here neutrons) can take over support. This internal kinetic energy is largely frozen, and for conventional neutron stars with $M \approx 1\ M_\odot$ and $\rho \approx 10^{15}$

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* Rotating models have also been discussed by OZERNOY 1966 and PIDDINGTON 1967.

g/cm^3, the configuration has become stable and rigid at R about 3 × Schwarzschild radius, R_s They stored rotational energy during the initial collapse which gave them birth, and live ever afterwards on this stockpile, much as slowly braked flywheels. Even for the fastest spinning object — NP0531 — the observed rotation frequency Ω would be "slow" in this sense: $\Omega^2/G\rho \ll 1$, now and perhaps even in the past (Woltjer 1970): if so, the conversion from gravitational into rotational energy would not be very efficient here: $\eta_2 = \Omega^2_{\mathrm{MAX}}/G\rho \ll 1$. However, it is this best-known pulsar which suggests strongly a very high efficiency in the e.m. conversion of spin energy: $\dot{W} = I\,\Omega^2\,\dot{\Omega}/\Omega$ (with canonical $I = 10^{45}$ g cm^2, $\Omega \sim 190$ s^{-1} and $\dot{\Omega}/\Omega \simeq 1/2400$ yr^{-1}) results in a few times 10^{38} erg/s, i.e. a few times the total e.m. luminosity of the Crab Nebula.

Although the e.m. conversion is far from fully understood, it should be basically independent of the static equilibrium. It hinges essentially upon the presence of coherent large-scale electric fields near the body, whether of "electrostatic" (Goldreich and Julian 1969) or radiant "e.m." (Deutsch 1955, Pacini 1967, Gunn and Ostriker 1969) and hydromagnetic origin. On the other hand, the striking analogies between the phenomena of the Crab Nebula and those in extragalactic sources (making allowance for the huge overall scaling) are well-recognized (Woltjer 1966, 1970): injection of relativistic electrons with a flat energy spectrum and corresponding emission of nonthermal e.m. energy, high concentration of the energy source, line-emitting regions; possibly mass loss ($\Delta M/M \approx 10^{-10}$ yr^{-1} for NP0531), jets and bursts, and even periodicity. Something like a displacement of accent is apparent, however: the more powerful sources show on the whole far less complete coherence, less periodicity, less rigidity, but more emission of jets and of diffuse matter.

Centers of activity in QS and galactic nuclei can be examined from the point of view of a parametric sequence of spinars of decreasing activity. A single object with $\lesssim 10^{62}$

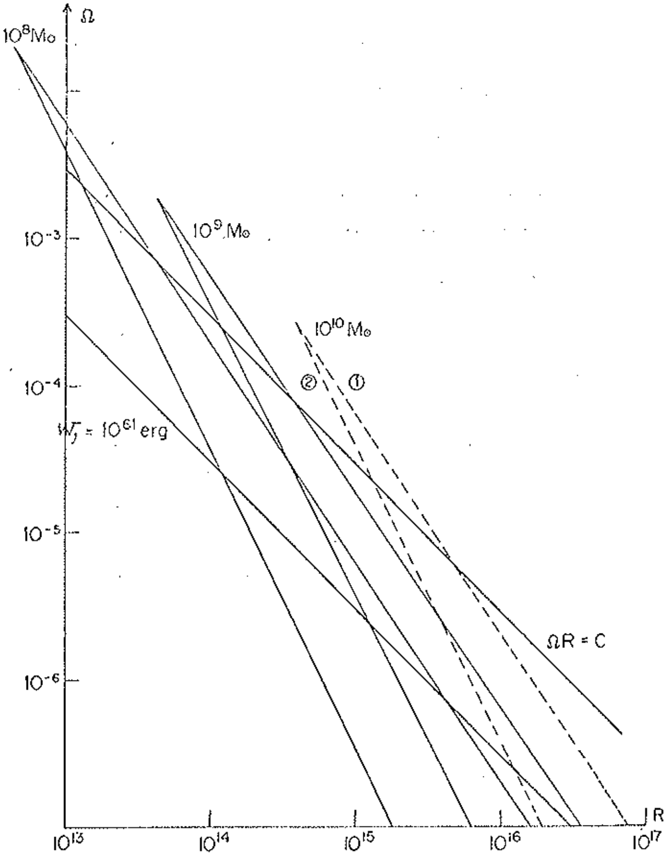

FIG. 1 — For each of three mass values, two lines (drawn from limiting models) roughly define a triangular region of possible evolution in the radius - angular velocity plane. The upper line (curve 1 and parallel to it) is the limit of rotational stability, $\Omega \approx \sqrt{G\rho}$; the lower (curve 2) is the limit for a high-entropy supermassive star (WAGONER 1969). Two other lines (of equal slope) mark the bound for peripheral speed, $\Omega R = c$; and a locus of constant rotational energy for $M = 10^9 M_\odot$.

erg must have $M \approx 10^9\, M_\odot$ if it reaches $R \approx 3\, R_s$ with efficiency $\approx 10\%$. The other extreme, a swarm of $\approx 10^9$ separate pulsars closely packed, does not improve the ratio $\frac{\text{total energy}}{\text{total mass}}$ and poses all but insuperable problems of synchronization. We will be mainly interested in clusters of one single to a few massive Spinars, with $M/M_\odot \gg 1$.

As long as they are observable, massive spinars must be *evolving*. Their luminosity L is extracted solely from W; for approximately rigid motions, the angular momentum decreases as $\dot{J} = T \approx - L/\Omega$. Since J or W determine the secular equilibrium, the massive spinars are forced to evolve by any loss of J. Their evolution must imply contraction — except possibly for short violent episodes — so that gravitational energy is continuously made available throughout this "quasi-static" stage of their life. In the following, our aim will be limited to some preliminary considerations and orders of magnitude relevant to separate stages of evolution; here we consider mainly the limit of rigid rotation, whereas in real life some differential rotation can be inevitable, or in fact necessary for extended stability.

3. *Formation*

The spinar sort of conditions can be conceivably reached along different evolutionary lines.

The formation of a high entropy supermassive object, from a supermassive cluster of stars at the center of a galaxy, is reviewed in this volume by Spitzer (1970); rotating supermassive stars are dynamically unstable to collapse at large radii (Wagoner 1969), but fare better if differentially rotating. Low entropy, thin disks are thought to resist much better in the relativistic regime, but fragment easily (Wagoner 1969).

We explore briefly an alternative evolution line, which could wholly or mainly by-pass the completely fragmented stage into stars and retain coherence in space and in energy. Here the problems are to some extent complementary to those of evolution of pre-protostars (see MESTEL 1965, BIRD 1964); the uncertainties are obviously greater·

Continued collapse from an initial dispersed state requires gravitational boundedness:

$$(1) \qquad m_i + V_i < 0 ,$$

$$\text{with } m = \frac{B^2 R^3}{3} \equiv \frac{\Phi^2}{3R} \text{ and } V = -\frac{3}{5}\frac{G M^2}{R} . \quad \text{(isotropy)}$$

This sets a minimum mass for given B_i, ρ_i:

$$(2) \qquad M > \frac{1}{50}\frac{1}{G^{3/2}}\frac{B_i^3}{\rho_i^2} ;$$

or equivalently requires that the transit time t_{ci} of magnetic disturbances across R_i exceeds the time for the free collapse, as necessary to break magnetic communication:

$$(3) \qquad t_{ci} > \frac{1}{\sqrt{G\rho_i}} .$$

Note that $t_c \sqrt{G\rho} \sim \rho^{2/3}/B$, again for spherical collapse. This quantity is conserved to the extent that the flux $\Phi \sim B/\rho^{2/3}$ is frozen. This suggests that if the body ever later on undergoes dynamical variations with a characteristic time as short as $1/\sqrt{G\rho}$, it cannot maintain coherence.

Continued collapse requires also:

$$(4) \qquad 2\, W_i + V_i < 0 .$$

As long as J is conserved, however, and the contraction can proceed, this condition must break down since $W/V \sim 1/R$; the corresponding density is $\rho_{eq} \approx \rho_i \; (6 \; G \; \rho_i/\Omega_i^2)^3$. Here azimuthal rotational support is reached, while axial collapse proceeds; the object tends to flatten.

The subsequent evolution is likely to depend on the geometry of the magnetic field. If $\boldsymbol{B} \parallel \Omega$, preferential motion along the field, assisted by the anisotropic gravitational field, can lower $B/\rho^{2/3}$; the critical mass falls well below the initial value, communication is lost, and extended fragmentation is expected: this starts the formation of a supermassive cluster of strongly magnetic objects. But in the other case, $\boldsymbol{B} \perp \Omega$, flow along B is counteracted by the centrifugal forces if the initial configuration is prolate about B; contraction along Ω (or even in two dimensions perpendicular to $\boldsymbol{B}$) increases $B/\sqrt{\rho}$, and increases $\sqrt{G\rho}$ also, but so that fragmentation is opposed and longitudinal communication is slightly improved. The axial halt occurs once the corresponding communication time reaches the value $t_{c\parallel} \approx 1/\sqrt{G\rho}$; the longitudinal support is centrifugal. Configurations of the type of quasi-Jacobi ellipsoids or quasi-McLaurin spheroids of MESTEL (1965), which satisfy this condition, shrink homologously for slow changes of J and are therefore as resistant to fragmentation as initially; but their overall stability, both dynamical and magnetic, is still largely unexplored (*).

Average conditions of Galactic medium set into the limiting relation (2), say $B_i \approx 3 \times 10^{-6}\, G$ and density $\rho \lesssim 1$ hydrogen atom per cc, would give initial masses up to about 10^6 to $10^7\, M_\odot$. "Normal" galactic nuclei seem to be close to these values. Very massive spinars require conditions slightly different (higher B_i^3/ρ_i^2) if they are not to exceed the critical

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* Note that the condition $t_c > \Omega^{-1}$ ($\approx 1/\sqrt{G\rho}$, see eq. 8) or $V_r > V_{\text{Alfvén}}$ would allow for some differential rotation against B (OZERNOY 1966).

mass by a large factor; it is tempting here to speculate about a limited fragmentation, sometimes halted by way of axial readjustment, if $\boldsymbol{B} \perp \Omega$. We do not believe however that the above order-of-magnitude estimates can be carried that far; nor does the knowledge of the conditions of interstellar matter in other galaxies warrant it. Continued accretion can be important, too. We rather point out that such large pre-protostars can try to form only at the center of galaxies since tidal forces would tend to tear them up at any other location. (Outside of the center, we might expect smaller, short lived, low power coherent objects (HUGHES 1969)). It is possible that early conditions in big ellipticals favor the condensation of large mass with high fields, corresponding to the comparatively rare active quasars; the range of spinar masses is perhaps less than the spread over four decades in the masses of known galaxies. It has been proposed (REES 1970, SHKLOVSKII 1969) that the narrow absorption lines of the quasars originate in a filament of gas which was once part of the main body. If so, then the main bodies must contain heavy elements, and reflect the presence of some star formation before the spinar formed. This suggests that spinars formed in galaxies after at least one early generation of stars had lived out its life (OZERNOY 1966).

4. *The quasi-static evolution*

After reaching an equilibrium configuration, the body is coupled to the external world by the flow of angular momentum and energy, both material and e.m., and perhaps also by radiation of gravitational waves.

For very weak poloidal field B_s, the outflow of angular momentum is entirely due to the thermal "wind". A finite value of $\frac{\text{magnetic stress}}{\text{material stress}}$ mixes the material and e.m. angular momentum. The detailed mechanisms differ: when $\boldsymbol{B}_s \perp \Omega$, flow of radiation — e.m. or hydromagnetic — from a critical surface, inside of which the field is static; when $\boldsymbol{B}_s \parallel \Omega$ instead, flow of mass, slung out and enforced to corotate, with the accompanying magnetic tension, up to a critical surface where disconnection occurs.

However, the magnitude of the torque

$$(5) \qquad T = \frac{\Phi_s^2}{v_c}\, \Omega\, \eta$$

and the associated luminosity $L \approx T\,\Omega$, depend mainly on the structure of the average field inside the critical surface through the shape factor: $\eta = 1$ for nearly radial field, $\eta = (R/R_c)^2$ for dipolar field; R_c is the equatorial radius of the critical surface (an implicit function of B and Ω); v_c is the velocity of magnetic communication there (again depending on B, Ω). In the relativistic limit $v_c \rightarrow c$, $R_c \rightarrow c/\Omega$ holds, and the expression for T, eq. (5), can be made explicit, with the corresponding characteristic times for loss of angular momentum $\tau \approx W/L$:

$$T \approx \frac{\Phi_s^2}{c}\, \Omega\,, \qquad \tau \approx \frac{Rc}{v_b^2} > \frac{R}{v_b} \qquad \text{radial field;}$$

$$(6)$$

$$T \approx \frac{\Phi_s^2}{c^3}\, \Omega^2 R^2\,, \qquad \tau \approx \frac{Rc}{v_b^2}\,\frac{R}{R_s}\,\frac{G\rho}{\Omega^2} > \frac{R}{v_b} \quad \text{dipolar field;}$$

($v_b \equiv B/\sqrt{4\pi\rho}$). It is plain that loss via e.m. torques is slow compared with communication times. The corresponding losses of J are unlikely to modify the initial collapse.* Once the body has reached rotational support, evolution is driven quasi-statically by just those losses. The evolution therefore implies *spin up*. If the shape is constant and $R \sim k\,\Omega^{l}$ then, as long as $\Omega_s \approx$ const:

$$\dot{\Omega} \simeq -\frac{1}{2\,l+1}\,\frac{\Phi_s^{\,2}}{f\,M\,c\,k^2}\,\Omega^{1-2\,l}\,\eta\,. \tag{7}$$

Note that $l = -1/2$ corresponds to $J =$ const, and $l = -2/3$ corresponds to $\Omega \approx \sqrt{G\,\rho}$, that is, to pure rotational support:

$$2\,W + V = 0\,. \tag{8}$$

The mass loss in eq. (8) is only important for $B = 0$ and for rotation near the Jeans frequency; then $\rho =$ const (and $\Omega =$ const) holds. For $B \neq 0$ and $l < -1/2$, spin up occurs, $\dot{\Omega} > 0$. (Compare with the case of the pulsars, whose rigidity corresponds to the value $l = 0$ so that $\dot{\Omega} < 0$).

In particular, for the relativistic torque relation the evolution is given explicitly by:

dip. field

$$\Omega = \frac{\Omega_0}{\sqrt{1 - t/\tau_0}}\,; \quad R = R_0\,(1 - t/\tau_0)^{-l/2}; \tag{9}$$

$$L = \frac{L_0}{(1 - t/\tau_0)^{l+2}}\,; \quad B_c = \frac{B_{c0}}{(1 - t/\tau_0)^{\frac{l+3}{2}}}\,; \quad J = J_0(1 - t/\tau_0)^{-(l+1/2}$$

$$\left(\tau_0 = \frac{|\,2\,l+1\,|}{2}\,\frac{f\,M\,c^3}{\Phi_s^{\,2}\,\Omega_0^{\,2}}\right).$$

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* During early collapse, loss of J by twist of magnetic lines is also slower than freefall.

For $l = -2/3$ (centrifugal equilibrium): $-l/2 = 1/3$, $l + 2 = 4/3$,

$$\frac{l+3}{2} = +7/6, \left(l + \frac{1}{2}\right) = -1/6.$$

See also Appendix.

rad. field

$$\left(\tau_0 \equiv \frac{|2l+1|}{|2l|} \frac{f\,Mc\,R_0^2}{\Phi_s^2}\right) ; \quad \Omega = \frac{\Omega_0}{(1 - t/\tau_0)^{1/|2l|}} ;$$

$$R = R_0\,(1 - t/\tau_0)^{1/4};$$

$$L = \frac{L_0}{(1 - t/\tau_0)^{1/|1l|}} ; \quad B_c = \frac{B_{c0}}{(1 - t/\tau_0)^{1/|l|}} ;$$

$$J = J_0\,(1 - t/\tau_0)^{|(2l+1)/2l|}$$

again for $l = -2/3$: $1/|2l| = 3/4$; $1/|l| = 3/2$;
$|2l + 1|/|l| = 1/4$.

We stress that the spinar model leads to an evolution in which the oldest object tends to become extreme; the power emitted and the magnetic field at the critical surface both formally diverge at a finite time. If a reasonable fraction of this power is given to relativistic electrons, a source with continuously *increasing* injection (and higher magnetic fields) would result. This "catastrophe" is Newtonian; if however this evolution could proceed unperturbed, it would lead eventually to a general-relativistic, rotating (but with $J(t) \to 0$) collapse.

We refer to WOLTJER'S discussion in this volume for added detail on these points. Let us here emphasize the differences between his view and ours, not because we do not agree, but rather because we *do* broadly agree. We list two open points:

i) The evolutionary curve:

He prefers to use a definite model of the torque as a function of the spinar rotation frequency, field and size. We would incline to leave this somewhat more open, because it

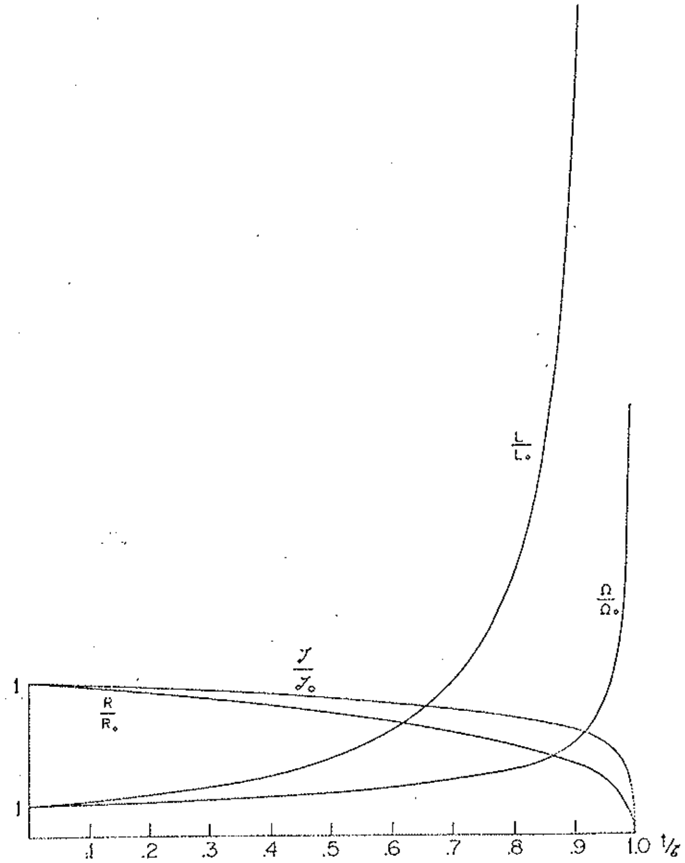

FIG. 2 — Plot of equations 9.

may well be affected by field configurations. This does not lead to qualitative differences.

ii) The normalization:

He prefers to fix spinar size by identifying the brightest objects we now see with objects very far evolved, at the relativistic limit. This clearly increases $\eta_1 = V/Mc^2$; therefore small masses, small sizes, small magnetic fluxes, and high spin frequencies obtain. On the other hand, such objects may pass through a highly fragmented state; they may suffer increasing magnetic shear; they evolve into the truly relativistic regime, where lifetime may be cut off. We prefer to take the hint given by 3C 345 (which is strengthened by the recent results of T. KINMAN and N. VISVANATHAN) which puts our typical spin speed lower and our masses larger, with radii staying above the relativistic limit. This difference is significant for the whole parameter range. Only more observations can settle the issue.

5. *Mass loss, instabilities*

The observed phenomena require that a smooth average course, as described, be accompanied by a continuous mass loss, and be disturbed as well by faster fluctuations, in particular by impulsive mass losses, on any scale up to a major splitting. The model implies similar processes.

Note first that, if the body remains "cold", instabilities (PARKER 1967) will coarsen the surface magnetic field into smaller tongue-like structures with correspondingly shorter life. Only at some distance from the body can we approximate by a spatially smooth field increasing slowly in time.

Continuous mass loss is intimately connected with the very process of loss of J. A self-consistent evaluation of the mass loss in the relativistic limit is not yet available, for we know no proper theory of a relativistic electro-magnetically driven wind.

On approaching the Jeans frequency, the centrifugal forces accelerate the flow to very high velocity, thus increasing the loss of angular momentum. Oscillations set in; a small amplitude analysis of fast motions (for which $J \approx$ const) of a "cold" body near the slowly-varying Jeans frequency, gives a characteristic time $\approx 1/\sqrt{G\rho}$ below which the body cannot deform coherently (see eq. 3), at least along the field. Equatorial release of large masses is expected, especially from the tips of any ellipsoidal configurations; after this, the body can bounce away from the Jeans frequency. These phenomena at the smaller scales can be associated with the van der Laan radio-burst clouds (VAN DER LAAN 1966, KELLERMAN and PAULINY-TOTH 1968).

We recall another mechanism often proposed (KARDASHEV 1965, PIDDINGTON 1966, OZERNOY 1966, STURROCK and FELDMAN 1968) for acceleration of diffuse mass along the polar axis. Winding up of the magnetic lines increases the magnetic pressure as $\frac{B^2}{8\pi} \approx \Phi_s^2\ t^2\ \Omega^2/d^4$ (d is the distance of the ejected mass from the main body), and the total kinetic energy of the ejected mass remains greater than the driving magnetic energy. This mechanism tends to accelerate masses axially out of both poles of a primary body. It suffers however from the Rayleigh-Taylor instability, except perhaps for *large* enough self-gravitating masses. It is appealing to associate with this process a morphology as suggested by Centaurus A: repeated diffuse axial bursts.

Five sorts of mass loss are therefore open to such bodies:

1. The steady loss of mass in diffuse form by spinning off. This may be extended to include the oscillatory loss of clouds or tongues.

2. The large sudden axial loss of mass by magnetic thrust.

3. Equatorial loss of small secondary spinars, the process perhaps seen in the jet of M 87, and possibly in other jets. Small secondary sources appear to exist along the jet of M 87, at least in the radio; they have been suggested even optically (DE VAUCOULEURS). Continuous acceleration of elec-

trons on the spot would make lifetime problems easier (cf. BURBIDGE 1970).

4. Equatorial splitting — binary fission — into two secondary spinars. This can take place only if the secondaries release enough gravitational energy for the overall separation to infinity by changing shape back toward the spherical form, or if they come off very much excited, so that their kinetic energy content (and binding) are high. These spinars we expect are now spinning within the twin large radio clouds seen in 3C 47, or in many radio galaxies. Objects like 3C 47 or 3C 9, which have two large distant radio clouds plus a strong condensed central optical source, may have contained a close cluster of a few spinars to begin with, only one of which has fissioned.

5. The more or less isotropic explosions, like those in NGC 1275, and perhaps in M 82, might be of nuclear or even thermal origin; they are much smaller in energy content than those of the radio galaxies or quasars.

6. *The end*

What dynamical evolution ends the e.m. life of these bodies is very speculative. One other speculation stems from the ground that an unperturbed quasi-static contraction caused by any poloidal B_s must lead eventually to relativistic conditions. This regime is interesting but poorly known. The simple weak-field approximation would indicate that gravitational radiation can overwhelm the other emissions and suddenly reduce the rotational Q value to the neighborhood of unity. The magnitude of the gravitational torque on a body of eccentricity ε is

$$T_g \approx 6\varepsilon^2 \frac{G}{c^5} I^2 \Omega^5 ,$$

so that the associated characteristic time is:

$$\tau_g = \frac{W}{T_g\,\Omega} \approx \frac{R}{\varepsilon^2 c}\left(\frac{c}{\Omega R_s}\right)^2 \frac{G\rho}{\Omega^2}\ .$$

The ratio $T_g/T \approx \varepsilon^2 W/B_s^2 R^3 \left(\frac{\sqrt{G\rho}\,R}{c}\right)^2$ becomes large in the relativistic regime, if ε remains appreciable. Likewise $\tau_g \sqrt{G\rho} \approx 1/\varepsilon^2\ (c/R_s\,\Omega)\ (c/R\,\Omega)^2$ approaches unity. The radiation reaction, for incompressible fluids, tends to decrease ε but the limiting spheroidal configuration is secularly unstable (CHANDRASEKHAR 1970). If, however, τ_g matches the communication time, one suspects that an elongated configuration may directly lose equilibrium under this sudden, violent, differential radiative braking. It is still conjectural that such an event could imply splitting; however, only a closely axisymmetric configuration would be expected to undergo a steep but smooth dimming of the observed $L\ (t)$ and a decrease of observed $\Omega\ (t)$ after a maximum. Here the integrated e.m. output can approach Mc^2 itself, but the maximum luminosity lasts only a matter of years (cf. HOYLE and FOWLER, 1965).

A fraction at least of the initial mass would eventually reach a "black-hole" type of configuration. A spinning black hole may become the sink of a protracted emission drain on the rest of galactic matter, in the mode proposed by Lynden-Bell (LYNDEN-BELL 1969).

But another wholly different end-point is not hard to foresee, even if splitting and the birth of twin objects is avoided. The visibility of a spinar is due to the external poloidal magnetic fields rooted in the plasma. The large torques which accompany high spin rates and lumped ejections must affect these fields, stressing the plasma roots. It is plausible that these stresses would in time be relaxed by various field-smoothing motions, resulting in a field which was almost entirely toroidal, so that it exerted little external torque ($\sim \Phi_s^2$) and no longer conducted fast particles outside the spinar itself. Then the spinar would become "silent" to all our detectors. This would represent a decline of the rate of rotational work after reaching some maximum L_M (t) just *this* side of relativistic collapse. The life-time of the object would then rise by several orders of magnitude after a modest change of magnetic configuration. It will require detailed knowledge to detect such silent spinars in the hearts of galaxies by their small residual emissions, by an occasional instability, or by their gravitational effects.

7. *Thermal Properties*

A "cold" evolution, where the support is mainly non-thermal, at least in two dimensions, is bound by limits which become stringent for $M > 10^9\ M_\odot$. It is useful to follow, as one limit, the thermal history of a nearly spherical object on a diagram of the excess $F = 2\ W + V$ over a purely centrifugal equilibrium (see figure 3), although the real object becomes strongly flattened and possibly differentially rotating.

During the initial collapse, transparency is able to dispose of any internal thermal energy by radiation. The contraction kinetic energy at halt, however, remains of the order of F_M. Again this is disposed of radiatively, unless adequate opacity is reached before the end of this phase, in which case the dissociation and ionization of the gas could absorb all of it only if $\frac{1}{3}\ V_o^2/W_o <$ energy for (dissociation + ionization). The alternatives depend on factors like the presence of grains, on which no information is available. After complete ionization, even electron scattering is adequate and the diffusion time $\tau_d \approx \sigma_T/4mc\ M/R$ is close to the evolutionary times. The adiabatic increase of thermal energy could balance the rotational along a "cold" Jeans path only for compression ratios $R/R_0 \approx K\, T_0\, R_0/GMm$.

It is here that the objects discussed differ most from the classical weakly rotating super-massive stars discussed by Fowler (FOWLER 1966) (see also FAHLMAN 1970). In those objects the support is thermal; nuclear energy release and high thermal radiation density play a sizeable role in evolution.

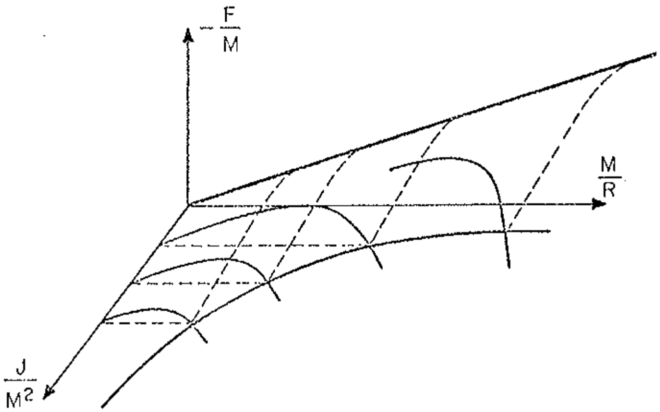

FIG. 3 — Plot of $\frac{2W+V}{M} \equiv \frac{F}{M}$ for a spherical body. For $J \neq 0$ along any path J = const there is a maximum of F, $F_{\max} = \frac{1}{4}\frac{V_0^2}{W_0}$ at $V_{\max} = \frac{1}{2}\frac{V_0^2}{W_0}$.

Such thermal luminosity can constitute a problem from the observational point of view, and for high efficiency in non-thermal emission. A "good spinar" would draw its emission rather from macroscopic, ordered kinetic energy.

The cold evolution is threatened mainly by non-adiabatic inflow of energy. We have seen that the rotational motion is at least transalfvenic; considerable alterations of state which took place in one period might induce shocks and thereby dissipate much flow energy into heat. Snapping of the lines of force after flinging out lumped masses can originate such non-adiabatic increase of internal energy, to be adiabatically enhanced further on. Thus a limit can be set for the amount of mass impulsively ejected during cold evolution; We might place this limit at $10^7\ M_\odot$ for an object of $10^9\ M_\odot$, $B_s \approx 10^5\ G$, emitting bursts of $\approx 10^{55}$ erg, and $\approx 1\ M_\odot$.

Conclusions

The model is far from complete. At this stage, it includes various possibilities for evolutions, for instabilities, for final states. In part, this may conform to the nature of the wide class of the objects to be covered: but in fact, closer scrutiny is needed; not everything will come from the model!

The major problem open is to bound more closely the overall efficiency. High values of η_1 require approaching the relativistic conditions, but then the value of η_2 may decrease. Dynamical stability and dynamical coherence seem to be sometimes complementary: disks as contrasted with supermassive stars are one example; and differential rotation while increasing dynamical stability also increases dissipation, if only through continuous building of large toroidal field energy. Magnetic axial support needs analysis.

We can count to the credit of the model:

i) condensation in space: by definition.

ii) efficient non-thermal emission: by analogy with pulsars and by a general thermodynamical argument.

iii) the life-time T and total luminosity L of QS can be made consistent with plausible conditions: $M \leqslant 10^9\ M_\odot$, $B \lesssim 10^5\ G$, $R \lesssim 10^{17}$ cm, with initial conditions numerically not far from Galactic type.

iv) a parametric sequence including "normal" galactic nuclei, Seyferts and QS appears possible in principle.

v) time variations, periodic and aperiodic: see section 5.

vi) mass loss and morphology: continuous and burst-like mass losses are accounted for quite naturally. Jets and knots, widely felt to require local acceleration of particles and gravitational confinement, are explained by the presence of secondary spinars; the dynamics of such dramatic ejections is unclear. It may be easier to understand axial, extended clouds. Probably the more isotropic explosions (like NGC 1275 and perhaps M 82) have a different origin still.

vii) A typical spectrum radio: IR, optical and x-ray, can be accounted for within the physical conditions of the model, see CAVALIERE, MORRISON and PACINI 1970 and figure 4.

viii) A rather steep luminosity function follows from $L\ (t)$: for a dipolar field, $\dfrac{\mathrm{d}N}{\mathrm{d}L} \sim L^{-1.75}$ as discussed in WOLTJER 1970; steeper functions obtain for multipolar fields.

APPENDIX

We put on record some relationships, easily derived from equations 5, 7, 8, 9, for the dipolar field model, to connect any observed periodicity Ω, and e.m. luminiosity $L_{\mathrm{e.m.}}$ (η_3 is

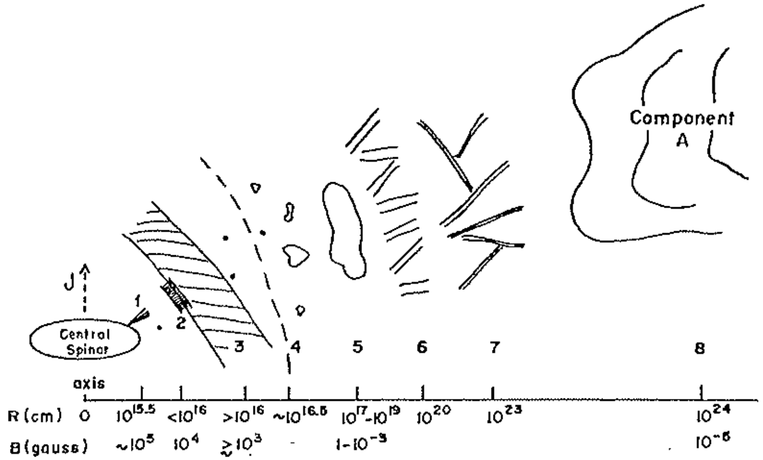

FIG. 4 — Schematic diagram of a typical strong source (not to scale; also, the actual sizes of 3C 273B can be slightly larger). Numbered regions are as follows: 0, spin axis: spinar with angular momentum J, mass $\approx 10^9 M_\odot$; $\Omega \approx 10^{-7}$ sec^{-1}. 1, surface of spinar: poloidal field enhancement. 2, synchrotron emission of infrared. 3, Compton-recoil emission of optical and X-ray continua. 4, critical surface $R_{cr} \approx c/\Omega$. 5, radio-burst clouds, radiofrequency emission (expanding as they move out) (VAN DER LAAN 1966). 6, emission-line optical source, excited gas filaments (OSTERBROCK and PARKER 1966). 7, absorption-line optical source, fast-moving cooled gas filaments (REES 1970). 8, weak-field synchrotron plasma, radio frequency mainly $\lambda > 1$ m. Particle acceleration continues throughout region 2, and perhaps beyond. The general B field falls about as $1/r^2$ or $1/r^3$ (or steeper for multipoles higher than dipole) until the critical surface is reached; outside that, it is mainly toroidal, and falls as $1/r$. The whole volume is traversed by a large output of relativistic protons.

the efficiency for converting rotational into e.m. energy) with constitutive parameters of the body:

$$R \approx 5 \times 10^8 \, \Omega^{-2/3} \, (M/M_\odot)^{1/3} \ ,$$

$$L_{\mathrm{e.m.}} \approx \eta_3 \, 2 \times 10^{21} \, B^2 \, (M/M_\odot)^2 \ .$$

The time scale for evolution at the observed stage is

$$\tau \approx 10^{21} \, \Omega^{2/3} \, B^{-2} \, (M/M_\odot)^{-1/3} \text{ yrs} \ ,$$

to be related with the statistics; $\tau_o = \tau\, \Omega^2/\Omega_o^2$ is the scale of a "latent" quasi-static evolution, after reaching the equilibrium up to the present stage.

The total energy emitted is

$$\Delta E_m \simeq 3\, L_o\, \tau_o\, R_o/R_m = W_m = \frac{V_m}{2}$$

up to the time t_m when a dimming begins. Obviously $\Delta E \simeq 3\, L\, \tau = W = V/2$ is, before dimming, a lower bound to the total energetics. Note also

$$V \approx 10^{51}\, \Omega^{2/3}\, (M/M_\odot)^{5/3} \ .$$

The above estimates neglect geometrical factors in front of T, of GM^2/R and $1/2\, MR^2\, \Omega^2$.

A choice fitting 3C 345 data could be $\Omega \simeq 3 \times 10^{-7}\, s^{-1}$, $M \approx 3 \times 10^8\, M_\odot$; $Bs \approx 10^4$ Gauss; $R \approx 5 \times 10^{15}$ cm, $L \approx 2 \times 10^{46}$ erg/s ($\eta \approx 10\%$), $\tau \lesssim 10^6$ yr.

A powerful ($L \approx 10^{49}$ erg/s) object would need $Bs \approx 3 \times 10^4$ Gauss, $M \approx 10^9\, M_\odot$ and would live $< 10^5$ yr at *that* power level.

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ROTATION & PULSATION PERIODS FOR PULSAR MODELS OF QUASARS

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In diagnosing pulsar-like symptons in quasars, MORRISON, WOLTJER and CAVALIERE, PACINI & SETTI have revived interest in rotating supermassive stars ($M > 10^6\ M_\odot$) which HOYLE and I suggested early in 1963 as possible sources of energy for strong radio sources and, after their discovery, for quasars. In our first discussions of rotating supermassive stars we noted that angular momentum problems must arise during contraction and that angular momentum and rotational energy would necessarily be transferred to surrounding material. At the same time, in the presence of magnetic fields, electromagnetic processes would generate radiation and relativistic particles. Our mechanism for this involved the toroidal winding of the magnetic field between the star and the surrounding material. Following HOYLE, NARLIKAR & WHEELER, GOLD and PACINI, this idea has been replaced, in current fashion, by radiation and acceleration involving the rotation of a field as simple as that of a dipole but with retardation effects at the velocity of light circle.

Through the work of FEYNMAN, CHANDRASEKHAR and myself it soon came to be realized that non-rotating supermassive stars suffered from a general relativistic instability which led to hydrodynamic collapse early in their evolution. In order to achieve life times for hydrostatic stability of the order of 10^6 years DURNEY & ROXBURGH and I investigated rotational effects and found that uniform rotation would stabilize masses of the order of 10^6 $M_\odot$. In addition I found that differential rotation would stabilize masses of the order of 10^9 $M_\odot$. These studies led to estimates for the rotation and pulsation periods of supermassive stars of the order of several tens to a few hundred days. A brief review of these results (1) is in order at this time because the periods are somewhat greater than those just discussed by WOLTJER. It may prove significant that they are of the order of the periods attributed to the light variations in 3C 345 and other quasars which MORRISON has discussed here and in previous publications.

As is usually done I took it that angular momentum loss commences when

$$\omega_R^2 R^3 = \alpha^2 GM$$

and maintains this relation thereafter. The notation is standard except that ω_R is the peripheral, equatorial angular velocity in the case of differential rotation and α is of the order of unity or somewhat less and is model dependent. For STOECKLY's differential rotation with cylindrical symmetry, $\alpha^2 = 0.456$, which is the value I have used. The rotational period can be written as

$$P_R = \frac{2\pi}{\omega_R} = \left(\frac{32\pi^2}{x^3}\right)^{\frac{1}{2}} \frac{GM}{\alpha c^3}$$

$$= 1.3 \times 10^{-4}\, x^{-3/2} \frac{M}{M_\odot} \text{ sec.} = 1.5 \times 10^{-9}\, x^{-3/2} \frac{M}{M_\odot} \text{ day}$$

where

$$x = \frac{R_s}{R} = \frac{2\,GM}{R\,c^2}$$

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(1) For details of these calculations and for relevant bibliography see W.A. FOWLER: Proc. Inter. School of Physics "Enrico Fermi", Varenna 1965, High Energy Astrophysics (Academic Press, New York, 1966) p. 313.

is the ratio of the Schwarzschild radius, R_s, to the coordinate radius, R.

The binding energy of a rotating supermassive star with STOECKLY's differential rotation in hydrostatic equilibrium reaches a maximum at $x \approx 1/9$ or $R \approx 9R_s$. At this point further energy cannot be emitted without the star undergoing hydrodynamic collapse on a relatively short time scale. Thus the long time scale regime of interest involves $x \lesssim 1/9$ and one-half of this maximum, $x = 1/18$, is characteristic of this regime. This leads to

$$\begin{aligned} P_R &\approx 10^{-2} \frac{M}{M_\odot} \text{ sec.} \\ &\approx 10^{-7} \frac{M}{M_\odot} \text{ day} \end{aligned}$$

Some evidence for a rest frame period of 200 days has been found for 3C 345. The mass required for this according to the above expression is $M = 2 \times 10^9 M_\odot$.

The fundamental mode of radial pulsation of a star has a period which depends critically on its physical properties, in particular, on CHANDRASEKHAR's adiabatic coefficient, $\Gamma_1 \equiv - dln\, p / dln\, V$. For a supermassive star the main pressure support is due to radiation and $\Gamma_1 \approx 4/3$. In this case one finds

$$\left(\frac{\sigma}{\omega_R}\right)^2 = \left(\frac{P_R}{\Pi}\right)^2 \approx \frac{2}{3}\left(\frac{K}{k}\right)^2 \left[1 - 4\left(\frac{\zeta}{K^2 \alpha^2}\right) x \right]$$

where σ is the pulsational angular frequency, Π is the pulsational period, k is the dimensionless radius of gyration, K is an 'effective' radius of gyration for differential rotation and ζ is a measure of Post-Newtonian general relativistic effects. With $\Gamma_1 \approx 4/3$ supermassive stars can be treated approximately as polytropes of index 3 for which $k^2 = 0.075$ and $\zeta = 1.265$. STOECKLY's model for differential rotation with cylindrical symmetry for poytropes of index 3 yields $K^2 = 2.47$. Thus

$$\left(\frac{P_R}{\Pi}\right)^2 \approx \frac{2}{3}\left(\frac{K}{k}\right)^2 \left[\,1 - 4.5\,x\,\right]$$

$$\approx \left(\frac{2}{3} \rightarrow \frac{1}{3}\right)\left(\frac{K}{k}\right)^2 \approx 22 \rightarrow 11 \qquad \text{for} \quad 0 \leqslant x \leqslant 1/9$$

$$\approx \frac{1}{2}\left(\frac{K}{k}\right)^2 \approx 16 \qquad \text{for} \qquad x = 1/18$$

Thus $\Pi \approx P_R/4 \approx 50$ days for 3C 345, which is interesting in that some evidence for a rest frame period of this value has also been found.

It is to be emphasized that the results just described are quite different than the customary results for uniform rotation ($K = k$) without the general relativistic corrections, namely $(P_R/\Pi)^2 = 2/3$. In addition the first order term in (P_R/Π) is independent of the uncertain parameter α. However it is quite sensitive to the polytropic index. At $x = 0$, $P_R/\Pi = 2.2$, 4.8 and 15.0 for $n = 2$, 3 and 4 respectively. It is of crucial importance to monitor quasars continuously to ascertain whether regular periods are characteristic of these objects. The differentially rotating supermassive star model has readily calculable periods as indicated here and comparison with observation is required to test the validity of the model.

DISCUSSION

Chairman: E.E. SALPETER

LYNDEN-BELL

I had the impression some years ago that the observers favoured more axial rather than equatorial ejection in the equatorial plane. I would like to know what the position is on this.

MORRISON

If you are referring to the double radio sources, I don't see how they are going to tell us. How can you be sure from the rather poor and irregular images of the central galaxy? In the single case of Centaurus A there is probably a multiple affair, which I would think may well be due to several of these objects splitting. The other large radio sources seem ambiguous.

E. M. BURBIDGE

In Centaurus A, the angle between the inner double source and the axis of rotation (and there is a well defined axis of rotation in that galaxy — it is at right angles to that broad dust lane) is about 20°. The for the outer greater extended source which appears to be the result of a previous outburst, I think the angle is about 30° the other side. It is almost as though you have an ejection which, as it got further out, swept past the rotation axis. I believe Dr. SCHMIDT's observation of 3C 33 suggested that the double source lay along the axis of rotation.

SCHMIDT

Yes, that is correct, but didn't SEARLE have another object in the southern hemisphere in which case the axis was fairly close to the line connecting the two radio sources?

SARGENT

The case studied by SEARLE, which is in Nature for 1965, is NGC 1316 in which he was able to present evidence that the radio blobs are in the equatorial plane.

G. R. BURBIDGE

I just wanted to make the point that in these observations you have to be very careful how you interpret them. In Centaurus A and Fornax A there are not likely to be difficulties because you have an axis of rotation which is measured from quite a lot of data, including some absorption line data. But where you just see tilted emission lines in the gas, as is the case in 3C 33, then you have to be very careful, because that may be due to ejection of gas and not to rotation at all. You cannot distinguish between these cases in an object like that.

SALPETER

You think of low Q phenomenon in the rotation. Wouldn't it be easier to look for that by doing a Fourier analysis of the light curve rather than look for features in the time plot?

MORRISON

The solid curve drawn in that graph was indeed a fit from a power spectrum analysis to the first three harmonics. But it is hopeless to get a spike with a lifetime of 10 days out of 300 days by any such fit, until at least you have seen dozens of them come by. Therefore, I just don't think that is going to do much. It will not discriminate against the general background of the pool around the stuff. If you ever see a closely coherent rotation, it won't be shown that way because one feeds mainly too high harmonics into the analysis.

WOLTJER

In regard to the remarks by Dr. FOWLER, I should say, in the first place, that I did not propose to use more than a few per cent of mc^2 for conversion into useful energy. Secondly, the mass for which I obtained a comparatively short period was 10^8 solar masses. If one goes up to 3×10^9 solar masses, then, even on the simple rotator picture, one already has a period of a number of days.

SPITZER

I would like to make a general comment about the energy sources we are discussing. The two previous papers have shown the possibility of obtaining the energy from a single large mass rotating at nearly relativistic speeds. I am wondering whether it is not simpler from the standpoint of the energy source to assume that there are large numbers of pulsars or neutron stars present. The amount of energy released would be comparable. The one thing which one loses, of course, with such an assumption is a natural explanation for the bursts. There are other ways, perhaps, of getting such time dependent emission even with a relatively constant flow of energy. One can think, for example, of a supply of gas building up, then a stock of relativistic particles accumulating and accelerating the gas to large energies and then new supplies of gas accumulating again. In other words, one might attribute the bursts to relaxation processes associated with plasma dynamics rather than to the time dependence of the energy sources.

MORRISON

It certainly is not excluded and has, as you say, many attractive features if we knew more about it. But it doesn't seem to me to be at all like the pictures of the data, particularly 3C 33, as was emphasized by GEOFFREY BURBIDGE yesterday. I don't see how any incoherent material can work unless extraordinarily well confined.

I doubt the stability of a jet which must end with two tips which are 50 times as far apart as their size, each one of which contains something like 10^{58} ergs or more. This is way out of any stellar mass possibility. You have to do that by ejecting a great fraction of these pulsars with the same speed, which is perhaps possible. But I really think that the arguments favour a coherent mass. This is not from any deep understanding, but just from trying to look at the kinematical picture presented by these remarkable objects.

WOLTJER

For Dr. SPITZER's mechanism to work, one would probably have to get 10^{52} ergs, or a little more, per pulsar. If you look at the Crab nebula and the other supernova remnants, there is no evidence that this amount of energy is actually there.

MORRISON

Another remark: if you do the scaling of the phenomenon, the time scale of the release of energy is much greater if you sub-divide the object into many tiny objects each losing energy by torques. Therefore, I find it very hard to make these objects, like the many pulsars, emit over a protracted time like 10^8 years. If we need to do that, then I think these schemes won't work. It is the same remark really that Prof. WOLTJER has just made, put in another form. The time scale is very different for these small objects, if evidence from the Crab etc. has bearing on the topic.

REES

If one assume that you can indeed get $\gtrsim 10^{52}$ ergs from newly forming pulsars, or from collapsing stars which radiate rotational energy electromagnetically, then I think it is possible to get quite a nice picture for the extended radio galaxies. Galactic nuclei could then be powerful sources of electromagnetic waves at 50 or 100 Hertz. These waves cannot propagate freely, even through a low density gas, such as you would find in haloes or in the intergalactic medium because they are below the plasma frequency.

They will therefore blow out a large cavity in the intergalactic medium. One can appeal to various kinds of directionality to channel this energy into narrow cones and I think there is no problem in explaining even 3C 33, which is an extreme case. In this cavity relativistic particles, but not thermal particles, could exist, and they would radiate in the electromagnetic radiation itself. There is then no need for *any* large-scale ordered magnetic fields in extended radio sources. The energy radiated by the nucleus could cause particle acceleration at the present radius of the object, so you don't have to worry either about adiabatic losses. I think these represent important advantages over conventional models for extended sources. Also one does not require any large coherent mass at the centre of the galaxies. Another possible snag associated with the single "Spinar" model is that a very low charge density can shield the radiation field. Then it is not clear that any particles will move relativistically relative to the field, which is what you need to get radiation. For 50 or 100 cycles per second radiation this is no problem — the particles cannot shield the radiation field so they will radiate in it, producing synchroton-like radiation.

MORRISON

That was a very interesting new idea, but is it really so that you can get something with $l = 100$ out of a dipole?

REES

Suppose that this goes on inside of a disk of gas. That provides initial bifurcation because the radiation will get out where the density of gas is lowest. Then you can appeal either to Rayleigh-Taylor type instabilities, or perhaps to a pre-existing very weak intergalactic field.

MORRISON

Does your picture not lead to the probability of a source with a central object and a number of blobs on the outside, which might be small and dense, and so on, but have no tendencies to line up in a straight line with the central object?

REES

If one were to appeal to a very weak pre-existing magnetic field, then one could say that the particles are channelled along the field even if that field is 10^{-8} gauss and therefore too weak to affect the radiation itself. If there is no pre-existing magnetic field at all, I agree there is no obvious reason to expect two rather than more.

SCHMIDT

I would like to ask Dr. WOLTJER to illustrate the evolution of his model of 3C 273 by giving us the properties at 1/10th and 1/100th of the present luminosity. What was the period at this stage?

WOLTJER

Taking into account the relation between Ω and R we obtain $\Omega \propto L^{3/8}$. Consequently at 1% of the present luminosity the period was about six times longer, or somewhat less than a day, for the 10^8 solar mass object.

AMBARTSUMIAN

I have a question to Prof. WOLTJER: you have given τ to be of the order of 10^5 years. Do you mean that this corresponds to the mean lifetime of these objects (quasars or Seyfert nuclei)? Do you really think that this also corresponds to the reality?

WOLTJER

The number of 10^5 years corresponds to the lifetime of the most powerful quasar phase. Seyfert galaxies as well as the fainter quasars could last much longer.

HOYLE

First, a comment on the dimensions of these large systems, e.g. we have one on the board there. The radius of that particular case is something like 10^{16} cm, which gives a light travel time of a few days. This fits pretty well to the most rapid fluctuations that are found in these objects and also is below the smallest angular diameters that are obtained by the radio-interferometric method, which come out at about 10^{17} cm. My second comment is that I do not see how it is possible to keep such an object stable indefinitely. I expect it would evolve not so much by radial contraction as by contracting to a disk form, in which case one might think that it would break up into a large number of fragments, each fragment having a radius comparable to the thickness of the disk. So I'd rather expect that in the evolution of that very large kind of system, it would break up into many pieces.

WOLTJER

I would like to ask what kind of evidence there is on the shortest time scale on which quasars do vary. I remember that in KINMAN's observations there was a case in which, from one night to the next, there was a substantial variation. Is there any evidence for or against shorter time scales?

SANDAGE

A rate of 0.5 magnitudes per day is the data from KINMAN, and from others, on some of these violently optical variable events. In 3C 48 I followed it for five hours on one night in 1964 and got no variations above the statistical limit, but 3C 48 is a very bad case because it is not an optically violent variable. I think this is a problem we can now do quite easily with, say, a 10-second time scale, dumping the data every ten seconds, for 3C 446; and on the basis of what you said, I think we surely must try. OSTRICKER and HESSER at Princeton did try 3C 273 with negative results at the 1% level over periods from minutes to hours.

G. R. BURBIDGE

I just wanted to make the point that there is this object BL Lac. We don't know where it is, but it is probably an extra-galactic object and it shows very rapid variations.

SANDAGE

Why do you say it is probably extra-galactic?

G. R. BURBIDGE

Because of its radio properties and its infrared properties. Because it has all the characteristics of a non-thermal radio source and a very peculiar infrared source. I know of nothing like that in the galaxy.

SPINRAD

Can the distance to BL Lac be determined from 21 cm absorption measurements like the quasars?

KELLERMANN

This was tried at NRAO just a few weeks ago. There was no absorption seen, which does not prove anything. It will be necessary to look at regions just adjacent to it. There is another 3C source very close to BL Lac. If that does show absorption then it might be meaningful. It is inconclusive so far.

LYNDEN-BELL

I would like to ask FOWLER why there is an apparent difference between his results and the results of BARDEEN and WAGONER with respect to a rapidly rotating general-relativistic disc. It seems that FOWLER runs out of equilibria, whereas BARDEEN and WAGONER do not run out of equilibria.

SALPETER

May I try to answer or re-ask the question? Isn't the difference that in what FOWLER talked about you still have a pressure? You do not attempt to balance the gravitational force 100% by centrifugal force, but start with hydrostatic pressure which is mainly radiation pressure, so that, for a given size, you have much more angular momentum in the purely centrifugal models than you do in the models which FOWLER described. And radiation pressure favours gravitational instability.

LYNDEN-BELL

Then I don't understand the remark about collapse as being a final outcome. If it is a fact that the pressure causes the relativistic collapse, why does not the angular momentum keep it out? And why is collapse a possible source of instability? I don't see why the angular momentum does not stop that collapse.

SALPETER

I meant to say that for the same radius, and therefore the same present gravitational energy, on FOWLER'S model you have *much less* angular momentum than for BARDEEN and WAGONER'S disks. Radiation pressure, unlike centrifugal force, cannot stabilize against collapse.

SALPETER

I want to report on two unpublished additions to the work of BARDEEN and WAGONER on thin, uniformly rotating relativistic disks.

(i) For zero-temperature disks at densities typical of white dwarfs or neutron stars, estimates are now available for the ratio of disk thickness W to disk radius R. It is (to within factors of 2 or 3)

$$\frac{W}{R} \sim 0.15 \left(\frac{M_\odot}{M}\right)^{\frac{1}{2}} ,$$

where M is the mass of the disk.

(ii) Accretion of matter tends to increase the angular momentum per mass of a disk, magnetic coupling to the outside world tends to decrease it till the properties of a Kerr metric are approached. One might conjecture that this coupling weakens as the Kerr metric is approached so that, with even modest rates of accretion, a disk may stay near the threshold of collapse for a very long time without actually crossing it.

LYNDEN-BELL

But that collapse cannot be the final outcome because finally it will stabilize again as a result of its angular momentum.

FOWLER

I think there is some misunderstanding about the word "collapse". The collapse in this case is parallel to the axis of rotation and the object becomes a disk or a cigar-shaped object. In the latter case fission results. I prefer SPITZER's disk as the ultimate end of such a very large gas mass, since it fragments into many stars, neutron stars, if you wish. WAGONER and BARDEEN have shown that the energy available in this eventual situation can be 37% of the rest-mass energy. I have attempted to show that in the very early stages a few per cent becomes available and that, if one takes the masses large enough, then the available energy is 10^{60} ergs, or even greater.

VAN DER LAAN

If it is the case that the large double radio sources with compact components do in fact have particle-producing "machines" *in situ* then it would be necessary to have several massive objects which have rotation axes that have no relation either to each other or to the rotation axis of the surrounding galaxy. Such systems would probably imply equatorial fissure of the central rotating objects and the radio brightness distributions indicate, the complex ones do at least, that you can have multiple double radio sources where the axes connecting the components of each double have no particular relation to each other nor to the orientation of the galaxy itself. But is that plausible?

MORRISON

It is very hard to demonstrate "plausibility". but I know of only one case of the sort you mention, the Centaurus A case. I would like to know about the others, but that is independent of this. I don't know the answer. I would think that a small cluster of these objects is quite possible.

VAN DER LAAN

Well, if you look at the radio brightness distribution pictures you will find quite a number. One of the most striking is 3C 315, which I think is two double components of comparable size, making an angle of about 70° with each other.

FORMATION AND EVOLUTION OF BRIGHT BLACK HOLES

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ABSTRACT

Friction in the primaeval galaxy increases the angular momentum of the outermost parts and causes the central parts to move inwards. Quasars are small discs of glowing gas heated by this friction as they condense towards their Schwarzschild radii. About a third of the rest mass energy is given out before this size is achieved. Thereafter the quasar disappears but further accretion of interstellar gas driven inwards by friction causes the Seyfert phenomenon. A flux inwards of 1 $M_\odot$/year produces an energy via friction of 10^{46} ergs/sec, nearly 10^{13} $L_\odot$.

To explain quasars and the associated phenomena seen in galactic nuclei we need firstly to explain how a large mass gets into a small volume, how it produces a prolific supply of energy, and why that energy supply has periods of steady production interspersed with periods of violent and irregular activity.

In order to get the small sizes GOLD, SPITZER and others, have noticed that a very dense star cluster of say 10^9 $M_\odot$ may evolve by stellar encounters to produce a much denser, less

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massive core. It is possible to set the parameter so that within the available time the stars of this core collide and strip off one another's envelopes. However, in order to do this the initial star density has to be very large. If we ask about the evolution prior to the formation of this dense star cluster, when the material was gaseous, several interesting facts emerge.

1. The material before it fragmented into stars was already very opaque due to electron scattering. For a mass to light ratio of 10 a surface brightness of 20th magnitude per square second gives a surface density of the order of 1 gm/cm^2. Thus, if we take the observed central brightness of the Andromeda nebula from KINMAN, we find of the order of 2000 gm/cm^2. Star cluster models of quasars require considerably greater initial surface densities so we conclude that the initial optical depth due to electron scattering when the stars were created must have been much greater than a thousand. Now HOYLE in an important paper emphasized that fragmentation can only work efficiently if there is sufficient energy loss to keep the material isothermal. We deduce that there is some doubt whether fragmentation will occur at all at the high densities required by this model and if fragmentation does occur we expect it to proceed less far and less efficiently than under more normal circumstances.

2. Because gas clouds unlike stars are large and dissipative any relaxation that may occur among stars will be outstripped by the growth of a central core of the gas left over with a considerably shorter timescale.

3. Since the stellar model involves the stars tearing themselves apart to make gas, it seems that there is a considerable economy of hypothesis in assuming that the gas never made stars to start with.

Noting that fragmentation may be difficult but perhaps not impossible, MCCREA asks the important question, "How does a lump of gas know that it has too large a mass to make a star before it has tried?". Finding no answer McCREA assumes that it does try and finds that such masses would make temporary stars which collapse only to blow up upon igniting the carbon nitrogen cycle. This hypothesis gets around many of the difficulties associated with the multiple supernova model, for the energies in single events may be greater and periods of enhanced activity can be identified with the formation of a small cluster of temporary stars. However if we are to consider the Seyfert phenomenon as the same as the quasar phenomenon but with a much reduced power, then the work of CROMWELL and WEYMANN tells us that the scale of the continuum emission is less than 10^{15} cms. Such small scales tie in with rapid light variations seen in some quasars but they also pose a severe angular momentum problem to all theories. In what follows we shall assume that the angular momentum problem dominates the evolution of the central parts of a proto-galaxy and that fragmentation and star formation are somewhat inhibited. Our interest centers on the evolution of the dissipative gaseous component. Because of the strong dissipation we may expect gas clouds to take up orbits of minimum energy for their angular momenta and to arrange things so that these orbits do not cross one another. This implies that the orbits are circular and coplanar perpendicular to the total angular momentum vector. We are thus led to consider differentially rotating discs. We find a plausible initial distribution of material in the disc as follows. Consider the cloud that will eventually form the central region of the Galaxy. It is not unreasonable that the transformation from a cloud to a disc occurs in the free-fall time and that that time is too short for angular momentum transference through the cloud. We take the portion of the cloud near the axis of rotation to have uniform surface density Σ_0 projected down that axis and to rotate uniformly. Initially then the mass M(h) with specific angular momentum less than h will be $\int_0^{R_0}$ $2\pi R$

$\Sigma_0\, dR$ where $R_0^2\, \Omega_0 = h$. Hence $M(h) = \pi\Sigma_0 h/\Omega_0$. If we now ask how this same material will distribute itself in a disc when centrifugal force balances gravity we write

$$\frac{G\,M(h)}{R^2} = \frac{h^2}{R^3} = \frac{V^2}{R} \tag{1}$$

This assumes no angular momentum transference during the collapse so that $M(h)$ is conserved. From equation (1) $V^2\,R = \dfrac{G\pi\Sigma_0}{\Omega_0}\,h = \dfrac{h^2}{R}$ so h is proportional to R which implies the rotation law $V = \text{const}$. The surface density in the balanced disc is

$$\Sigma = V^2/(2\pi G R) \tag{2}$$

MESTEL first performed a more refined version of this theory that allows for the flattening when calculating the gravity of the disc in equation (1). However in the central parts of the disc for which we use our equation it is in fact exact. HOYLE and CRAMPIN have pointed out that the $M(h)$ for galaxies bear a striking resemblance to those of uniformly rotating protoclouds, indicating perhaps that the assumption of little angular momentum transference is not bad. Since for many galaxies we know V is of the order of 200 km/sec equation (2) gives us a natural initial distribution for a disc. In particular it yields the following where $M(R) = \dfrac{V^2}{G}\,R$ is the mass in the central R parsecs

$$M(1) = 9.10^6\, M_\odot, \quad M(100) = 9.10^8\, M_\odot, \quad M(10^4) = 9.10^{10}\, M_\odot$$

Let us now allow for the effects of friction in the evolution of such a gaseous disc. The secular effect is clearly the reduction of the angular momentum of the inner parts and the increase of the angular momentum of the outer parts. However, a given angular momentum change has a far greater effect near the middle, for there the angular momenta are small. Thus it is at the middle that frictional effects are most important and the center will condense as it loses angular momentum. The friction coefficient is not simple to determine, but a crude estimate is arrived at by letting the disc have a thickness to radius ratio of 1 to 20 and then estimating magnetic pressures on the gas to be comparable to the components of gravity perpendicular to the disc. Following PARKER we know that when a sizeable fraction of the weight of the gas is borne by the magnetic field then the situation is unstable. Hence the field is limited to a somewhat smaller value. We take

$$\frac{B^2}{8\pi} \sim \frac{1}{10} \int_0^{\infty} g\rho dz = \frac{1}{10} \int 2\pi G \Sigma \frac{d\Sigma}{2} = \frac{\pi G \Sigma^2}{20}$$

Notice that the stars contribute to the gravity but not to the mass of the gas so if the system has only a fraction μ of gas we get

$$\frac{B^2}{8\pi} = \frac{\pi G \Sigma_g^2}{20\mu} = \frac{V^2}{40R} \Sigma_g$$

where Σ_g is the surface density of the gas alone. This formula gives $B \sim 7.10^{-6}$ gauss in the solar neighborhood. If we assume that one tenth of the maximum possible stress from such a field is so oriented as to oppose the shearing by the differential rotation then the shearing stress per unit length is

$$\frac{1}{10}\frac{B^2}{8\pi}\cdot\frac{R}{20} = \frac{V^2}{R}\frac{\Sigma_g}{400}\frac{R}{20}$$

so the couple at radius R is

$$g = \pi R^2 V^2 \Sigma_g/4000$$

We now determine the inward motion as a result of this couple. Evidently the couple causes the loss of angular momentum so, ignoring the change in the overall gravity field, we have

$$2\pi R\Sigma_g V_r \frac{\partial h}{\partial R} = \frac{\partial g}{\partial R}$$

where V_r is the inward velocity caused by the friction. For our initial distribution this yields

$$V_r = V/4000$$

Thus the drift inwards is a very small fraction of the circular velocity. The radial mass flux is

$$2\pi R\,\Sigma_g(R)\,V_r = \frac{\pi}{2000} R\Sigma V = \frac{1}{4000}\frac{V^3}{G} =$$

$$= 3 \cdot 10^{25}\ \mathrm{gm/sec} = 0.5\ M_\odot/\mathrm{year}.$$

Notice that this flux is independent of radius and that in one galactic year of 2.10^8 years this flux will build a central mass of 10^8 $M_\odot$. The building of such a mass does not denude the central region, for the mass is replaced from the parts of the galaxy further out. Only at large distances where the $\Sigma \propto \frac{1}{R}$ law ceases to hold will angular momentum be gained by the gas rather than lost.

We now ask whether the disc is capable of radiating away the energy generated via the magnetic friction. We have already demonstrated that the central region where most of the energy is generated will be optically thick. The power generated between R and R + dR will be

$$2\pi R\, p(R) = F\, \frac{GM(R)}{2R^2}$$

where M(R) is the mass within R, F is the inward flux of mass and p(R) is the power per unit area of disc. The surface temperature necessary to radiate this energy is given by

$$2\sigma T^4 = p = F\, \frac{GM}{4\pi R^3}$$

For the initial model this gives $T = 30\,(R_1)^{-\frac{1}{2}}$ where R_1 is R in parsecs and T is in ^{0}K. Radiation pressure does not become comparable to gravity until $\frac{4\pi g}{p}$ achieves a mass to light ratio of 3.10^{-5}. This does not occur until R is of the order of 1 astronomical unit $\sim 10^{13}$ cms, where the temperature is about 10^4 ^{0}K. In practice it is likely that patches of the disc will be kept ionized by the presence of hot stars surrounding it so these will not be realistic temperatures. If we follow the evolution of such a disc to the end we must find a relativistic spinning disc. Bardeen and Wagoner have shown that as such discs are acted on by a couple they shrink and eventually disappear leaving behind a Kerr metric. The binding energy at which the discs disappear is about $1/3\ Mc^2$. This energy will be given out as such a central black hole forms. Further accretion by such a spinning black hole may readily be studied. As accreted material spirals downward under the influence of friction the binding energy is given up to frictional dissipation; our picture is that described by Salpeter and Lynden-Bell in which the material gives up its binding energy until it reaches the last stable circular orbit after which it plunges down the black hole. The energy that became available to the world is thus the binding energy of the material at the last stable circular orbit. Our aim now is to determine this for Kerr metrics.

A Kerr metric is specified by two parameters, ℓc an angular momentum per unit mass and $m = GM/c^2$. Kerr metrics with the same ratio ℓ/m are similar. Those with $\ell > m$ are non-physical with closed time like world lines and causality violation of the worst type so that all the wonders of H. G. Wells' time machine may be found together with the "contradictions" associated with them. Kerr metrics with $\ell \leq m$ do not have this trouble but they have horizons similar to the Schwarzschild metric horizon at $r = 2m$. For Kerr metrics created from shrinking bodies nothing can pass outwards through these horizons. Kerr metrics are usually written in terms of a spheroidal coordinate r which *on* the equator is related to the circumference of a circle $2\pi R$ by the formula

$$R^2 = r^2 + \ell^2 + 2m\ell^2/r$$

Tedious algebra on the circular orbits of the Kerr metric yields their specific angular momenta $h = \mathrm{L}c$ and total specific energy $\mathrm{E}c^2$

$$\begin{aligned} \mathrm{L} &= \pm \frac{m^{1/2}}{r} \, \frac{r^2 + \ell^2 \mp 2\,(m/r)^{1/2}\, r\ell}{[r - 3m \pm 2\,(m/r)^{1/2}\ell]^{1/2}} \\ &\qquad\qquad\qquad\qquad\qquad\qquad (3) \\ \mathrm{E}^2 - 1 &= -\, m/r \left[\frac{r - 4m - \ell^2/r \pm 4\,\ell(m/r)^{1/2}}{(r - 3m) \pm 2\,(m/r)^{1/2}\ell} \right] \end{aligned}$$

Upper signs are to be taken for direct orbits spinning in the same sense as the singularity and lower signs for retrograde orbits. The smallest stable circular orbit has $\mathrm{E}^2 - 1 = -\,2/3\; m/r$ Hence from equation (3) its r satisfies

$$r - 6m - 3\ell^2/r + 8\ell(m/r)^{1/2} = 0$$

The binding energies $(1 - \mathrm{E})\, c^2$ of these last stable circular orbits vary from the Schwarzschild case $\ell = 0$

$$\mathrm{R} = r = 6m,\ (1 - \mathrm{E})\, c^2 = \left(\frac{3 - 2\sqrt{2}}{3}\right) c^2,\ h = \mathrm{L}c = 2\sqrt{3}\, mc$$

to the last physical case $\ell = m$

$$\mathrm{R} = 2m,\ r = m,\ (1 - \mathrm{E})\, c^2 = \left[1 - \frac{1}{\sqrt{3}}\right] c^2,\ h = \mathrm{L}c = \frac{2}{\sqrt{3}}\, mc$$

A flat body that shrinks slowly due to angular momentum loss will leave behind it a Kerr metric with ℓ close to m. However, further accretion involves the accretion of angular momentum as well as mass. Thus both ℓ and m change. It is of interest to seek the particular Kerr solution that will remain self similar so that $\frac{\ell}{m}$ remains constant as it accretes. On accretion of a small rest mass δ the total mass increases by $E\delta$ and the angular momentum by $Lc\delta$. Thus $\frac{\ell}{m} = \frac{\ell m}{m^2}$ changes to $\frac{\ell m + L\delta}{(m + E\delta)^2}$. Thus there is no change on accretion when $L = 2E\ell$ which occurs in our special case $\frac{\ell}{m} = 1$. It is simple to show that the Kerr parameter is increased on accretion when it is less than unity so that any initial singularity will approach this state on accreting enough material with one sense of spin. Notice that since the specific binding energy of the last stable circular orbit is $\left(1 - \frac{1}{\sqrt{3}}\right)c^2 = (0.42)\, c^2$ hence 42% of the rest energy of accreted material will be given up via the frictional heating as the material spirals in towards the black hole. BARDEEN points out that some of this heat will be radiated into the black hole itself so that the energy finally available to the outside world will be somewhat less, probably again about one third of the rest energy of the accreted material.

We estimated earlier that the outer parts of the galaxy would provide an inward flux of $0.5 M_\odot$ per year. The energy that becomes available if this flux makes a central black hole is

$$\frac{1}{3} \cdot 0.5 M_\odot\, c^2 \text{ per year} = 10^{46} \text{ ergs/sec.}$$

We therefore suggest that associated with the formation of galactic nuclei there are created central black holes in the nuclei of galaxies. Once it is accepted that such black holes are present, there they may be re-enlivened by accretion of more gas to give rise to the radio galaxy and Seyfert phenomena. The numbers to remember in explanation of these processes are that a flux of $1 M_\odot$/year yields 2.10^{46} ergs/sec $= 5.10^{12}$ $L_\odot$ and that the inward velocities are a very small fraction like 1/4000 of the circular velocities. If too much mass accumulates in the nucleus near the central black hole the friction will try to force the black hole to overeat. This occurs whenever the mass to light ratio of the black hole is less than 3.10^{-5} at which point the radiation pressure on particles exceeds gravity. We suggest that this has happened in many of the most exciting cases and that material is blown out of Seyfert nuclei by radiation pressure. Since the time scale of the frictional accretion may not be regulated by the radiation pressure when the disc is optically thick edge on, it is possible that violent overfeeding of a black hole leads to an explosion of relativistic plasma driven out along the rotation axis by a very high radiation pressure, but such speculations need stronger derivations before they can be applied usefully to radio outbursts. However it should be clear that this theory predicts a very slow drift of material inwards which can be violently reversed if too much material is accreted. In the most exciting objects such an overbalance of gravity by radiation pressure occurs and gives rise to the impression that the material is in general flowing outwards whereas according to these ideas a rather unexciting slow drift inwards is the norm.

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MECHANISMS FOR JETS (*)

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DIRECTIVITY VS. ENERGY

One returning to reconsider the quasistellar sources after a period away from the evidence is struck by two changes in the emphasis. First, as compared to five years ago, there is less certainty now that one has to call on a process that will provide nearly 100 percent conversion of mass into energy. On the energy itself the estimates are unchanged in order of magnitude, but on the mass out of which this energy is developed the evidence is not so clear as it once seemed. Second, the directivity of the energy output claims rising attention. One continues to discover centers of radio emission evidently ejected in opposite directions from a common center. From the nucleus of our own galaxy, we know from the work of the Leiden group [1], two clouds of ionized matter are ejected in nearly opposite directions, with comparable velocities ($\sim$ 130 km/sec), and each with a mass of the order of $10^6 - 10^8\ M_\odot$. We even see cases where two radio sources were evidently shot out in opposite directions from a common center, and then, along a new axis, two more in opposite directions (Fig. 1). The radio source 3C 452 shows the two

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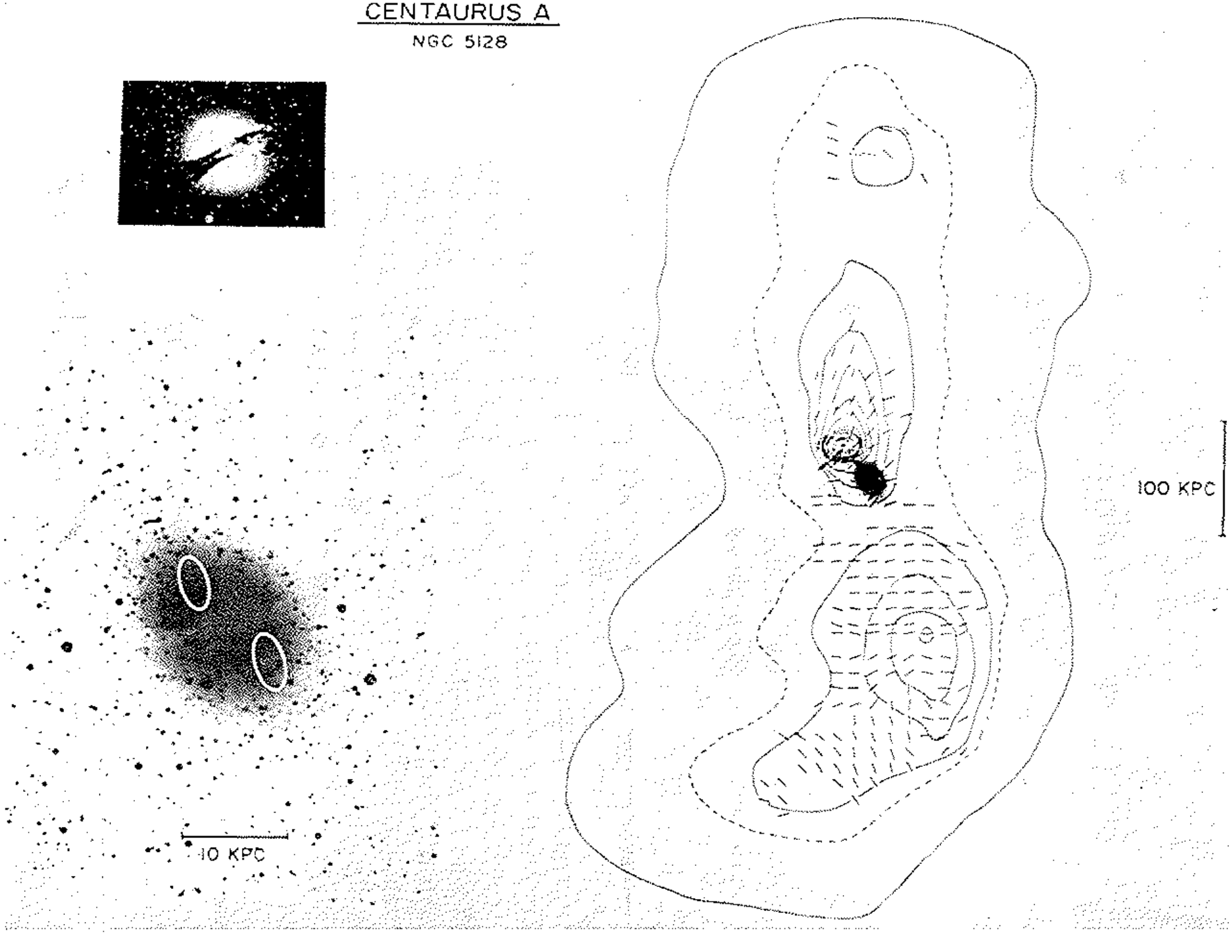

FIG. 1 — Centaurus A (as reproduced from MATTHEWS [2]). At right are shown the intensity contours and polarization vectors (⊥ to the direction of maximum electric field) for the extended radio source, the position of NGC 5128 is shown. At lower left is a negative photograph of NGC 5128 in red light, with the positions of the central radio source components shown. At upper left is a positive photograph in blue light, showing the dark lane.

pairs in the same line, one pair considerably closer in and weaker than the other. To JOHN MOFFET I owe the suggestion that another case may be a similar "in-line" event, with the apparent out-of-line character arising from the action of a large-scale magnetic field upon the weaker pair.

In not every event are the two oppositely emerging sources of emission of equal strength. Nor is identity of power received to be expected even when power given off is identical (M. REES [3]). Thus, when there is a component of velocity along the line of sight, the times of peaking of intensity of the two sources, if identical in the local reference of the center of ejection, will not be identical in the reference frame of the radiotelescope. Also Doppler effect will cut down the apparent intensity of the receding source as compared to that of the approaching source. In addition the density of the intergalactic medium can be expected to have a strong influence on the intensity of the radioemission from the jet that ploughs into it. These considerations of timing, Doppler effect and density give much opportunity for a symmetric mechanism to show up unsymmetric in the observations. On the other hand 3C 273 so clearly shows a jet going one way, and is so wanting in evidence for a jet going the other way, that it becomes a matter of very great interest to know whether (1) there are two distinct mechanisms for producing jets, one symmetric, the other monodirectional or (2) there is only a symmetric mechanism. The following discussion reviews the new mechanism of LE BLANC and WILSON [4] for producing symmetric jets and asks how a black hole might be conceived to produce a monodirectional jet ("jet" throughout means "ejected blob", not continuing emission).

Directive Mechanisms in Hydrodynamics

In looking for an astrophysical mechanism to drive energy in a given direction, it is natural to recall the best known directive mechanisms out of other branches of physics. Most of them one cannot call on because they demand an organization of the material at the start which it is too much to expect nature to provide.

Take a thin-walled hollow sphere of copper with a radius of half a meter. It can be pumped up with air without giving way, but it cannot withstand a vacuum. Part of the sphere turns inside out and forms a dimple. Disconnect the dimpled sphere from the vacuum line and suddenly connect it to the compressed air line to unfold the dimple. The pressure supplies more and more kinetic energy (Fig. 2). The mass that carries this kinetic energy grows smaller and smaller. The velocity rises almost without limit, as in the familiar "snap-the-whip" mechanism. The process terminates with a mass of copper breaking loose and flying off with the velocity of a bullet. This process makes good use of the low pressure energy that is available. It provides a source of highly directed energy. However, it is difficult to imagine matter in space organizing itself so perfectly as to give the focussing power seen here.

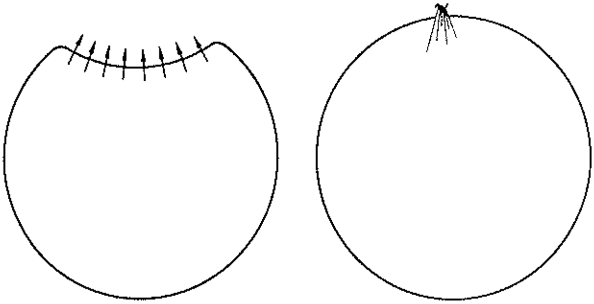

Fig. 2 — Dimple in hollow copper sphere being undone by reason of pressure generated inside. The progress of the implosion puts more and more kinetic energy onto a smaller mass of metal, and eventually a slug of copper is ejected with speed in excess of the speed of sound.

A remote approximation to the thin copper sphere is provided by the atmosphere of a star. Let this star be struck on one side by head-on or nearly head-on impact of another star. A pressure wave will travel round the star to the antipodal point and eject matter there, as already indicated by preliminary calculations [5].

The Munroe jet [6] is another mechanism for the concentration of energy familiar from laboratory experiments (Fig. 3).

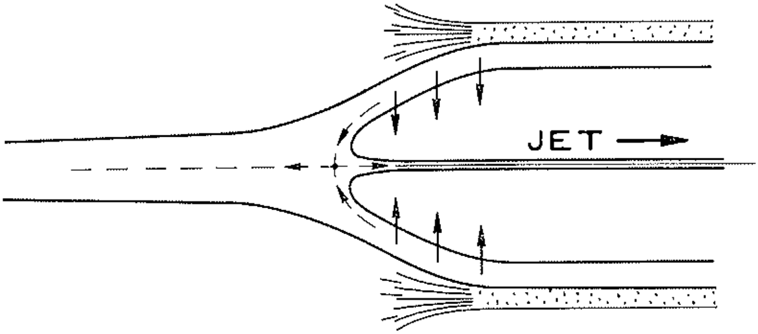

FIG. 3 — Munroe jet produced when high explosive burning from left to right drives together the walls of the metal cylinder.

A metal cylinder is wrapped with high explosive. The high explosive is ignited at one end. The resulting compression wave runs down the cylinder. One section of the cylinder after another implodes. From the indicated point of stagnation of the flow a jet takes its origin. It can carry a third or more or less of the energy imparted to the cylinder. It shoots out with a velocity many times the speed of sound.

For this mechanism it is difficult to see an astrophysical analog, unless it is again the impact of one star on another, with a pressure wave travelling around the surface and giving rise to a jet at the antipodal point [5].

Cosmic Rays via the "Snap-the-Whip" Mechanism

These examples of directionality reveal the importance of precise organization prior to the event if a jet is to follow after the event. They also bring realization that astrophysics, as it stands today, provides one and only one mechanism to organize matter into a geometrically simple configuration: gravitation itself, drawing matter together into a sphere.

Out of matter assembled into a sphere one knows how to get matter ejected as close to the speed of light as one could wish. Let gravitational collapse of the interior down to a neutron star, or any other sudden source of energy output, send a pressure pulse outward through the material of the star. Travelling through a material of ever lower density it acquires an ever higher amplitude. In the process it becomes a shock. This shock continues to augment in velocity. According to the calculations of COLGATE and JOHNSON [7] on the production of cosmic rays in a supernova event, the outermost material is ultimately driven out with the highest speed. The material a little deeper in the atmosphere has to push on that outermost material and so does not itself acquire so high a speed. In the case they considered, according to their estimates the material at 30 g/cm^3 is shocked to a relativistic level; the protons at 1 g/cm^3 are accelerated to about 10 Ge V; those at 10^{-5} g/cm^3, to energies of the order of 10^4 Ge V; and those at 10^{-12} g/cm^3, to around 10^8 Ge V. In conclusion, this process gives energy, yes; directionality, no.

The "Squeezed Tube of Toothpaste" Mechanism

A process that gives directionality but not, he concludes, enough energy to be of interest has been proposed by Physicist X in unpublished work [8]. It starts again with spherical symmetry but this time the symmetry produced by complete gravitational collapse to a standard Schwarzschild black hole [9]. This black hole is envisaged as so massive that it has a far greater radius than the star that is going to fall into it. To have a radius $r = 2m = 3 \times 10^4$ M$_\odot$, twice as large as the radius of a white dwarf star, it should have a mass of 10^4 M$_\odot$. To have a radius $2 \times 7 \times 10^{10}$ cm, twice as large as the radius of the sun, it should have a mass of 5×10^5 M$_\odot$. The infalling star is subjected to powerful tidal forces. These forces draw out the material of the star along the radial direction. They squeeze it in in the two perpendicular directions. Like a tube of toothpaste gripped tight about its middle, the system squirts matter out of both ends. What goes down is lost into the black hole and so, too, is most of the rest of the star. What is shot out is estimated to carry off in the form of kinetic energy of the order of one percent of the rest mass of the original star. That this tidal effect gives a fractional conversion of mass into energy no larger in order of magnitude than what one already achieves in thermonuclear reactions was reason enough five years ago to look at it no further as a potential mechanism for the quasi-stellar sources. It has received little further attention since. It can appropriately receive re-examination here, in view of the greater understanding of black hole physics achieved in the meantime.

Formation of Black Holes

Black holes have risen from possibilities in astrophysics to probabilities. The same kind of collapse of a star with white dwarf core that is calculated by COLGATE, MAY and WHITE [10] to lead to a neutron star when the core is smaller than a certain critical mass $m_{\text{crit}} \sim$ M$_\odot$ is calculated by MAY and WHITE [10] to lead to a black hole when the imploding core has a larger mass. On this account the number of extra-nuclear black holes per galaxy is reasonably believed to be of the same order as, or up or down an order of magnitude from the number of neutron stars; that is, on present views, from the number of stars that were once pulsars.

Within a dense galactic nucleus the proportion of black holes and the typical mass of a black hole can be expected to be higher than outside. It is enough in this connection to refer to the evolutionary process considered by SANDERS [11] and SPITZER [12]: Stars collected in a cluster exchange energy. Some acquire energy and move out into a halo. Others lose energy and make a more compact cluster. This process of segregation continues. The cluster becomes so compact that collisions ensue and gas is driven off. The gas moves towards the center of the gravitational potential well. Out of it new stars form. The process continues. SANDERS and SPITZER cut off the analysis for the time being. Continued, the S-S segregation process cannot fail to produce black holes. It would seem quite conceivable for one such object to build itself up by accretion to the point where it contains as much as half the mass of the galactic nucleus: mass 10^9 $M_{\odot}$, for example, and Schwarzschild radius $2\ m = 2 \times 10^9\ M_{\odot} = 2 \times 10^9 \times 1.47$ km $\simeq 3$ lhr.

It may not be out of place to recall some of the well-known features of a black hole. Fig. 4 illustrates that the scale of time for falling is very different according as it is measured by someone on the object falling in ("proper time"; finite; total proper time to fall in to $r = 0$ given by Newtonian formula for ordinary time, $\tau = (\pi^2\ r^3_{\odot}/8m)^{\frac{1}{2}})$ or as it is measured by a faraway observer ("Schwarzschild time coordinate"; connected with distances in the final stages of approach to the Schwarzschild radius by the formula $(r/2m) = 1 + \text{const} \times \exp(-t/2m)$; goes to infinity as r approaches $2m$). The units here are geometrical units, $m = (G/c^2)\ m_{\text{conv}} = (0.742 \times 10^{-28}\ \text{cm/g})\ m_{\text{conv}}$ (g) or for the sun $m = 1.47$ km, $2\ m = 3$ km, with a corresponding characteristic time, $2\ m$, of 3 km/(3×10^5 km/sec) = 10 μ sec. No matter how long

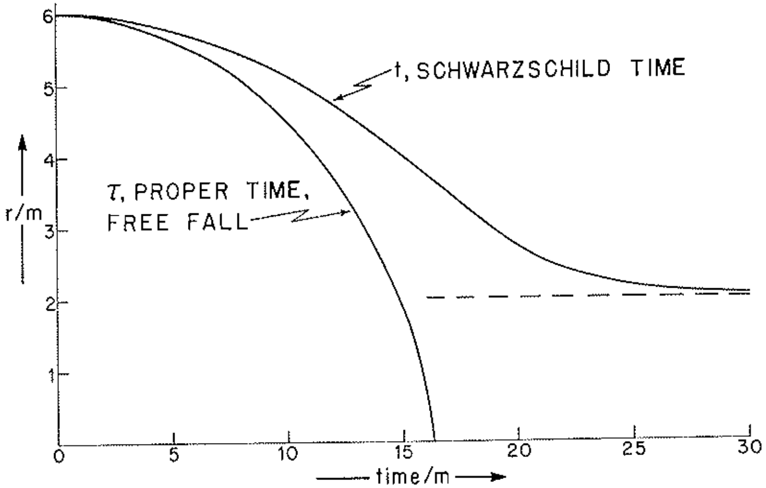

Fig. 4 — Fragment falling straight in to a Schwarzschild black hole from rest at $r = 6\ m$. The time to fall as measured on a comoving clock is finite; but to an observer far away the object is not seen to fall as far in as $r = 2\ m$ in even an infinite time (Schwarzschild coordinate time).

the faraway observer waits, he never receives any signal from an object that has fallen closer to the center than $r = 2\ m$. However, the apparent distance from $R = 2\ m$ falls by a factor $e = 2.718$ every 10 μ sec, so that in one second it has fallen by 10^5 (not 5!) factors of e.

Fig. 5 recalls the calculations of Colgate, May and White [10] on the collapse of a system originally endowed with a mass of 2 $M_\odot$, radius 1700 km, average density $\sim 2 \times 10^8$ g/cm^3 (most naturally envisaged as the "white dwarf core" of a much more extended star). The inner part of this system falls fastest. It compacts to a neutron star. It is so highly heated by the energy of compaction that it generates a shock wave. It runs out and drives off a shell that contains a substantial part of the mass of the system ("supernova"). When the mass of the inner part of the system

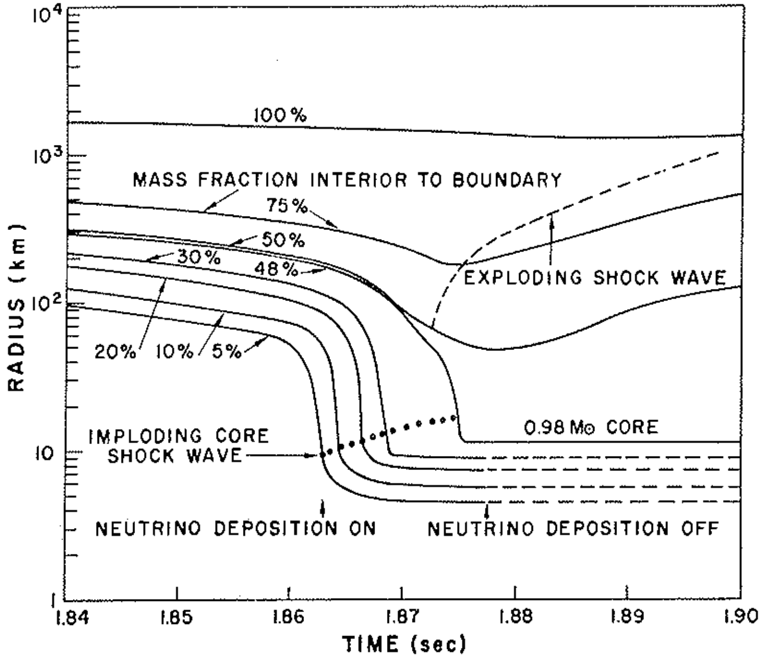

FIG. 5 — Collapse of a white dwarf core to a neutron star, according to COLGATE, MAY and WHITE [10]. Of the total mass of this object, 48 percent initially lies inside a radius of $r = 300$ km. This collapses to a radius only a little more than 10 km.

is larger, the "neutron star" is only a fleeting way station on the road to complete collapse (formation of a black hole; details and curves in ref. 10; the amount of material thrown off from the outer part of the system, and also the energy given to this material is reasonably believed to be reduced as compared to a supernova, perhaps even taking the event out of the supernova category).

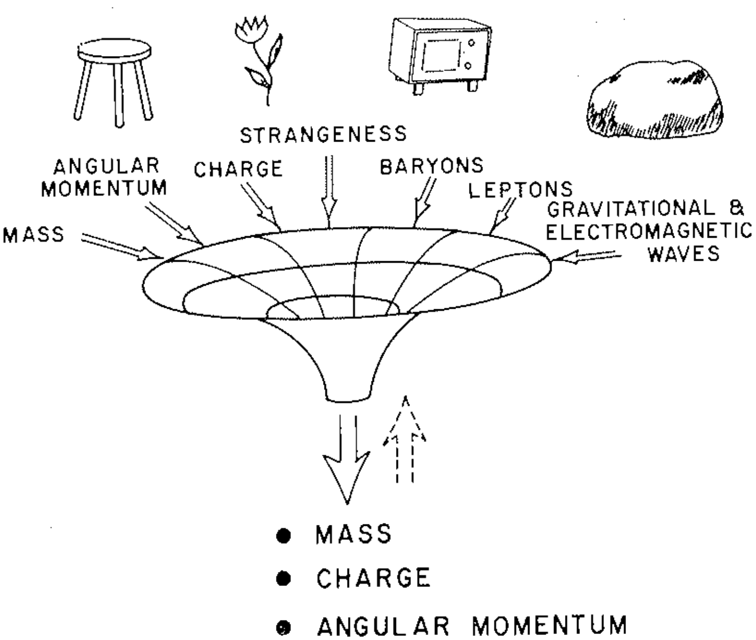

Fig. 6 — A black hole provides a means to reduce matter, whatever its particularities, to a system with mass, charge and angular momentum as its sole determinants, thus "transcending" the laws of conservation of lepton number and baryon number.

Mass, Charge and Angular Momentum

Fig. 6 recalls that a black hole is a very simple object. So far as we are able to judge, it has no property, no "determinant", other than mass, charge and angular momentum. No one has ever found, nor is there the slightest indication that anyone ever will or can find, any way to distinguish black holes of the same determinants, but of different provenance: one built for example out of matter, another built out of antimatter, and a third built half from matter and half from input of radiation. The mass can be determined, yes, from the period of motion of a satellite in a Keplerian orbit. The charge can be found from the perturbing effect on a charged satellite. The angular momentum reveals itself in the difference in the rate of precession of Keplerian orbits according as the angular momentum of the satellite is parallel to or antiparallel to the angular momentum of the black hole. However, no way whatever offers itself to tell how many leptons and how many baryons have been dropped in to make the black hole. In this sense the formation of a black hole, if it does not violate the long established laws of conservation of lepton number and baryon number, at least transcends these laws.

Mechanism for Change of Proportion of Matter and Antimatter

Did the universe at the start of this cycle of its dynamics contain fifty percent matter and fifty percent antimatter? Then in principle a sufficiently industrious set of Maxwell demons (or Alfvén-Klein demons!) could build up black holes here and there throughout all space, sort out the antimatter, and by dropping it into these black holes extinguish it, to leave the world today with nothing but matter: indistinguishable, except perhaps for the amount of matter soaked up in black holes, from a universe formed at the start out of pure matter. Naturally it would still be of interest to establish that the universe today consists only of matter — if it does. Earlier such an observation might have rated as not merely interesting, but a deep point of principle. Not so now, it would seem, when one realizes that black holes transcend the law of conservation of baryons!

How Particularities Disappear in a Black Hole

How clear is it that a black hole erases the particularities of anything that approaches? A small mass dropped into the black hole ends up only at $r \sim 2\ m$ from the point of view of the faraway observer. Therefore, might not this bit of matter with all its special properties be imagined to end up plastered for all time on a particular point on a sphere of radius $r = 2\ m$? And if this bit of information about the past is retained, will not every other bit of information be kept on the "spotted surface" of the sphere? Not so. All this information is wiped out. As illustration, consider a charge e attached to a bit of matter lowered by a string to a distance r very close to $r = 2\ m$. Will not the resulting system possess an electric dipole moment of the order of magnitude $2\ me$? Can one not determine this dipole moment by the simplest of measurements, made from a distance? Will not this moment reveal for all time where the charge went in? No, the electric lines of force are bent by the gravitational field (Fig. 7). They appear to emerge from a point close to the center. The electric dipole moment goes rapidly to zero as r approaches

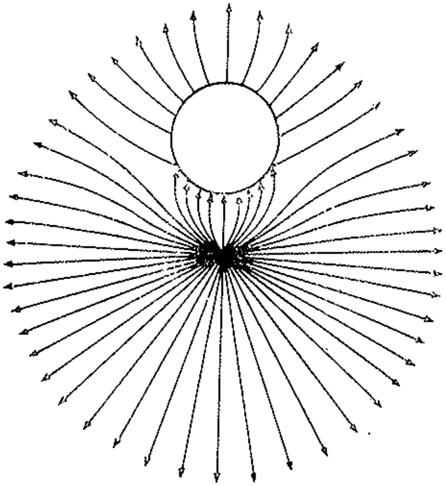

FIG. 7 — Lines of force of a charge e momentarily at rest in the neighborhood of a Schwarzschild black hole (schematic). The lines are so bent by the gravitational field of the black hole that the dipole moment goes to zero as r approaches $2m$.

$2\ m$. Similarly mass quadrupole moment goes to zero as infall proceeds, when the final system has zero angular momentum. When the system ends up with a finite angular momentum, the quadrupole moment approaches rapidly the standard value for a black hole of this angular momentum. No particularities remain!

Mass versus Angular Momentum

How much angular momentum can a small mass μ give to a black hole of mass m? The answer depends upon how much angular momentum L the black hole already has. Consider accretion. Let the mass go by with impact parameter b and with a velocity that is a small fraction β of the speed of light. If the angular momentum of the small mass about the black hole is in such a sense as to augment the angular momentum of the black hole, capture will take place when the impact parameter is less than

$$b = (2\ m/\beta)\ [1 + (1 - L/m^2)^{\frac{1}{2}}]$$

("corotation"); and in the opposite case ("counterrotation") when the impact parameter is less than

$$b = (2\ m/\beta)\ [1 + (1 + L/m^2)^{\frac{1}{2}}]$$

(GODFREY [13]; see ZEL'DOVICH and NOVIKOV [9] for the effect of gravitational radiation in augmenting the "reach" of the black hole in the case $L = 0$). Consider for example the case of a black hole with mass equal to the mass of the sun, $m_{\text{conv}} = 1.987 \times 10^{33}$ g, $m = 1.47$ km, and a small mass flying by at 300 km/sec, $\beta = 0.001$. In the absence of angular momentum the critical impact parameter is 6000 km. When the angular momentum is maximal ($L = m^2$) the impact parameter falls to 3000 km for capture of a corotating mass, but rises to 7200 km for capture of a counterrotating mass. It is impressive out to how large a distance the gravitational effect of the angular momentum can reach. One consequence is simple. Accretion from a random cloud of small masses flying by reduces the angular momentum of a black hole (DOROSHKEVITCH [14]).

The masses flying by near a black hole need not have random velocities. They and the black hole may arise from fragmentation of a spinning disc of matter. Such a pancake will be formed by collapse of the rotating white dwarf core of a star that has grown unstable in the course of thermonuclear evolution (Fig. 8). Consider a single one of these fragments, one which has a mass μ small compared to the mass m of the black hole. As the fragment goes around it will lose

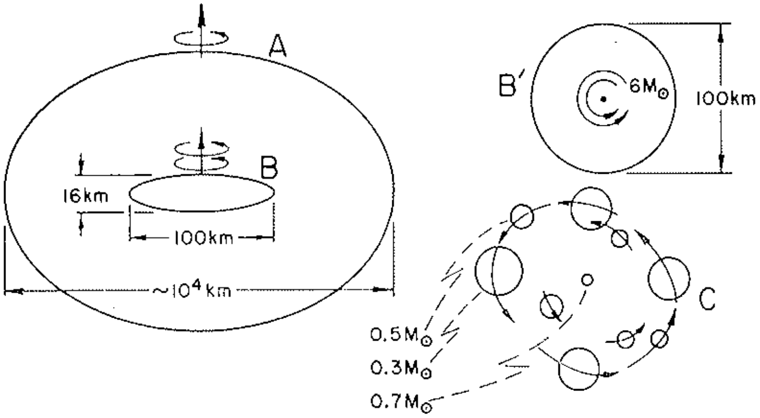

FIG. 8 — Formation and fragmentation of a "pancake" of nuclear matter (schematic; adapted from RUFFINI and WHEELER [9]). A: rotating white dwarf core of a star that has become unstable and starts to collapse. B: resulting "pancake" of nuclear matter, turning much more rapidly. B′: same, seen from observer looking "down" along the axis of rotation. C: fragmentation of this pancake into neutron stars. Eventually these stars lose enough angular momentum by gravitational radiation that they can coalesce step-wise into a black hole.

energy by gravitational radiation and spiral in. Having at the start too much angular momentum to be captured, it eventually loses enough angular momentum so it can be captured.

The gradual spiralling in ends with a last stable circular orbit at $r = 6\ m$, followed by a single arcing leap into the black hole, $r = 2\ m$, in the case when that center of attraction has no angular momentum. When it does have corotating angular momentum, the spiralling goes further in before the leap; and the leap, when it occurs, is shorter. When the angular momentum is maximal, $L = m^2$, there is no "leap" at all. The fragment spirals in all the way to the surface ("horizon") of the black hole, now located at $r = m$. This center then receives an augmentation of mass equal to $\delta m = \mu/3^{\frac{1}{2}}$ (the rest of the mass of the fragment has been radiated away as angular momentum of gravitational radiation [JAMES BARDEEN]) and of angular momentum equal to $\delta L = 2\ m\mu/3^{\frac{1}{2}}$. The increase of angular momentum, relative to the increase of mass, has a value for this process equal to

$$\frac{\delta L}{\delta m} = 2m.$$

This happens to be identical to what is achieved by capture of a slow moving particle coming in from infinity,

$$\frac{\delta L}{\delta m} = \frac{\mu\beta b}{\mu} = 2m.$$

When the black hole has less than maximal momentum one can also determine the largest increase in angular momentum, per increase in mass, that is at all in principle possible, finding (DEMETRIOS CHRISTODOULOU [15])

$$\frac{LdL}{mdm} = [m + (m^2 - L^2/m^2)^{\frac{1}{2}}]^2 + L^2/m^2.$$

It follows from this formula [15] that the mass of a black hole increases with its angular momentum according to the formula

$$m^2 = m^2_{\mathrm{ir}} + L^2/4m^2_{\mathrm{ir}}$$

when this mass increase is made most "efficiently".

Reversible and Irreversible Transformations in Black Hole Physics

CHRISTODOULOU concludes that one has to distinguish between reversible and inversible transformations in black hole physics in the following sense: (1) The squared mass is made of two components, one an "irreducible mass", m_{ir}, and the other a "rotational part", associated with the angular momentum L. (2) By a reversible transformation the rotational part can be increased or decreased without affecting the irreducible part, up to a peak value $L = m^2 = 2m_{\mathrm{ir}}{}^2$ ("extreme Kerr black hole"). (3) Any irreversible transformation (example: head-on impact of a small mass μ upon a standard Schwarzschild black hole) will increase the irreversible mass, but there is no process which will decrease the irreversible mass.

The normal process of formation of a black hole will generally result in maximal or near maximal angular momentum, as pointed out by JAMES BARDEEN and illustrated in Fig. 8. The considerations of CHRISTODOULOU say that a fraction of this mass-energy is available for use, a fraction equal to $(m - m_{ir})/m_{ir} = 1 - 2^{-1/2}$ or 29.3 percent. This is an enormous stockpile of energy on which to draw in the case of a black hole that has engulfed a substantial fraction of the mass of a galactic nucleus.

PENROSE was the first to suggest a process by which to extract the rotational energy of a black hole. It makes use of the ergosphere (Fig. 9), the region between the horizon and the surface of infinite red shift (Fig. 10).

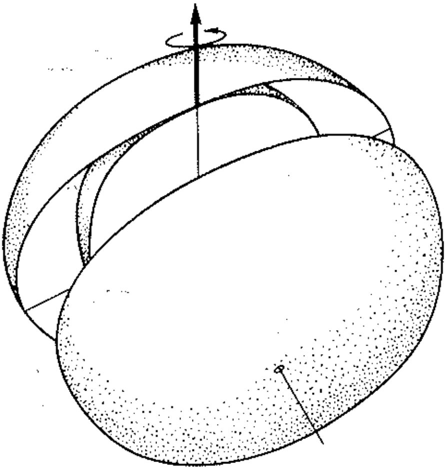

FIG. 9 — "Ergosphere" (terminology and drawing from RUFFINI and WHEELER [9]), the region between the surface of infinite red shift (flattened figure of revolution, $r = m + (m^2 - L^2 \cos^2\theta/m^2)^{1/2}$) and the "one way membrane" or "horizon" (inner sphere, $r = m + (m^2 - L^2/m^2)^{1/2}$). A particle entering the ergosphere and emitting a disintegration product down into the black hole can emerge (R. PENROSE [16]) with more energy (rest-plus-kinetic) than it had when it entered.

Fig. 11 illustrates how an object coming in from infinity with rest-plus-kinetic energy E_0, and disintegrating in the ergosphere, can send back out to infinity an object of rest-

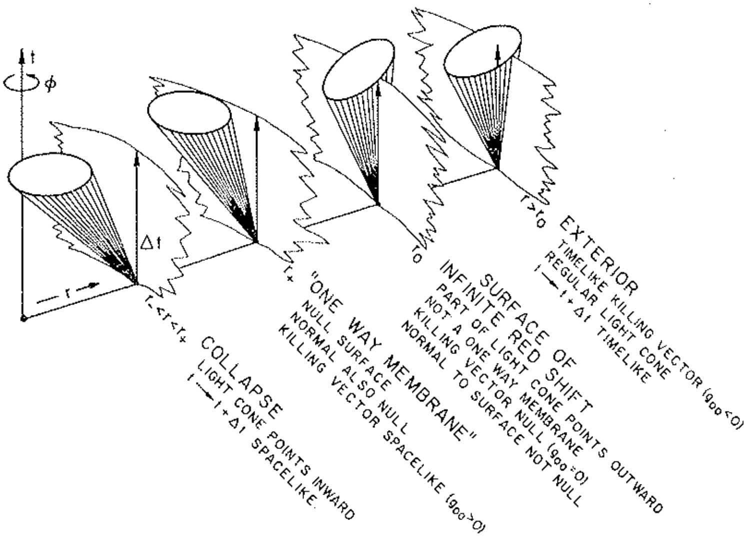

FIG. 10 — Course of light cones distinguishing horizon from surface of infinite red shift. Nothing prevents a particle that comes inside the surface of infinite red shift from reemerging; but once inside the horizon it can never escape.

plus-kinetic energy E_2 greater than E_0. The product of disintegration has a positive energy in the local Lorentz frame of the incoming object at the moment of its decay, but a negative energy as "measured" from far away (only possible by virtue of being inside the surface of infinite red shift). This circumstance means that it depletes the stock of mass energy in the black hole when it enters.

The perfection of the black hole, evidenced in its exact rotational symmetry, might have made it seem a hopeless object out of which to extract energy. Not so! It is only necessary that it possess an ergosphere; and for this it is only necessary that it possess a non-zero angular momentum (actual mass greater than irreducible mass!).

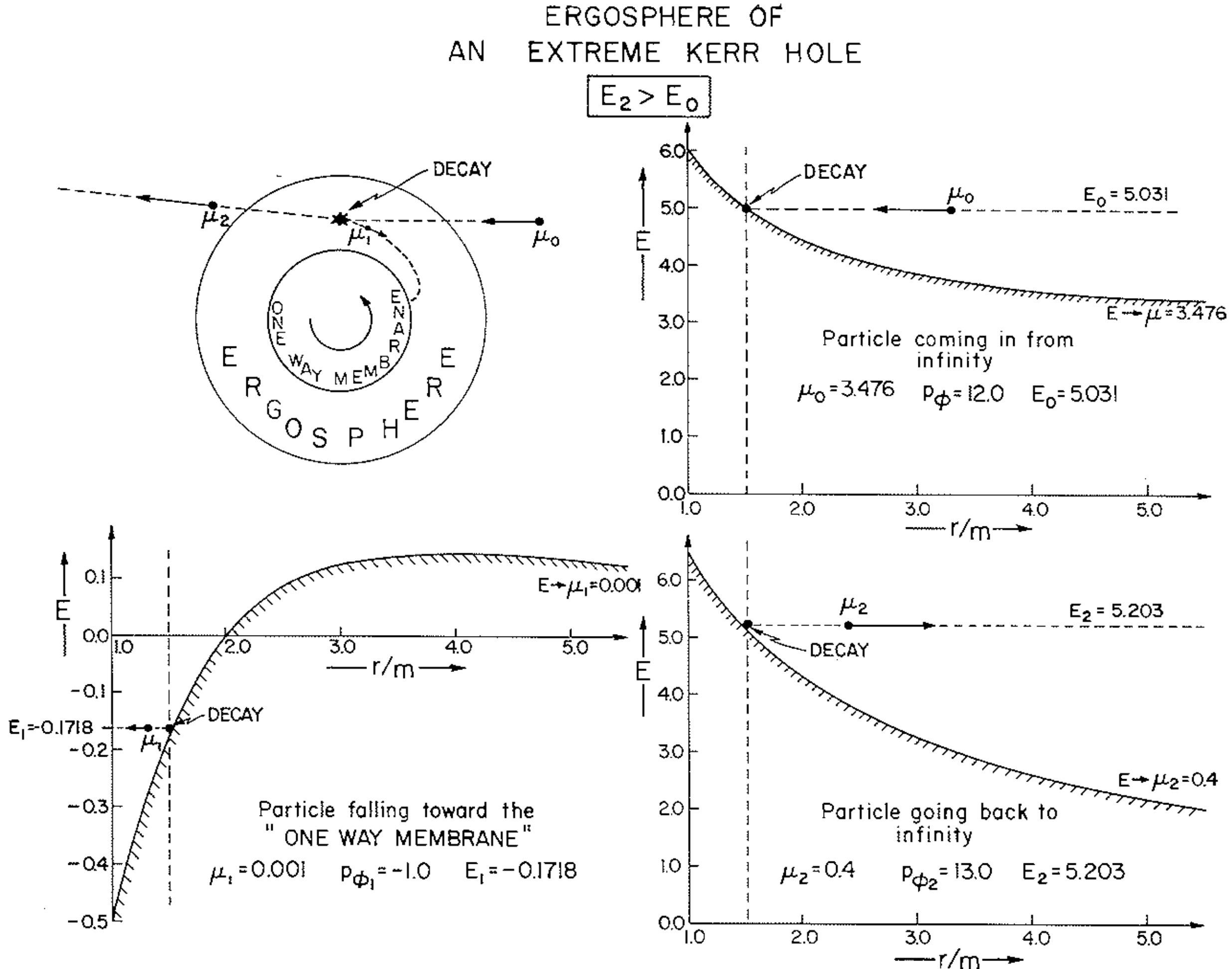

FIG. 11 — A particle of rest mass μ_0 comes into the ergosphere of a black hole of extremal angular momentum, expels a counter-revolving particle of rest mass μ_1 into the black hole, and emerges with a rest-plus-kinetic energy E_2 greater than it had when it entered. The decay product, of positive energy in the local Lorentz frame, has negative energy according to the "common market" standard of energy at infinity. The energy gained in the decay

There is nothing that requires the process of extraction of energy to be accomplished by an elementary particle decay process. In principle one can ride a rocket into the ergosphere, let it eject its burnt gas down into the black hole, and have it emerge with more rest-plus-kinetic energy than it had when it came in.

Combine Ergosphere Effect with Tube-of-Toothpaste Effect to Get Jet

Can nature itself design the rocket? Let a star with the right angular momentum ("corevolving") come into the ergosphere of a black hole which is larger than the star by a considerable factor. For this it is more than enough that the black hole should contain some substantial fraction of the mass of a galactic nucleus. The star will experience the "squeezed-tube-of-toothpaste" effect. It will automatically in some sense become a rocket. It seems not at all impossible that the ejecta from this "rocket" under the right conditions should go into the black hole and extract from it some of its enormous stockpile of energy. In this event it would seem that energies of a relativistic order of magnitude are to be expected for the emerging remainder of the "star that was". Moreover, considerable directivity would be expected for the outgoing burst of star debris. It is hard to imagine this process giving rise to a symmetric pair of jets. However, something grossly similar to a single jet would seem a not unnatural outcome of this combination of the "ergosphere effect" and the "tube-of-toothpaste effect".

If this assessment is reasonable, then one would seem to have in such "ergosphere jets", if and when they occur, the possibilities of a third tool for investigating black holes observationally, the other two [9] being (1) gravitational radiation given off in the process of formation of the black hole and (2) x-rays given off by matter accreting onto the black hole after its formation (ingoing matter from interstellar space or ingoing gas coming from atmosphere of a normal companion star compressed (convergence factor!) and heated to the point (10^{10} or 10^{11} °K) where it emits x-rays).

The LEBLANC - WILSON *Double Jet Mechanism*

Turn now from a mechanism that may produce only one jet to the new LEBLANC - WILSON mechanism [4] that produces two jets. They arrived at this mechanism in analyzing the process of collapse of a star of quite normal mass ($m \sim 7\ M_\odot$; density $\sim 10^8$ g/cm^3; matter already "burned out" so far as thermonuclear combustion is concerned). Whether the same process makes sense for an object of mass $\sim 10^8\ M_\odot$ is a question which they have still under investigation at Livermore.

The kind of collapse treated by LEBLANC and WILSON is like that already treated by COLGATE, MAY and WHITE [10] and illustrated in Fig. 5 with one exception: they give up spherical symmetry and go to two dimensional hydrodynamics. Not to make the problem overwhelmingly difficult to treat on a digital computer they retreat from general relativity hydrodynamics to Newtonian hydrodynamics. No order-of-magnitude alteration in the results is to be expected from this simplification in the problem they ran.

The new features that destroy spherical symmetry are (1) rotation, with the rotational kinetic energy amounting to one fourth of one percent of the energy of gravitational binding and (2) a polar magnetic field whose energy is one fortieth of one percent of the gravitational energy. By judicious order of magnitude estimates ahead of time these values were concluded to be right to produce an interesting kind of implosion.

As the collapse proceeds the moment of inertia of the inner part of the system decreases first. Therefore it turns faster than the outside. Thus the first step in the LeBlanc - Wilson process is the conversion of gravitational energy into kinetic energy of rotation.

The inner part winds up the magnetic lines of force like threads on a spool of thread. The magnetic lines of force become packed immensely more densely than they were packed before. Moreover the lines of force, originally entirely meridianal, are now predominantly azimuthal. The Faraday - Maxwell tension along these lines of force extracts energy out of the rotation and stores it in the form of "$B^2/8\pi$". Thus the second step in the LeBlanc - Wilson process is the conversion of rotational energy into magnetic energy.

At right angles to the lines of force there develops a very large Faraday - Maxwell pressure. In effect one has a compressed spring running along the axis of the star. This spring is anchored in the material of a "core" that runs from South pole to North pole. It pushes this core out of the two poles. Thus the third stage in the new Livermore process is the conversion of stored magnetic energy into kinetic energy of a double jet.

The most impressive single number about the calculated jets is the speed: one seventh the speed of light. The calculated ejection of mass from the two poles together is $\sim 2 \times 10^{31}$ g. The kinetic energy is $\sim 1.6 \times 10^{50}$ erg. The energy stored in the magnetic field at the moment of maximum stored energy was $\sim 3.5 \times 10^{49}$ ergs (in the jet itself).

More details of the process appear in Figs. 12 and 13, taken from the paper of LEBLANC and WILSON.

The LeBlanc - Wilson mechanism starts with quite natural conditions and gives quite impressive results. There is no obvious reason why it cannot operate at a variety of scales, up to the scale of 10^8 $M_\odot$, for example, even though the first and only calculation so far was run for a system of mass only $m = 7$ $M_\odot$.

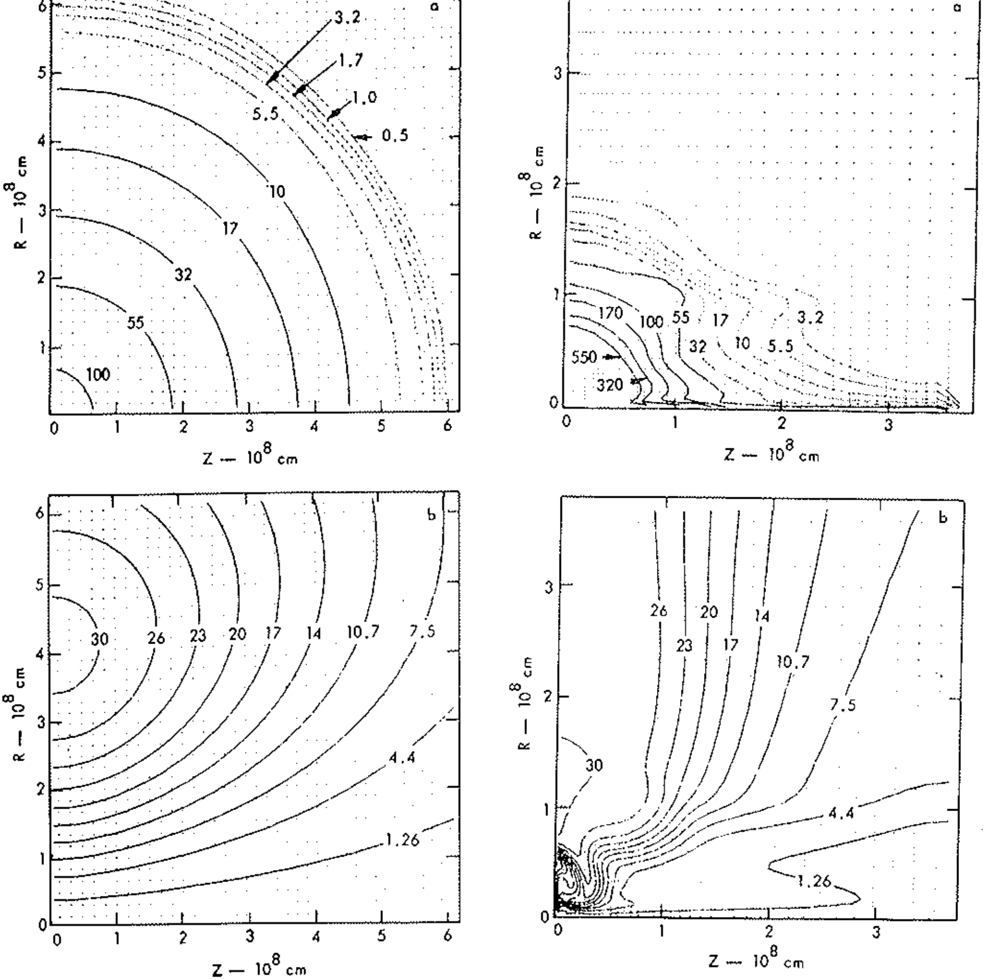

FIG. 12 — The LeBlanc-Wilson jet mechanism. Isodensity contours and magnetic flux contours parallel to the z axis for the gravitational collapse of a 7 $M_\odot$ rotating magnetic star as computed by J. M. LEBLANC and J. R. WILSON and reproduced directly from their paper [4]. They have considered a star in which all the material has been burned to the end point of thermonuclear evolution. The star is also assumed to be initially in uniform rotation with an initial angular velocity of 0.7 rad/sec (angular momentum ∽ 4.6×10^{50} g cm^2/sec) and to have a magnetic field parallel to the z axis with an energy of the order of 0.025% the gravitational energy of the star. The computations are started from an equilibrium configuration. After a few seconds enough energy has been lost by neutrino emission that the star starts to collapse.

As the collapse proceeds the temperature of an interior region rises above the iron decomposition temperature and the collapse rapidly accelerates. During the collapse non-radial motions develop due to the increasing of centrifugal force and the angular velocity approaches a vortex configuration. The shear in the velocity generates large magnetic fields along the axis of rotation. The multiplication of magnetic energy by this process is a hundred times larger than the one expected from simple compression. The collapse is stopped at a density of the order of 10^{11} g/cm^3. The combined effect of rotation and magnetic field produces a jet in the axial direction with a speed of the order of one tenth of the speed of light. This jet carries a mass of the order of ∽ 2×10^{31} ergs and a total energy of 1.6×10^{50} ergs, largely kinetic but witn a considerable amount of magnetic energy (∽ 3.5×10^{49} ergs with fields of ∽ 10^{13} gauss). The two graphs in the upper part of the figure give the isodensity contours in units of 10^6 g/cm^3 at 0.72 sec and 2.67 sec after the beginning of gravitational collapse. With R is indicated the distance in the equatorial plane from the rotational axis (z axis) in units of 10^8 cm.

The two graphs in the lower part indicate the magnetic field contours parallel to the z axis in units of 10^{22} gauss cm^2 again at 0.72 sec and at 2.67 sec. The magnetic field was initially chosen to be parallel to the z axis and with an energy of 0.025% of the gravitational energy of the star.

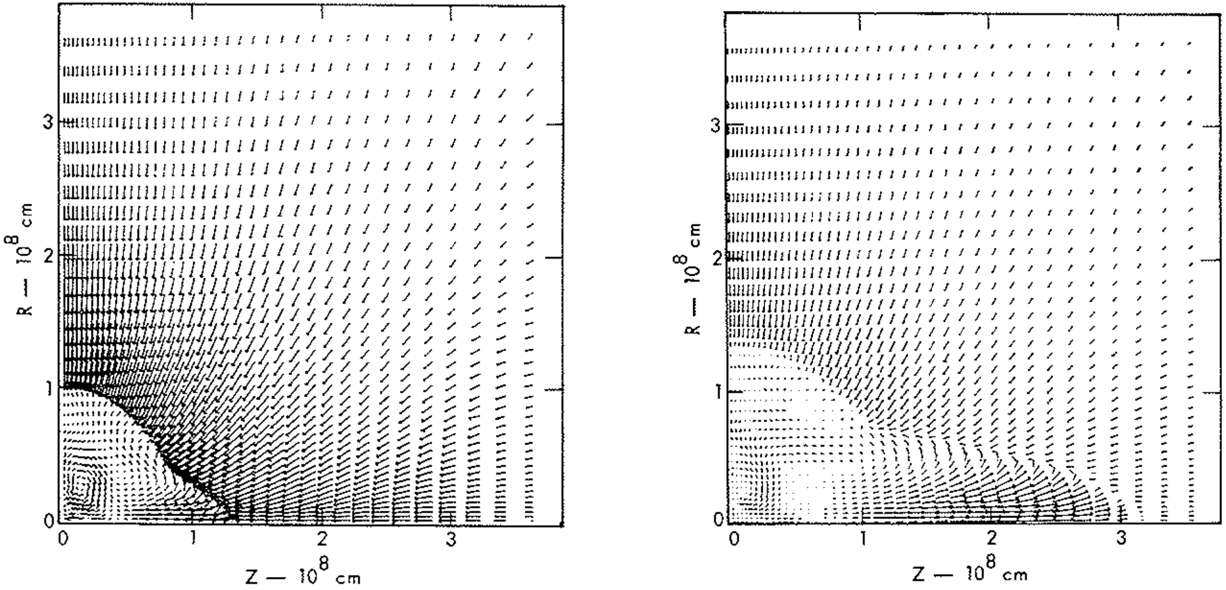

FIG. 13 — Velocity developed in the LeBlanc - Wilson mechanism (diagram reproduced from their paper [4]). The arrows give the velocity vector throughout the system. Special attention is drawn to the velocity of the jet. It originates from collapse of the same 7 $M_\odot$ star described in the caption of Fig. 12. R gives the distance in the equatorial plane from the rotation axis (z direction) in units of 10^8 cm. The graph at the left refers to a configuration 2.61 sec after $t = 0$ (start of gravitational collapse). The maximum velocity magnitude is 2.43×10^9 cm/sec. The graph at the right refers to a configuration 2.64 sec after $t = 0.0$ with a maximum velocity of 4.38×10^9 cm/sec.

At least two features of this process lend themselves to further analysis and test. The first is the pattern in the jet of magnetic lines of force, and particles circulating around these lines of force, giving rise to a pattern of polarized radiation. The second is the characteristic evolution in time of the dynamics of the jet: not a continuous process, but a one-shot process, with a definite and calculable time scale.

Narrowing the Jet

How a jet, once driven out at all, acquires the sharp directivity of some of the observed events, would seem to be a separate question, involving a separate mechanism. Most obvious in this connection is the mechanism of confinement of the outgoing radio-emissive cloud by the ram-pressure of the extragalactic medium, a model developed by DE YOUNG and AXFORD [17], modified by STURROCK [18] by consideration of the effect of the trapped magnetic field, and further analyzed by MILLS and STURROCK [19] (Fig. 14).

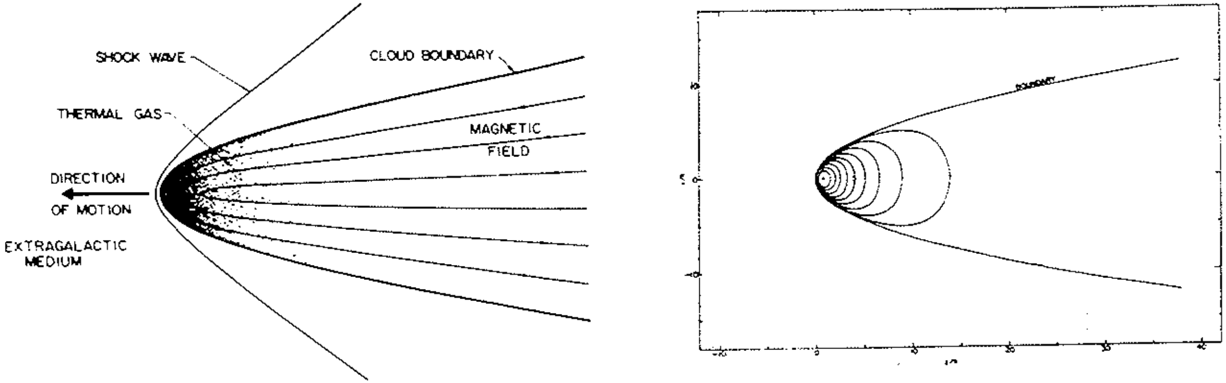

FIG. 14 — Schematic model of radio cloud, according to MILLS and STURROCK [19], based on (a) mass of non-relativistic turbulent gas ejected from the parent object; (b) a magnetic field that threads through this gas; (c) a low density relativistic electron gas caught up by (a) and (b) and ultimately to serve as the source of the radioemission; and (d) the low density intergalactic medium into which the cloud plows. By the "snow plow effect" or ram pressure it constrains the cloud to dimensions much less than one might have expected from the spread of velocities in the original cloud.

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DISCUSSION

Chairman: W.A. FOWLER

WHEELER

For the sake of completeness may I mention one point which I left out this morning, about the physics of black holes in the kind of potential that SPITZER talked about yesterday. There we have stars collecting and black holes collecting and neutron stars collecting. There will be a certain probability for a black hole to coalesce with an ordinary star. Nothing is evident that would keep the black hole from falling to the center of the ordinary star and, after a certain number of oscillations, settling down there to make a "seeded star". No catastrophe happens. The black hole simply absorbs matter slowly from the enveloping star. The rate of absorption is limited by the back pressure of radiation (matter streaming in heated by convergence-compression to the point where it radiates). The "seeded star" will radiate more rapidly than normal.

MORRISON

This is just a question about the physics of black holes and Kerr holes. There seems to be no scale naturally fixed for these objects. That is to say, they could occur on most scales from 1 to 10^{10} solar masses; I suppose the spin too can be anything below the Kerr limit. One raises the question that these things ought to be rather plentiful if they are made at all, and you suggested they live inside the stars! Are there any signs of individual ones, or ways to look for individual ones at 10 solar masses or a hundred or a thousand or any other number?

WHEELER

The mechanism of production of x-rays by matter accreting onto a black hole is promising in any scale or size, from one solar mass to a hundred solar masses. Perhaps for 10^{10} solar masses the physics is rather different and I don't want to propose that x-ray emission is necessarily the most promising of the indicators for an object of such a mass.

LYNDEN-BELL

I'd just like to make the remark that I tried to estimate the number of black holes in the ten solar mass range. I found that if most stars of ten or twenty solar masses made black holes, then the nearest one to us now would be probably within 20 parsecs and about fifth bolometric magnitude. Most of its emission will be in the x-ray region, or the far ultraviolet at least.

SPITZER

If most of the energy goes into the x-rays and corresponds to the fifth bolometric magnitude, should this x-ray flux be easily measurable?

LYNDEN-BELL

That was a slip of the tongue, I think that most of the emission is in the ultraviolet and not in the easily observable part of the x-rays, but I have not worked out whether it is easily measurable.

SPITZER

Is it something that an ultraviolet search may help, or is it shortwards of the Lyman limit?

LYNDEN-BELL

It's a long way shortwards of the Lyman limit, again it's temperatures of the order of hundreds of thousands.

McCREA

My first remark is a rather frivolous one in connection with Prof. MORRISON's question. In a sense a cosmological model makes the universe as a whole a black hole and that is the only one we really know about definitely. I have to put two remarks to Prof. WHEELER. I have discussed this directional problem with an expert on explosions, and apparently if an explosion is formed under water, the material which is thrown out is thrown vertically out in a fairly narrow column. Also there are calculations about explosions in the atmosphere, and I think the calculations there show that ultimately most of the material that is set in motion will be moving vertically out in a fairly narrow column. I don't think this will explain the narrow jets we see in astronomy, but it is an example of a fairly directional effect. If I may now ask my question on a different matter. Dr. WHEELER, as I understood him, said that if anti-matter goes into a black hole, it disappeared; or did he say it added to the mass in the same way that ordinary matter does? I think he said that black holes would ensure that the universe as a whole would be all matter, as I understood it.

WHEELER

Many others have also felt uncomfortable about a universe that is all matter and no anti-matter. Therefore it is interesting to see that in principle there is no difficulty at all about getting from a universe which is symmetric to a universe which is completely unsymmetric, as we suspect our own to be. To go from "in principle" to "in actuality" is another matter! I am not going to propose any mechanism to collect the anti-matter and put it down black holes! However, I gather that your comment is simply this: Is a black hole made of anti-matter any different from a black hole made of matter? The answer is, no different. There is absolutely no known method to distinguish a black hole formed out of anti-matter from a black hole formed out of matter after they are once made. The only tools available to try to distinguish between them are gravitational attraction and the gravitational analog of a magnetic force (associated with angular momentum). With only these two tools on hand to try to give evidence of their presence, the baryon number, the lepton number, and the strangeness number have passed beyond the possibility of being measured, and in that sense have lost their meaning.

SANDAGE

Could I ask Prof. WHEELER or Dr. LYNDEN-BELL if they believe it is significant that the two identified x-ray stars, Sco X-1 and Cygnus X-2 are, perhaps, binaries? The periods of these, [or rather the characteristic times for the variations in their radial velocities of the order of 200 — 300 km sec] are less than a day. Would these parameters fit what you would expect from what you were saying this morning of a black hole and an orbiting normal star giving rise to x-rays?

WHEELER

These are periodic, are they?

SANDAGE

The hydrogen and helium lines in emission vary in opposite directions. We've not been able to follow the stars long enough to see if they are strictly periodic, but over the period of time of observation it looked as if there was some systematic phenomenon in the motion of the emission and absorption lines, suggesting both to MARGARET BURBIDGE and to us binary motion for Cygnus X-2, with similar results from our plates on Sco X-1.

WHEELER

It would be most interesting to look at these systems with a view to seeing if each can be interpreted as having a neutron star component, or black hole component, sopping up the matter cast off in the normal way from the normal component.

SANDAGE

We thought the period of Sco X-1 was about four hours, but the data surely were not as good as real spectroscopists would say were first class data for good spectroscopic binaries. There are still observational difficulties, but it certainly seems like there are some systematic motions in both of these.

WHEELER

This period would seem to mean a separation close enough so that a good fraction of the matter from the normal star can fall in on the black hole or neutron star to give x-rays.

SANDAGE

The inferred separation of the components was of the order of the sum of the radii of the stars, but more data are required.

G. R. BURBIDGE

One interesting point is the question of how much mass can exist in the form of a black hole at the center of a galaxy. Dr. WOLFE and I have recently made some calculations using the observed properties of giant elliptical galaxies, in particular the light distribution and the velocity dispersion in the centers, and we have been able to estimate upper limits for the masses of black holes if they exist in such galaxies. The masses of central black holes must be less than about 10^{10} solar masses in some of the best studied ellipticals.

OORT

I should like to ask Dr. LYNDEN-BELL whether he believes that the gas which one sees flowing at a velocity of about 40 km/sec into the non-thermal component of Sagittarius A could have any significance in connection with the black hole. This flow has been observed in OH, but not in H I.

LYNDEN-BELL

OH, all right, once you say OH, I'm happy. Well, this is an individual cloud, and I have a feeling that if you try to put a cloud as close as 10^{15} cms from a source, then since this source is emitting, the cloud will be ionised even if it is quite dense, and so I'm rather worried that it is OH that we see.

OORT

It couldn't be very close, of course, but it might be part of the phenomenon of the dragging in of the disk into the galactic nucleus.

LYNDEN-BELL

I agree it might be, but the velocities observed here are much greater than the velocities that you would naturally get from a frictional mechanism which is less than a thousandth of the circular velocity of the kind considered, whereas these velocities are of the order of a tenth or a twentieth. They are much too large as velocities, although they might well carry the right sort of amount of flux.

OORT

I am still wondering what may be the explanation for the 40 km/sec velocity, a very remarkable phenomenon indeed.

LYNDEN-BELL

I am too!

MCCREA

I would like to ask Dr. LYNDEN-BELL about the BARDEEN critical case. He said this was the one self-consistent case, as I understood it. But is it self-perpetuating, that is, if matter falls into one of these bodies — critical systems — does it only do so so as to preserve the critical character?

LYNDEN-BELL

The answer to that is slightly complicated, if you take the simplest calculations and assume that everything is going in with 0.58 of the rest energy and with the total angular momentum for the last stable circular orbit, then there is an idealised answer, "yes", and it is the only self-consistent metric and it would just go on and grow in mass and angular momentum. If, however, you take the point of view that the black hole itself is eating some of the radiation, or if you take slightly non-circular orbits and say they are the typical orbits close in, then you would get a self-consistent case with a slightly smaller value of the angular momentum per unit mass squared.

McCREA

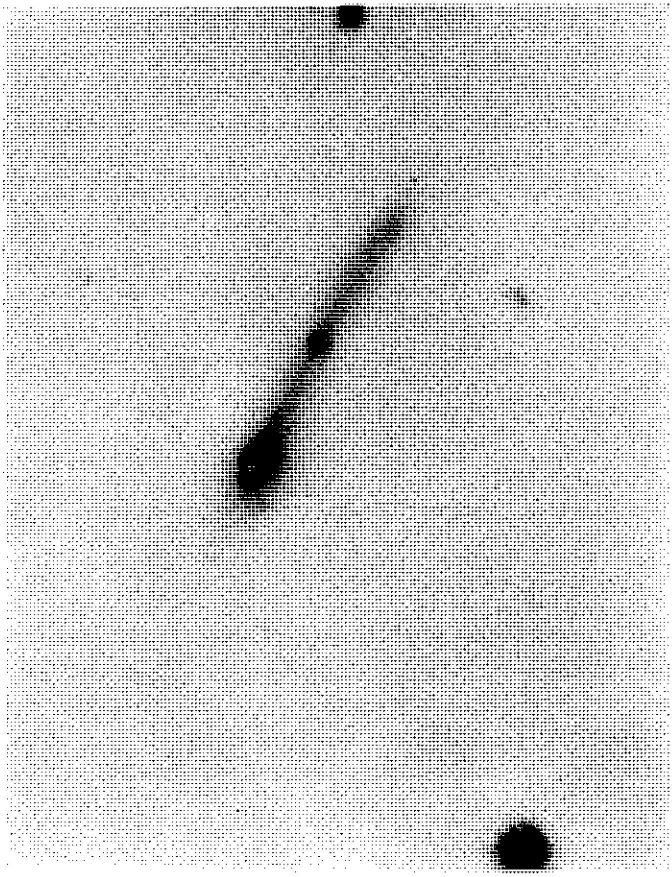
Well, will this make a system grow or will it stop it growing?

LYNDEN-BELL

Neither case will stop it growing. It will always grow just due to the fact that friction always adds mass in. There are two parameters, the mass of the object and the angular momentum per unit mass squared. The question is which is a self-similar growth. All of them grow but only certain growths are self-similar.

SARGENT

Since there was talk of jets this morning, I would like to show a photograph of an object which looks as though it has a jet on it. This object is VV 144 which is also an object in MARKARIAN's list of blue galaxies. The object on the right is a Seyfert galaxy as was discovered by the BURBIDGES and confirmed by me. It has a red shift of about 6100 km/sec and last year I was interested in the blob which is half way along the jet-like structure. The jet-like structure is about 20 kiloparsecs long projected on the plane of the sky. I found that the spectrum of the blob is that of an early type galaxy and that it shows hydrogen lines in



VV 144 referred to by SARGENT in the discussion. The original was obtained by ARP at the prime focus of the Hale telescope.

absorption with a red shift of 6,400 km/sec, that is, 300 km/sec bigger than the red shift of the Seyfert galaxy. If this difference is interpreted as a rotation then it leads to a mas of about 10^{11} solar masses for the more massive component — whichever it is. I have attempted to get a spectrum of the jet itself by putting the slit along it and, although it is easily visible to the eye on the slit of the spectograph, it did not produce an emission line spectrum, I just got a continuum. It's a puzzle to me whether this object really should be interpreted as an ejection from the Seyfert galaxy. As you can see, if it is an ejection it is in the equatorial plane of the Seyfert galaxy. However, it could be a system of two galaxies with material which has been knocked off one of them.

FOWLER

Can one believe that condensation has not occurred in the material on the left, whereas it has clearly occurred on the right?

SARGENT

I don't know.

SPITZER

Can you estimate the magnitude of the Seyfert galaxy in the arc?

SARGENT

I think the magnitude of the Seyfert galaxy is about 16½ and the magnitude of the blob is about 17½ and this leads to an absolute magnitude, if I remember rightly, of about − 18 for the Seyfert galaxy and − 17 for the condensation.

SANDAGE

Could I ask SARGENT if any of this could be interpreted in the way that ALAR TOOMRE is attempting to interpret some of these long thin filaments with blobs on the end, in terms of tidal action? His calculations, I believe, show that in quite a number of cases the long arms with the secondary galaxy at the end can just as well be interpreted as stuff coming out of the main galaxy by tidal action, insead of an expulsion of matter by another process along the jet.

SARGENT

Well I too have seen TOOMRE's computer-type data and they look very convincing to me; that at least some of ARP's cases could be produced this way, but this system doesn't look to me to be like a spiral galaxy to start with.

FOWLER

OORT has suggested, and I second the motion, that SARGENT supply each one of us with a print of this photograph.

SARGENT

I'd be glad to supply you with a print. I should say, however, that the picture was taken by Dr. ARP but I'm sure he would also agree to give you a copy.

FOWLER

I'm sure he would. I would like to ask either WHEELER or LYNDEN-BELL the following question: It has always been my impression that the black hole phenomenon, if true, implies a certain amount of spherical symmetry in the formation of the black hole. I have also heard that if there is sufficient rotation a black hole will not form.

WHEELER

If one has two black holes, each one of twice solar mass, separated by a hundred kilometers and rotating about their common center of gravity with a period of a hundredth of a second, then they have too much angular momentum to assimilate into one single black hole. However, they will dissipate this angular momentum by gravitational radiation in a time of about half a second. Then they will unite to form one single black hole. All the asymmetry of the system will fade out in a characteristic relaxation time of some micro-seconds, giving one at this point the ideal rotating black hole. How much of the energy of the original system comes out as gravitational radiation has only been calculated for head-on impact. The amount of mass lost in the form of gravitational radiation will be expected to be a little greater in the case of two masses going around each other. Does this account agree with you, Donald?

LYNDEN-BELL

Well, if you start with two large bodies I think you know more about the problem than I do, so it certainly checks with me. If you start by putting smaller bodies in, of course, you can make the amount of gravitational radiation go down, if you feed matter in gradually then you get essentially no gravitational radiation radiated and certainly you can make a black hole out of a perfectly flat disk. If BARDEEN and WAGONER disks are remotely stable, then you can make them quite quiescent by gradually letting them shrink and give out their angular momentum. The one restriction on black holes is of course that the angular momentum per unit mass squared must be lower than one in relativistic units in which $G = c = 1$.

SCHMIDT

May I show a slide? This is a slide of the jet of 3C 273. People have often asked about what the spectrum of the jet looks like and this does and does not answer the question. The jet itself has a total magnitude estimated by OKE to be between 20 and 21, and since it is about 10 seconds of arc long, and perhaps up to a second of arc wide, it means that it simulates 10 stars lying in a row, each of 23rd magnitude, so it is difficult to get a spectrum. This one was taken three years ago with the fastest camera available with the nebular spectrograph at the two hundred inch telescope on an O plate exposed for five hours. The streak that runs right through the upper comparison lines, is the spectrum of the star-like object 3C 273. It has been only exposed intermittently to check that the alignment was correct. So it has been exposed for a total of the order of two minutes. The jet extends from 10 to 20 seconds of arc from the starlike object in 3C 273.

I can see it on the original from about 3600Å up to perhaps 4700Å, and it will be quite obvious to you that if there were any emission lines in the spectrum of the jet, or absorption lines, they would have to be really strong to be seen in competition with the night sky. All one can say is that there is a probably bluish continuum.

FOWLER

Are there any questions concerning Prof. SCHMIDT's jet? If not, let me return to interrogation of our general relativists. It is my impression that even the post-Newtonian terms in general relativity are suspect. What features of general relativity, or what feature, guarantees the black holes? What aspects of general relativity are different from classical physics?

WHEELER

The same factors come into the analysis of the black hole as come into the cosmology of the universe, except on a different distance scale. If one has too much mass, then the geometry closes itself up. In applying general relativity there is no evident stopping point between the scale of distances of a few kilometers associated with stars and the scale that applies to the universe, of 10^{10} light years. We do not see any natural escape from saying that black holes, like neutron stars, must exist. One remembers that from the time of the prediction of neutron stars in 1934 to the observation of pulsars and the conclusion that they are neutron stars was 34 years. One remembers that black holes were predicted 5 years later than neutron stars — 1939. If one wants to add 34 years onto 1939 he can make his own calculations.

I have never heard of the black hole geometry as being thought of in the days of KARL SCHWARZSCHILD as an object by itself. Was it not always rather the idealized exterior geometry that was going to be joined onto some every-day object? His distinction between the exterior solution and the interior solution was one that so far as I know he always made. To the best of my knowledge he never thought of taking the exterior solution as the whole thing.

LYNDEN-BELL

I'd like to give a strange answer to Prof. FOWLER. I think NEWTON, using the ballistic theory of light and Newtonian gravity, would have predicted black holes.

MCCREA

Physics seem to demand something like this, because if we move a small particle towards a big one slowly we lose potential energy. If that potential energy exceeds the rest-mass of the particle, it must have gone into a black hole. So the concept is not a very difficult one. But whether nature ever realises this in practice is quite a different problem, and I think that is what Prof. FOWLER is really thinking.

FOWLER

Let me put it even more pointedly. What if some of the more accurate tests of general relativity turned out to fail, in the sense that the predictions of general relativity are no longer verified, then will we still want to believe in black holes? What I am trying to get at is this: Is the ultimate singularity much more fundamental than, say, the post-Newtonian or the post-post-Newtonian terms?

WHEELER

I would cite calculations of RUFFINI on the properties of neutron stars using one and the same equation of state throughout but using three different theories of gravity. Calculation one uses general relativity. It gives a critical mass of 0.715 $M_\odot$ for the upper limit of any stable neutron star. Calculation two, with the same equation of state, but using Newtonian physics, gives

1.666 $M_\odot$ for the critical mass. So here is a case where general relativity makes more than a factor two difference. Calculation three uses the Brans-Dicke scalar-tensor theory of gravitation. This gave for the critical mass 0.730 $M_\odot$, two percent more than the general relativity figure for the critical mass. If one says that a neutron star is really very far on the way towards a black hole, this result would indicate that the features of a black hole will be very little different in the Brans-Dicke theory than in general relativity theory. This is in line with the comments which were made earlier about even Newtonian theory demanding something like a black hole.

FOWLER

Thank you.

OF THE NATURE OF COMPACT OBJECTS

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It is possible to avoid the appearance of relativistic singularities in a discussion of compact objects by supposing that we have to deal with a starlike association of matter generating energy internally by nuclear processes. HOYLE and FOWLER [1] obtained the following results for such a superstar,

$$L \simeq 5 \cdot 10^4 \frac{M}{M_\odot} L_\odot \, ,$$
$$R \simeq 5.8 \times 10^{10} (M/M_\odot)^{\frac{1}{2}} \text{ cm},$$
$$T_s \simeq 8 \times 10^4 \text{ K} \, .$$

Masses greater than $\sim 10^5$ $M_\odot$ cannot be stable in spherically symmetric form. Since the total output of nuclear energy from 10^5 $M_\odot$ is only 10^{57} erg, much less than the output from many compact objects, it is necessary to invoke masses larger than this. HOYLE and FOWLER [2] pointed out that the stability issue for a spherically symmetric configuration is avoided by introducing rotation, in the sense that centrifugal force provides support against gravity for directions perpendicular to the axis of rotation. This model was investigated in detail by Fow-

LER [3]. The model has considerable similarity to that recently discussed by MORRISON [4].

The rotating configuration becomes highly flattened when the mass M exceeds $\sim 10^5$ $M_\odot$ by a large factor. In a disk-like form it persists for $\sim 10^6$ years. Thereafter a collapse into a swarm of objects of much smaller masses ensues [2]. It is possible to argue that such a collapsing phase is associated with violent outbursts of the kind found in radio sources.

This is the simplest picture for a compact object. If moreover one supposes that the object manages to accumulate from debris falling towards a gravitating centre — whether from star collisions or some other mechanism — the model relies on concepts that place little strain on the imagination.

The main difficulties are:

a) Spectra associated with a hot star-like surface have not been found. The spectra of QSOs, for example, are more akin to planetary nebulae than to such a surface.

b) There is no evidence to support infall of matter. Observation shows outflow not inflow.

c) After $\sim 10^6$ years nuclear energy is exhausted. Following the collapse of the disk into fragments, the fragments themselves implode into singularities. Thus ultimately the singularity problem cannot be avoided.

This brings me to the second possible model for a compact object. In this second model a singularity is already in the process of being formed. To an external observer the object is close to its Schwarzschild radius. Radiation from it is very highly reddened. It is not possible therefore in this model to appeal to the object itself as the energy source. Instead we must regard the energy output as coming from the exterior of the object, from some kind of magnetosphere perhaps. It was suggested first by SALPETER [5] and then by LYNDEN-

Bell [6] that infall of matter from the exterior might supply a continuous energy source.

The difficulties now are that details of the processes of energy emission have not been satisfactory and that infall of matter is not observed — outflow is observed. These difficulties were discussed at the first Texas Symposium. The situation today is not much different from what it was then.

There is a further difficulty of an abstract nature. The equivalence of observers plays a key role in discussions of relativity theory. Yet the equivalence of observers is destroyed by singularities. It is possible for two observers initially outside a singularity to pass each other, to synchronize clocks, compare their experience of the world, and for one observer to remain outside the singularity and for the other to fall into it. The latter observer reaches the singularity in a finite proper time. On reaching the singularity he experiences a new world not shared by the first observer. The principle of equivalence is destroyed.

Attempts have been made to associate such a model with "islands" left over from a big-bang origin of the universe. This idea does not work correctly, however, as can be seen by inverting time. An observer attached to the object does not arrive at the singularity contiguous to an external observer. This is a necessary condition in order that a big-bang origin of the universe be defined appropriately. Instead of a universal origin one has a situation much more akin to the steady-state model in which the origin of matter is distributed with respect to time.

These considerations all rest heavily on Einstein's general theory of relativity applied to strong gravitational fields. It is as well to realise that the theory has so far been tested by observation only for weak fields. Whether one applies it for strong fields therefore rests on its logical structure. Is this so compelling that any alternative can be considered out of the question? The answer to this question is surely negative, since the appearance of singularities can be taken as a serious logical defect. The issue is rather that, if we are to deviate from EINSTEIN'S theory for strong fields, which among the many possiblities that may then be considered to arise are we to adopt?

The suggestion which I am now going to discuss has been published by NARLIKAR and myself [7, 8] in the technical literature, and has been reviewed in more general terms in a recent contribution to the Gamow Memorial Volume.

New developments in physics have so far satisfied two criteria:

1) The logical structure becomes more elegant, and (once one understands it) simpler.

2) The consequences become more complex.

The ever-present trap in seeking new developments is to invert [1] and [2]. PLATO wanted the planetary motions to be compounded from circles. The laws that would be needed to satisfy PLATO would, as we know, be most complex — so we would have complex laws leading to simple consequences, the wrong way round. EINSTEIN'S theory is logically more elegant than NEWTON'S and its consequences are much harder to work out, the right way round. By implication if we are to make a change from EINSTEIN we must proceed further in the same direction.

Physicists have arrived at a rather precise understanding of what it is that constitutes logical elegance. It lies in the concepts of invariance — that there are many ways of looking at the world, all equivalent to one other. The route from NEWTON to EINSTEIN lies in the concept that physical theories must be invariant with respect to transformations of space-time. Recent progress in high energy physics has come from extending the concept of invariance outside space-time, first to isospin and then to a combination in SU_3 of isospin and strangeness.

The best procedure if we are to change from EINSTEIN'S theory would therefore seem to be to bring in a wider concept of invariance, because if EINSTEIN'S is not the correct theory, the correct theory will very likely possess wider invariance.

The importance of these considerations is that they limit the search for new possibilities. On the face of it one might suppose that abandoning EINSTEIN'S theory (for strong fields) would be to open the door to a veritable multitude of possibilities, but if one takes account of these criteria this is not so. The possibilities are restricted.

It is known that electromagnetic theory satisfies a wider invariance than that of space-time transformations. It also satisfies conformal invariance. Electromagnetic theory is invariant to changes of the length scale, different space-time points having different scale changes. What this means physically is that the real content of the theory lies in dimensionless numbers which must be constructed from physical quantities *taken at the same point,* not from physical quantities taken at different points.

NARLIKAR and I set out to answer the question of whether a gravitational theory could be found that satisfied conformal invariance, as well as the coordinate invariance of EINSTEIN'S theory. The answer we found to be affirmative. The theory is the same as EINSTEIN'S for weak fields but not for strong fields. It satisfies the criteria of being simpler in statement but more complex in consequences. EINSTEIN'S theory is derived from an action formula

$$S = -\sum_a m_a \int da + \frac{1}{16\pi G} \int R \sqrt{-g}\, d^4 x \tag{1}$$

Here m_a is the mass of particle a, and $\sum_a$ is a summation over all particles. For the conformally invariant theory the action takes the simpler form

$$S = -\sum_a \int m_a \, da \, . \tag{2}$$

The mass m_a is written inside the integral sign for a reason that I will explain later. Proceeding now to the consequences of the theory, which are contained in field equations, these take the form

$$\text{Einstein's Terms} + \text{New Terms} = 0 \, . \tag{3}$$

The new terms here are negligible in many-particle system for weak fields, but can be dominant for strong fields. In the sense that we have to deal with these new terms the theory is more complex in its consequences than EINSTEIN'S.

I come now to an important connection with the topic of this Semaine. For strong fields the new terms in (3) can have the same effect as $T_{44} < 0$ in EINSTEIN'S theory. It is well-known that theorems on implosion into singularities by PENROSE [6] and by HAWKING and ELLIS [7] depend on $T_{44} > 0$. The situation concerning singularities is therefore changed, and in fact the solution of the one-particle problem shows that collapse into a singularity does not occur.

The mass m_a in (2) differs from m_a in (1). In (1), m_a is a quantity associated with particle a. In (2), m_a arises from the interaction of particle a with other particles in the Universe. To the extent that this relation changes along the path of particle a the mass m_a changes. This is why m_a is placed under the integral sign in (2).

Under weak field conditions m_a is dominated by the relation of particle a to the large scale structure of the Universe, i. e. to distant matter. So under weak field conditions m_a is essentially a constant, which causes us to mistake it for a quantity associated only with particle a itself. But in strong fields m_a is affected by nearby matter. m_a is then space-time dependent and it is the derivatives of m_a (and of the masses of other particles) that constitute the new terms in (3).

Because of these new terms it is no longer correct to think of a highly compact body as being isolated. This we can do in EINSTEIN'S theory because $T_{ik} = 0$ outside the body, or nearly so. Here the equivalent of T_{ik} is not zero outside the body. The body must be thought of as always tightly coupled to the Universe. It would be quite wrong in these circumstances to seek in all cases to apply conservation ideas to the body by itself. Under suitable circumstances there can be a flow of energy between the Universe and the body.

The present considerations serve as a warning against being trapped by oversimplified theories. It is not so much a question of whether or not this theory is "right" as that it serves as an example of just how far we could be wrong in following conventional lines, which are in fact followed only because they are conventional not because there is hard evidence in favour of them.

I wish to end by expressing an opinion as to how further progress can be made. On the observational side evidently by more observation. On the theoretical side perhaps by forgetting the astronomy for a while and by examining the implications of a mass interaction for physics. The above considerations are all on a classical level. The next step may well be to see if these concepts can be matched to modern particle physics. In the past ten years progress has come from studying symmetries at a point, substantially without relating different points of space-time. Mass plays a mysterious role in this disconnected situation. The issue now is to see whether new light is thrown by a mass interaction on the at present awkward relation of such symmetries as SU_3 with the space-time structure.

It is often said that at some stage there must be a meeting point of particle physics with astronomy. What I am now saying is that I suspect the meeting point may be here, the nature of mass.

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DISCUSSION

Chairman: W. A. FOWLER

LYNDEN-BELL

I would like to ask if there is causality violation in this theory or not.

HOYLE

Not that I am aware of. There is no retreat inside a Schwarzschild radius, so causality problems do not seem to be a worry. There is no inversion of space-like and time-like coordinates, and that kind of thing, which would lead you to fear that there might be troubles.

LYNDEN-BELL

Well I would fear it when energy was not conserved. Have you got energy conserved or not?

HOYLE

Yes. Energy may not be conserved locally, but energy is conserved in the large.

WHEELER

Sometimes the word "fourth test of relativity" is used for SHAPIRO's experiment for light passing the sun on its way to Venus. However, historically one can believe that the fourth test of relativity was the prediction that the Universe was dynamically expanding. It was so fantastic that EINSTEIN couldn't believe it, as we all remember, and he even distrusted the prediction and introduced the cosmological term to kill the prediction, until HUBBLE came along and showed that the expansion was really there, so that one calls that really a confirmation of EINSTEIN's theory, perhaps not quantatively but qualitatively. Could you say how it comes out here on the cosmology that you get from this approach?

HOYLE

If there is conservation of matter the cosmological structure of the theory is the same as EINSTEIN's. But the new terms permit particle creation. This leads to cosmologies different from those given by EINSTEIN's theory. The theory, being classical, does not decide whether there is conservation, however.

SALPETER

I want to see if I understand your non-local conservation of energy. You are saying, aren't you, that if I have some rest mass in a star or system, and I stand away from it many Schwarzschild radii, but a small fraction of the radius of the Universe, then I can measure more light energy coming out of that place than the total rest-mass energy. If this is due to the far reaches of the Universe contributing energy to this little system, does this mean that the expansion slows down a little?

HOYLE

When the external influence on a local system is constant the normal conservation theorems hold. But, if the large-scale structure of the Universe changes, then the couplings to local systems change and this can show as an apparent non-conservation locally.

SALPETER

I am curious what the very tiny, but non-zero, effect on the Universe is; is it a slowing down of the expansion or what? If you always take energy from the Universe to these systems and let it shine in its neighbourhood, do you know what the sign of the effect will be?

HOYLE

The sense of the effect is that local inflow of energy accelerates the expansion of the Universe.

FOWLER

What worries me, if I understand you correctly, was that the post-Newtonian terms, as you say, are identical with the Einstein terms. For one whe looks for experimental or observational tests that's rather too bad, because we would hope, with sufficient accuracy in these first order terms, to be able to say something about the correct theory. DICKE has emphasized this. Whether you like his Brans-Dicke theory or not, he has pointed out where the differences arise. Are there no differences in that first order terms?

HOYLE

If you could look at one particle, say a proton, and do an experiment in relation to its gravitational field, then differences appear in the post-Newtonian terms. But as soon as you have an enormous number of particles, there is no difference for weak fields.

FOWLER

One other question that comes to my mind is that you say that there's nothing similar to the Schwarzschild limit. Can you describe in somewhat simpler terms just what you mean by that?

HOYLE

I know the answer for the single particle and there is *no* retreat inside a Schwarzschild radius. The particle has a finite, stable equilibrium structure.

FOWLER

What if one considers the case of a neutron star?

HOYLE

The problem of many particles is much harder to solve. Although a quantitative solution for a body composed of many particles is not yet available, I would expect the conclusion would be the same as for one particle — no retreat inside a Schwarzschild radius — no black hole.

McCREA

Professor Hoyle has referred to the singularities, rather I think as a criticism of general relativity; but I think they can be claimed as a merit of the theory because the theory fails at just the point where you would like it to fail. I mean, if anything like the big bang is right, there must be an epoch when the sort of approximation that you expect of general relativity, (or any macroscopic theory like it) must fail. Then it seems to me very fortunate that if fails by producing a singularity.

HOYLE

I think this is a matter of taste. I would hope for a system of physics that didn't fail.

McCREA

General relativity tries to tell us about what any particular matter must do if it exists; it does not tell us what sort of matter exists. By failing at that stage, it leaves room for some more elaborate theory. I think it would be very unfortunate if it didn't fail.

AMBARTSUMIAN

I wonder if I understood that your theory is essentially the theory which takes into account the particles. The solution for one particle is in principle different from the solution for a star. In the macroscopic theory there is no difference in the two cases.

HOYLE

Yes. All gravitational theories are non-linear. In a power series expansion in terms of $1/R$ you can add the $1/R$ terms linearly for many particles, but you can't add the $1/R^2$ terms.

AMBARTSUMIAN

Is there any hope to have a solution for a neutron star for example?

HOYLE

Weak field problems — i.e. problems where an expansion in $1/R$ can be used — involving many particles are the same as in EINSTEIN's theory. Strong field problems, where expansion in $1/R$ cannot be used, are different. It is an interesting issue as to which case a neutron star corresponds to.

LYNDEN-BELL

What happens when many particles are on their way to forming a black hole?

HOYLE

A repulsive effect develops which stops implosion into a black hole. The problem is different from the usual theory in that the new terms are *non-zero outside* the body. At least this is the situation in the single particle case.

LYNDEN-BELL

But it might well be the same as for a neutron star.

HOYLE

I would expect the same answer as for the single particle.

LYNDEN-BELL

But then in the formation of a black hole, if we have a large enough mass, that need never happen.

HOYLE

It need never happen, but I'm not sure that it doesn't. I am conjecturing from the single particle case.

SANDAGE

If EINSTEIN'S theory is the same as yours in the case of many particles, does the Universe have many particles?

HOYLE

Yes.

SANDAGE

Then what difference is there between this theory and EINSTEIN'S?

HOYLE

The theory is different cosmologically in that matter need not be conserved. It is different locally when the gravitational field is strong — i.e. when the expansion with respect to 1/R is not permitted. The cosmological difference can affect the choice of model for the Universe, while the local difference is important in relation to the black hole problem.

IV.

OBSERVATIONAL COSMOLOGY AND GALAXY EVOLUTION

THE AGE OF THE GALAXIES AND GLOBULAR CLUSTERS: PROBLEMS OF FINDING THE HUBBLE CONSTANT AND DECELERATION PARAMETER

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This report deals with partial observational data on certain difficult, controversial questions in classical cosmology: (1) Are all galaxies the same age? (2) If so, what is this age? (3) When did star formation start in the galactic system? (4) Is there a connection between these ages and the FRIEDMANN time of the expanding universe?

Clean, positive answers are clearly not yet available. Nevertheless, quite significant progress has been made over the past 20 years by very many people; if not directly toward solution, then at least in the formulation of the difficulties. The position today is considerably better than say 40 years ago due to the general broadening of knowledge concerning stellar evolution, the stellar content of galaxies, specific cosmic processes, and the expansion properties of the universe.

I. ARE ALL GALAXIES THE SAME AGE?

Galaxies along the Hubble sequence present very different population characteristics. Elliptical systems and the centers of Sa, Sb galaxies show no evidence for recent star formation. These regions are uniformally red, with surprisingly similar $U - B$, $B - V$ colors (if we restrict the samples to narrow ranges of total absolute luminosities). For Sc, Sd, and Sm galaxies at the other end of the sequence, bright OB stars, H II regions, gas, and dust all indicate recent star formation. This does not, however, mean that the oldest stars in these galaxies are young. Direct photographs of galaxies in the Local Group invariably show the presence of a background sheet of red stars which resemble, in color and absolute magnitude, the background sheet of M 31, NGC 205, and M 33, which BAADE (1944) originally resolved into stars.

The brightest stars of this sheet are undoubtedly at the top of the giant branch of a globular-clusterlike population. BAADE'S arguments for this identification have been essentially unchanged since 1944. That the bulk of the light from the sheet (especially in the more central regions of M 31) probably comes from a higher metal-abundance, NGC 188-type population, as first shown by MORGAN and later by WOOD, SPINRAD, MCCLURE, VAN DEN BERGH, and others, does not militate against the sprinkling of globular-clusterlike stars as the brightest component at $M_V \simeq - 3.0$.

All members of the Local Group have the underlying sheet. It is especially visible over the whole of the disc of M 33 on deep yellow and red plates taken with the 200-inch Palomar reflector. M. E. DIXON at Stromlo has recently measured the apparent magnitude as $V = 21.5 \pm 0.2$ for the brightest sheet-stars in M 33 from 200-inch plates, relative to a faint photoelectric sequence in the area determined some time ago by JOHNSON and SANDAGE (unpublished). The apparent yellow modulus of M 33 is $(m - M)_{AV} = 24.6$, as determined from Cepheids, giving $M_V = - 3.1 \pm 0.2$ for these stars. For M 31, VAN DEN BERGH and RACINE (1967) showed that $V = 21.8 \pm 0.3$ for the brightest stars that BAADE resolved, giving $M_V = -2{,}85 \pm 0.3$ if $(m - M)_{AV} = 24.64$, obtained from Cepheids (BAADE and SWOPE 1963) using $E\ (B - V) = 0.16$.

For IC 1613, a dwarf member of the Local Group, $(m - M)_{AV} = 24.5$ from a rediscussion of BAADE's extensive work on the Cepheids. The background red sheet resolves near $V \simeq 21.5 \pm 0.2$, giving $M_V = -3.0$.

If these stars are identified with the globular-cluster population, the sheets in the galaxies must be old. Equally important, the agreement in $M_V \simeq -3.0$ to within $\pm$ 0.2 mag shows that the age of the sheets are the same to within ~ 20%. The same conclusion follows from the discovery of RR Lyrae stars in the Large and Small Magellanic Clouds by THACKERAY and WESSELINK (1955). It is clear that these variables must have nearly the same M_V distribution as RR Lyrae variables in galactic globular clusters because the distribution of periods is so similar (THACKERAY 1959). The first results from a remarkable new study by JOHN GRAHAM, who used the Cerro Tololo 60-inch reflector, confirms THACKERAY'S results, and adds many new data. GRAHAM has found 75 new variables, 37 of which are undoubtedly RR Lyraes. The median blue magnitude of the group is $B = 19.25 \pm 0.10$. The apparent blue modulus of LMC is $(m - M)_{AB} = 18.65 \pm 0.2$ (SANDAGE and TAMMANN 1968), which gives $\langle M_B \rangle = 0.60$, or $\langle M_V \rangle \simeq 0.40 \pm 0.3$. This is the same value as in our Galaxy to within the errors. Therefore, despite the impression that the LMC and SMC are young, they are as old as the oldest stars in our Galaxy, in M 31, M 33, NGC 205, M 32, and IC 1613. The evidence then is consistent with the hypothesis of coeval formation to at least $\Delta T/T \simeq 0.2$ (i.e., 20% in age), and these Local Group members could have a much smaller age spread in view of the probable errors of the data.

What about galaxies beyond the Local Group? A very striking result from STEBBINS and WHITFORD'S early photoelectric photometry was the homogeneity of colors of elliptical galaxies and of the central regions of Sa and Sb systems. The results have often been confirmed by many further studies by many authors who show that only a very small cosmic dispersion exists in $U - B$, $B - V$ colors for galaxies of high luminosity. Even more convincing evidence is available from the similarity (to within $\sim 5\%$) of $I(\lambda)$ curves for giant ellipticals (cf. OKE and SANDAGE 1968, WHITFORD 1970). Arguing from the similarity of the M 31 $I(\lambda)_{\text{center}}$ and $I(\lambda)_{\text{E galaxy}}$ permits limits to be placed on the age difference between Local Group members and the giant E systems of the general field. Here the argument is not as straightforward as that from the resolved red sheet because knowledge of the form of the H-R diagram is required. One needs to know the sensitivity of $I(\lambda)$ to changes in the level of the main-sequence termination point. SPINRAD (see the discussion of his paper at this conference) puts limits to the age spread of about 40% ($\Delta M \simeq 0.4$ mag for termination point) from these arguments. These data are then consistent with the statement that all galaxies could have the same age, although the method is relatively insensitive.

In view of the results on the Magellanic Clouds (very old stars underlying a young overcoating of OB stars that dominate first appearances), it would seem very difficult to prove the existence of truly young systems. In view of the high uniformity of the colors for brightest cluster galaxies, where no young (blue) giant ellipticals have ever been found although extensively searched for, there seemed (until this conference) no evidence for young galaxies. However, the results of SARGENT and SEARLE must cause some hesitation for this view (see the paper by SARGENT on the two blue extragalactic objects). Nevertheless, the previous results just discussed remain quite remarkable, and apparently can be reasonably explained only if giant ellipticals, galaxies in clusters, and most of the field objects have nearly the same age.

II. What is This Age?

Arguments by Baade concerning characteristics of his type II population first led him, and later others, to the view that the earliest stars which formed in our Galaxy did so on a rapid time scale (a massive initial burst of star formation). It is usually argued that this view is supported by kinematic and dynamical arguments based on data for individual stars (e.g., Eggen *et al.* 1962), and on the small degree of flattening in the halo of our Galaxy and in early ellipticals (Sandage, Freeman, and Stokes 1970). Therefore, if these oldest stars can be located and age-dated, the time when the galaxy began its initial collapse might be found. Well-known general arguments suggest that globular clusters are these sought-for first generation objects. Two problems can be discussed: (*a*) the absolute values of cluster ages to compare eventually with the Friedmann expansion time, and (*b*) the relative ages to test the prediction of the small age spread ($\Delta T/T \simeq 0.02$), which is required if the galaxy rapidly collapsed.

a. Absolute Ages of Halo Globular Clusters

Estimates of cluster ages have been made by many workers over the past 20 years. Input data to the problem have steadily improved, both in the observations leading to the main-sequence termination luminosity and in theory, which gives age = f ($L_{t.o.}$, helium, and metal abundances). Recent improvements in the theory have been made by Demarque *et al.* (1970), and by Iben and Rood (1970) in a series of independent and complicated calculations that agree with one another to within 20%. The agreement is encouraging because different opacity formulations were used, together with different computational methods for the evolution.

Recent observational results have given new estimates of the main-sequence termination points for the four clusters M 3, M 13, M 15, and M 92. New faint photoelectric photometry (SANDAGE 1970) calibrates the apparent color-magnitude diagram to V fainter than 21 mag in each case. Distances, and hence M_V values, were obtained by main-sequence fitting to a series of trigonometric parallax stars, taking into account metal abundance differences. A second method of fitting was to adopt CHRISTY's calculated M_V for the RR Lyrae stars as a function of their period distribution and to apply the relevant M_V for each cluster to the measured apparent magnitude of these variables. The result is shown in Figure 1. M 13 was placed in

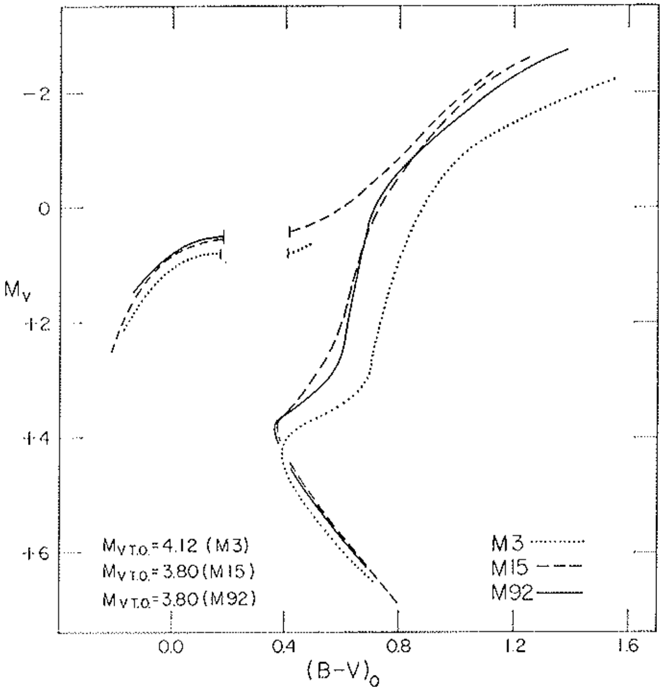

FIG. 1 — Color-magnitude diagram for the globular clusters M 3, M 15, and M 92 normalized by CHRISTY's theoretical M_v values for RR Lyrae stars. The cluster M 13 (not shown) agrees closely with the position of M 3.

a similar diagram by a variant of the RR Lyrae method and has M_V (t.o.) = 4.08, close to that of M 3 [M_V (t.o.) = 4.12], but definitely fainter than M 15 and M 92 [M_V (t.o.) = 3.80].

The helium abundance of each cluster was estimated from the observed temperature (color) of the blue edge of the RR Lyrae instability strip (CHRISTY 1966), while the metal abundance was taken from spectroscopic studies of giants in M 13 and M 92 (HELFER *et al.* 1959) as supplemented by the observed ultraviolet excess $\delta\ (U - B)$ for main-sequence dwarfs in the clusters.

Application of the $T = f\ (L_{t.o.}, Y, Z)$ equations of DEMARQUE *et al.*, and of IBEN and ROOD, using the data given in Table 1, gives ages tabulated in the last several columns of this table. Here T (DMA) and T (IR) refer to the two sets of theoretical models.

These ages are considerably lower than had been estimated before. The observational uncertainties are estimated to be $\pm$ 0.2 mag in M_{bol}, $\Delta Y \simeq \pm 0.1$, and $\Delta \log Z \simeq \pm 0.5$, leading to an rms age error of $\varepsilon T/T \simeq \pm 0.28$, which is about 3×10^9 years.

TABLE 1 — *Input data and ages for four clusters.*

Cluster	M_{bol} (t.o.)	Y	Log Z	T (DMA) $\times 10^9$ yr	T (IR) $\times 10^9$ yr
M 3	3.99	0.306	—3.3*	11.5	13.8
M 3	3.99	.306	—2.9	9.9	11.9
M 13	(3.94)	(.357)	—3.1	(9.4)	(11.3)
M 15	3.66	.351	—3.8	9.4	11.3
M 92	3.66	0.328	—3.8	9.7	11.6

* Log $Z = -3.3$ is the more likely value for M 3, although the evidence is conflicting and the second value is possible.

The main conclusion from these recent results is that $\langle T \rangle \simeq 10 \times 10^9$ years to within 30% for these four clusters. Is this representative of the cluster system as a whole? Two arguments suggest it is.

1. Similar, but less complete, data exist for 47 Tuc (Tifft 1963), NGC 6397 (Eggen 1960), ω Cen (Belserene 1959), and M 2 and M 5 (Arp 1959). These show that the main-sequence termination points are all close to $M_V = + 4$, as in Figure 1, and that the helium and metal abundances cannot be greatly different from those in Table 1.

2. The periods of RR Lyrae stars in all clusters studied to date in our Galaxy (more than 50 cases) are in the narrow range $0.8 > P_{\text{ab}} > 0.4$ days. Much of this work is due to Helen Sawyer Hogg. The result requires that the horizontal branches (HB) of all clusters are within 0.5 mag of each other in M_V. And because the HB and main-sequence termination luminosities stand in a fixed ratio (both observationally and theoretically) to within narrow limits, there cannot be a wide dispersion in the termination luminosities away from $\langle M_V \text{ (t.o.)} \rangle = + 4.0$. Consequently, there is no evidence for young globular clusters in our Galaxy.

b. Relative Ages

The absolute ages in Table 1 have such large errors (30%) that no accurate test is available here on the cosmic age spread amongst the clusters. There is, however, an additional and more sensitive test obtained from the properties of Figure 1. The main-sequence termination points are staggered such that clusters with low metal abundance (M 15, M 92) have brighter $M_{\text{t.o.}}$ than those of high Z (M 3, and M 13 not shown). The sense of this ordering, which was made by considerations of the HB alone, is what is required by the theory of Simoda and Iben (1968) *if the clusters have equal age* but different Z (keeping Y fixed). The theory has been independently verified from calculations by DEMARQUE, MENGEL, and AIZENMAN (1970).

Estimates of $\Delta T/T$ using this effect can be obtained as follows. The data for M 3, M 13, M 15, and M 92 show that ΔM_V between the main-sequence turnoff and the RR Lyrae instability region on the horizontal branch is the same for all four clusters to within the observational accuracy (i.e., $\Delta M_V = 3.35 \pm 0.1$). Hence, if the main-sequence termination points move up or down, the horizontal branches follow step (Fig. 1). Therefore, the ratio of the metal abundance, $\Delta \log Z$, to the M_V difference between RR Lyrae stars of different mean period (the generalized OOSTERHOFF-SAWYER effect) will be the same for the HB as for the main sequence. The ratio $\Delta M_V/\Delta \log Z$ is more accurately determined for RR Lyrae stars because ΔM_V need not be measured directly (a very difficult task) but can be inferred from the period ratio of the variables in the OOSTERHOFF-SAWYER groups (SANDAGE 1958; CHRISTY 1966). The estimate is that $\Delta M_V = 0.30$ mag between the Oosterhoff group I and II variables, and that $\Delta \log Z = 0.50$ between the same groups. This route gives $\Delta M_V/\Delta \log Z = 0.60$, in the sense that brighter M_V go with lower metal abundance, i.e., clusters with longer mean periods for the RR Lyrae stars have smaller Z. Substituting this *observed* ratio in the age-dating equation $T = f\,(L_{t.o.}, Y, Z)$ of SIMODA and IBEN (1968) gives $\Delta T/T \simeq 0.014$. Such a result, if true, would support a picture of rapid, primeval-galaxy collapse.

The error on $\Delta T/T = 0.014$ is high, due to present uncertainties in $\Delta \log Z$ between clusters of the two Oosterhoff-Sawyer classes. However, what seems to be highly significant is that this train of argument apparently explains the long known and very mysterious correlation between the mean period of the RR Lyrae stars and the metal abundance (ARP 1955; PRESTON 1959). The explanation follows naturally via the SIMODA-IBEN effect if all clusters, regardless of their metal abundance, are closely the same age.

III. The Hubble Constant

Some progress can be reported on the redetermination of H_0, although an answer using those new calibrations that can now be obtained appears to be several years away. The principal difficulty still centers around the possibly large effects of the local anisotropy, discovered by de Vaucouleurs, i.e., the absence of a pure Hubble flow for redshifts smaller than $\sim$ 4000 km/sec. Although there is no question that the anisotropy disappears for larger redshifts, the distance indicators in individual galaxies have sunk below plate limit once $(m - M) \geq 31$. Methods must be devised to bridge the gap between "local" galaxies, where Cepheids, H II regions, and brightest stars can be used, and the more distant galaxies where the redshift is a single-valued and linear function of distance.

One such method involves using Racine's photometry of globular clusters in the halo of M 87 (Virgo cluster) to obtain $(m - M)$ for the cluster, and hence M_V of the first-ranked E galaxy (NGC 4472) therein. The difficulty is lack of knowledge of the bright end of the luminosity function of globular clusters as the population sample increases. An *upper* limit of $H_0 = 75$ km/sec Mpc (or a lower limit $H_0^{-1} = 13 \times 10^9$ years) was derived from this method (Sandage 1968). Globular-cluster photometry in the halo of M 87 is exceedingly difficult due to the steep intensity gradient from M 87 itself, and additional methods for H_0 are needed.

Recent work has been directed to calibration of distance indicators such as (*a*) M_B for the brightest resolved blue and red stars, and (*b*) linear sizes of the H II regions. Once calibrated, these objects permit distance determinations to be made for resolved galaxies (Sb, Sc, Sm, Im) between the Local Group and those whose moduli are smaller than $m - M \simeq 30$. The sample of galaxies within this distance is not large. It includes members of the M 81 (NGC 2403) group, the M 101 group, certain groups within the Ursa Major cloud, the south polar group (NGC 300, etc.), the NGC 925 Andromeda group, and a few others.

Although all these groups are too close to avoid the local anisotropy, they can be used collectively to calibrate the total luminosity (M_B or M_V integrated) of galaxies in the various VAN DEN BERGH luminosity classes. What VAN DEN BERGH showed, and recent work confirms, is that galaxies classed (by form) according to the luminosity scheme Sc I, Sc II, Sc III, etc., have *small dispersion in* M_B within each class [$\sigma(M_B) \simeq 0.3$ mag for Sc I and Sc II], and such objects can be used as standard candles far out (in the same way as first-ranked E galaxies in clusters where $\sigma(M)$ is also known to be very small). Therefore, the problem is to calibrate $\langle M_B \rangle$ for Sc I.

The only good Sc I galaxy within the distance range of the primary calibrators (i.e., Cepheids, resolved stars, sizes of H II regions) is M 101. TAMMANN and SANDAGE have made a new effort to obtain a precise modulus for this galaxy, with quite unexpected results. We had previously believed that the distance to M 101 was only slightly greater than to NGC 2403, i.e., $(m - M)_{AB} \simeq 27.8$. Early, but very preliminary, work by HUBBLE, BAADE, HOLMBERG, VAN DEN BERGH, and ourselves suggested this position. However, new calibrations of M_B for brightest stars and H II regions and their measurement in M 101 (SANDAGE and TAMMANN 1971), together with four other methods, show the modulus to be considerably larger.

1) The resolvability of the face of M 101 into stars is much poorer than in either M 81 or NGC 2403 by at least 1 magnitude. This requires $(m - M)_{AB} > 28.8$.

2) No Cepheids have been found in M 101 from careful inspection of 50 plates taken with the 200-inch, whereas they

are easily found in NGC 2403 (Tammann and Sandage 1968). This null result shows M 101 to be at least 0.5 mag further than NGC 2403, and with less certainty more than 1.0 mag further, i.e., $(m - M)_{AB} > 28.3$ to $(m - M)^{AB} \geq 28.8$.

3) There are no resolved red supergiants ($M_V \simeq - 8.0$) to $V = 21.0$. Hence $(m - M)_{AV} > 29.0$.

4) The H II regions for three dwarfs in the M 101 group (NGC 5457, 5474, 5477), when fitted to the present calibration of H II sizes = f (luminosity class for Sc, Sd, Sm galaxies), gives $(m - M)_0 = 29.0 \pm 0.3$.

5) The calibration of M_B (total) = f (luminosity class) using galaxies in the Local Group and M 81 group as applied to four of the M 101 dwarfs gives $(m - M)_0 = 28.9 \pm 0.3$.

6) Brightest resolved blue stars in M 101 appear at $B \geq 19.3$. Applying the calibration of M_B (stars) = f (M_B, total) derived from Local Group and M 81 group members gives $(m - M)_{AB} \geq 29.3$.

At the moment we are adopting $(m - M)_B = 29.2$. This gives $M_B{}^{0,i} = - 21.0$ for M 101 itself (corrected for galactic absorption and to the face-on configuration). This value is 1 mag brighter than van den Bergh's assumption for M 101, and is also 1.0 mag brighter than his $\langle M_B \rangle$ for Sc I systems.

What does this mean for H_0? Van den Bergh has shown that if $\langle M_B \rangle = - 20.0$ for Sc I, then $H_0 = 100$ km/sec Mpc from his analysis of the available Hubble diagram for field galaxies. Changing the calibration by 1 magnitude brighter requires, using van den Bergh's precepts, $H_0 = 63$ km/sec Mpc. However, van den Bergh's precepts neglect the local anisotropy, and this value is therefore in doubt. However, it is clear that if $\langle M_B \rangle$ for Sc I galaxies can be calibrated through M 101 [and other nearby groups that have Sc II and Sc III systems (NGC 925 group, NGC 300 group, etc.) so that the Sc I luminosity can be inferred by the known ΔM_B between the classes], then this calibration can be used to obtain H_0 *as soon as the Hubble diagram for Sc I galaxies can be obtained at redshifts greater than 4000 km/sec.* We are now working on this observational program by obtaining redshifts and photoelectric magnitudes for Sc I candidates, but there is nothing to report at this time.

It is, however, interesting that neglecting the local anisotropy for the M 81, M 101 groups and the Virgo cluster gives the following results:

a. M 81 group: $\langle v \rangle = 220$ km/sec; $(m - M)_0 = 27.56$, $r = 3.26$ Mpc, $H_0 = 220/3.28 = 68$ km/sec Mpc.

b. M 101 group: $\langle v \rangle = 409$ km/sec; $(m - M)_0 = 29.2$, $r = 6.92$ Mpc, $H_0 = 409/6.92 = 59$ km/sec Mpc.

c. Virgo cluster: $\langle v \rangle \simeq 1136$ km/sec (uncertain); $(m - M)_0 = 31.1$ obtained from $\langle M_B \rangle = -21.0$ for Sc I, and $\langle B \rangle = 10.11$ for the Sc I galaxies in the cluster (NGC 4254, 4303, 4321, and 4535), $r = 16.6$ Mpc, $H_0 = 1136/16.6 = 68$ km/sec Mpc.

We cannot, of course, neglect the local anisotropy, which is the reason for the present program of redshifts and photoelectric total magnitudes for Sc I galaxies fainter than $V = 13$. Nevertheless, these isolated results are fascinating in view of their great difference from Hubble's 1936 value of $H_0 = 530$ km/sec Mpc and the known, relatively small, effects of the anisotropy (i.e., usually smaller than a factor of 2).

My belief from the current data is that an *upper limit* to H_0 is $\simeq 75$ km/sec Mpc (or $H_0^{-1} \gtrsim 13 \times 10^9$ years). I am also reasonably confident that programs now in progress should give definitive results within several years. Much of the above analysis, especially the work on M 101, has been done jointly with G. A. TAMMANN of the Hale Observatories, who is also heavily involved in the extended programs.

IV. THE DECELERATION PARAMETER

The Friedmann time cannot be found from H_0^{-1} unless the deceleration (q_0) is known. It is well known that this number can be found by the deviation from linearity of the Hubble diagram, as constructed from sources with precisely the same absolute magnitude (over some range of proper wavelengths). The present controversy concerning use of the Hubble diagram centers around questions of the stability of this absolute magnitude for objects chosen to be the standard candles, i.e.: (*a*) how effective are the corrections to proper wavelength (K corrections), (*b*) what is the effect of evolution of L (proper) with time, (*c*) is L (proper) for the standard candles stable against differences in the population from which they are sampled?

The choice of the standard candles is obviously crucial to the problem. Work by HUBBLE, HUMASON, MAYALL, PETERSON, and others has shown empirically that the brightest few E galaxies in the great clusters of galaxies (i.e., CrB, Boötes, UMa I, UMa II, Coma, etc.) have very small dispersion in the Hubble diagram. The dispersion is further decreased by use of the first-ranked E galaxy alone in each cluster. Details of the empirical evidence, the K correction, the metric-aperture correction, the Scott effect, the evolutionary effect in the light travel time, and the galactic-absorption correction are to be discussed in an article in *The Astrophysical Journal,* and only the results need be mentioned here.

Figure 2 is the Hubble diagram for the first-ranked E galaxy in 40 great clusters. Most of the redshifts are from HUMASON, as tabulated in the Humason-Mayall redshift catalog (*Astron. J.*, *61*, 97, 1956). All photometry is photoelectric, either by BAUM (triangles) or SANDAGE (crosses and circles). Standard corrections for aperture effect, K correction, and

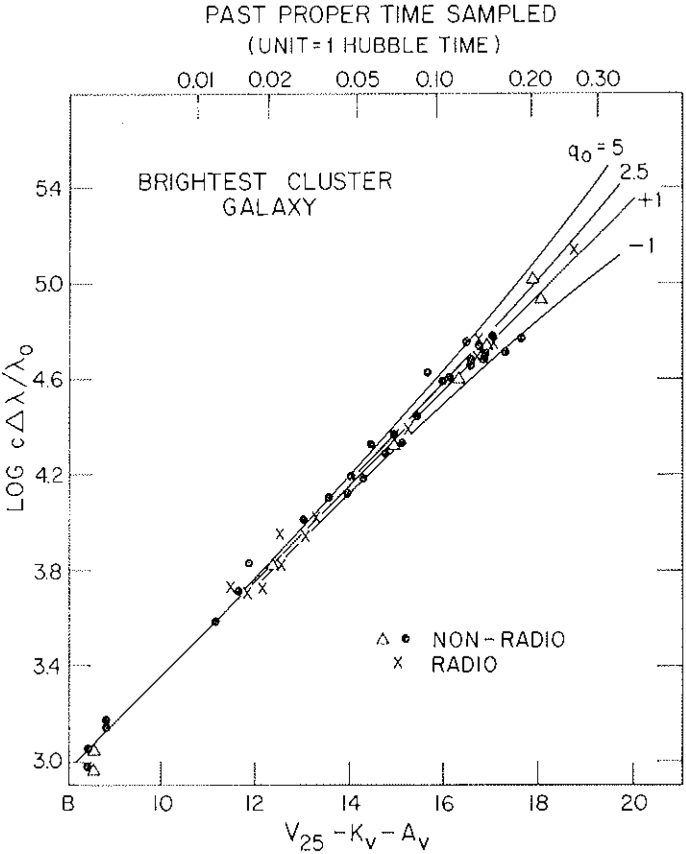

FIG. 2 — The redshift-apparent magnitude relation for first-ranked E galaxies in clusters. Triangles plus the largest redshift object (cross) are galaxies measured by BAUM; other crosses and dots by the author. Theoretical lines for various q_0 values are superposed.

galactic absorption (A_V) have been applied to the data. Lines from the theoretical Friedmann models (i.e., cosmological constant is zero) for different q_0 values are shown. An eye fit to the data shows that $q_0 \simeq +1$ is a good first approximation, but that the result depends so sensitively on the three points with largest redshift.

A more quantitative evaluation is shown in Figure 3, which shows the magnitude difference of each cluster (dots) from the $q_0 = +1$ line as a function of redshift. Five normal points are shown as filled triangles. Note that without the last three clusters with redshifts of $z = 0.29$, 0.33, and 0.461, the solution through the remaining four "normal" points

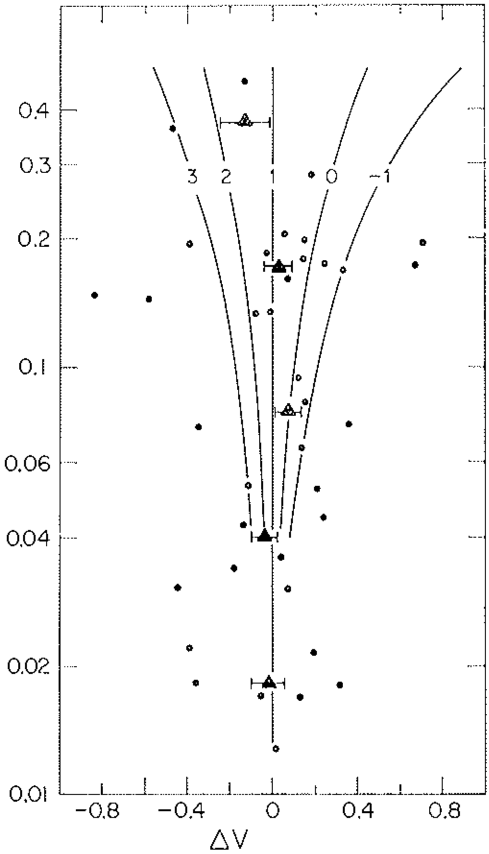

FIG. 3 — Same as Fig. 2 except differences from the line $V_c = 5 \log z + C$ (i.e., the $q_0 = +1$ line) are plotted versus redshift. Each point represents the first-ranked galaxy in a cluster. Triangles are normal points.

would give q_0 slightly less than 1.0. The addition of this fifth normal point throws the solution the other way.

Construction of the "normal" points in Figure 3 is somewhat arbitrary. The only statistically correct solution for q_0 is to perform a rigorous least-squares solution using the fundamental equation for all 40 points. In the presence of constant standard candles in a Friedmann universe, m_{bol} and z are related by

$$(1) \quad m_{\text{bol}} = 5 \log \frac{1}{q_0^2} \{q_0 Z + (q_0 - 1) [(2 q_0 z + 1)^{\frac{1}{2}}]\} + C,$$

where

$$C = M_{\text{bol}} - 5 \log H_0 + 52.386,$$

if H_0 is expressed in km/sec Mpc. The parameter C is a constant if M_{bol} is constant; otherwise it has the distribution which the absolute magnitudes themselves possess. This distribution is shown by the scatter of the points in Figure 3. The scatter cannot be appreciably reduced by adding more data because it is the cosmic scatter of the first-ranked E galaxy. (However, more data will, of course, increase the statistical certainty of the solution).

The most probable value of q_0 was found by minimizing the sum of the squares of the residuals obtained from equation (1) for all 40 clusters, permitting C and q_0 to vary. The problem is a two-dimensional least-squares search, and was done by computer to find the smallest value of

$$\Sigma (\Delta m i)^2 = \sum_{i=1}^{i=40} \left\{ m_{\text{obs},\, i} - \left[5 \log \frac{1}{q_0^2} \{q_0 Z + (q_0 - 1) [(2 q_0 z + 1)^{1/2}]\} + C \right] \right\}^2$$

as q_0 and C were given different discrete values with small interval spacings. The solution is shown in Figure 4, using the particular points given in Figures 2 and 3. Using all the data (i.e., including the last three points from BAUM) gives $q_0 = 1.03$. Formal probable errors are difficult to assign, but this can be done in the following approximate fashion.

In the q_0, C matrix [whose entry at each q_0, C value is $\sum_i (\Delta\, m\, i)^2$], there is one smallest value for $\sum_i \Delta\, m\, i$. This is taken to define the distribution of the true parent population. Distributions at other points of the matrix differ from the parent distribution, and the chi-squared probability can be computed at each matrix point. Figure 4 shows the resulting $P\ (x^2)$ for various q_0 values, computed as if C had no error. There is a range of C as well, so as to remain within the 2 σ level [95% confidence that q_0 is within ($q_0 > \pm$ the limits)]. Analysis of the $P\ (x^2)$ ellipse in the q_0, C matrix at the 95% confidence level gave

$$q_0 = 1.03^{+0.43}_{-0.26} ,$$

where the limits are probable errors (i.e., 0.6745 σ).

A new solution, neglecting the three clusters of largest redshift where BAUM's aperture corrections are uncertain (were metric or isophotal diameter corrections applied?), gave a smaller value (evident from Fig. 3) of

$$q_0 \simeq 0.65^{+0.5}_{-0.3} \quad \text{probable error.}$$

At present, none of this must be considered very seriously. We need many more clusters whose redshifts are greater than $z = 0.2$ for a satisfactory solution. The only conclusion which

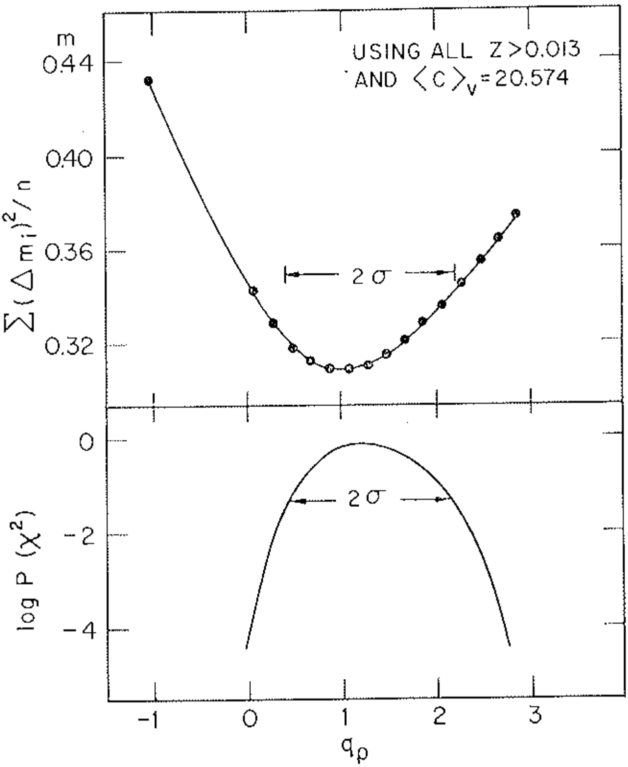

FIG. 4 — Illustrative solution for q_0. Bottom shows chi-squared probability probability that given q_0 values can come from the parent distribution defined by that at the minimum q_0. Probability that $q_0 = -1$ is less than 10^{-10}.

I believe is currently warranted is that the steady-state solution seems far from being probable. The formal chi-squared probability that $q_0 = -1$ can fit the data is less than 10^{-10}.

We must, however, know q_0 to considerably closer limits than $q_0 = 1 \pm 1$ if there is any hope of finding the Friedmann time accurately. Clusters more distant than 3C 295 can now be routinely found, and a new program has begun at Palomar to extend Figure 2 to redshifts between $z = 0.2$ and 0.6. It is estimated that, at the present rate of progress, perhaps five years will be required for the solution, but optimistic observers can see no unsolvable problem blocking the road.

V. CONCLUSIONS

If $H_0 = 50$ km/sec Mpc ($H_0^{-1} = 19.5 \times 10^9$ years), and if $q_0 = 0.5$, then the Friedmann time is $T = 2/3\ H_0^{-1} = 13 \times 10^9$ years. Although there is no conflict between globular-cluster ages at $(10 \pm 3) \times 10^9$ years and this Friedmann time, it is also obvious that errors on H_0 and q_0 are still so large that no highly satisfactory comparison can yet be made at the 15% level. I believe there is every hope that current programs on H_0 and q_0 will reach this goal. At the moment, the only fair statement is that no conflict exists in the two time scales to within the large errors of the current estimates. Critics of this view could equally well state that there is no evidence for equality of the time scales to within almost a factor of 2. Nevertheless, agreement to within even these wide limits seems so unbelievably remarkable (for such different processes as the ages of stars and the redshifts of galaxies) that some fundamental connection must surely exist between them.

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DISCUSSION

Chairman: W.A. FOWLER

HOYLE

If you stretch your predilections as far as you possibly can, how low do you think H could be made?

SANDAGE

I could give you an answer to the upper limit. It has got to be smaller than 150. For the lower limit I would not be absolutely surprised if it is as small as 40 km/sec/Mpc.

MCCREA

I would like to ask Professor SANDAGE if he ever thinks of putting back lambda, because this is rather formal work in a way. It would be rather convincing if you could show from it that lambda is there or could get a better fit with lambda not there.

SANDAGE

From an observer's point of view, one has to increase the precision and amount of the data to such an extent that the introduction of an additional parameter causes the solution to be even more indeterminate. The solutions with $\Lambda \neq 0$ are so similar with those of $\Lambda = 0$ in the $\Delta V = f(z, q, \Lambda)$ diagram for $z \leqslant 0.3$ that the data must be much increased from the 40 points we now have before I would believe a formal answer for both q_0 and Λ. PEACH has looked at the data with the old K corrections and concludes that lambda is zero within certain rather wide limits.

But I think the data are just not sufficent to make the analysis amenable to that additional parameter at present. We, of course, will be much more secure when we get 200 $[m, z]$ pairs, and Λ can then be included in a future analysis with some certainty.

HOYLE

As far as I could judge from your B-V calibration, the K corrections that are used at the largest red-shifts would be of the order of 5 or 6 tenths of a magnitude. Would that be right?

SANDAGE

The K_V at $z = 0.20$ is $0^m.40$, while $K_B = 1^m.0$ at the same redshift.

OORT

We have recently made some investigations on the origin of the structural features in the distribution of galaxies which you were referring to, and I think one can understand a little bit how these structures were formed and how the internal motions in these structures should be. This might help to solve the local difficulties that you spoke about.

SANDAGE

Can you say what the shape of the shear-field is?

OORT

The actual structures that one sees are probably long cigar-like shapes that have been drawn out along the long axis, and that bave collapsed along the shorter axes; it looks as though at the present time the expansion along the long axis will be very much smaller than the average expansion in the universe. I think that, considering this, one could improve on the discussion of the data of the brighter galaxies.

SANDAGE

That is a very important development.

FOWLER

I am somewhat puzzled by the fact that you give as much weight to the low points on your diagram, when intuitively I feel they have nothing to do with q_0 but have to do with the inevitable errors of your beautiful observations.

SANDAGE

The nearby clusters are as important as the more distant ones, because those with small redshift set the constant (or zero point) in the theoretical $m = f(q_0, z)$ relation. Changing this zero point [i.e. the *horizontal* placement of the mean line in the m, z (Hubble) diagram], changes the value of q_0. We therefore need as many observations of nearby clusters as of distant ones.

AMBARTSUMIAN

I am very much impressed with the many interesting observations you have made. They are very important, I think. My general impression always was that the Hubble constant must be lower. I think it is very important, but you use for your derivation nearby galaxies, but of course it is very important to have data about the more distant galaxies. Of course, I understand that you are now going to transfer these data about nearby Sc galaxies, to the more distant objects, thus making the whole thing in two steps, so to speak. Are there any possibilities to make something using, for example, the brightest stars?

SANDAGE

The brightest stars in ScI galaxies are about $M_B = -9.5$ to -10. This means that at modulus 34 you are going to 24th apparent magnitude. That takes you to about 4,000 kilometers a second, which is very good. We can't do that now. The present limit for reliable work is about $B = 22$ mag. The hope is that the ScI's of VAN DEN BERGH have such a narrow absolute magnitude dispersion that it will be possible to transfer from the nearby calibrating galaxies to the distant general field where the local anisotropy is absent. We have to find the distant ScI's first and then get their redshifts.

AMBARTSUMIAN

My second remark is about the ages. You have emphasized that the ages that you give are the ages of normal galaxies. But normal galaxies are the galaxies that have about the ages of the same order. If we observed something unusual which is connected with the youth of a given galaxy, we say that is is not a normal galaxy. Of course, we shall always have in mind two things; first that you use as a basis for your investigation the current theories of stellar evolution which, of course, *in some degree* correspond to reality. I am not sure that we cannot find things here which can complicate the matter. — The second point is that we all agree that in many galaxies, in non-ellipticals at least, we have the formation of stars. For example, in the Large Magellanic cloud there is the globular cluster NGC 1866 which is a young cluster. Apparently when you speak about the age of the galaxy you understand the age of their oldest members. Do we really find the oldest members? Do you feel that there is some selection in this which will make the dispersion of ages less than it is in reality?

SANDAGE

In our Galaxy the selection of the oldest stars, in terms of the globular clusters, can be tested by finding the lower envelope of the color-magnitude diagram for field stars. If you look at O.C. WILSON's diagram for nearby stars where the phase mixing of the orbits must be quite good (so you are getting stars from various parts of the galaxy), the lower envelope is quite close to the observed subgiant envelope of NGC 188. Then the question is what is the age difference between NGC 188 and the globular clusters? In the disk I think, from the Wilson diagram, the oldest stars had been located, and these are not much older (perhaps $\Delta T/T \simeq 0.2$) than NGC 188.

AMBARTSUMIAN

Of course, we could expect that the members of local clusters are approximately of the same age.

SANDAGE

If the galaxies are built up from their nuclei, would you have expected that the activity in, say, the nucleus of M 31, the nucleus of M 33 and the nucleus of our own Galaxy would have gone off within, say, 20% of the same time, which the present data indicate to be an upper limit to the age spread $\Delta T/T$?

AMBARTSUMIAN

My view is that some bodies are divided into two parts, and, from each of these parts coming from the nucleus, one galaxy can form. In the local cluster we think that all the galaxies have approximately the same age. The same must be true for the galaxies in other groups or in a cluster.

VAN DER LAAN

Your efforts to find more distant clusters is a beautiful example of combining radio and optical techniques, and I wonder would you profit from much improved radio positions beyond the accuracy already attained to the extent of one second of arc?

SANDAGE

I think the positional accuracies are now quite adequate, and I think the positions of the Cambridge group at 2 or 3 seconds of arc are quite adequate as well. So I think the empty field program could have been started two years ago with the many impressive positions that have come from Cambridge, Malvern and Green Bank. I think 1″ is surely all we need. The other interesting thing is that the agreement of the optical and radio data show there is no difference between the position of the optical and radio sources within half a second in most of these cases, and that is pleasing. Of course, these were all unresolved radio sources so that WADE's new radio technique could be tested. The sources are not the double ones, so they were a highly selected group confined to the single sources themselves.

VAN DER LAAN

And you have all the positions you need, or can you handle many more of them?

SANDAGE

No, we surely need many more like those of WADE's or Cambridge or ADGIE and GENT's and from the catalogue you will produce. When that comes I think we will surely have got many identifications with distant clusters of galaxies.

AMBARTSUMIAN

If we go to the bright radio galaxies, shall we have selection effects, since we take only radio sources?

SANDAGE

This has been tested. Ten of the objects in the Hubble diagram that you saw were radio sources. They were themselves the brightest members of clusters and the question was whether any non-thermal radiation existed there to artificially increase the apparent luminosity of the stars, and that is not the case. Then the test was made whether the inferred absolute luminosity was higher for those particular clusters, and a third test was made whether there was a relation of M with total cluster membership (i.e. the Scott effect), and none of these effects were found.

AMBARTSUMIAN

I am satisfied with your answer.

OSTERBROCK

Some years ago the sizes of the largest H II regions in galaxies didn't seem to be very good distance indicators. This situation has now improved partly because there are more observations, and also partly because you classify the galaxies and study the H II regions as a function of absolute magnitude of the galaxies. Have you thought of trying to do the same thing with the size of the whole galaxy, instead of H II regions?

SANDAGE

I think that the size of the galaxies classified by VAN DEN BERGH into luminosity classes are certainly more homogeneous within each luminosity class. I don't yet know what the sigma is for the ScI or ScII, but that is a good suggestion.

MORRISON

I hesitate to say that I know, rather I am a little concerned about the H II regions, because of the present view of their homogeneous origin from early stars. It would be very helpful to have some feeling that you were going to find regularities in size, but I think the recent signs of hotter objects which are not at all stellar in nature, yet have a transient but large post-Lyman α radiation, makes me worry a bit. There may be two or three distinct classes of H II regions which we will gradually pick up.

SANDAGE

That is something that we surely will look for.

SCHMIDT

If one were bold enough to believe that, if the quasars seem to have been mostly formed at z around 2, then the galaxies were formed at that period of time also, then the ages of the galaxies would have to be multiplied by 1.2 to get to the age of the universe.

SANDAGE

At LYNDS' largest redshift (of $z = 2.8$) the time into the past is 89% of the way to the FRIEDMANN singularity. At least for this point, the factor is 1.1.

SCHMIDT

Well, it depends on where the density maximum is.

MCCREA

I was going to ask Dr. SANDAGE about the expectation of getting a better q_0 from looking at more distant objects. We know from the radio counts that, when you go to apparently more distant objects, the evolutionary effects swamp any possibility of discriminating between models there. Would you not expect similar difficulties here?

SANDAGE

From the calculations of the forms of the H-R diagram in E galaxies the dL/dT is of the order of 0.00 magnitudes per 10^9 years. The formal value is something like $\pm\ 0^m.03/10^9$yr, depending on the exact form of the luminosity function near $M_v \simeq +4$. That is smaller than the deviation, say, of the $q = 1$ curve from the $q = 0$ curve, and hopefully one could take SPINRAD's models and get the refined value for that, but that is surely a problem for larger look-back times than we encounter to $z = 0.46$.

SPINRAD

I would think that this is no problem at all to a z of 0.4 or 0.5, but at 0.6 or 0.7 the luminosity function extrapolation is substantial, and that will create more of a problem.

REES

The isotropy of the microwave background sets a pretty good upper limit to the peculiar velocity of our galaxy which is incompatible with the existence of any very large deviation in the local velocity fields, unless we are sitting in some preferred central position. Is it still reasonable to suppose that a local fluctuation in the velocity field exists which is large enough to seriously modify the Hubble constant?

SANDAGE

No, it's only the completely local field out to 3,000 km/sec, where you are talking about 200 to 300 kilometers mean random motion. So the local anisotropy, I think, is of the order of maybe 500 km/sec over and above the Hubble flow, but only locally. Unfortunately it is in this local region ($m - M \leqslant 34$) where galaxies are resolved and where these precise distances can be found. It is here that the Hubble constant must be calibrated, and we must therefore know the local shear (non-Hubble) flow.

OORT

I wonder if there is any reason to expect any random motion in the universe except for the random motions that are caused by the gravitational field of clusters. Don't you think, Dr. REES, that in the expanding universe all the random motions should have long disappeared, except those that have reappeared by the concentration of the clusters?

REES

But if the so-called local supercluster centred on the Virgo Cluster stopped expanding, we would have a peculiar velocity of about 1,000 km/sec. We know that doesn't exist, from the microwave background isotropy, and we can similarly rule out a transverse velocity of the order which would be expected if the supercluster were a rotating system. And out to a distance at which the Hubble velocity ought to be 3,000 km/sec the fluctuations could be at most about 5%.

SANDAGE

That's fine then. That will not bother the Hubble constant by more than 5%.

REES

Right. So surely one need not worry about the factor of 2?

SANDAGE

Except in the local region betwen us and three times the distance of the Virgo Cluster, which is the only interval where we can get distances. The local anisotropy here is believed to be very great, and we must know its velocity components so as to subtract them from the observed radial velocities to get the true expansion flow. Although our galaxy may not be moving randomly relative to the microwave background by more than a 5% anisotropy, other galaxies out to 3 times the Virgo Cluster distance are moving randomly by a large factor, as shown by DE VAUCOULEURS and others. This random motion must be mapped and accurately subtracted from each nearby galaxy where distance is obtained by "precision" methods before the Hubble constant can be found.

FOWLER

Professor HOYLE asked you a question about the ages of the globular clusters; whether or not IBEN was using the correct ^{7}Be (p, γ) cross section. IBEN is using the correct one, and with that value there are no corrections for neutrino losses. In fact the low cross section makes is very difficult to detect neutrinos from the sun.

THE EVOLUTION OF RADIO SOURCES

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In this paper I shall try to summarise some current ideas on how an individual radio source evolves, and on how the properties of sources depend on cosmic epoch. Since the radio data alone do not reveal any clear-cut distinction between radio galaxies and QSSs, my discussion will apply to strong radio sources as a whole.

Those radio sources which have identified optical counterparts, and whose distances can therefore be determined, exhibit a large spread both in radio power and in linear dimensions. The luminosity function stretches over a range of at least a million — from $P_{408} \simeq 3 \times 10^{27}$ w Hz^{-1} ster^{-1} for Cygnus A (and for many QSSs with large redshifts, assuming the latter to be cosmological) down to $P_{408} \simeq 10^{21} - 10^{22}$ w Hz^{-1} ster^{-1} for normal galaxies. The sizes range from the very small components a few light years across described by KELLERMANN elsewhere in these proceedings, up to double sources with separations of hundreds of kiloparsecs. I shall be concerned only with "strong" sources, for which $P_{408} \gtrsim 10^{25}$ w Hz^{-1} ster^{-1}. The overwhelming majority of resolved sources in this class display a characteristic double structure, and the energy of the relativistic particles and magnetic fields contained within the extended doubles may well be in the range 10^{60} — 10^{62} ergs. This energy must have originated in the central parent object.

It is natural to suppose that compact sources eventually developed into extended doubles, and to consider whether all the sources can be interpreted as different stages in the development of a single phenomenon. That this might indeed be the case was indicated by the work of AIZU *et al* (1964) who plotted volume emissivity against P, and by HEESCHEN (1966) who plotted surface brightness against P. Despite the limited and inhomogeneous data available to these authors, there appeared to be a tendency for the most compact sources to be more powerful than very extended doubles.

RYLE and LONGAIR (1966) have proposed a possible general scheme for interpreting the data on strong sources in terms of an evolutionary sequence. They assume that the required energy of 10^{60} — 10^{62} ergs is generated in a single event with a short time-scale (which is tentatively associated with the quasar phenomenon) and they distinguish three phases in the development of a strong radio source.

1) The initial stage ($0 < t \lesssim 10^3$ years), during which the radio emitting region occupies a volume comparable with that of the gas cloud responsible for the optical emission. The magnetic field is assumed to be only $\sim 10^{-5}$ gauss.

2) A period ($10^3 \lesssim t \lesssim 10^5$ years) when the ejected plasma cloud, having bifurcated into a double structure, expands to galactic dimensions. There may be no further injection of energy during this phase, but the field must amplify to $\sim 10^{-3}$ gauss (the equipartition value at the end of phase 2) at the expense of the relativistic particle energy in order that the radio luminosity at high frequencies should

remain constant despite the adiabatic expansion. Synchrotron self-absorption would still be important at low frequencies during this phase.

3) A final phase ($t \gtrsim 10^5$ years) during which the two components, having travelled beyond the confines of their parent galaxy, continue to expand adiabatically. The expansion velocity is taken to be uniform and the radio luminosity decreases as $t^{-2(2\alpha+1)}$, α being the spectral index.

The ejection velocity of the plasma clouds was taken to be (0.1 — 0.9) c. This estimate follows from the hypothesis that the two components are intrinsically identical and that apparent asymmetries are a consequence of the different light travel time, which results in our observing them at different stages in their development. RYLE and LONGAIR'S degree of success in fitting the strong identified source into this pattern is shown in Fig. 1. LONGAIR and MACDONALD (1969) have compared the "P — surface brightness" and "P — linear size" correlations predicted by the model with the data on a complete sample of 3C sources.

The behaviour of compact sources must plainly be highly dependent on the character of the initial "violent event". Until this is understood at least in outline, attempts to elaborate on RYLE and LONGAIR'S simple phenomenological discussion of the early phases of radio source evolution are unlikely to prove fruitful. On the other hand, the later stages of a source's development may be comparatively insensitive to the details of the initiatory outburst. VAN DER LAAN and PEROLA (1969) show that the observed absence of sources with spectral breaks in the radio band favours the idea that the relativistic electrons are ejected repeatedly rather than in a single outburst. Several workers have recently devised models for extended double

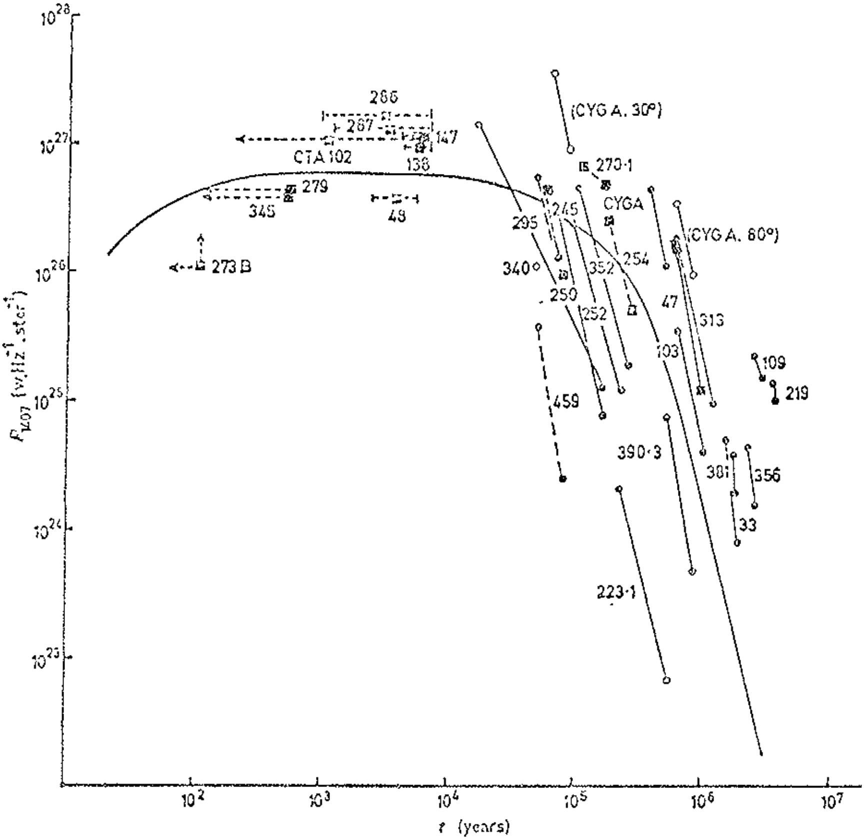

FIG. 1 — The evolution of radio source components at 1400 MHz according to the model of RYLE and LONGAIR (1967). The continuous curve shows the predictions of the model. The ejection velocities, and thus the ages of sources, are estimated from the degree of asymmetry of the components. An ejection axis at 60° to the line of sight is assumed in all cases (except for Cygnus A, where three different choices of angle are plotted). Components of radio galaxies are denoted by filled circles, and components of QSSs by squares.

(RYLE and LONGAIR 1967 Fig. 2)

sources on the hypothesis that dynamical interaction with an external medium plays the key role.

A plasma cloud consisting only of relativistic particles and magnetic fields would expand, in its own frame, at a speed $\sim c$. One thus has to introduce some other effects in order to account for source components whose dimensions are small compared with their separation. (At first sight one might think that this problem would be solved if the outward motion was *ultra*-relativistic, so that there was a large time dilation in the frame of the plasma cloud, but this idea leads to too great an asymmetry between the two components). This problem has been aggravated now that higher resolution maps have revealed that the components of double sources are often even smaller in relation to their separation than was previously supposed. For example, Fig. 2 shows the structure of Cygnus A, and there are other objects, for example 3C 33, which possess even smaller components. If the plasma clouds expand into an ambient medium of density ρ and temperature T°K, the flow will be hypersonic provided that the velocities are $\gg (T/10^{13})^{\frac{1}{2}} c$. If this condition is fulfilled (as current views on the intergalactic gas suggest will be the case), the force exerted on the boundary of the plasma cloud is $\rho\, v_{\perp}^2$, when $v_{\perp}$ is the velocity component normal to the interface. DE YOUNG and AXFORD (1967) were the first to discuss the deceleration of a moving plasma cloud caused by this external "ram pressure", and the resulting shape of the cloud. This idea has been further developed by CHRISTIANSEN (1969) and by MILLS and STURROCK (1970). The required external density turns out to be $\sim 10^{-27} - 10^{-28}$ gm cm^{-3}. While this is manifestly too high for a universal intergalactic medium, it is an acceptable density for the gas within clusters of galaxies. Qualitatively, the external medium can confine the plasma clouds provided they are moving fast enough. However, the "ram pressure" has a braking effect on the overall motion of the clouds, and as they slow down they expand more rapidly in transverse directions. This

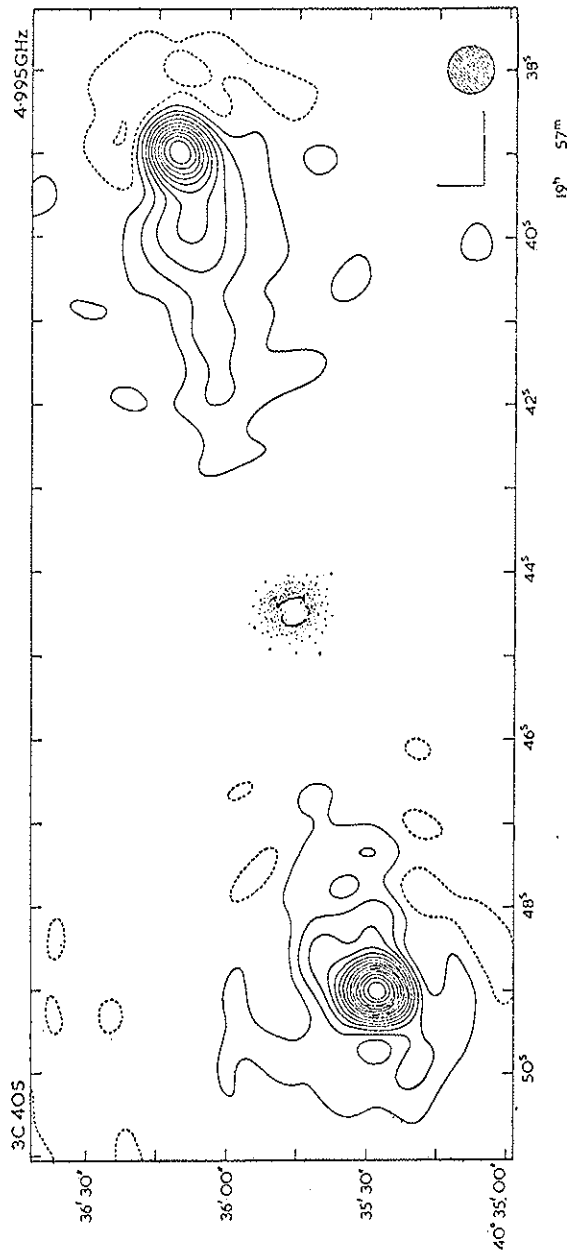

FIG. 2 — The structure of Cygnus A at 5000 MHz. The beam size is shown at bottom right.

(MITTON and RYLE 1969 Fig. 2)

increases their effective cross-section, which in turn makes the braking more efficient, and as a result the separation of the components would reach a finite maximum instead of increasing indefinitely.

There are two ways in which this general idea could be tested. First, a more refined analysis along the lines followed by RYLE and LONGAIR could determine how satisfactorily sources lie on the type of "evolutionary track" predicted by the model. Second, more refined models should predict the brightness distribution across a single source, which can be compared with maps of strong extended sources.

If future observations rule out an intergalactic medium of the required density, alternative confinement mechanisms would have to be explored. For example, the components may contain gravitationally bound masses ejected from the parent object, from which relativistic particles leak out (BURBIDGE 1967). A further possibility is that a large mass of thermal gas in the radio clouds is coupled to the relativistic particles via the magnetic field, and its inertia retards the free expansion of the clouds. Problems with this view are discussed by SCHEUER (1967). The kinetic energy of the requisite material increases the overall energy requirements. Moreover, there are other observations — e.g. Faraday rotation, x-ray and γ-ray limits, and the absence of free-free absorption at low radio frequencies — which set stringent constraints on the properties of the thermal gas.

The rapid decrease of P with component size for the extended sources is presumably mainly a consequence of adiabatic expansion. An additional contributing factor may be inverse Compton losses due to scattering of the microwave background photons by relativistic electrons. This causes a "quenching" of the sources which may be especially important at large redshifts (REES and SETTI 1968).

One prediction common to almost all proposed models is that the lifetime of a strong source should be only 10^6 — 10^7

years. (The same objects could, however, continue to emit at a lower power level for a much longer period. SCHMIDT's (1966) work on the lifetime of sources associated with elliptical galaxies suggests that this indeed happens). If sources live for a time much smaller than the Hubble age, then at any cosmic epoch one must observe sources on every part of their "evolutionary track". The relative number of sources at each particular stage of development would be inversely related to the rate at which they evolve through that stage. Consequently observation of radio sources with large redshifts do not reveal objects which are *individually* "younger" than similar nearby objects (in the sense that this is the case for (e.g.) normal galaxies). Any epoch-dependence of the coordinate density or characteristic properties of sources must therefore reflect a change either in the evolutionary track followed by each source, or in the source birth-rate (or, more probably, in both).

Because no type of radio source behaves as a "standard candle", it is analyses of the source counts that have provided the main radio evidence pertaining to cosmology. The most extensive source counts yet published are those at 408 MHz obtained by combining the results of the second 5C survey, which covers ∾ 0.002 steradians down to a flux level of $S_{408} = 0.01 \times 10^{-26}$ W m^{-2} Hz^{-1}, with the counts based on the 3CR and 4C sources (POOLEY and RYLE 1968). (The earlier surveys, covering most of the northern sky, were carried out at 178 MHz. The 408 MHz flux of most 3C sources could be interpolated from known spectral data, but it was necessary to reobserve a sample of 4C sources at 408 MHz in a separate fan-beam survey). When plotted in the traditional form of log N versus log S, N being the number of sources per steradian whose flux density exceeds S, the curve shown in Fig. 3 is obtained. The slope is about — 1.8 at high fluxes corresponding to the 3C sources, but flattens gradually as one moves towards the fainter sources. Close to the 5C limit the curve has flattened to a slope of ∾ — 0.8.

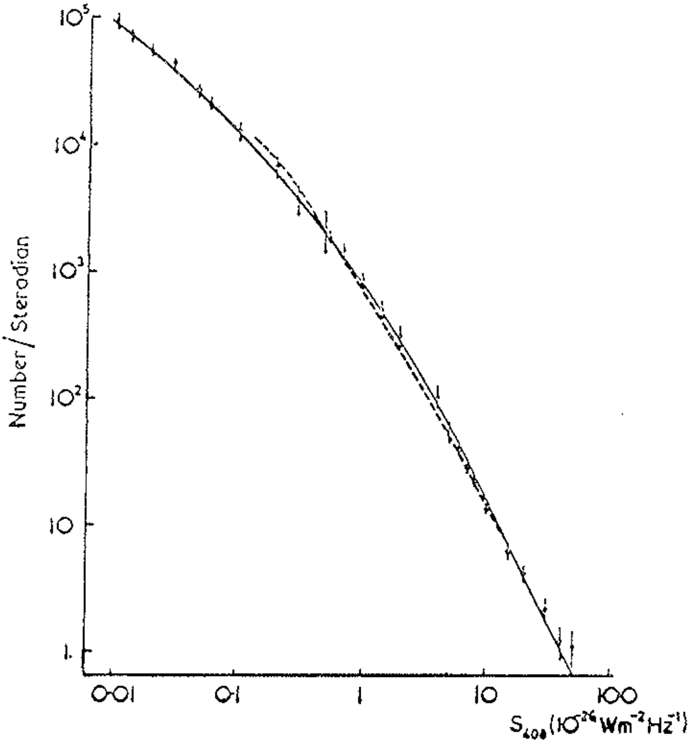

FIG. 3 — The Cambridge source counts at 408 MHz. The dashed line shows the $N(S)$ curve at 178 MHz from the 3C and 4C surveys scaled on the assumption that all the sources have a spectral index of 0.7.

(RYLE 1968 Fig. 2)

The crucial significance of figure 3, as is now well known, springs from the fact that all the standard cosmological models predict a slope *flatter* than the Euclidean value of — 1.5 if the coordinate density of sources is independent of redshift. This conclusion holds — barring local fluctuations — for any luminosity function, however broad its spread. The detailed shape of the curve does, however, depend on the luminosity function, since the deviations from the Euclidean slope result from redshift and curvature effects.

The disparity between the observed counts and the predictions of various models is displayed more strikingly if one phots N/N_0 against S, where $N_0(S)$ is the source density expected in a static Euclidean model. Fig. 4, again taken from

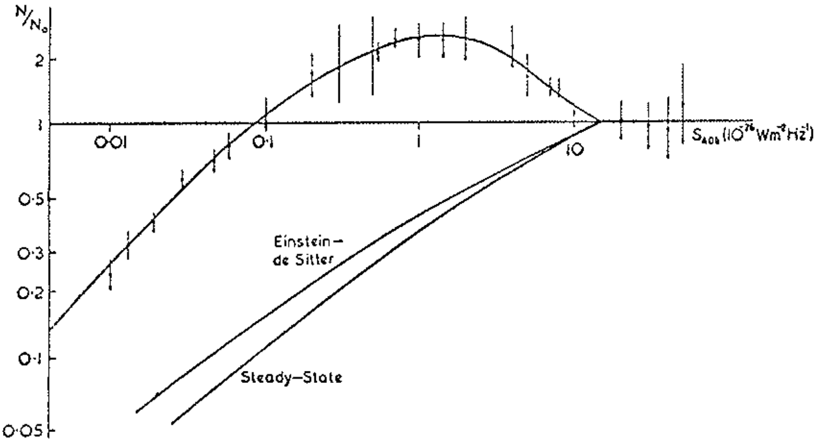

FIG. 4 — The same data as in figure 3 plotted in terms of N/N_0, when $N_0(S)$ represents the number of sources with flux density greater than S if the counts had the Euclidean slope —1.5. The other curves show the expected forms of the curve in Steady-State and EINSTEIN-DE SITTER cosmologies, if the sources had the same luminosity function, and the same coordinate density, at all redshifts.

(RYLE 1968 Fig. 3)

POOLEY and RYLE'S work, shows the same data as figure 3 plotted in this manner. N_0 is chosen so as to normalise to the Euclidean slope at $S_{408} \simeq 10 \times 10^{-26}$ W m^{-2} Hz^{-1}. Also plotted in this diagram are the curves expected in a strict steady state theory, and for an EINSTEIN-DE SITTER cosmology with uniform comoving source density. In deriving these curves, the inferred local distribution of source luminosities and spectral indices have been utilised. (The requirement that the total integrated radio background be finite obviously requires that the slope of the counts should asymptotically become flatter than -1).

This conflict with the predictions of all "source conserving" models is conventionally adduced as evidence for a higher density of strong sources in the past. Fig. 4 shows that the disparity is most significant for $S_{408} = (1 - 2) \times 10^{-26}$ W m^{-2} Hz^{-1}, and by suitably evolving the local luminosity function so as to increase the coordinate density of powerful sources at early cosmic epochs, the "excess" of sources around this flux density can be attributed to objects at large redshifts. I shall not discuss the details of the models here: they are reviewed by, for example, RYLE (1968) or SCHEUER (1970). (In the steady state theory, where of course no secular dependence of mean source properties on epoch is permitted, Fig. 4 must be interpreted as indicating a deficiency of nearby strong sources (HOYLE 1968). Severe constraints on such models are provided by (i) the isotropy of the counts over the northern sky, and (ii) the fact that the sources detected in the surveys contribute at least $\sim 1/3$ of the total extragalactic radio background. Because of (i), we must be at the centre of the hypothetical "local hole"; also (ii) forbids us from postulating a population of intrinsically weak nearby sources, because the integrated background from unresolved sources belonging to this population then becomes excessive unless we arrogate to ourselves an especially privileged position).

Although I have drawn on the Cambridge data to illustrate the above comments, counts based on other independent surveys have yielded similar results (though not necessarily with the same statistical significance), and so pose the same interpretative problems. These surveys have generally been done at similar frequencies to the Cambridge counts, and until recently there were no high frequency surveys extensive enough to yield reliable counts. Two years ago, however, SHIMMINS, BOLTON and WALL (1968) presented counts at 2700 MHz (11 cm). These were based on a survey of 0.35 steradians down to $S_{2700} = 0.4 \times 10^{-26}$ w m^{-2} Hz^{-1}, together with a deeper survey down to 0.08 flux units covering a smaller area. They obtained a log N/log S curve with a slope — 1.4 ± 0.1, and suggested that this was discrepant with the Cambridge counts. However, in relating different counts it is important to make the comparison at similar values of N (POOLEY 1968), and the 2700 MHz counts should therefore be compared with the "4C" part of the Cambridge counts, where the slope is also ~ -1.5. Though there is some indication that the 2700 MHz curve does not steepen at small N to the same extent as the Cambridge counts, the numbers involved in the former are too small for the difference to be significant. WALL (1970) has carried out a detailed study of the results of the 2700 MHz survey, taking into account the optical identifications, and he concludes "If no evolution [in the sources] is assumed, difficulties in reconciling the observed relations at 2700 MHz with those calculated are severe, and are similar to those encountered in previous investigations of the low frequency counts... A cosmological interpretation of redshifts of QSOs has been assumed; if this is in error, the difficulty of reconciling the calculated number-flux density relation for radio galaxies with the observed relation persists".

A further point to bear in mind is that because sources do not all have the same spectral index, there is in any case no reason to expect the same N (S) curve at different frequencies. The high frequency surveys are weighted in favour of flat-spectrum sources, and there is no a priori reason to expect these to display the same evolutionary behaviour as sources with steeper spectra (KELLERMANN *et al* 1968). There is indeed some evidence that the apparent failure of the 2700 MHz survey to steepen at high flux densities is attributable to the presence of a few sources, with flat spectra, which do not appear in the 3C catalogue.

Beyond posing severe problems for the steady-state theory, the source counts unfortunately provide no help in discriminating between different FRIEDMANN-type models. This is because for any choice of the geometry of the universe it is possible to pick some form of evolution which reproduces the observed $N(S)$ curve. At present no astrophysical considerations place any constraints on this evolutionary behaviour (as they do, for instance, on the z-dependence of the optical luminosity of normal galaxies), and it is more interesting to invert the problem and use the counts to infer something about the epoch-dependence of the source parameters. The quantitative details obviously depend on the assumed cosmological model, but the crucial message of the counts is that in *any* cosmology (except possibly in certain LEMAÎTRE-type universes) one has to invoke remarkably strong evolution: typically, the coordinate density of powerful radio sources at $z \simeq 2$ must be $10^2 - 10^3$ times higher than at the present epoch. Furthermore, even in a particular cosmology, the form of evolution is by no means uniquely determined. The local luminosity function must change with epoch in the general sense that there is an increase in the number of powerful sources at large redshifts without a corresponding increment in the coordinate density of the weak sources (since the latter must not make an excessive contribution to the integrated background).

Forms of evolution have been considered in which either the luminosity or the coordinate density of a class of sources varies as some function $f(z)$. (One should note, however, that the often-drawn distinction between "density evolution" and "luminosity evolution" has at the moment little significance: all that we can meaningfully discuss on the basis of the radio evidence is the change in shape of the luminosity function, "density evolution" being merely a special case). Much attention has been given to the case $f(z) \propto (1 + z)^n$. LONGAIR (1966), for example, was able to fit the counts, and satisfy the constraints on the integrated radio background, on the supposition that the coordinate density of sources with $P_{408} \gtrsim 5 \times 10^{25}$ W Hz^{-1} ster^{-1} varied as $(1 + z)^{5.5}$. (SCHMIDT (1968) found a similar result for the QSSs in the 3C survey). Power-law forms of $f(z)$ must be truncated at some redshift z^* to ensure convergence: LONGAIR originally chose z^* to be 3 or 4, and tentatively associated this value with the epoch of galaxy formation. Power-law forms of evolution have been discussed mainly for computational convenience. It is not clear that there are astrophysical grounds for expecting $f(z)$ to follow a power-law, but I shall return to this point in a moment. Another mathematically simple possibility is $f(z) \propto e^{-kt/t_0}$, where t is cosmic time (this corresponds to $e^{\frac{2}{3}k\left[1-(1+z)^{-3/2}\right]}$ in an EINSTEIN-DE SITTER model, and to $e^{k\left[1-(1+z)^{-1}\right]}$ in a very low density universe). Exponential evolution has been discussed by ROWAN-ROBINSON (1968) and DOROSHKEVICH *et al* (1970). It is unnecessary in this case to impose a large redshift cut-off in order to ensure that the radio background converges.

Of course there is no reason to expect the evolution to obey any simple analytic law, and it is perhaps premature to discuss the form of $f(z)$ until we know whether it is all sources, or just some particular type, which partake in this evolution. It may nonetheless be amusing to speculate on some effects which may contribute to the apparent epoch-dependence of radio source properties. Two quantities which are relevant to the behaviour of a source, at least in its later extended phases, are the density ρ of the external medium and the temperature T of the microwave background. The "ram pressure" which brakes the source components, and retards their expansion, is proportional to ρ; and the inverse Compton losses are proportional to T^4. The epoch dependence of ρ depends on how uniformly the gas is distributed, and on whether it is concentrated in clusters, but we might expect a general tendency for it to vary as $(1 + z)^3$ even though its present value is highly uncertain; also, we expect $T \propto (1 + z)$

with very high precision. Even if neither the source formation rate nor the character of the initial outburst depended on z, these effects would cause the coordinate density of powerful sources to vary as $(1 + z)^{3/2}$ There would not, however, be a corresponding increase in the number of weak sources, because these would be preferentially "quenched" by inverse Compton losses at large redshifts (REES and SETTI 1968).

T and ρ are the only relevant parameters whose epoch-dependence can be quantified, and it is interesting that they contribute a power-law dependence to the evolutionary behaviour of the sources. But these are probably only subsidiary effects, since the main factor which governs the coordinate density of the sources is likely to be the probability of occurrence of "violent events". (SCHMIDT's evidence that radio-quiet objects exhibit the same evolution, which is reported elsewhere in this volume, supports this view). There are as yet no theoretical arguments which favour any particular redshift-dependence for the source formation rate. It is interesting that one could reproduce a power-law evolution on the basis of either the stellar collision model or the "spinar" model if one assumes that all galactic nuclei form at a certain redshift with a uniform spread in the initial density and mass (and, for the "spinar" model, the magnetic field). This is because the time such an object takes to collapse catastrophically depends on various powers of these quantities — objects closest to the verge of instability would collapse first, and the event rate would subsequently decrease with time.

Attempts to plot separate source counts for different types of source — for example, high surface brightness sources, scintillators, or objects with flat spectra — could in principle enable us to determine, on the basis of radio data alone, the evolutionary behaviour of each type. However, this procedure introduces selection effects, and reduces the statistical signicance of the data because of the smaller numbers involved in each category.

Knowledge of the redshifts of the sources should in principle enable the form of $f(z)$ to be determined by the "luminosity-volume" test (SCHMIDT 1968) but so far, owing to the large scatter in both radio and optical luminosities, the optical identifications have helped surprisingly little. Fig. 5 illustrates the proportion of sources so far identified with radio galaxies or QSSs. The bigger proportion of the latter in high frequency surveys reflects the tendency of many QSSs to have flat spectra (due probably to compact self-absorbed components). The unidentified sources are believed to belong mainly to the radio galaxy category, for the following reasons: (i) The spectral indices of the unidentified sources are, if anything, even steeper than for the identified radio galaxies. (ii) The fraction showing interplanetary scintillation (an indication that components with small angular size are present) is intermediate between the fractions for QSSs and for radio galaxies. Thus, if the unidentified sources have linear sizes characteristic of one of the two classes, but are more distant, they are likely to be galaxies. (iii) The distribution of optical magnitudes of identified objects appears to cut off at the plate limit for galaxies, but about a magnitude brighter for QSSs. Thus the obvious selection effect against identifying faint objects is more severe for the radio galaxies.

If all the unidentified sources are grouped with the radio galaxies, one finds similar $N(S)$ curves for radio galaxies and for QSOs. This would indicate that the coordinate density of both types of object evolves with epoch in the same manner. However, according to BOLTON (private communication), recent spectral data indicate that $\sim$ 25 per cent of the unidentified sources are QSSs. The initial slopes of the 408 MHz $\log N/\log S$ curve should then be ~ -1.7 for galaxies and ~ -1.9 for the QSSs).

Helpful correspondence from Dr J. G. BOLTON is gratefully

acknowledged. This review was prepared during a visit to the Institute for Advanced Study, Princeton, and I thank Dr CARL KAYSEN for his hospitality.

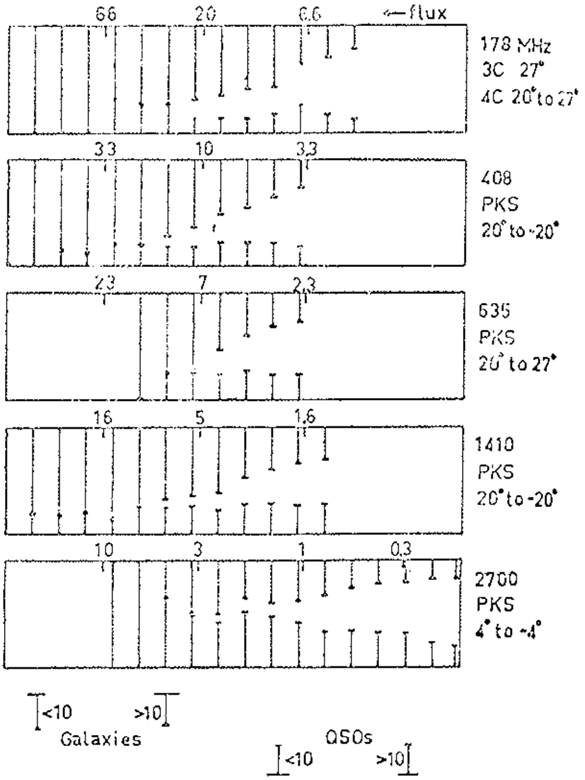

FIG. 5 — The identification content of radio surveys at different frequencies. The abscissa is the flux density on a logarithmic scale, and scales of the five diagrams are adjusted to give similar source densities at the same horizontal locations. The fraction of sources which are identified with radio galaxies above a given flux level is shown as a line extending *downwards*, and the fraction which are QSSs as a line extending *upwards*. The gap thus indicates the unidentified fraction. The strongest sources in the low frequency Cambridge survey tend to be radio galaxies, whereas the opposite is true for the higher frequency Parkes surveys. The N (S) curve for unidentified sources will obviously be steeper than the curve for all sources, because the unidentified fraction naturally increases as S decreases.

(BOLTON 1969 Fig. 13)

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DISCUSSION

Chairman: G.R. BURBIDGE

SPITZER

I have one question concerning the interpretation. Is it possible from the theoretical analysis of the observations to test the assumption that the radio sources have not changed with time and that it is only the birth rate function that has been altered? Would such an assumption be consistent or inconsistent with the observations?

REES

I would say that it is consistent with the present observations. This somewhat depends on what one thinks the unidentified sources are.

KELLERMANN

One could in fact reverse your argument about the nature of the unidentified sources and argue that they are quasars. We know that the identified galaxies and the identified quasars statistically have different properties, but we also know that the range of properties is identical. One can argue that in the identification process one tends to miss the large extended sources with power law spectra because the position agreement is not so good and that it is easier to make an identification with only moderate position agreement with a galaxy than with a quasi-stellar object.

REES

Also, unidentified radio galaxies would tend to be higher in their intrinsic power than the identified ones, and that may lead to another systematic difference

THE CURIOUS MYSTERY OF log N - log S

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First let us note how the Euclidean slope of — 1.5 arises for the log N — log S curve. The volume of a sphere of radius r is $\frac{4}{3} \pi r^3$, and the number of sources N within such a sphere is clearly proportional to r^3, provided the sources are uniformly distributed. If the sources also have the same intrinsic emission the faintest source within the sphere, as seen from its centre, has flux S proportional to r^{-2}. Evidently $N\ S^{3/2}$ is independent of r, and $N \propto S^{-3/2}$ with N the number of sources brighter than S.

A recent Parkes survey [1] up to $N \simeq 3000$ sources per steradian gives a log N — log S slope of — 1.45, close to the Euclidean value. The frequency of the survey was 2700 Mc/s. For $\sim 3000 \geqslant N \geqslant \sim 100$ sources per steradian the data plotted by Pooley and Ryle [2] also indicates a slope close to — 1.5. For $N < \sim 100$ sources per steradian Pooley and Ryle give a slope of about — 1.8, however. This is for a frequency of 408 Mc/s. Expressed in terms of numbers this difference is slight. Thus we have the following related N values for slopes — 1.5 and — 1.8

S	1 (standard)	$2^{2/3}$	$2^{4/3}$	4	$2^{8/3}$	
N (— 1.5):	100	50	25	12	6	(Australian 2700 Mc/s)
N (— 1.8):	100	44	19	8	4	(Cambridge 408 Mc/s)

Where 50 sources per steradian would be counted for a slope of — 1.5, the number for a slope of — 1.8 is 44. And similarly for the other columns of this table. The differences are too small to be of serious cosmological consequence. So for the purpose of the present paper I shall adopt the Australian slope of about — 1.5 as applying for all values of N up to at least 3000 per steradian.

The most extensive study of the relation of radio and optical properties of sources has been done for the 3CR survey. Red-shift values available for about 40 QSOs in this survey and for about 70 radiogalaxies. Excluding sources close to the galactic plane leaves about 250 cases, so red-shift data is available for about half of the survey. When the data is presented in a log z — log S plot both QSOs and radiogalaxies show a scatter diagram [3, 4]. Yet both give a log N — log S plot close to — 1.5.

In the QSO case it is possible to argue that the z-values are not related to distance. This view can be supported by appealing to the optical M_v — log z diagram which is also close to being a scatter diagram. The situation is different, however, for radiogalaxies. The M_v — log z diagram for radiogalaxies satisfies the classic Hubble relation so that z must reasonably be taken as a measure of distance. Moreover the red-shift values for the radiogalaxies are small so that evolutionary effects on the intrinsic radio properties should also be small. How then are we to explain the log z — log S scatter diagram for the radiogalaxies? In terms of the luminosity function for radiogalaxies, which must be of a form close to

$$\text{(1)} \qquad n\,(L)\,dL \propto \frac{dL}{L^{5/2}}\,,$$

where n (L) is the space density of radiogalaxies with intrinsic radio luminosity between L and $L + dL$.

For the moment suppose that all radiogalaxies emit the same frequency spectrum. In the Euclidean case the number of sources in the spherical shell r to r + dr with fluxes $> S$ is proportional to

$$\text{(2)} \qquad 4\pi\, r^2\, dr \int_{4\pi r^2 S}^{\infty} \frac{dL}{L^{5/2}}\,.$$

The lower limit to the integral arises because L must be $> 4\pi\, r^2\, S$ in order that the flux be $> S$ when the distance is r. Hence the number with fluxes $> S$ is proportional to

$$\text{(3)} \qquad S^{-3/2}\,\frac{dr}{r}\,.$$

For sources with small red-shift it is accurate enough to take $z = H\,r$ so that (3) can be written as

$$\text{(4)} \qquad S^{-3/2}\,\frac{dz}{z}\,.$$

The log N — log S slope from the shell is — 1.5.

In (4) we have the important result that equal logarithmic intervals in z contribute equal numbers to the source count. For the radiogalaxies in 3CR, those with red-shifts, we have the following situation:

z *range*	< 0.02	0.02—0.04	0.04—0.08	0.08—0.16	0.16—0.32
Number	11	16	14	13	13

in excellent agreement with (4), except that the region $z < 0.02$ needs further discussion.

In blocks of 14 the QSOs of 3CR, those with red-shifts > 0.3, have the following distribution with respect to z:

Block Number	14	14	14
Red-shift Range	0.30—0.65	0.65—1.03	1.03—1.95

The fact that the QSOs continue to fit (4) quite well can be taken to support the view that QSOs are at cosmological distances and that the QSO phenomenon is an extension of that which occurs in radiogalaxies.

The proportionality (4) was deduced for Euclidean space and is valid for all cosmologies when z is small. When z is not small we have the following situation for the steady-state cosmology and for the $q_o = +1$ FRIEDMANN model:

$$\text{(5)} \qquad S^{-3/2}\frac{dz}{z} \cdot \begin{cases} \dfrac{1}{(1+z)^6}\,, & \text{Steady-state}\,. \\[2ex] \dfrac{1}{(1+z)^4}\,, & q_o = +1\,. \end{cases}$$

The data as presented above would seem to indicate that an evolutionary effect exists in the source space density which exactly compensates for the extra cosmological factor in (5). This is a strange and curious circumstance. If the above indications from one-half of the 3CR sample are confirmed in general, there is a requirement for a close coupling between the cosmological structure and the evolutionary factor for the sources.

The count fails at $z = 0.02$ to give equal numbers per unit logarithmic increment of z. This implies a lower limit to L in the luminosity function $dL/L^{5/2}$. Numerically, the distribution fails below $\sim 10^{31}$ erg per sec $(c/s)^{-1}$, at 178 Mc/s.

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DISCUSSION

Chairman: G.R. BURBIDGE

SPITZER

It seems me that Dr. HOYLE's approach to the observations is an extremely interesting one. To take account of the z distribution as well as the distribution of Log L and Log S will surely increase our insight into what is going on. I have one question about the specific luminosity function which he has assumed. I am wondering if perhaps the singularities of his assumed velocity distribution function are not, perhaps, influencing his results. One particular property of the $1/L^{5/2}$ function is that it leads to weak singularities at both zero R and infinite R. Any other simple power — law distribution has a strong singularity either at infinity or at zero. I think it might be very interesting, although, of course, it is much more complicated analytically, to put in a Gaussian distribution, and see if one got the same Y as a function of z.

HOYLE

I think the power law dL/L^n must have n very close to $5/2$. The singularity $L \rightarrow \infty$ turns out not to be at all worrying.

SPITZER

You have singularities both at zero and at infinity.

HOYLE

I have avoided the singularity at zero by means of the cut-off for $L < L_0$, $L_0 \simeq 10^{31}$ erg sec^{-1} $(c/s)^{-1}$.

SPITZER

Could you not assume a Maxwellian distribution that is conventional?

HOYLE

Yes, you could have a Gaussian distribution. This would affect the count in respect of the innermost spherical region, $z < 0.02$.

MORRISON

How does this luminosity function compare with those obtained by wide band methods, when we take spectra?

HOYLE

Inevitably I think there must be a close similarity.

SCHMIDT

Per magnitude interval, what is the number ratio between successive magnitudes for this luminosity function?

HOYLE

The ratio between successive magnitudes is given by the factor $L^{-3/2}$.

SCHMIDT

This would be an effect of 4 per magnitude then? The observations suggest something of the order of 5.

Hoyle

That is not a large difference in relation to the size of the sample.

Schmidt

You showed a slide plotting the *N* (*S*) for the identified 3C quasars. I believe that the slope of that relation must be affected by the fact that the sources must be identified and it is for that reason that that relation is flattened, flatter than it would be if you took all 3CR quasars. In order to take into account cases like that, where you have two selection effects at once, the optical limit and the radio flux limit, about three years ago I devised the V/V_m method in which, for every identified quasar, you compute the ratio of V, the volume out in the universe to which the source is actually seen, over V_m, the maximum volume in the universe over which it could be seen still brighter than 18.5 magnitude and still belong to the 3CR. The mean value of V/V_m was about .70 and I believe that this is still evidence against the uniform distribution of these objects. I would like to add that this evidence is completely independent of evolutionary effects derived from the counts of optically selected QSOs, that show a gradient of about 6 per magnitude. The fact that the two pieces of evidence agree so well seems to me to indicate that the Cambridge *N*(*S*) slope at high flux density is indeed correct.

Hoyle

I must simply repeat that the differences here are only about 5 sources per steradian. In my opinion this difference is not statistically significant.

Schmidt

As far as your procedure here is concerned, I would like to submit that it is incomplete, in that you have not taken into account the selection effect imposed upon observed redshifts by the fact that the object must have been identified, and therefore brighter than 18 or 18.5 magnitude. And in the case of the quasars this makes a large difference. In the case of the radio galaxies you are all right up to 16% redshifts, I would say.

HOYLE

I think that it is fair to point out that this is a session on observational cosmology. I have simply taken the best data as they now exist.

SCHMIDT

I think, however, that is should be recognized that in all observations, however complete we try to work, there are limits of flux density to which you can only work completely and limits of optical magnitude, and I think these should be directly and specifically included in the analysis.

HOYLE

It may well be. This is a matter of personal judgment. I have a strong preference for working with data which I regard as of first class quality. This to me means working with sources for which redshifts are known. If no redshifts were known at all I think most of us would expect the usual Hubble correlation between S and z, and we would support this opinion by arguing that the slope of the log N-log S curve is not too far away from —1.5. The strange thing is that none of the first quality data, whether for radiogalaxies or quasi-stellar objects, turn out to support this expectation.

MCCREA

It seems to me that a lot depends on whether you accept that the difference between 1.5 and something else comes in at N equals 100, or at N equals 300 as Dr. Rees said. I have for a different purpose a long time ago drawn the curves after dividing the sky up into four parts. I got in this respect similar curves to the Cambridge ones for each of the four parts of the sky, which rather suggests that the shape is significant.

HOYLE

If one reads the centre of the error bars in the Cambridge data $N = 100$ is correct. Because of the error bars, there is of course ambiguity in what one takes for N. If one were to take $N = 300$ instead, the issue would involve a total of about 15 sources per steradian and this would still be too small to have general cosmological significance.

REES

If one accepts that the radio galaxies (at least) are cosmological then one should compare the observed counts not with the Euclidean slope of 1.5 but with something substantially flatter than 1.5. This enhances the disparity between the data and the non-evolutionary predictions. It also makes the numbers involved greater and the effect consequently more significant, because the peak disparity then shifts to a lower flux on the slide you have just shown.

HOYLE

I am not denying that an evolutionary effect is involved, what I am saying is that we have a curious situation in which the evolutionary effect cancels the cosmological effect.

SALPETER

You mainly talked about the function for radio-luminosity, but do you assume the same kind of function optically?

HOYLE

No, the optical data satisfies the Hubble diagram, not a scatter diagram.

KELLERMANN

Just a comment on the question of the slope at the high flux density end of the curve. A survey made at NRAO at 6 cm, and which has about the same number of sources as the Parkes survey, appears to have a steep slope at the high end, in more or less agreement with Cambridge but not with Parkes. However, like the Parkes result, the slope is not too significant, as the number of sources at the high end is small. The main evidence for a steep slope comes from the Parkes 408 MHz survey and the Cambridge 3C and 4C surveys. For both of these, where you compare individual flux densities measured by other people, the agreement is not very good. Discrepancies exist in the order of 20 and 30%, when Parkes fluxes are compared with measurements made at Arecibo or with the new Mills Cross. When you compare the 3C data with values interpolated from the spectra the result is also not very good. Since the individual fluxes seem to have much larger errors than the surveys originally indicated, one has to be very cautious about drawing statistical results. In particular it is well known that large random errors in individual flux densities will result in the apparent steep ending of the number-flux relation.

SANDAGE

Since the optical luminosity function was just mentioned, I don't believe the absolute magnitudes are precisely the same amongst the radio galaxies. I think there is a Gaussian distribution with a dispersion of $\sigma \approx 0.5$ mag., with the distribution having the same bright end as for the first ranked cluster members, but distributed more widely towards fainter magnitudes.

SCHMIDT

Could you explain that further? For objects of given absolute luminosity you expect in the Euclidean case a slope of 1.5. Any admixture of luminosities will give the same slope, and I do not see that any uncertainty comes in through the wide luminosity distribution.

HOYLE

If in any sample the log z — log S plot is a scatter diagram then plainly the S values must be dominated by the luminosity function.

SCHMIDT

But I don't understand the significance of this remark in connection with what you have been saying earlier — it just shows that there is a wide luminosity function.

HOYLE

The remark was intended to emphasise the point that in view of the scatter diagram for log z — log S any argument about the steepness of the log N — log S slope is not very relevant.

X-RAY BACKGROUND RADIATION

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X-ray astronomy first revealed evidence of a diffuse background radiation [1] in 1963. Numerous measurements have since been made [2-15] and the spectrum has been relatively well defined over the wide range from 1 kev to 100 Mev (Figure 1). More recently, efforts have been made to extend the spectrum to energies as low as 100 ev. At the higher energies ($E > 10$ kev) the spectrum is well approximated by a power law with an index of about —2.3 for the energy dependence of the differential photon flux. At lower energies (1-10 kev), the spectrum flattens to an index of —1.4 to —1.7. At still lower energies ($E < 1$ kev), evidence exists for diffuse radiation in excess of a simple extrapolation of the spectrum from 1 to 10 kev. The observed isotropy is about ± 10 percent for energies greater than 10 kev, for which galactic absorption is negligible. In the very soft x-ray range, the flux falls off with decreasing galactic latitude because of interstellar absorption in the galactic disk. These characteristics are consistent with an extragalactic origin.

The energy density (2-1000 kev) of the background x-radiation is about 6×10^{-5} ev/cm^3. For comparison, the energy density of radio waves (1-1000 MHz) is about 10^{-7} ev/cm^3; the 2.7 K cosmological background has a density of about 0.3

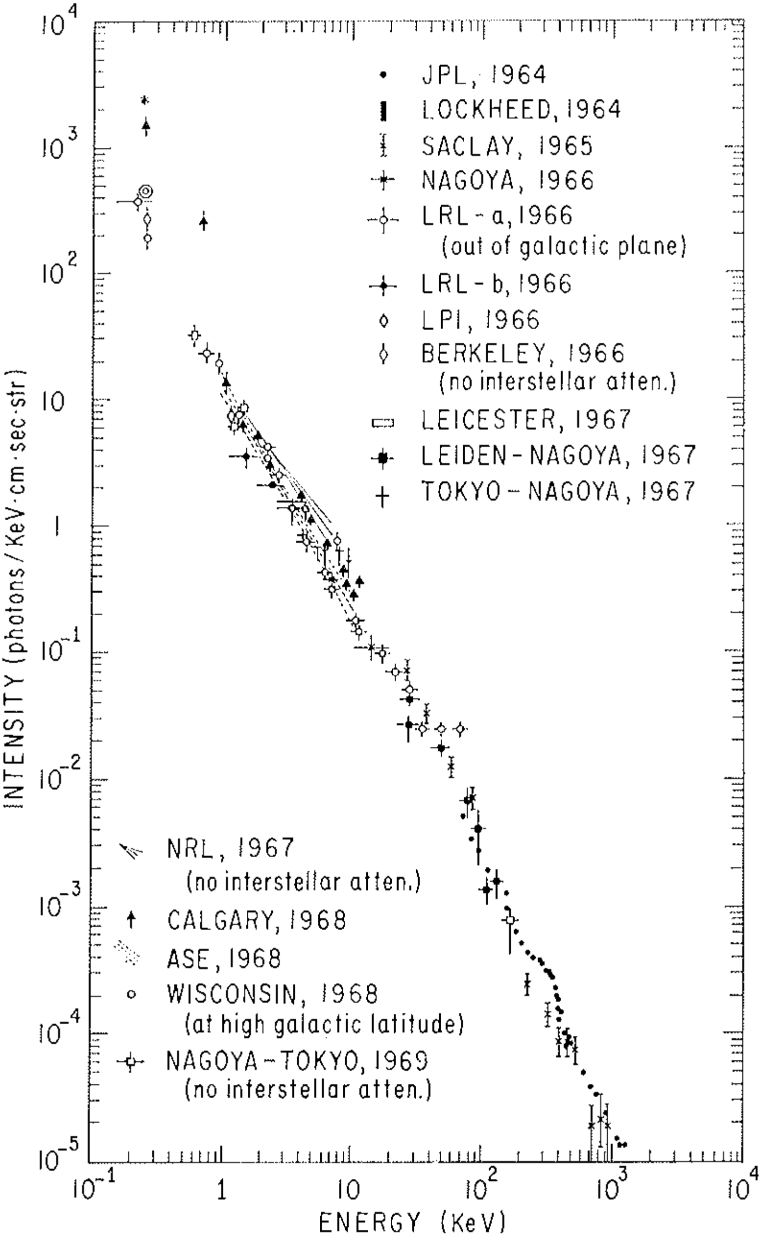

FIG. 1 — The diffuse x-ray background spectrum from 0.27 kev to 1000 kev (After ODA, ref. 7).

ev/cm^3; and the content of metagalactic optical photons is about 10^{-2} ev/cm^3. From an energetic standpoint, the x-ray content is small compared to the total output of galaxies at longer wavelengths, but is a thousand times greater than radio emission from all the extragalactic radio sources. If the background derives from relativistic electrons originating in galaxies, they must lose very little of their energy in generating radio waves and nearly all of it in producing x-rays.

In the following, I shall start with a discussion of evidence for x-ray emission from discrete sources and their possible contribution to the background. The paper will then deal with the Inverse Compton mechanism that may operate both within galaxies and in intergalactic space. Finally, we shall consider the question of the existence and origin of a very soft component, $E < 1$ kev, attributable to intergalactic bremsstrahlung.

THE GALAXY

As soon as it became known that the Galaxy contained a number of discrete x-ray sources detectable against an isotropic x-ray background, theoretical estimates were made to interpret the background as the sum of contributions from all normal galaxies. A simple summation over a sphere of Hubble radius, 10^{28} centimeters, with an average space density of galaxies, 10^{-75} per cm^3, provided only 1 to 10% of the required background [16]. In recent years, the number of sources detected within the Galaxy has risen to more than forty, and it is possible to make better estimates of the galactic x-ray luminosity. Some of these sources have been identified with known objects and information has been obtained on spectral shape, variability and space distribution within the Galaxy [17, 18]. Well known supernova remnants such as the Crab Nebula, Tycho Brahe SN 1572, and Cassiopeia A are powerful x-ray sources with luminosities of about 10^{36} to 10^{37} erg/sec. Sco

XR-1 and Cyg XR-2 are identified with blue star-like objects whose optical variations and radial velocities suggest binary pairs. There is a suggestion of a 4-hour periodicity in the spectral data from Sco XR-1. The x-ray spectra in some cases are best fitted to thermal bremsstrahlung ($T = 6 \times 10^6$ to 10^9 °K) and in other cases are better matched to power laws (spectral index of differential energy flux ~ 1). At x-ray energies lower than 2 kev, the influence of interstellar absorption is often evident and provides a clue to distance.

The distribution of galactic sources is concentrated toward the galactic plane and clusters in two longitudinal groupings, L_{II} 315-40 degrees and L_{II} 60-120 degrees [17]. The former group, which includes the direction of the galactic center, is concentrated to within ± 3.5 degrees of the plane of the Galaxy. If we assume that the sources are distributed in latitude like the general stellar distribution with a mean displacement of about 150 parsecs from the galactic plane, their average distance from earth would be roughly 2.5 kiloparsecs, about the distance of the Sagittarius arm of the Galaxy. The second group of sources in the direction of Cyg-Cas speads about ± 7 degrees from the galactic equator, and would appear to lie in the Cygnus-Orion arm at a distance of about 1.25 kiloparsecs. There are clear misfits within these two groupings, however, which show that the description of homogeneous groupings is only a crude approximation. If this analysis is pursued, it leads to the conclusion that most of the observed sources are in the two nearest galactic spiral arms, and that inverse square law attenuation puts more distant sources below the threshold of detectability with present instrumentation. The observed sources then represent a sampling of about two percent of the galactic disk. The full disk would contain 1000 to 1500 sources and the luminosity of the Galaxy would be about 10^{39} erg/sec.

More recent identifications have shown that at least two of the sources, Cas A and the Tycho Brahe Supernova, are well beyond the assumed maximum distance of 2.5 kiloparsecs. Furthermore, spectral measurement [19, 20, 21, 22] show that some sources suffer interstellar extinction at energies below 2 kev, which implies that they may be considerably more distant than the Sagittarius arm, or that they have gaseous envelopes. It is also significant that newer surveys have not filled in the gaps in the longitudinal distribution. If we assume that most of the sources observed toward the general direction of the galactic center are actually as far away as the galactic center and that these represent a large fraction of all the sources in the Galaxy (about 100 total), the individual sources must be several times more luminous. We then derive an estimate of the galactic luminosity nearly the same as that based on the model of a larger collection of weaker sources.

The x-ray flux for the large Magellanic cloud has been reported [23] to be a few times 10^{-9} erg/cm^2 sec but the measurement was marginal. The luminosity of the LMC, or at least its upper limit, is therefore about one-tenth that of our Galaxy, consistent with the ratio of the number of stars in the two galaxies.

If we compute the background radiation from the sum of all normal galaxies in the universe, we obtain about two orders of magnitude less than the observed background of 2×10^{-7} erg/cm^2/sec/ster. An attempt can be made to compensate for the deficiency by introducing evolutionary effects that provide for much higher x-ray luminosity in the past than at present, and thus greatly enhance the contribution at large redshifts. The basis for postulating such an evolution is a presumed analogy with the evolution of strong radio galaxies, but the observed limit of the extragalactic radio bacground contradicts the assumption that the radio powers of spiral galaxies evolve in the manner required for the x-ray powers.

Since normal galaxies appear to be inadequate to supply the x-ray background, we must explore the possibility that far more powerful discrete extragalactic sources contribute to the background. Any present estimates must be based largely on theoretical grounds since positive evidence of the existence of x-ray galaxies is limited to only one such source, M 87 (NGC 4486) and marginal evidence for x-rays from Centaurus A (NGC 5128). Borderline evidence also exists for x-rays from the quasar 3C 273. In the following, a description is given of the available x-ray evidence and some of the current ideas for emission mechanisms.

M 87

M 87 is the third brightest radio galaxy. Its x-ray emission was first detected in 1965 and several measurements have subsequently been made [24, 25, 26, 27, 28]. The radio galaxy can be characterized as a core-halo source. An extended optical jet emerges from the nucleus to a distance of 4000 light-years. The observed x-ray luminosity ranges between 10^{42} and 10^{43} erg/sec, which is one to two orders of magniture greater than the radio and optical luminosities (5×10^{41} erg/sec). Table I lists observations of x-ray flux from 1965-1969. All efforts to detect the source at $E > 20$ kev with balloon techniques have

TABLE I — *Observations of X-rays from M 87.*

Observer	Flux (erg/cm² · sec)	Energy Range (kev)
(24) NRL (1965)	$(2 \pm 1) \times 10^{-9}$	1 — 10
(25) NRL (1967)	$(8.7 \pm 2) \times 10^{-10}$	1 — 10
(26) MIT (1967)	$(5 \pm 2) \times 10^{-10}$	1.5 — 6
(27) Leicester (1968)	$(1.5 \pm 0.3) \times 10^{-9}$	1.5 — 5
(28) NRL (1969)	$(1.9 \pm 0.2) \times 10^{-10}$	0.8 — 4

provided only upper limits [29, 30]. Recent refinements in both optical [31] and radio resolution [32] have revealed that the jet is composed of several optically bright knots no more than a second of arc in diameter and that the radio core contains a compact source with a diameter of 2.5 light-months and a luminosity of 10^{39} erg/sec in a band of 10^{10} cycles at a frequency of 0.23×10^{10} Hz.

The earliest x-ray results at 1 to 10 kev could be fitted to a single power law spectrum with index —0.7 extending all the way from radio through optical to the x-ray wavelengths. This remarkable fit over more than nine decades of frequency suggested the possibility that synchrotron radiation, generated by relativistic electrons emerging from the core and traversing the jet, was responsible for the entire spectrum [31]. However, the lifetime of the electrons would be too short to cover the distance from the core to the end of the jet. To avoid the problems of electron lifetime, it was proposed that the relativistic electrons were generated within knots of the jet by proton collision processes of the $p \rightarrow \pi \rightarrow \mu \rightarrow e$ type [34]. This model suffers from difficulties in explaining the absence of gamma ray emission from π° decays [35]. The predicted gamma photon flux of $4 \cdot 10^{-10}/\mathrm{cm}^2 \cdot \mathrm{sec}$ is well above the observational upper limit of about $5 \cdot 10^{-11}/\mathrm{cm}^2$. It also requires a sufficiently high ambient gas density (about 700 per cc) to prevent disruption of the jet by internal cosmic ray pressure [36]. The spectral observations (Fig. 2) show no evidence of gaseous absorption at x-ray energies as low as 0.9 kev which sets an upper limit of less than $3 \cdot 10^{21}$ atoms per square centimeter column in the line of sight. Since the optical diameter of the brightest knot in the jet is about 36 pc, the x-ray spectrum imposes an upper limit of about 50 per cc on the density of neutral gas in the knot [27, 28].

The evidence for variability in Table I and Fig. 2 lends support to models which associate the emission with compact sources. BURBIDGE proposes [37] that the energy density of

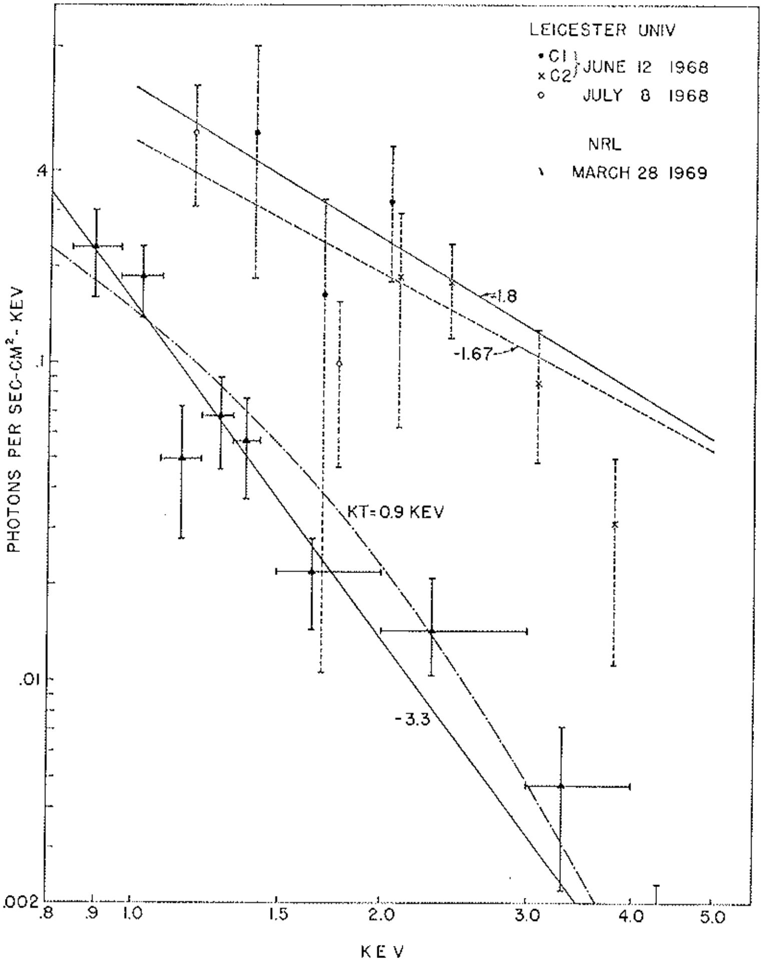

Fig. 2 — X-ray spectra of M 87. The upper spectra obtained in 1968 fit quite well with a straight extrapolation of the radio synchrotron spectrum. The 1969 spectrum is much steeper and is almost two orders of magnitude weaker at 4 kev.

radio photons and the energy content of relativistic electrons in the compact nuclear core may be sufficient to provide the observed x-ray emission by Compton scattering. He also suggests that the knots on the jet may be clusters of massive compact objects surrounded by magnetospheres, which are expelled from the nucleus. If these are pulsar-like stars, as many as 10^6 to 10^7 per optical knot would be required. Such models would predict that x-ray emission is to be expected from most galaxies with compact nuclei and evidence of the expulsion of massive objects. The symmetrical dumbbell-shaped radio double sources would not fit the requirement for x-ray emission and, in fact, Cyg A has not shown detectable x-rays [38] at a level comparable to M 87 even though its total radio flux is an order of magnitude greater. Recently, a condensation has been resolved within one of the radio plasmons of Cyg A. It will be interesting to search again for x-ray emission with improved detection sensitivity.

CENTAURUS A

The radio power of Centaurus A is about six times as great as Virgo A (M 87). A straight extrapolation of its spectrum to x-ray wavelengths would predict an order of magnitude greater x-ray flux than M 87. However, it appears to be a much weaker x-ray source.

Figure 3 shows the contours of radio brightness of Centaurus A. Two radio plasmons are symmetrically located within the optical galaxy, about 10,000 light-years on opposite sides of the galactic center. Further out are two broad radio emitting lobes with positions of peak intensities about 100,000 light-years from the galactic center. Because the radio galaxy is only about 10 megaparsecs distant, its angular spread in the sky is several degrees and it should be possible to separate x-ray emission originating in the lobes from that produced

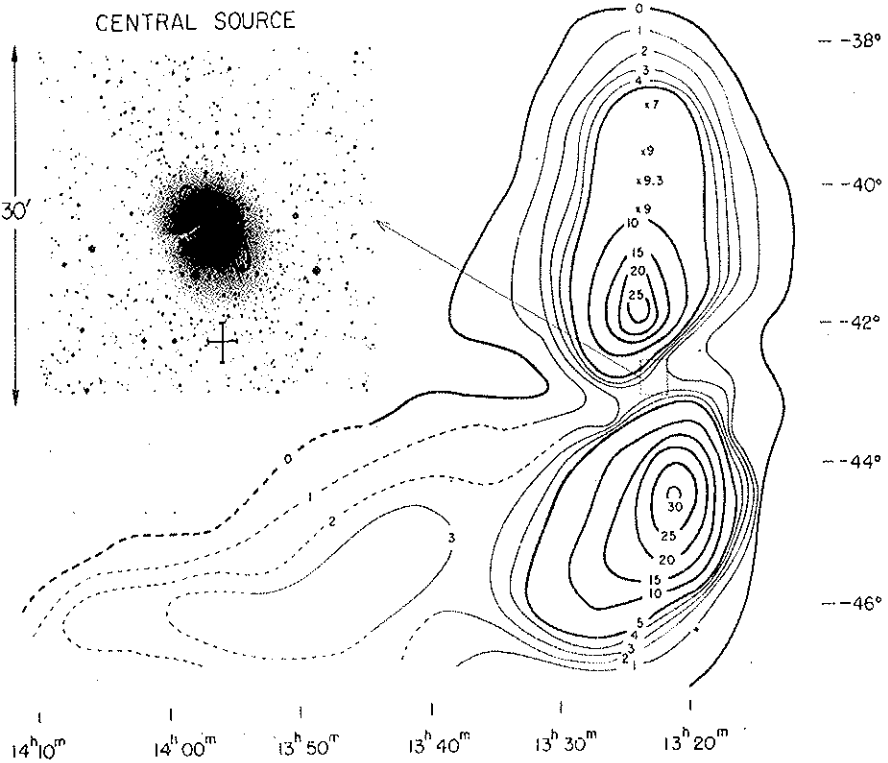

Fig. 3 — Contours of radio intensity of Centaurus A at 965 MHz (Bolton and Clark, 1960). The optical galaxy NGC 5128 is 14 minutes in diameter and contains a double radio source within it.

within the confines of the optical galaxy. In 1968 Byram, Chubb and Friedman (NRL) attempted a fan-beam scan of Centaurus A in the 1-10Å range with detectors carried aboard an Aerobee rocket [39]. The scan track ran from north to south through the radio lobes and the optical galaxy. Evidence for x-ray emission was marginal when analyzed with a spatial resolution of 0.1 degree. However, when the flux was summed over wider intervals, a 3 Σ detection was obtained for the interval covering the northern lobe up to the edge of the optical galaxy. The signal from the southern lobe was only 1.5 Σ. Background was taken to be the average over all of the scanned track from —37° to —50° declination.

The above result is significant, even if taken only as an upper limit. X-ray emission should be expected from the radio lobes as a result of Compton scattering of the 3°K background radiation by the relativistic electrons in the radio emitting region. If equipartition is assumed and all the particle energy is in relativistic electrons, the predicted flux according to SHKLOVSKY [40] should be about 10^{-10} erg/cm^2 sec. SETTI and WOLTJER [41] have computed a lower flux, $\sim 2 \times 10^{-11}$ erg/cm$^2 \cdot$ sec. The NRL observations of a 3 Σ signal in the northern lobe is equivalent to $\sim 3 \times 10^{-11}$ erg/cm$^2 \cdot$ sec (1-10 A). Accordingly, the observed x-ray flux of the equivalent upper limit is comparable to the lower theoretical estimate of the Compton flux with a 3-degree background. If the background were as high as 8 degrees, the flux would be two orders of magnitude greater, which is clearly ruled out by the x-ray observation.

Based on the evidence of Cen A, we can conclude that the background contribution from the extended plasmon type of radio galaxies is negligible. Such galaxies, which radiate $> 10^{42}$ erg/sec have a space density of about 10^{-6}/Mpc^3. The x-ray power would need to be about a thousand times greater than the radio power.

QUASARS

In 1967 a scan was made [25] of the position of the quasar 3C 273. Some evidence was obtained of detectable x-ray flux at a level of $\sim 2 \times 10^{-10}$ erg/cm$^2 \cdot$ sec (1-10 kev), but the statistical measure of the signal was no more than 2 Σ. If taken as an upper limit, the measurement required that the x-ray power not exceed 7 × 10^{45} erg/sec. A simple extrapolation of the —0.7 radio-optical spectral index to the x-ray range would predict a flux of about five times the limit of the 1967 observation.

A second attempt to detect x-rays from 3C 273 was made by the NRL group in 1969 with the results shown in Fig. 4. If background is taken to be the average over the entire 20-degree scan track from —2° to + 24° declination (with the M 87 counts removed), the signal at the position of 3C 273 was 3 Σ_{bgd}. The spectral range was 1-4.5 kev and the flux was 6 × 10^{-11} erg/cm^2 sec, about one-fifth of M 87. The corresponding x-ray power is ∾ 2 × 10^{45} erg/sec. REES and SETTI [42] have pointed out that if all quasars emitted x-rays like 3C 273, we would need 10^{-6} per cubic megaparsec to provide the diffuse x-ray background. But the local space density of objects like 3C 273 is only about 10^{-9} Mpc^{-3}, according to SCHMIDT [42].

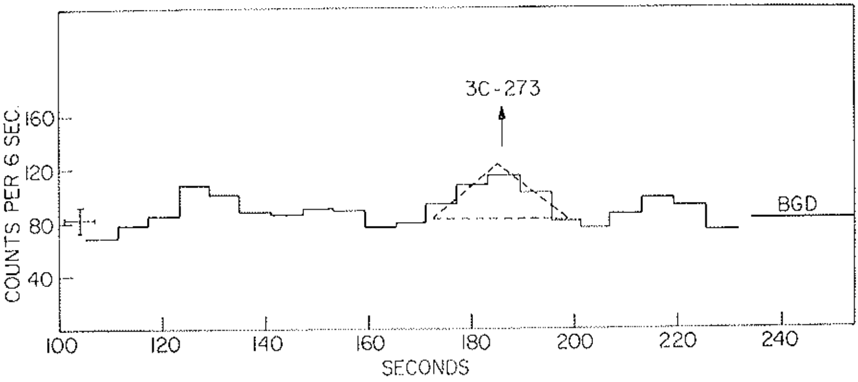

FIG. 4 — Counts observed during 1969 scan through 3C 273 (Naval Research Laboratory).

SEYFERT GALAXIES

It is evident from Fig. 2 that the lower spectrum of M 87 can be approximated about as well by a thermal distribution as by a power law. Thermal models for x-ray galaxies have been proposed by several authors [43, 33, 44, 45]. In general, these models relate x-ray emission to radio sources. SARTORI and MORRISON, for example, suggest that the explosion which gives rise to the relativistic gas responsible for nonthermal radio emission is also the source of a dilute hot plasma capable of radiating an intense flux of bremsstrahlung. The explosion process is presumed to transform an appreciable amount of the available energy into kinetic energy of bulk gas motion, magnetic fields and hydromagnetic waves. By some form of FERMI process, electrons may be accelerated to relativistic energies, but the process would also lead to the growth of hot plasma. SARTORI and MORRISON conclude that perhaps one hundred times as much energy can go into hot plasma as into relativistic electrons, whereas GINZBURG estimates more nearly equal proportions.

Thermal x-ray emission has also been proposed for Seyfert galaxies. In support of these suggestions is the evidence of large Doppler motions, 500-4000 km per second, flare-like ejection of gas from the nuclear regions and radio emission presumably associated with relativistic electrons. Predicted x-ray fluxes are comparable to that observed from M 87, but coarse scans of the sky have thus far not revealed any x-ray emission associated with Seyferts at a level comparable to the flux from M 87. TUCKER and TARTER [46] calculated the thermal emission to be expected from NGC 1068 and derived a luminosity of 10^{43} erg/sec in the 1.5 to 6 kev range. The expected flux at earth would be 6×10^{-10} erg/cm^2 sec, which is about half the detectability limit obtained in coarse general sky surveys through the region of NGC 1068.

The discovery of intense infrared radiation from the nuclei of Seyfert galaxies suggests that Compton scattering within the nucleus could be a major source of x-ray emission. LONGAIR and SUNYAEV [47] have developed a model incorporating two main stages in the dissipation of relativistic electron energy. Roughly equal amounts of energy are lost within the galactic nucleus to produce hard x-rays and by electrons escaping into intergalactic space to produce the softer x-rays. They adjust the parameters of the nucleus so that a break appears in the theoretical spectrum at 40 kev. The magnetic field in the nuclear region must not exceed 10^{-6} gauss and the electrons must escape in 10^5 to 10^6 years to keep the radio background at 178 MHz below 1° K. If the x-ray background is the integral of emission from a random superposition of discrete sources in Seyfert galaxies, a lower limit of 5 percent is predicted for the expected fluctuations in the hard x-ray spectrum on a scale of one degree.

PULSARS

The discovery of x-ray emission from the Crab Nebula has led to speculation that pulsars may make an important contribution to the diffuse background. In the spectral range, 1 to 10 kev, the Crab pulsar radiates 10^{36} erg/sec. This power is about 10 times the optical luminosity and about 1000 times the radio luminosity. APPARAO [47a] proposes that a new pulsar may have as much as 10^{52} ergs of rotational kinetic energy. If the efficiency of conversion of rotational energy to x-ray emission is of the order of one percent, 10^{50} ergs would be radiated in the lifetime of the pulsar. At the rate of one supernova per hundred years per galaxy, pulsars would suffice to give the observed diffuse background of about 10^{-7} erg/ /cm^2 • sec • ster. The estimate of the initial energy of rotation is very uncertain, however. GUNN and OSTRIKER [48] prescribe an initial rotation rate of about 1600 Hz, which is about the maximum for a neutron star. This gives an initial kinetic energy of about 1.5×10^{53} ergs and they suggest that 5×10^{51} ergs could be released in electromagnetic modes. On the other hand, WOLTJER [49] concludes that the extrapolation of the rotation rate of a pulsar, back to the time of formation of the Crab Nebula, gives a frequency of 65 Hz and a rotational energy of the order of 5×10^{49} ergs.

INTERGALACTIC PROCESSES

FELTEN and MORRISON [50] first attempted to explain the x-ray background in terms of Compton scattering of cosmic ray electrons on the background of starlight photons. The computed flux was insufficient by several orders of magnitude, even if the locally observed cosmic ray flux was taken to be universal. With the discovery of the 2.7° K black-body radiation, the number of available low energy photons was increased a thousandfold. The black-body photons have energies of the order of 10^{-3} ev; when scattered by electrons of Lorentz factor, $\gamma = \frac{E}{mc^2}$ the energy of the photons is raised by a factor of γ^2. To produce x-rays from 1 kev to 1 Mev, γ must range from 10^3 to $10^{4.5}$.

The cosmic ray electron distribution observed near earth has a power law spectrum with an energy index of —2.6 for the range 3 Gev to 300 Gev. At lower energies down to 0.3 Gev, the spectrum flattens to an index of —1.6. These electrons produce galactic radio synchrotron radiation and the majority of normal galaxies are known to have spectra similar to our galaxy. The break in the electron energy spectrum between 2 Gev and 5 Gev is consistent with the bend observed between 200 and 1200 MHz for most radio galaxies. A break in the electron spectrum must be reflected in the x-ray spectrum, which is generated by Compton scattering on the 2.7° K background. The computed position of the x-ray spectral bend is approximately 40 kev, which fits quite well with the observations. However, this apparently satisfying agreement is much too simple a picture to fit with other requirements.

If the x-ray background is produced by cosmic ray electrons which are confined to the galaxy, we can estimate the accompanying galactic radio synchrotron emission. The result is dependent on the magnetic field strength. The available evidence for the galactic magnetic field indicates a lower limit of about 10^{-6} gauss and the number of electrons required to produce the radio background in this field would yield an x-ray background less than one percent of that observed [42].

A number of theorists (Felten and Morrison [50], Brecher and Morrison [51], Bergamini et al. [52], Rees and Setti [42], Longair [53], Felten and Rees [54]) have sought to attribute the background > 1 kev to relativistic electrons leaking out of radio sources and Compton scattering on the intergalactic gas. The parameters of the galactic medium and the leakage process can be adjusted so that a spectral break appears in approximately the correct range, but considerable difficulties remain. To obtain the required energy density of background radiation, evolution must be included so that contributions are derived from sources in remote epochs. Such processes, operating at large red-shifts, are enhanced by the evolution of both radio sources and the black-body radiation, which was more dense in the earlier epochs. A model by Rees and Setti assigns the origin of most of the flux to red-shifts of 4 to 5.

Soft X-rays ($E < 1$ kev)

During the past two years considerable attention has been paid to the very soft end of the x-ray background spectrum, between 0.1 and 1 kev. Bowyer, Field and Mack, (BFM) [9], observed a flux at 1/4 kev which they interpreted as a simple extension of the background spectrum observed at higher energies from 2 to 10 kev. HENRY *et al.* (NRL) [10] observed a somewhat higher flux at 1/4 kev and also found that the spectrum from 1 to 10 kev was significantly flatter than at E > 10 kev. They concluded that an extrapolation of the spectrum from 1 to 10 kev fell considerably below the observed flux of 1/4 kev, and interpreted the soft radiations as bremsstrahlung from hot intergalactic gas rather than Inverse Compton scattering. Using the hydrogen concentration derived from 21 - cm observations toward the direction of the galactic pole, the NRL group applied an absorption correction of 4.6 to the observational point at 0.27 kev, and concluded that the observed flux could be produced by a hot intergalactic gas at a temperature $(3-8) \times 10^5$ °K and a gas density of about $10^{-5}/\text{cm}^3$. Great interest attaches to the validity of this conclusion because, if correct, it would be the first direct evidence in support of the existence of sufficient mass of intergalactic gas to close the universe. It was recognized that an alternative explanation would be to attribute the higher density to gas within clusters of galaxies. If, for example, the cluster gas density were $10^{-4}/\text{cm}^3$, the universal average would need to be only $10^{-6}/\text{cm}^3$ in order to produce the observed background emission. Some evidence is available that the x-ray flux from the Coma cluster does not exceed the surrounding background, but it is also known that the Coma cluster is particularly free of intergalactic gas.

Subsequent measurements have not provided an unequivocal answer to the question of the existence of a soft x-ray flux in excess of that expected from a straightforward extrapolation of the higher energy spectrum derived from Compton scattering. BUNNER *et al.* [15] obtained a flux at 0.27 kev within 20% of that reported by BFM. On the other hand, BAXTER *et al.* (1969) [11] find the flux even higher than that observed by the NRL group.

The magnitude of interstellar absorption is a crucial factor in interpreting the true extragalactic soft x-ray flux. BFM found that the background flux decreased less rapidly with galactic latitude than required by the 21-cm hydrogen data. Their results could be explained by a very low helium-to-hydrogen ratio (about 0.03). If the helium-to-hydrogen ratio were the normal 10%, they would require a hydrogen density only one-third of that derived from 21-cm observations. They, therefore, proposed a cloud model for the interstellar hydrogen; a given amount of hydrogen collected in clouds would give less x-ray absorption than a smooth distribution. However, for the effect to be as great as required by BFM, more than 60% of the neutral hydrogen must be clumped in large clouds. These clouds would need to be about 25 parsecs in diameter so that at distances within the galactic disk, they would subtend angles greater than the beam width of the x-ray detectors which were used for the observations.

It was suggested by the NRL group that the galactic latitude effect may be compensated by contributions from discrete soft x-ray sources within the galaxy. Only two such sources have been detected thus far in discrete source surveys, but the observations have been few and have been limited to small regions of the sky.

Shklovsky [55] has proposed that the soft x-ray background comes largely from O VII and O VIII ($\lambda = 21.7$ and 18.9 Å) originating in nebular remnants of type II supernovae. Heiles [56] had earlier shown that much of the kinetic energy of the expanding envelope is converted to such line emission. By introducing an evolutionary contribution corresponding to $z \backsimeq 1.5$, the 20Å emission lines are shifted to the 50Å region and the predicted flux is close to that observed.

Sunyaev [57] claims that the soft x-ray bremsstrahlung curve derived by Weyman and which was adopted to explain the NRL observations at 0.27 kev provides sufficient ultraviolet to ionize hydrogen in the peripheral regions of galaxies.

This would be inconsistent with observations of H I in the outer parts of M 31. SUNYAEV required an upper limit to the intergalactic ultraviolet flux of 10^{-23} erg/cm^2 • sec • Hz • ster. BUNNER *et al* claimed that their soft x-ray measurements could be fit by a higher temperature, $\sim 3 \times 10^6$ °K and a lower intergalactic density ($\sim 10^{-6}$/cm^3), which would be sufficient to reduce the ultraviolet flux below SUNYAEV'S critical limit.

EXTRAGALACTIC ABSORPTION

All of the estimates of diffuse background radiation require strong contributions from sources at distances out to the Hubble radius. With an intergalactic gas density of 10^{-5}/cm^3 and a path length of 10^{-28} cm, the column density of hydrogen is 10^{23}/cm^2. For the optical depth to be < 1, the intergalactic hydrogen must be at least 99% ionized and helium must be doubly ionized. A temperature greater than 10^5 degrees would provide this degree of ionization.

An interesting conclusion can be derived about the abundance of elements heavier than helium in the intergalactic gas [58]. If the temperature were less than 10^6 degrees, the degree of ionization would not include the innershell electrons and optical depth unity would be reached only at energies less than 4 kev. This would introduce no difficulties for the harder x-ray background but does set restrictions on the cosmological interpretation of a softer x-ray background. For the universe to have less than unity optical depth at 0.27 kev, the cosmic abundances of intergalactic CNO would need to be less than two percent of the normal cosmic abundances. Although it would not be expected that the abundances of heavy elements would approach the normal values in intergalactic space, it is still significant that the abundance can be set so low by the observation of the soft x-ray background, for it limits the contamination of intergalactic space by ejecta from explosive events within galaxies during the evolution of the universe.

CONCLUSION

It is difficult to single out any hypothesis for the x-ray background as being clearly preferred. Perhaps all of the discrete source and diffuse mechanisms discussed here play a significant role, but in the absence of more observational data no clear assessments are possible. Particularly desirable would be improved observations of the shape of the high energy spectrum and the position of spectral breaks. At the other extreme of the spectrum, $E < 1$ kev, higher spacial resolution is necessary to clarify the relationship to hydrogen cloud structure, local soft x-ray sources and diffuse processes within the disk. Higher resolution is needed to establish the degree of isotropy at all energies. With evidence of x-ray emission being available only for M 87, 3C 273 and Cen A, our knowledge of discrete extragalactic x-ray sources is very limited. Theory predicts detectability of numerous other objects with one or two orders of magnitude improvement in sensitivity. Such advances in observational power are clearly possible and may materialize in the next few years.

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DISCUSSION

Chairman: G.R. Burbidge

Kellermann

What is the potential for extending the measurements to higher energies in objects like M 87 in the near future?

Friedman

To higher energies?

Kellermann

Yes, and to get more spectral detail.

Friedman

The prospects are good in both respects. There will be a major advance in the observations when a NASA small astronomical satellite for x-ray astronomy is launched at the end of this year. Instead of looking for 3 minutes per rocket flight, this will have a lifetime of hopefully half a year to a year, and it will cover a range from about 1 kev to about 20 kev. It will not extend our spectral information very far, but it will certainly sharpen up the shape of the spectrum, and will give us sources to much lower flux levels, probably another 2 orders of magnitude below the limits I have shown here for rocket observations. NASA is also asking for proposals now on what will be a very large payload high energy astronomy observatory, which is planned to be a Titan III C launch with a capability of about 20,000-25,000 pounds of payload. We would like for it to carry an x-ray detector with an area of the order of 100 sq.ft. covering the range from about 0.1 kev up to about 100 kev. At the same time it could carry a large gamma ray spark chamber with about a square meter aperture, and various other instruments for high energy astronomy. And that would perhaps add another two decades of flux range.

WOLTJER

I noticed on your record of 3C 273 that there were 2 major bumps. Are these coincident with the earlier results?

FRIEDMAN

The one at the beginning of the slide is not significant. The rocket was manoeuvering at that point and it lumped together a great area of sky previous to the start of the controlled scan. The second bump coincides with one which we have seen in an earlier flight, but I don't believe that we can attach much significance to it. We used the cross collimators on this second flight and the source would have to be right on the scan line to correspond to the earlier position measurement. We can only say that it is not inconsistent with earlier results.

LOW

How does the flux that you reported here compare with the flux in the original detection of 3C 273?

FRIEDMAN

It is about 1/3 of the value we claimed in the earlier measurement. That is within the range of statistics, so that we would not claim that there is any strong evidence for a decrease in luminosity in that time period.

AMBARTSUMIAN

Would you speak about the background radiation? What is the lowest power we can say that it is continuous background with such and such approximation?

FRIEDMAN

The observations have mostly been made with very large fields of view, of the order of 50 to 100 sq degrees. Any of the models which build up the background from discrete sources would show inhomogeneities on a much finer scale. For example, LONGAIR and SUNYAEV suggest that, if all of the background were built up from Seyfert galaxies, there would be a lower limit to the fluctuations of the order of 5 per cent per sq degree. None of the measurements have yet been made with such a small field of view.

OORT

You mention the objection that SUNYAEV made to the large density of the intergalactic gas. This may not be so serious as it seemed, because the interstellar gas in the outer regions of the galaxies may be partly concentrated in clouds, in which case the gas density will be higher and the influence of the x-ray flux from the universe will be less. The limits he derived can then be eased somewhat.

G. R. BURBIDGE

FELTEN and BERGERON have pointed out that there are ways around this. At the same time I do not think that you have to deduce from these results that the density of the hot gas is the critical density. The mean density might well be considerably less than 10^{-29} gm/cm^3, and the observations could still be explained.

FRIEDMAN

Yes, there is a possibility that we observe clusters of galaxies in which case you could have a density of 10^{-4} in a cluster and an average density of 10^{-6}. We have a rather poor observation, a scan across the Coma cluster, which doesn't show any increment over the surrounding background.

I should mention one other observation which is important for the question of the amount of interstellar hydrogen. Estimates in the past have been based on the Crab nebula, whose distance we know. The absence of any appreciable absorption at 1 Kev sets an upper limit of the order of about .3 particles per cc. We have pushed the measurement now to 0.7 Kev, about 18 Angströms, and there we get a measurable absorption so that a precise answer of .3 atoms per cc is obtained.

WOLTJER

Dr. SETTI and I have made an attempt to estimate upper limits on the x-ray luminosities of the optically selected quasi-stellar objects from the condition that the integrated effect of all quasi-stellar objects that have been counted should not exceed the background. Probably the simplest way to present these results is in terms of the mean spectral index between the optical and the x-ray wavelengths. If one only takes the blue objects that have been counted by BRACCESI down to $19^{m}.4$, the mean spectral index cannot be less than 1.0. If one takes SCHMIDT's extrapolation to the 23rd magnitude the limit becomes 1.3, and if one takes a local theory of quasi-stellars the limit becomes about 1.8. It is clear, therefore, that the spectra of the quasi-stellar objects must steepen considerably towards the x-ray wavelengths.

FRIEDMAN

I think the flux which we bave quoted here for 3C 273 is consistent with that picture, that it is well below the straight line extrapolation of the long wavelength radio spectrum, probably by an order of magnitude.

OORT

You mentioned observations of the Coma cluster, but the Coma cluster may not contain very much gas; I think the Virgo cluster would be a more interesting object.

TWO DIFFUSE BACKGROUND RADIATION FIELDS

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Two broad spectral ranges display a diffuse background radiation. By that we mean a radiation flux which simply does not vary perceptibly in time or in direction, whether over years and steradians or over very small cones like starlight. Let us summarize the situation:

Background	Measured Range of Photon Energy	Mean Energy Density	Spectrum
x-ray	1/2 keV — 100 MeV	100 to 200 micro-electron volts/cc	power-law decrease
microwave	20 cm to half-millimeter wavelength (ca 0.1 — 1 milli-eV)	$\leq$ 0.5 eV/cc (extrapolated)	Rayleigh-Jeans to $\backsim$ 1 mm; falls thereafter
starlight (for reference)	2 — 5 eV	1 eV/cc in galaxy; about 10^{-2} eV/cc over all space	$\backsim 10^4$ K black body

We shall treat the two distinct regions separately.

I. *The x-ray background*

It is all but sure that there is a background of x-rays which is non-thermal in origin, which arises at distances beyond the galaxy, and which extends from the helium K-edge, above which large-scale transparency first sets in, up to the region of 100 MeV, where we must find the decay gamma rays from decay of cosmic-ray secondary neutral pions. The arguments one needs are two:

1. There is no angular variation to disclose the limited extent of the source, as any dependence on the ecliptic or the galactic plane, or on the solar direction, would imply. This is true with modest accuracy, but to better than a few percent at least, for broad beam-widths of tens of degrees.

2. There is no important absorber which could form a diffuse local source. This is surely true within the Galaxy, for we see distant galactic x-ray sources without visible strong absorption in the keV region, and outside the Galaxy we have little chance of enough mass lying close enough. The direct argument also applies to extragalactic sources, in view of Dr. FRIEDMAN's report, but less sharply.

Once these points are granted, and they are rather secure, it follows that the x-ray background must originate in a volume of space large enough to contain very many galaxies. Hence it is of interest in cosmology.

The spectrum has been studied very extensively. Broadly speaking, the photon flux per unit energy varies like $1/E^n$ from about a half keV up to an MeV. The index n seems likely to change, showing a steepening by about one-half to one unit, from near 1 to say near 2 (of course the log-log straight line is only approximate) somewhere at a few tens of keV. There is good if not certain evidence that above a few MeV there is a small region of flattening again, and that the curve falls off more or less sharply somewhere between a few MeV and a hundred MeV, where at least an upper limit is known. These details are not better than probable.

The power-law spectrum has long been used to connect the x-rays with the cosmic-ray electron energy spectrum. One mechanism which might do this is the inverse Compton scattering of fast electrons on the overall isotropic background of the supposed three-degree thermal radiation which fills space. That background – thus strongly connected with the x-ray observations in a somewhat surprising way – is the topic of the latter half of this account. Suffice it to say here that this scheme gives a plausible fit to the shape of the spectrum over the range from below 1 keV up to a few MeV at least, but it does not directly give an adequate energy density in x-rays. To do this it is either necessary to postulate an electron density in space outside the galaxies larger by a factor of some ten to thirty than one might naively expect, or to increase the CR output of the average galaxy by the same factor. It will not do merely to increase the thermal photon density because that will reduce the CR electron lifetime, if galactic magnetic fields are as we expect from radio astronomy. The whole topic is beset with uncertainty: since only a normalizing factor is needed, it seems a little artificial to elaborate theories of this kind which introduce one nnverified number to explain one fact. This is the somewhat negative conclusion which seems to me best at this time, following the critical review of BRECHER and BURBIDGE. Many explanations may be possible; none is clear.

Another tack would be to give up the whole idea of CR electrons colliding with the thermal photon background in extragalactic space as an origin mechanism. One alternative is to place a large CR burst back in the past, and reduce the energies by a large red-shift. This is plainly still more *ad hoc,* though not logically excluded. Another is to seek some source of electrons in the energy range of the x-ray photons themselves, radiating by bremsstrahlung and not by the indirect photon collisions with thermal photons. Many possible sources exist in various explosive phenomena, either within galaxies or even outside. The total energy is not large, much less than starlight, so the task is not hopeless.

One must conclude that we have no really satisfying theory of the x-ray background, but rather several possibilities, none of which can yet be verified nor excluded. There may be important surprises for cosmology in any such problematic issue, but it seems that now we need to think of new experiments which might cut more sharply. The high degree of isotropy claimed from recent satellite data gives another constraint on the theories.

The discrete x-ray sources in distant galaxies are of great interest for themselves, in that they indicate the presence of strong electron energy gain processes in such objects. They probably cannot sum to the overall background.

Finally, below 1/2 keV photon energy, the gas of space is an important absorber on a galactic scale. Studies here are thus difficult to interpret as extragalactic background, for isotropy is lost. Yet it is in this range that a possible ionized gas between the galaxies could make it itself known by thermal thin-source emission. The experiments so far are too fragmentary in angle and energy discrimination to give unambiguous results either way, though claims have been made from time to time. Here is a fruitful, if difficult, domain for the near future.

II. *The so-called thermal or microwave background*

The radio-frequency flux (watts per cycle) decreases rapidly with increasing frequency, if we look apart from discrete sources, say towards the galactic pole, until about 20 centimeters. From there shortward a rising background is to be found. By the time 5 centimeters is reached, there is clear evidence for an astonishingly strong and isotropic radiation flux, following the Rayleigh-Jeans law, $I(\nu) \sim \nu^2$ from perhaps

20 (or even 50) cm (at such long wavelengths a subtraction of the low-frequency background, which falls with decreasing wavelength, is a serious source of error) up to around 0.8 cm, with one point even at 0.3 cm. The (frequency)^2 law is quantitative – say the exponent is 2 ± 0.1 – over this substantial frequency domain. Above that frequency, ground-based measurements are not possible.

The ground-based measures reveal an energy density of radiation of perhaps 0.1 ev/cc. This is so large compared to all known sources, and the isotropy is so good (better than 1/300 over large angles, and in high angular harmonics, at least ten times better still), and the Rayleigh-Jeans limit is so well fitted by a black body at 2.7 K, with a temperature error of less than 0.2 or 0.3 K, that it is very tempting to regard this background as the black-body radiation predicted in a hot big-bang cosmology. It predicts about that intensity, originating in the early epoch when photons in thermal equilibrium dominated the overall energy density. They then were Doppler-shifted by expansion, ever since the matter became thin to such radiation (after the recombination of hydrogen at some 3 or 4 $\times$ 10^3 K) with a red-shift of about 1,000 or more. These photons thus go back to a time far before galaxy origins. The argument is seductive – I believe it – but is so final that we must move with caution.

Note that most of the energy predicted has not yet been observed. The black body peak occurs beyond the ground-based observational limit, at about 1.5 mm wavelength. What do we know about the peak of the expected Planck curve?

One unexpected set of results is a measurement of the flux at one or a few narrow line positions within the millimeter region. This is done by looking for the excited rotationally-split states of the electronic absorption long known in intersellar CN radical (first seen in 1939!). Using a half-dozen near bright stars, P. THADDEUS and co-workers have done the latest work. They easily see absorption by the first excited rotational state of the lower electronic state of CN. Its intensity ratio to the main transition gives a temperature very close to 2.7 K, with perhaps 0.1 K error. This refers to one specific wavelength, of course, about 1.2 mm. The agreement is excellent, and the frequency sampled satisfyingly near the peak. The second state, and a few states in other radicals, like CH, give at least upper limits, which demonstrate that the Rayleigh-Jeans rise cannot continue shortward of say 1 millimeter. All this is grist to the black-body mill. But it ought to be recalled that we do not very well understand the excitation of interstellar molecules. There are certainly negative temperature effects in some OH lines, for example. While it is satisfying that agreement is obtained for thermal equilibrium with the presumed immersing Planck radiation, it cannot be denied that some additional excitation might be present. One would expect such effects, say, collisional, to increase the temperature. This would give the interstellar value the force of an upper limit. Since one gets instead a direct agreement, and, moreover, agreement for several stars in different galactic regions (none very far away to be sure), the matter seems simpler than we might expect. We are lucky, it appears, but we ought not to rest a key argument on such a fortunate outcome.

The task which remains is clear: we need observations from beyond the atmosphere, looking for the peak and the high-frequency fall-off of the Planck radiation shortward of a millimeter or two. It is not much use to do this through the water, CO_2, O_3 and O_2 lines from the lower atmosphere.

Two distinct experiments above the atmosphere have been done. Both used liquid-helium cooled semi-conductor bolometers, with wideband response in the region from under 1 mm to a couple of tenths. The rocket group (which has made two consistent flights) report a much higher radiation flux, amounting if thermal to about 8 K temperature, which is in contradiction with the limits set by the interstellar absorption lines. The other group, which has made one flight to high balloon altitudes, has a set of three high-pass filter measures. They report a similar high flux, but their data would fit no black body curve.

All of these high-altitude experiments are very difficult. The phenomena can all be saved if one imagines that there are strong lines in the deep I.R. which miss the molecular states, but do record in the wide-band instruments. One ingenious effort has been made by WAGONER to examine the cosmological consequences of a strong galactic I.R. line which would fit the sub-millimeter measurements, and would, by the effects of red shift on the assumed (unknown) universal cause of such a line in all galaxies, simulate the Rayleigh-Jeans long-wave observations in the microwave. It seems a bit difficult to gain the isotropy needed - which would imply looking very far away - and to do without severe evolutionary effects, which ought to show up in the long wave region, where the data seem very simply Rayleigh-Jeans. The simplest solution - to which I tentatively adhere - is to deny the high-altitude experiments. They are most important, and beg for careful replication. Ground reflection from metal parts viewed by the balloon detector seems possible, for example.

Indirect arguments exist against an eight-degree black body. The large photon density implied would affect CR particles, and produce secondary gamma rays and x-rays by Compton recoil, probably in excess of what is seen, for example, in our galaxy and maybe in some strong radio galaxies. But any strong deviations from the single 3K black-body curve would certainly rule out the simple cosmological big-bang explanation even if they fall far short of being an 8 K thermal radiation. Isotropy, too, can be too good. One must expect eventually to see the effect of the sun's galactic orbital velocity. The final decision rests with the experimenters. For the present, unless you weigh as definitive the balloon and rocket results, the simple 3 K picture fits all the other lines of argument, and has the impressive merit of simplicity and *a priori* prediction. Those merits, it should be plain to all, fall short of proof.

This has been a brief pedagogical exposition to raise the issues involved in this record in a preliminary way. The literature is already large. I cite here a very few references of critical sort which would guide the reader to the whole discussion.

For the x-rays:

A brief critical review, with a fine bibliography, is the paper by BRECHER, K., and BURBIDGE, G.R., 1970, *Comments on Astrophysics and Space Science, 2,* 75.

For the thermal background:

The best effort at an alternate theory serves as a good review of data and the arguments:

WAGONER, ROBERT V. 1969, *Nature, 244,* 481.

The latest balloon data are given in:

MUEHLNER, D., and WEISS, R. 1970, *Phys. Rev. Letters 24,* 742.

DISCUSSION

Chairman: G.R. BURBIDGE

HOYLE

I don't want to enter into a discussion on whether the balloon and rocket values are correct, because presumably this will be settled fairly soon by repetition of the work. But I think considerable care was taken in the balloon work. The radiometer was suspended 2,000 ft. below the balloon. The direction in which the axis of the horn could point varied from 5° to 27° to the zenith. I would have thought at 27° everything was clear of the balloon — of course there could be side lobes, but the statement is made that, when the zenith angle varied from 5° to 27°, no change of signal was found.

MORRISON

I don't want to say these are not special measurements of course. At MIT I do know them in some detail. It was an excellent experiment, but I will say that one reason that he was going to drop that thing another 500 feet was that I argued that if he didn't do that I'd never believe he wasn't looking partly at the outgassing balloon. He agreed he could not show me that he was not doing that and for that reason decided to drop it another 500 feet. I thought that was a good test; so I believe you have to say this is still really a rather incomplete experiment. But it took a lot of hard work. Certain metal pieces may have been reflecting the ground in a frequency - dependent way. We have only to wait for another couple of experiments.

FOWLER

After 25 years of ground-based experimentation I've learned to be very skeptical of ground-based experiments. I think that as long as we're being critical, as we must be, of the balloon and rocket-borne experiments we should also be critical of the ground-based experiments and along these lines I should like to show a slide: This was first pointed out I believe by Dr. PHILLIP SOLOMON. I call your attention to the point which is taken to indicate that the curve is falling away from the Rayleigh-Jeans law and that a very small uncertainty has been assigned to this point. If you look at the actual paper you will find that there were nine observations which are shown on this second slide. These individual observations show a very wide spread from well over the average to a negative value. The experimenters have treated these observations as Gaussian in distribution and deduced a very small standard deviation. I submit that these data cannot be treated in this way and that it does not indicate a real deviation from the Rayleigh-Jeans law and, of course, no confirmation either.

SPITZER

I would like to point out a possible experimental problem with the balloon flight. Under some thermal conditions air next to the ballooon can be cooled by conduction to the cold upper surface of the balloon and then sink vertically downwards, carrying with it material which has evaporated from the balloon. Under such conditions, no amount of additional cable will help in the slightest.

(At this point there followed a technical discussion between Drs. LOW, G. BURBIDGE and HOYLE concerning the details of the measurements made by MUEHLNER and WEISS of the background, protted on a slide prepared by Dr. G. BURBIDGE and shown by Dr. MORRISON).

McCrea

There are two lines of evidence on this that could be mentioned and I would be very interested to hear what Dr. Morrison has to say about them. One is the possible cosmic ray cutoff at about 10^{21} electron volts. I imagine that if you put up the background radiation to something like 8°, this cutoff would be brought down considerably. Another line is about the Wagoner-Fowler-Hoyle calculations on the big bang. This seems rather good evidence for a background of about the order of 3°. It could be interesting to hear what Fowler and Hoyle would now say about this.

Morrison

Well, of course it is just that possibility, the cutoff, or the possible change of the composition from some heavy particles to protons only in the higher energy cosmic rays that I was referring to. If you look at the data not to get the best fit, but with a view to what we can really be sure of, how far they could reasonably be wrong in the experimental claims, then I don't think you can say that 8° could not be allowed. I believe it could be allowed. I think that we are just squeaking on the edge. If they had gotten 10° I would have felt it contradicted so much of cosmic ray work that it can hardly be right. But at 8°, while at first examination you see a contradiction you can say "Well how do we know the energy of the rays that come down, etc?". By squeezing everything you can just about squeeze by with 8°.

Hoyle

The observations, if they are correct, would increase the amount of energy by a factor of something like 2 or 3.

Kellermann

I'd like to take issue with the statement that you made that there's nothing magical about the number two. It is of course the number that any equilibrium radiation approaches and specifically in the case of optically thick synchrotron sources, which is what one might want to use to make this up, the absorption and re-radiation will give the slope of two in the optically thick part of the spectrum. And secondly, perhaps we should also all keep in mind the way this datum is taken. What is measured, of course, is an antenna temperature and one multiplies all the results by (frequency)^2 and then attaches some great significance to the slope of two.

MORRISON

I think that it is pretty hard to secure a universal exponent of two by self-absorption, as you say. You have to spread that very carefully through the sky in order to avoid that. You would expect to see a broken line, everywhere of the same slope, but with steps in it.

V.

SUMMARIES

SUMMARY OF OBSERVATIONAL RESULTS

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I. INTRODUCTION

The programme for this Study Week has been divided into two parts, a main section devoted to the properties of galactic nuclei, quasistellar objects, and related phenomena, and a shorter section on observational cosmology. My task is to summarize the observational results that have been presented and to try to extract from them those facts which appear to be now well established and others which are still in the realm of working hypotheses, interesting for further investigation but not yet on firm enough ground for general acceptance. There have also emerged during the discussions some ideas on observational programmes which might lead to new answers and new conclusions.

For the first part of the programme — galactic nuclei and related phenomena — I have listed the main observational results which I believe have emerged during the course of the week, as a basis around which to build the summary. Some of these points are not new, but we have spent considerable time in discussing them and their implications; some are quite new; some are perhaps being regarded now for the first time as being on a reasonably firm basis whereas, before, there was not sufficient evidence to warrant devoting theoretical effort to understanding them. In the concluding discussions people will raise other points which I have omitted, and will bring forward different points of view, so that this list can be added to and modified.

1. It has become increasingly clear that a large fraction of galactic nuclei have various degrees and forms of activity.
2. Matter is ejected from active galactic nuclei and QSOs.
3. There is strong evidence that massive clouds of gas, relativistic particles and perhaps coherent objects are ejected.
4. Very high star density exists in the nucleus of M 31 and probably in the nucleus of our Galaxy (see papers - OORT, SANDAGE).
5. There is increasing evidence that groups of galaxies with positive energy may exist. Their existence would raise problems for which there is at present no understanding.
6. The discovery of strong infrared fluxes has greatly increased estimates of the total power radiated from certain active nuclei.
7. It is now known that in the nuclei of many normal galaxies and strong radio sources and in QSOs there exist small radio components (diameter of the general order of 10^{18} cm).
8. M 87 is an x-ray source, and weaker evidence exists for other extragalactic sources at the present level of detectability.

9. There is extensive evidence of variability over a wide range of the electromagnetic spectrum in most of the active galactic nuclei and QSOs.

10. Galactic nuclei with substantial overabundances of some elements heavier than helium may exist.

II. FRAMEWORK FOR OBSERVATIONAL STUDY OF NUCLEI

The stage for the observational papers was set by the introductory talk by Professor AMBARTSUMIAN and the talk on nuclei and forms of galaxies by Professor MORGAN. Both in different ways emphasized the necessity for a morphological approach on the observational side. At the beginning and end of his talk, AMBARTSUMIAN made two important points. Firstly, before a theoretical explanation of the phenomena observed in active galactic nuclei and QSOs can be developed, it is necessary to find which are the important and meaningful correlations between the many and varied observations — a proper ordering and systematization of the data must be undertaken so that the connections between the different forms of activity can be elucidated. If this is not done, a large body of data may be amassed without its leading to any satisfactory theory. Then at the close of his introduction, AMBARTSUMIAN made another very important point of a philosophical nature: we have no right to expect natural phenomena to be so simple as to be comprehended by our simple minds at a first attempt. We should argue from the facts, rejecting nothing as impossible, being careful only to sort out the important from the trivial and the correct from the misleading or wrong.

A point not to be neglected in the search for an understanding of the phenomena occurring in active nuclei is that a nucleus is not an essential ingredient of a galaxy. AMBART-

SUMIAN reminded us that among the nearby objects it is the dwarf systems like the Small Magellanic Cloud and the Sculptor system that contain nothing like a nucleus (and one may add that, among more distant galaxies, there are examples of much larger dimensions). Such objects have to be accounted for in a comprehensive theory of galactic origin and evolution.

Turning, however, to the majority of galaxies, which do possess nuclei, one of the most significant of recent discoveries is how widespread is the occurrence of some degree, even relatively small, of activity. A galaxy like M 31, containing in the nuclear region an elderly stellar population, used to be regarded as a dead region where low-mass stars evolve and die, the supply of material for building new stars having long been exhausted. The first point to make, therefore, is that it now seems that most — and perhaps all — galactic nuclei contain some degree of activity. This may extend from a small scale like that in M 31, with a slow rate of ejection of gas and a small non-thermal source of radiation, where the activity would be hard to detect if the galaxy were not nearby, up to cases like NGC 1275, where AMBARTSUMIAN gave the mass of ejected gas as several times 10^8 $M_\odot$, equivalent to a small galactic mass, and where the scale of the activity links up with that exhibited by the QSS and QSOs (which I shall usually, hereafter, speak of collectively as the QSOs). Our own Galaxy also has an active nucleus, as shown by the 21-cm observations discussed by OORT, the radio continuum observations, and the infrared observations discussed by LOW. The source of energy in all cases appears to be a supply of high-energy particles, of dimensions $< 10^{16}$ cm, which produce variable non-thermal energy in dimensions less than a light month (the evidence for this is discussed in Section IV). The ultraviolet continuum energy in turn produces the great secondary activity in the form of gaseous ionization and excitation.

Relevant to the later discussion of the question whether dense objects are ejected from nuclei, was the point made by

AMBARTSUMIAN, that the ejected compact objects, as in the peculiar galaxies NGC 3561 and IC 1182 and the jet of M 87, behave like the active compact nuclei themselves. He had nothing to add to his original argument in which he felt that the actual process is more likely to be a fragmentation of primordial matter, and that, if it is a universal property, one might look to it for the production even of the whole galaxy. But the discussion here raised the problem of the angular momentum which is such a characteristic feature of galaxies; it is very difficult to produce net angular momentum from a small condensed origin, unless, as HOYLE pointed out, the ejection process carries a great deal of material to infinity. However, the magnitude of the angular momentum in spiral galaxies is most plausibly explained by the infall of slowly-rotating material from outside.

MORGAN's classification scheme, described in his paper, satisfies AMBARTSUMIAN's precept that one should make a physically meaningful ordering of the observations; the Yerkes form classification is taken as a basic framework in which one can see how the various degrees of activity, specifically in Seyfert galaxies and QSOs, relate to the ordinary forms. This classification is probably more basic than that of Hubble, in the light of our new understanding of the significance of nuclei, because it is based primarily on the relative importance of the nucleus. MORGAN regards the activity of nuclei as describable in terms of an "operator" acting on an ordinary galaxy, and raising the brightness of the innermost nucleus and of the region around it and suppressing the brightness of the outer part. Such a scheme encompasses the considerable range of Seyfert forms, from those like NGC 3227 and NGC 1068, with normal spiral arms and disks, to NGC 4151 with a peculiar and relatively faint outer part.

Finally, underlying the whole argument for making a logical classification, is the fact that the most active galaxies are few and far between so that the best examples are at considerable distances from us. It is therefore necessary to know how nearby lesser examples of activity would look at greater distances, and which features, enhanced, would convert them into the most active types. For example, one would very much like to know what Cygnus A would look like if it were nearby and were freed from the extinction it suffers from our own Galaxy. To set up a descriptive scale, in which the effects of distance can be eliminated as far as possible, is therefore very necessary.

III. UNDERLYING ENVIRONMENT OF ACTIVE NUCLEI: STELLAR POPULATIONS

It is important to understand thoroughly what constitutes the most normal component — the stars — in the nuclei of the most common types of galaxies. SPINRAD described work on a number of normal galaxies; the luminosity of the nuclear region is measured through narrow-band filters in wavelength regions carefully chosen to provide discrimination between spectral type, luminosity class, and chemical composition of the stellar population, and the results are matched to computations made with a large range of these variables in the integrated light from the stars. Separation of the parameters is difficult and not free of ambiguity, but there are now some interesting results from SPINRAD's group and from MCCLURE and VAN DEN BERGH.

Values of M/L as high as 45, as we heard, can now be fitted reasonably well if an increased population of M8 dwarfs is present; an enhancement in the "metal" abundance by a factor of 5 — 7 over solar-neighborhood abundances is required (where "metals" means everything heavier than helium, as in the sense used in work on stellar structure); the factor decreases outward from the center. Some ambiguity is unavoidable at this stage; it is noteworthy that either M 32 has a higher main-sequence turnoff than M 31, presumably implying a lesser age for the bulk of the stars in its nucleus, or it has a higher proportion of metal-poor globular-cluster-type stars, demonstrating an important difference between these two companion galaxies.

The discussions by OORT on the star density in the nucleus of our Galaxy, and by SANDAGE on that in M 31, are relevant here. Theoretical work on star collisions in regions of very high star density in the innermost nuclei of galaxies, less than a parsec in diameter, has suggested this mechanism as an energy source in active nuclei, but the observational estimates of density, set by the limitations of atmospheric seeing, have fallen short of the required density by a large factor. Now OORT has described a model of the innermost region of our Galaxy with 10^7 $M_\odot/pc^3$ within $R = 0.1$ pc, a much higher density than previous estimates; this model has been constructed by fitting with the near infrared profile of the nucleus of M 31, presumably coming from stars, and gives yet another example of the new information on galaxies being provided by the infrared observers. Although this density is still too low to make collisions important, it is of great interest when one thinks of it being scaled up in more massive galaxies of higher mean density.

In M 31 itself, SANDAGE showed that the existing photometry, combined with BAADE's delineation of the inner nucleus, yields a density of $10^5/pc^3$ for stars like the Sun. Remembering that there is a very large population of low-mass M8 dwarfs in the nucleus of M 31, the actual number of stars per pc^3 in the innermost tenth of a parsec must be much larger.

The new work on the stellar population in nuclei raises the question of how so many cool metal-rich red dwarfs of low mass have been formed in, for example, M 31. The contraction times for such stars are very long; how have they become enriched in metals? Did this occur through the acquiring of the products of nucleosynthesis in massive faster-evolving stars during the long process of contraction?

Finally, as we heard in SANDAGE's talk on cosmology, the stellar composition of giant ellipticals is of great importance in assessing the evolutionary change in luminosity of such galaxies. With the stellar populations described by SPINRAD, such a change is small and dL/dt is estimated to be less than 0.03 mag per 10^9 years.

IV. COMPACT GALAXIES AND QSOS

Compact Galaxies

The compact galaxies have for years received little attention except from Professors ZWICKY and MARKARIAN, and I believe would-be observers may have been inhibited by the fact that there was no easily accessible list of ZWICKY's compacts in the published literature; one had to write to obtain copies of the lists. I therefore urge publication of the complete lists.

From the work of SARGENT, however, there is finally a considerable body of spectroscopic and photometric data as well as direct photography. It appears that the compacts are quite numerous; the balance in the old controversy between HUBBLE and ZWICKY, about the faint end of the luminosity function for galaxies, seems to be tipping toward ZWICKY's viewpoint, that the function increases more at the faint end than previously believed.

Compact galaxies do not necessarily have the insignia of really active nuclei, since the spectra of about 1 in 4 of those observed by SARGENT show only absorption lines. The star density, however, is probably high and it is not easy to look for low-level activity in fairly distant objects. Apart from the absorption-line objects, ZWICKY's lists contain a heterogeneous sample of objects, ranging from galaxies like I Zw 1, which exhibit a strong effect of MORGAN'S "operator" and appear intermediate between Seyferts and QSOs, to galaxies of small redshift, small diameter, low mass, and narrow emission lines.

Two very interesting objects that may be young galaxies in the process of formation were described by SARGENT. In these, blue compact objects, with high-excitation emission-line spectra like gigantic O-associations, appear to be embedded in extensive volumes of H I of approximately the dimensions of a normal galaxy, possibly possessed of angular momentum, and with minimum masses of a few times 10^8 $M_\odot$. Although one cannot exclude the possibility that there is a substratum of a few very old stars which have recently captured some diffuse gas, it appears the the observed colors do show that the objects cannot contain an appreciable population of old stars. Because of SARGENT's conclusion that such objects may be very common in space, it would be worth making a search for them as well as detailed studies of the two known examples.

Quasi Stellar Objects

In discussing the spectra of QSOs, I gave a brief description of the emission lines — their identifications, relative strengths, widths; these are the data which provide the raw material for the analysis of the physical conditions in these objects, discussed by OSTERBROCK. Then I spent most of the of the time discussing the curious absorption-line spectra, because I believe these are produced in gas ejected from the central object, at velocities which can be as high as $c/3$ or $c/2$, and thus that they are directly related to the type of nuclear activity being discussed here. I related the observations of very narrow absorption lines, at multiple values of the redshift, to the case of one QSO known to have very broad but structured absorption bands, such as might be produced in a thick expanding shell around a gigantic supernova. There is a very direct comparison between these narrow multiple-redshift absorptions in QSOs and the narrow triple absorptions observed by ANDERSON and KRAFT in the spectrum of the nucleus of NGC 4151. SARGENT, in his talk on compact galaxies, described recent evidence for variability in these absorption lines in NGC 4151.

In the subsequent discussion, the possibility was raised that the multiple-redshift absorptions might be produced in jets originating in a multiple source, but this was later realized to conflict with the observed low residual intensity in the absorptions, which indicates that the absorbing gas completely covers the source of continuum. REES's model appears to be a good working hypothesis, with the ejection of high-energy plasma at appreciable fractions of the velocity of light, and its subsequent cooling and fragmentation into a filamentary structure. Transverse Doppler shifts seem able to account for the cases where $z_{abs} > z_{em}$, in which $z_{abs} - z_{em}$ can have values up to 0.03.

The observation by LYNDS and WILLS of an 18th magnitude QSO with $z = 2.88$ will surely lead to studies of the behavior of Ly-β and the Lyman continuum in this object.

Physical Conditions

As the observations have improved and as more quantitative data have become available, analyses of the emission-line spectra and continua of QSOs and active nuclei have been extended and refined. OSTERBROCK discussed models made by several workers. The physical conditions in Seyfert nuclei are similar to those in QSOs; dense regions embedded in a more tenuous medium have to be invoked. In all these objects the main difficulty is that the observations integrate over large non-homogeneous volumes, and in attempting to construct unambiguous physical models one faces similar basic problems as are involved in the attempts to deduce the stellar populations over finite volumes.

We can expect that the models will be further refined as the amount of quantitative information increases, covering wider ranges of observed wavelength, of redshift (and hence intrinsic wavelength), and of absolute intensity. Scanner measurements, e.g. those by OKE, NEUGEBAUER, and BECKLIN and by WAMPLER and MILLER, provide the best quantitative data, though there is some from photographic spectrophotometry which has also provided qualitative estimates of relative line intensities. More data on line profiles are needed; it is very desirable to try to determine whether the broad lines and extended wings of lines are caused by electron scattering or by high turbulent motions or both. Turbulent motions are suggested by the high-resolution observations by WALKER in, e.g. NGC 1068 and by the fact that shocks caused by such highly supersonic motions would be very efficient producers of ionizing ultraviolet radiation.

The actual mechanism for the gas outflow in NGC 4151, assessed by OSTERBROCK at about 1/2 $M_\odot$ per year in all directions, is unknown. But quantitatively it is sufficient to empty the nucleus of its existing gas in a time orders of magnitude shorter than the Hubble time; one may relate this to the long-known fact that the cloud velocities in Seyfert nuclei considerably exceed the escape velocities. The conclusion that clouds of gas, at least, come out at high velocity from active objects, results from the observed phenomena of expanding gas clouds in NGC 4151, the multiple absorptions in some QSOs, and the supernova-like absorptions in PHL 5200, and of course the large gas cloud associated with the Seyfert radio galaxy NGC 1275. One does not know what else might be ejected (e.g. dense massive compact objects), but there is at least direct evidence for clouds of gas as well as relativistic plasma.

Finally, mention should be made of analyses of chemical composition. We heard that the improved models and observations are leading now to definitive results. The overabundance of nitrogen in the gas in the centers of some galaxies is quite understandable in terms of stellar nucleosynthesis, and is in line with the "metal" enrichment observed in the stars in some nuclei. It is harder to understand the seemingly real underabundance of helium in the nucleus of NGC 4151 and in QSOs, when other heavier elements appear normal relative to hydrogen. It appears, however, that some other elements, such as O and Ne, may also have a lower than normal abundance in some objects.

Variability; Smallness of Sources

There have been several papers on the variability of QSOs and active galactic nuclei in different regions of the electromagnetic spectrum. As the data accumulate, it becomes ever more clear that variability is the rule rather than the exception. The observations are time-consuming and require care and accuracy; for the optical observations we are still very much dependent upon SANDAGE, who described photometric work on QSOs and N-type and other active galactic nuclei. Although optical variability is so common, there are few QSOs that vary by very large amounts; long-term monitoring as carried out, e.g. by KINMAN and by CANNON and PENSTON and the workers in the U.S.S.R., indicates which are particularly interesting objects to follow in detail.

In the infrared region, as discussed by LOW, the detection of variability requires care in calibration, and the question of how short a time scale is involved in the objects which have been studied, e.g. NGC 4151, NGC 1068, and M 82, is still not settled. The variability probably rules out dust models for the production of the far infrared radiation.

The variations in radio emission described by KELLERMANN, if fairly continuous monitoring is carried out at many frequencies, can lead to models for the sources of the radio emission (I shall not discuss the models in this observational summary). I just mention that measurement of polarization and variations in polarization during flux changes, at optical, radio, and, one hopes in the future, infrared frequencies, apparently can provide an important observational test of the models. The radio variations do not exhibit periodicity, but rather indicate the occurrence of bursts of high-energy particles. The exciting news that the x-ray source in M 87 is variable, as told us by FRIEDMAN, also indicated that jets of very high-energy electrons with short life-times against synchrotron radiation are involved.

An observational result to be emphasized is the very small dimensions of the sources of radiation in active nuclei and QSOs. Rapid optical variations indicate small dimensions, rapid infrared variations may occur although this is not yet certain, and at radio wavelengths not only are fairly rapid changes seen, but direct interferometric measures show that there are very small sources in both QSOs and in radio galaxies. Another new result is that small sources of radio emission are a common phenomenon in the nuclei of spiral galaxies, indicating how common is the phenomenon of low-level nuclear activity on a small scale.

To return to the optical observations, SANDAGE saw no strong evidence for periodicity in any QSOs. The measured changes in slope of the continuum at times of light variation indicate, as do the radio variations and the new x-ray observations in M 87, that the basic quantity that has varied is the high-energy particle injection from the ultimate source of energy. In the variable nuclei of N-type galaxies, it is the non-thermal component of radiation which varies; it is integrated in the measurements with the continuum coming from the underlying stellar population. This combination of components is what distinguishes the N-type nuclei from the QSOs in the two-color *U*, *B*, *V* diagram; MORGAN's "operator" is acting less strongly on N-type nuclei than on QSOs. There is no such separation in the colors between the radio-quiet and the radio-emitting QSOs (the QSS). As already mentioned, measurement of polarization changes at times of rapid optical variation in the strongly variable sources are important. This polarization indicates the presence of synchrotron radiation, but SANDAGE's recent observation of strongly polarized line radiation in M 82 has us all puzzled!

V. GROUPS OF GALAXIES; DISCREPANT VELOCITIES

The evidence for systems of positive energy among the small groups of galaxies, as originally postulated by AMBARTSUMIAN, has increased considerably since the Santa Barbara Conference on this subject in 1961. Data on many new systems, as well as on some well-known groups, have been obtained by SARGENT. I believe it is no longer reasonable to accept the very large mass-to-light ratios required in so many systems to balance the kinetic and potential energies and satisfy the virial theorem.

The question of systems with one member having a very discrepant velocity is another matter. Some five systems are known at present in which one component has a velocity many thousands of kilometers a second different from the rest, and the question of chance superposition of foreground and background objects has to be very carefully investigated. In my talk I placed in this category also the systems discussed by ARP; more observational work is needed and I indicated some lines of investigation.

However, so long as one is discussing discrepant velocities which amount to hundreds of km/sec, or even a few thousand, the phenomenon may perhaps be linked with the observations we have already discussed, namely, the ejection of masses of gas of at least small galactic dimensions, as, for example, in NGC 1275, where the velocity difference is 3000 km/sec, and in the multiple radio galaxy NGC 6166, where the spread in velocity among the elliptical galaxies comprising the object exceeds 2000 km/sec.

It is the very large velocity difference involved in, for example, VV 172, coupled with the fact that the discrepant object here contains stars and not merely gas, which poses the most severe theoretical problem if such cases prove to be close in space and of common origin. The time scale is the main difficulty; observational attempts to determine the age of the stellar population will be very valuable. One might have to consider the fission of a fast-rotating stellar aggregate, but this falls outside the realm of this observational summary. In any case, the time scale would pose an enormous problem, because of the rapidity with which objects at very different velocities will separate from each other in the sky.

VI. FURTHER REMARKS ON OBSERVATIONS AT OTHER THAN OPTICAL FREQUENCIES

Although so much astronomical knowledge has been acquired through measurement of radiation at optical wavelengths, the study of galactic nuclei is one field where certain information can be obtained only by using other frequencies, e.g. data on the nucleus of our Galaxy. Further, since the radiation from active nuclei is largely non-thermal, the frequencies where thermal contributions are small — radio, far infrared, and x-ray — are particularly informative. Finally, optical ground-based observations are seeing-limited whereas the *VLB* radio observations can circumvent this difficulty.

Infrared

The variability of active nuclei at infrared wavelengths has already been discussed, also the probability that radiation longward of 5μ wavelength has a non-thermal origin. The great surprise in recent years has been the large amount of energy emitted in the infrared by active nuclei and QSOs, and even in our Galaxy. Estimates of the necessary energy supply in active nuclei have been considerably increased as a result of the observations described by LOW.

Radio

Compact sources and variability have already been discussed. Let us briefly turn to the 21 cm observations in the nucleus of our Galaxy, discussed by OORT. Although ours is not a very active nucleus, this is perhaps an advantage, in addition to the advantage of its nearness, because it may be easier to sort out the different effects and thus gain an understanding of these phenomena by studying them on a relatively small scale. The complicated kinematic structure in our nuclear region has analogies with non-circular motions seen in the centers of other galaxies, particularly M 31. OORT mentioned that the ejection of gas at about 45° to the plane, in two oppositely directed streams, suggests that magnetic forces may be involved. The work of Mrs. PISMIS (*Bol. Tonantzintla y Tacubaya,* Nos. 19, 21, 23, 30) came to mind. She has suggested that a dipolar magnetic field in the center of a galaxy might be the mechanism for initiating double-armed spiral structure. Presumably the neutral gas flow seen in our nucleus carries ionized gas with it; in external galaxies the observations are made by means of emission lines from ionized gas.

X-rays

The first positively identified extragalactic x-ray source, M 87, is the galaxy that one would most have expected to be such a source. Now FRIEDMAN has told us, in addition to news of the variability of M 87, that both 3C 273 and NGC 5128 are also probable sources of x-ray emission. Improvement of the sensitivity of measurements, to be expected soon, may lead to the detection of many more extragalactic sources.

VII. OBSERVATIONAL COSMOLOGY

Perhaps I have spent too much time on the papers about nuclei and have left too little for those on observational cosmology. Topics covered have been the Hubble diagram, distributions of counts and redshifts and evolutionary effects, and diffuse background radiation. There is time only to say a few words about the first two.

Hubble Diagram

The new Hubble diagram, from the work of SANDAGE, has a much reduced scatter and this has resulted from his selection of the brightest galaxies of D or giant E-type in clusters. The main impediment to the determination of q_0 is now twofold: the lack of many redshift determinations for such galaxies beyond $z = 0.2$, and the long-standing problem of the K-corrections. It is also important to make a distinction between the very high-luminosity supergiant cD galaxies and the giant ellipticals like the Virgo Cluster giants, which have systematically lower absolute magnitudes. Determination of the K-corrections has been a very time-consuming task, beset with observational pitfalls, but the very recent development of multichannel scanners should yield more accurate results in a more reasonable time scale. I already referred to the indications, from work on the stellar populations, that evolutionary changes in luminosity are negligible for giant E-type galaxies. Too little is yet known about the cD systems to be absolutely sure this is the case for them. For the second part of the problem, the work on identifying objects in "empty fields" at accurate positions of radio sources, described by SANDAGE, is very exciting; again the obtaining of redshifts for these very faint objects will require sophisticated observing with large instruments.

A good reason to urge observers of QSOs always to publish the cases where they find mis-identification of a galactic star as a QSO, is that these rather good radio positions them become candidates for "empty field" studies.

Counts, Distributions, Evolutionary Effects

SCHMIDT has shown, in his work on QSOs, the importance of obtaining observations of a uniform and complete sample for analyses of distributions or evolutionary effects. From such work he has found a distribution with dependence on a high power of the redshift — $(1 + z)^6$ — which he interprets as a time-evolutionary effect. For the observers it is more difficult to work on complete samples, because of the exigencies of telescope scheduling and weather. One is tempted to cover a wide variety of identifications, from heterogeneous sources, over the whole sky, but it is clearly better to aim for homogeneous samples in the survey work on redshift determinations.

The discovery by LYNDS and WILLS that a 4C radio source, identified with a blue stellar object of magnitude 18, has a redshift $z = 2.88$, greatly increases the likelihood of reality of the apparent cut-off or very marked decrease in numbers of QSOs at values much larger than $z = 2$. In the discussion, SCHMIDT and I did not agree as to whether the steep rise in the redshift distribution near $z = 2$ is an effect of observational selection, due to ease in measuring C IV λ1549 and Ly-α emission lines, but that there is a sharp peak at $z = 1.95$, shown when the size of box used in redshift sampling is taken small enough and clearly visible on such histograms, is not affected by this argument. For the other effect, however, checks should be made by the observers who should make an accounting of their individual redshift determinations and numbers of objects examined where no conclusive redshift determination was possible.

Finally, for the radio counts, the long-standing question of the steep slope of the log *N*-log *S* plot at the high-intensity end was discussed. HOYLE showed that the bright sources with measured redshifts show no intensity-redshift correlation. The obtaining of redshifts for the complete 3C list of radio galaxies is most important; also the log *N*-log *S* plot for the brightest sources should be redone in order to sort out apparent differences from different radio telescopes at different frequencies.

DISCUSSION

Chairman: L. SPITZER JR.

MORRISON

What is the main nature of the activity seen in M 31? I seem to remember that Dr SPINRAD found little emission lines in the optical; perhaps it is the radio activity.

E. M. BURBIDGE

The outflow of gas from the centre, discovered some years ago by MÜNCH. There are non-circular motions measured along the minor axis and interpreted as the outflow of ionised gas from the centre. Then there are, of course, RUBIN and FORD's recent observations of non-circular motions, and the OAO observations of the ultraviolet source at the centre. The ultraviolet source may be small, perhaps less important than first thought, but there does seem to be some such ultraviolet sources which SPINRAD says cannot be due to a small number of O stars. It is best explained as a manifestation of the sort of activity we are discussing.

SPINRAD

Fine, you said all that I would have said but more simply. I would like to ask an associated question. How dead do you have to get before even this group will say that there is no life left? There are galaxies that at the moment look to me like they are less active than M 31, but without exception they are less well studied. Now maybe that's the whole answer. But it seems to me that it would be worth a little effort for some very mild-mannered person, who isn't interested in the bizarre activity end, to look into the quiescent ones: for example NGC 3379 is the standard photometric galaxy, which as far as we know has absolutely no emission lines, but presumably has not been observed yet by the OAO. I know several very static looking symmetric systems which have the outward appearance of being as dead as a doornail, but it would repay us now to look to look at them in the context of the various levels of activity brought up in this Conference.

LYNDEN-BELL

I would not like the list of the activity of M 31 to leave out the fact that there is a 5 C 3 radio source in the centre of M 31, albeit rather larger than Sagittarius A.

KELLERMANN

Why do you think that M 87 is the most likely thing to be an x-ray source, besides knowing that it is the only one?

E. M. BURBIDGE

Because M 87 is a source of optical synchrotron radiation, requiring high-energy particles, therefore it might well be expected to have the somewhat higher-energy particles and/or magnetic field which would produce synchrotron radiation in the x-ray range.

KELLERMANN

If the association of the x-ray source with the compact radio source is correct, these components have nothing to do with the optical synchrotron radiation, which is mostly coming from a different volume of space.

E. M. BURBIDGE

The optical synchrotron radiation comes from the condensations along the jet...

KELLERMANN

...With ultra compact radio sources at the nucleus.

E. M. BURBIDGE

Yes, and there's a very compact optical source out in the jet.

KELLERMANN

That's about a second of arc in size. That is too big to give x-rays by inverse Compton scattering.

KELLERMANN

There is no evidence that the nucleus has optical synchrotron emission, is there?

E. M. BURBIDGE

No. For the optical compact sources in the jet, the optical observations give you hardly any better than a second of arc resolution; we never can approach the resolution that the radio astronomers can achieve!

AMBARTSUMIAN

There has not been mentioned the very important problem of the variability of continuous light, of variability of quasars and nuclei in continuous light, as manifestations of activity. I think it is very important, especially in the case of quasars. The base line is very long and this is a very wonderful property of quasars, giving so long a base line of variability; therefore, I ask SANDAGE, can you say some of them are pausing for some time?

A study of this is very important, since I repeat that the lifetime is very long.

SCHMIDT

I am not sure if it is appropriate, because it is not about variability, but I would like to ask Dr. AMBARTSUMIAN why he thinks that quasars have so long a lifetime? When one looks at the space density and compares it with that of radio galaxies or of giant elliptical galaxies, one gets the impression that you cannot have lifetimes that are much longer than, say, 10^6 years for the most powerful quasars, but perhaps up to 10^8 years for the less powerful ones. Would you feel that longer lifetimes are necessary, or justified?

AMBARTSUMIAN

The conclusion that the lifetime of quasars is short is based on the assumption that the quasars are a stage in the life of a galaxy. But we don't know what they are, of course. However, one must take into account that the number of QSOs is about 1000 times larger than the number of quasars. I think that there is a kind of very long period of the quiet state which is a thousand times longer than the radio phase, but of course it is very difficult to give any absolute estimate. In any case it is something that deserves very careful study.

FOWLER

You mentioned it in your discussion, so I wonder if you would consider including SPINRAD's over-abundance of certain elements in galactic nuclei. Certainly for nuclear physicists it is most exciting. He may not want the factor of 5 to 7 pinned down for posterity, but maybe the term over-abundance could be used.

SPINRAD

But please not universality. That has not been proved.

SARGENT

I was going to bring up the general subject of the role of nuclei in the formation of the elements. In a recent Symposium to celebrate JESSE GREENSTEIN's birthday which we had in Pasadena, UNSÖLD was subjected to heavy bombardment on his belief that elements are formed in galactic nuclei.

I think we should at least mention this topic in the conclusion.

I would like to mention one additional property of the supposed young galaxies that bear on this problem. I mentioned this already this morning to OORT in a conversation and was reminded of it thereby. That is, there is a general belief that the heavier elements are formed in massive stars. There has been work on our galaxy which indicates that the rate of formation of massive stars was larger at the beginning of the galaxy than it is now and that most of the heavy elements were formed when there was a much larger rate of formation of massive stars. Now in those supposedly young galaxies, as I said, in each one there is an object which looks like one O association in a mass of gas which is roughly the same as the total mass of neutral gas in our galaxy, 10^9 or 10^8 solar masses. There is some possibility that these little galaxies are only 10^7 years old.

In the small Zwicky galaxies there is one O association in $10^8 - 10^9$ $M_\odot$ of neutral hydrogen. We may contrast this state of affairs with that in our galaxy where there in the same amount of gas but many, many more O associations. There is much more mass in young stars. Now in our galaxy we believe that the present rate of the enrichment of the interstellar medium is negligibly small, therefore in these young galaxies it should be even smaller still, since there is a smaller ratio of O associations to total mass of gas. It therefore seems to be even more surprising that in these young galaxies the element abundances are the same as they are in the Orion nebula.

OORT

With reference to the last point that Dr SARGENT brought up, we may consider the element formation in our galaxy which apparently took place in large part during the first contraction stage in the halo of our galaxy. Might not something similar have happened in these very young galaxies?

FOWLER

It does not seem to me that we have discussed element formation in our own galaxy adequately enough to draw this conclusion at the present time. If we are to discuss element formation then we must have a complete discussion of the production of shortlived radioactivities, Iodine-129 and Plutonium-244, whose decay products are found as anomalies in the isotopic constitution of Xenon in meteorites. These findings show that there was considerable element synthesis just prior to the formation of the solar system and not just during the first contraction stage of the galaxy.

I would put a quite different interpretation on SPINRAD'S discovery of supermetallicity in galactic centers. One must not argue that all of the elements have been formed in the galactic nucleus. It is necessary to argue only that there has been more stellar evolution in the nucleus than in the outlying regions. Element formation is still to be taken as proportional to the amount of stellar evolution. This is the first time we have discussed element formation, and much more discussion will be required if we are to reach general agreement.

LYNDEN-BELL

SARGENT has told us that the nuclei of these galaxies are normally abundant. This is an abnormally low abundance for a galactic nucleus, if we generalise the SPINRAD phenomenon.

OSTERBROCK

Perhaps another tentative conclusion could be the high densities of ionised gas in most active nuclei. In Seyfert galaxies there is evidence that nearly all nuclei have gas densities of 10^6 cm^{-3} shown by the [OIII] lines, and perhaps higher, as shown by the electron scattering.

McCREA

If it is agreed, I think we might call attention to the fact that the population studied by SPINRAD is probably a second or third generation of stars in the nucleus, and not the first generation. I think it is very relevant to what has been said in the last few remarks.

WHEELER

The strong intensity of emission in the infrared would seem to make it extremely important to look for individual lines in the infrared so that one can learn about the electron density and temperature in the emitting medium.

SUMMARY FROM THE THEORETICAL POINT OF VIEW

L. WOLTJER
Columbia University
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Even though no strong controversy has developed at this conference it is very clear that, if we try to write down a set of definite conclusions from the theoretical point of view, many of our old disagreements will come to the surface very quickly. This meeting has been extremely successful in part because some of our differences have been set aside for the moment; some of these seem by now to be more of a quantitative than of a qualitative nature. I have written down a set of proposed conclusions as follows.

1. The formation of compact nuclei by interaction of stars and gas is possible.

2. A consistent picture in which nuclei evolve through phases of increasing density and decreasing angular momentum can be constructed.

3. The formation of relativistic objects is probable.

4. Energy and mass are ejected in bursts - rather than continuously - of various intensities and time scales; the total energies range up to 10^{60} to 10^{62} ergs per object, and the typical mass ejection rates amount to one solar mass per year.

5. The fundamental question as to whether particles or objects which accelerate particles are ejected is at the moment open.

6. High efficiency of conversion of energy into relativistic electrons is possible.

7. Evolutionary effects are important in the quasi-stellar objects.

8. The limits of conventional physics have not yet been surpassed.

In surveying then what has been discussed at this conference, let me discuss the last conclusion first. The question has been raised here, and it probably is the most interesting question that one may get an answer to from the study of nuclei of galaxies, as to whether conventional physics is applicable and sufficient, that is whether local conservation of energy, momentum, and angular momentum apply. A possible theory was discussed by Prof. HOYLE in which a change at the base of general relativity leads to modified field equations which allow effective interaction between local regions and the universe at large. Evidence relating to this was discussed by Prof. HOYLE in connection with the luminosity function of radio galaxies. The question as to the validity of local conservation can also be put in a somewhat different form, namely, when we look at the nucleus of a galaxy, does everything move out, or does it first move in and then move out? The conventionalists have no choice but to give the latter answer. On this point there is an important difference of opinion. Clearly we could establish the need for nonconservation only by fully exploring the possibilities with conservation. It seems to me that all that we have heard has not demonstrated the need for energies in excess of 10^{62} ergs on time scales of 10^6 to 10^8 years, or perhaps 10^{63} ergs, in all, in the most extreme cases of very long lived Seyfert galaxies and I do not see any reason at the moment why such energies cannot be obtained on the basis of conventional theory; however, if we were to go up by a factor of a hundred more, serious difficulties would indeed arise.

At the same time I think that there are some causes for concern and among these I would list first of all, the observations by WEBER which, if taken literally, would indicate that the nucleus of our galaxy emits $10^{55\text{-}56}$ ergs per year in gravitational waves; the observations still need further confirmation. The second cause for concern, I would mention, is the dispersing of small groups. With the large clusters one can always discuss things in terms of expansion of the universe and the long time scale of the formation for the clusters, but in the small groups the time scales are so short that the problem seems particularly acute, as was discussed by MARGARET BURBIDGE and Prof. AMBARTSUMIAN. A third worry are the chains of galaxies with members with highly deviant velocities. As Dr. SARGENT told us, it is very difficult to believe that the large differences in redshift are associated with velocities, because then the objects would move away so quickly that the chance of finding such chains would be small. But if these Doppler shifts were not kinematical their origin becomes mysterious. Let me leave now this point and assume that we can discuss the problems in terms of a conventional physical framework.

All of us seem agreed that the basic objects, responsible for the activity in the nuclei, are very compact, with length scales less than one light year. This is demonstrated by the short time scale of the variations and also by the direct interferometry discussed by Dr. KELLERMANN. Secondly, it also is clear that these objects are extremely common. According to WADE's statistics, roughly one quarter of the spiral galaxies have very small diameter components. With regard to the formation and evolution of the objects in the nuclei it seems that, in a general way at least, many of us agree on the basic sequence, although there are considerable uncertainties in the details. The first phase was discussed by Prof. SPITZER who dealt with some of the problems encountered in the evolution from a fairly large galactic system to a dense nucleus. He showed how a stellar system after having formed would pass through a phase in which mass loss plays an important role; the mass loss would lead to the formation of a denser gas cloud in the central regions of the stellar system and subsequent star formation in the cloud would result in a stellar system with a radius, maybe, one tenth of the radius of the original system. By repeating this process a few times he finally achieved an object with a mass of 10^8 solar masses and a radius of the order of a parsec. Of course in all of this there remain large uncertainties; in particular one has to assume, as Dr. SPITZER mentioned, that the luminosity function for star formation is the same in these objects as it is in the solar neighbourhood and one also has to worry that much mass may disappear into black holes. We will await calculations in which angular momentum is incorporated with much interest.

In the following phase, after this dense stellar system with a radius of the order of a parsec has formed, the relaxation time for gravitational encounters between stars becomes short enough to be interesting. As a result further contraction occurs followed by coalescence of stars and by stellar collisions of a more destructive nature. From the numerical results by Drs. SANDERS and SPITZER it seems that the main energy output in the later phases of such an object is due to the luminosity created by the collisions between stellar bodies, the supernova output being of a comparatively minor importance. It is doubtful that in this phase great amounts of relativistic electrons will be produced, but then many of the active nuclei do not show evidence for strong radio emission.

After the phase with stellar collisions things become more uncertain. It is possible that as a result of the stellar collisions, or by entively different processes, dense, rotating, centrifugally supported objects with fairly strong magnetic fields arise which were discussed by Dr. MORRISON and myself. It was noted that such objects have the great advantage of allowing extremely high efficiency for conversion of energy into relativistic electrons. Prof. FOWLER considered the alternative possibility of an object supported primarily by radiation pressure and only partly by centrifugal forces and showed that in that case the object will collapse at a radius of several Schwarzschild radii; most likely the collapse results in the formation of a very thin disk, that again is centrifugally supported. As remarked here repeatedly, the main uncertainty concerning the thin centrifugally supported disks is their potential instability against fragmentation. If the disk breaks up in a number of dense objects and if these dense objects rotate they may again have many characteristics of the pulsars and efficient release of energy is still possible, and this may lead to the kind of a model discussed by Dr. REES. It may also be that enough diffuse matter remains between these condensations to keep the magnetic field anchored and so to prolong the phase discussed by Dr. MORRISON and myself.

What happens after this becomes much more uncertain. It may be, as Dr. MORRISON suggested, that the field is partly sheared off, which would decrease the angular momentum loss and lengthen the time scale for the evolution of the system, or some more catastrophic collapse may set in. I should mention here the very interesting calculations by LEBLANC and WILSON on which Prof. WHEELER reported. It was shown that during collapse conditions, differential rotation can wind up an existing poloidal magnetic field into a very tight helix and that the resulting magnetic pressure is sufficient to eject jets of considerable mass and energy along the axis of rotation. In addition during less dynamic phases hydromagnetic instabilities may lead to some mass ejection out of the equatorial plane. Prof. MORRISON has suggested that the rotating object may also by a kind of sling effect fling out blobs of matter in the equatorial plane. Clearly by a judicious combination of these possibilities one may account for a wide range of phenomena.

It is interesting to note that in the calculations of WILSON and LEBLANC the initial magnetic energy was only a very small fraction of the gravitational energy. Although these hydrodynamical calculations seem very suited to give us jets, it is not clear that they are equally suited to give us relativistic electrons because in any relativistic hydrodynamical expansion one risks giving electrons and protons the same velocity rather than the same energy.

Whatever the details of the earlier phases, it seems likely that finally the object will approach very closely to a black hole type of configuration. Unless one manages to stop all external torques and to make the object strictly axisymmetric without instabilities so that it cannot radiate gravitational waves it would seem that angular momentum loss must continue and in this case the object has no choice but to continue contracting until the limit is reached. Prof. WHEELER told us that such a black hole is an object into which all kinds of things can disappear without leaving much of a trace of their previous constitution. Also if the configuration which disappeared into the hole had an external magnetic field, this field will disappear during the formation of the hole. Such holes may be detectable by their x-ray emission, but it is to be noted that in our present stage of knowledge of x-ray sources it seems very difficult to distinguish between x-rays from the surroundings of a black hole and x-rays from the surroundings of white dwarfs or neutron stars. Dr. LYNDEN-BELL showed that inflow into a black hole in a galactic nucleus can be expected when a magnetic field embedded in the galactic gas allows us to transfer angular momentum outwards. He showed that an inflow of the order of one solar mass per year is not unreasonable quantitatively and that this would provide enough energy to maintain a Seyfert galaxy for a very long time. Again it is not clear how efficient electron acceleration will be in this case, but in most Seyfert galaxies there is not that much evidence that a large fraction of the energy goes into relativistic particles.

The observations of Low indicate that a copious amount of energy is emitted in a narrow infrared peak. At the moment there still are doubts that dust models can be completely excluded, but should future observations show that the time variations are as rapid (∼ 1 month) as some have suggested then the dust models will become very difficult. Of course the great attraction of using dust in the nuclei of Seyfert galaxies is that there is very direct observational evidence for such dust. Prof. OSTERBROCK indicated how by comparing the intensity ratios of spectral lines emitted from the same upper level one can unambiguously detect the reddening caused by the dust. In some Seyfert nuclei the interstellar absorption in the nucleus must be of the order of three magnitudes in the visual which would probably be adequate for any of the infrared dust models. With regard to the nature of the infrared radiation we note that even if it proves to be nonthermal, it does not follow that it is synchrotron radiation. There is a tendency anytime one finds polarised radiation to say that it must be synchrotron radiation; however, there are many kinds of plasma instabilities which can lead to the emission of radiation. In this context, Dr. LOW discussed the possibility of coherent synchrotron radiation. Returning for a moment to the emission lines in the nuclei of Seyfert galaxies Dr. OSTERBROCK considered the mechanisms for ionisation. He showed that both an extrapolation of the optical continuum and ultraviolet radiation from shockheated gas may accout for the ionisation. Unfortunately this makes it impossible to estimate the ultraviolet continuum unambiguously from the strength of the emission lines.

If we want to insert numerical values for the masses and other parameters of our models we will need to have some knowledge of the luminosities and luminosity functions, the life times and the efficiency factors. At this point I should note a truism namely that the larger the spectral range one observes the smaller the efficiency factor that one is allowed becomes.

Clearly when in the end one observes all the radiation and mass motion that is coming out of an object then the efficiency factor by definition would become unity.

In Dr. BURBIDGE'S table the output from several nuclei was listed. Although one could disagree with any particular item, it carried a certain conviction by the whole collection of data which leads us to conclude that in typical galaxies one solar mass per year is ejected from the nucleus. Even if this mass were to come out with velocities of 3,000 km/sec, like in NGC 1275, the total energy involved would be comparatively modest of the order of 10^{50} ergs per year. The observations by Professor OORT on the galactic centre and probably also those by Prof. LOW indicate that our galaxy fits in very nicely with the active nuclei; this confirms a suggestion that was made 10 or 15 years ago by, I believe, SHKLOVSKY, who noted the great similarity between Seyfert nuclei and our own galactic nucleus.

The important question was raised as to what are the absolute top energies (in nonthermal form) which are required in a single object and I think the answer that was given is that they are somewhere in the range of 10^{60} to 10^{62} ergs, which is equivalent to 10^6 to 10^8 $M_\odot c^2$. This energy appears partly in the form of bursts of relativistic particles. Dr. KELLERMANN estimated that in some of these the energy yield is 10^{58} ergs per event. If this number were correct the total energy over a time of say 10^6 years would be very large indeed. However, some of us seem not completely convinced by this number and in models with relativistic expansion one can change the conditions and reduce this energy by, I would think, two or three orders of magnitude.

The times scales were discussed by Dr. SCHMIDT who stressed in particular the permanence of radio emission in giant ellipticals. About ten per cent of these have radio emission which leads to a minimum duration for the total radio emitting phase of 10^9 years. A similar argument for the Seyfert galaxies leads to a lifetime of 10^8 years. It should be stressed, however, that during those 10^9 or 10^8 years we should expect the object to radiate most of the time at a level well below its maximum.

In the case of the radio galaxies we know that in addition to the time scale of the outbursts observed by Dr. KELLERMANN there must also be a different time scale involved. The large radio components around objects like Cygnus A indicate even larger outpourings of energy in a comparatively limited time. At the same time we note that though the typical bright radio galaxies must last for a total time of 10^9 years, the radio emitting regions cannot last so long because the energy losses of the particles would be too severe. This leads to the conclusion that we have repeated large outbursts for which, in fact, direct observational evidence is seen in the case of Centaurus A where two sets of double sources are observed with very different separations.

With regard to x-rays from extragalactic sources the most exciting discovery of Centaurus A and 3C 273, in addition to M 87, was announced by Prof. FRIEDMAN. The discovery of x-ray emission from Centaurus A is especially important because if the x-ray emission is due to the inverse Compton effect we may find out how many electrons there really are in the source and thus resolve the ambiguity that the equipartition estimates always have. But before this can be done we also will have to know what the radiation field (3^0K or otherwise) is with which the electrons interact.

The repeated outbursts of relativistic particles observed by Dr. KELLERMANN fit in a miraculous way the simple model first suggested by SHKLOVSKY and subsequently developed by KELLERMANN, PAULINY-TOTH, VAN DER LAAN and REES. In these models one assumes that a burst of particles is released in a magnetic field. Subsequently the region containing the particles expands at uniform velocity, while conserving magnetic flux and the particles expand adiabatically without important radiative losses. Self absorption plays a dominant role in the relation of the model to the observations; the models give a good fit to the way in which the peak of the emission moves in the time-frequency-intensity diagram. Of course at the moment it still is not clear what gives rise to the first injection of particles with a power law spectrum. Polarisation observations are of great interest in the study of these expanding models and Dr. VAN DER LAAN noted the steep rate of change at maximum intensity to be in agreement with the model. However one should remember that the optical variations, which are probably of a different nature, are also accompanied by strong polarisation changes; Dr. MORRISON has tried to interpret these by comparison with the situation in the pulsar. In the same connection Dr. REES constructed a very economical model where he used the relativistic particles, that first are seen in these bursts to later give rise — after having cooled sufficiently by expansion — to the high velocity absorption red shifts found in some quasi-stellar objects; this leads to the very exciting possibility that by an analysis of these absorption lines one may learn something of the chemical composition of the relativistic particles. Among the rapid variables mention was also made a number of times of the curious object BL Lacertae and it was stated that this may be a galactic object. If so, it might provide us with an opportunity to study phenomena related to our subject at close range.

The origin of the magnetic flux remains mysterious on all scales; in particular in the expanding models one has to wonder where the magnetic flux for every subsequent burst comes from, unless the particles move parallel to a quasi radial field. Maybe the magnetic flux is related to the electromagnetic conditions around a rotating object. It is also possible that, although Dr. BURBIDGE has stressed the difficulties, the intergalactic field has something to do with the situation. As mentioned by Dr. VAN DER LAAN it may be possible to use polarisation observations to distinguish between the different cases.

A very fundamental question remains in the double sources. One can envisage two rather different situations, namely, I) that the particles are accelerated in the nucleus and later fill up the two regions where the emission takes place, or II) as has been suggested by Dr. BURBIDGE in particular, that whole objects are ejected which then accelerate the particles in situ. The most suggestive evidence for the latter point of view probably comes from the optical jet in M 87, 3C 33 with components that subtend only a very small solid angle as seen from the associated galaxy, and perhaps also Cygnus A, if, as Dr. KELLERMANN tentatively suggested, one of the components would again be a double radio source. Perhaps one should put in the same category also the blue objects in NGC 1275 reported by Dr. SANDAGE. It seems to me that at this time the basic issue is open; it may well be that the possibilities I and II are not mutually exclusive, that in some objects the one, and in others the other is realized. Detailed polarisation and x-ray observations will be helpful in this connection. The latter are particularly useful because of the short lifetime of x-ray electrons which makes it impossible to transport them a great distance from their point of origin. Somewhat as an aside, I note that if possibility II were realised, every giant elliptical galaxy would during its radio phase eject a number of fairly massive, fast moving bodies. With one giant elliptical per 10^4 Mpc^3, as estimated by Dr. SCHMIDT, and with a hundred of these bodies ejected per giant elliptical the space density would become of the order of $10^{-2}/\mathrm{Mpc}^3$ and clearly Dr. BURBIDGE would be able to put these objects to good use! But I believe that in a strictly local theory of the quasi-stellar objects one would need a higher space density than this.

We finally come to the topic of evolution of nuclei in relation to the evolution of the Universe. Dr. SCHMIDT showed that the observations seem to indicate that the number density of the quasi-stellar objects increases into the past approximately as $(1 + z)^6$ out to a red shift of about 2.5. What happens at larger values of z is unclear; perhaps the density remains constant or maybe it even decreases. Assuming that the luminosity function remains constant, that is assuming that there is the same proportion of low luminosity objects at $z = 2.5$ as in our neighbourhood, Dr. SCHMIDT found that there are approximately 10^7 quasi-stellar objects observable (in principle) at this moment and he contrasted this to the only 50,000 quasi-stellar objects believed to exist in the Universe at the present time. Dr. SALPETER discussed similar statistics in the framework of a Lemaître universe and was able to reproduce the peak near $z = 2$ that seems to exist in most of the observational material. Subsequently a discussion developed as to whether this peak was meaningful and at this moment the observers seem to disagree. It is worth noting that also in Dr. SALPETER'S analysis some evolution had to be invoked to fit the counts for values of z somewhat below 2. Professor OORT related the cut off in the distribution of the quasars to the formation process of galaxies and expressed the opinion that the galaxies form only comparatively late in the expansion of the Universe; one must also take into account that after the galaxies have formed more time is needed to form the nuclei by the kind of process that Prof. SPITZER has discussed. Of course Dr. SCHMIDT'S $(1 + z)^6$ law is at the moment not at all quantitatively understood.

Dr. SANDAGE discussed the conclusions to be drawn from ordinary galaxies and he confirmed the optical similarity of the giant E galaxies independent of their radio emission. However only the most luminous E-type galaxies seem to have the ability to become strong radio sources. The situation appears slightly different perhaps in the quasi-stellar objects, for which Dr. SCHMIDT found that the radio and optical fluxes are only correlated by some probability distribution of great width; however the centre of the probability distribution shifts to higher radio fluxes when the optical flux increases.

The Log N/Log S relation was discussed by Drs. HOYLE and Rees this morning, and it appears that there was a considerable divergence of opinion on the reliability and completeness of the data and the significance of the steep slopes found by most radio and optical observers. The need for further identifications in the 3C revised catalogue was stressed repeatedly. It would be most valuable to have also Log N-Log S relations for x-ray and infrared objects, but with only one or two x-ray sources detected, and a dozen of extra-galactic infrared sources this can not yet be done. The only thing one can do is to look at the x-ray and infrared backgrounds which were discussed this morning by Dr. Friedman and Dr. Morrison. If sources are responsible for the background we may get direct information on the sources, if not, at least upper limits. At this moment however, as Dr. Morrison pointed out, the experimental situation in the infrared is extremely unclear while, as Dr. Friedman noted, in the x-ray region an infinity of mechanisms involving the inverse Compton effect, Bremsstrahlung and other processes all can explain the available, rather incomplete, data. Only a much larger sample of x-ray sources can help us to reach an unambiguous conclusion about the x-ray background.

DISCUSSION

Chairman: L. SPITZER JR.

AMBARTSUMIAN

I am delighted with the discussion given by Prof. WOLTJER. However, I have some comments. I begin with the last point: the limits of conventional psysics. Professor WOLTJER speaks about the limits of conventional physics, he means the conservation laws. I think that the problem is not only connected with the conservation laws, there is also the question whether the contemporary system of laws of physics is adequate to describe the phenomena in nuclei of galaxies and quasars. This is the question and it is difficult of course to answer. Of course nobody has shown that the laws of contemporary physics are surpassed, but at the same time contemporary physics has not shown its ability to describe these objects, not to speak about the prediction of them.

It seems to me that point 8, as written on the blackboard, is not an exact description of the situation. The situation is, we may say, that it must be shown that the limits have not yet been surpassed, but at the same time we must know that we have not reached the explanation of the phenomena on the basis of contemporary physics; and they have not been predicted at all.

The second thing is: I think that point 5 is a very good one, very important. I want to emphasise the importance of point 5. The fundamental question, of whether particles, or objects which accelerate particles, are ejected, remains open; of course, if it remains open, you can bring the arguments in favour or against. Now I think that it is necessary to formulate clearly the existence of two approaches. First, observe the expansions and ejections. Are they primary phenomena or are they only the consequence of condensation processes? Therefore I think that it is worth while saying that there are two possibilities, and one of the problems that we have before us is to clarify whether the nuclei are primary, or whether, as some people think, they are the consequence of the contractions.

The last point is about the first paragraph — "Formation of compact nuclei by interaction of stars and gas is possible". What does it mean to say that it is possible? We must show then realistically that we can form something like the nucleus. We can explain and show what the luminosity of such bodies, of such a system, will be, what masses it can eject and how long it must last, since apparently the activity of a nucleus is not so short a process, for now there is evidence that the nuclei of normal galaxies are also showing these processes. Therefore I think that the statement is too optimistic, and perhaps it is necessary to say that some work has been done in this direction, and it is not excluded that good results may come from this; but I think it is too optimistic, and too early, to make such a highly qualified statement.

SPITZER

If I understand Professor AMBARTSUMIAN correctly, he is questioning the emphasis in the first point. The theoretical picture which has been presented does indicate that through reasonable processes a high density of stars can result at the center of a galaxy. However, it is still conjectural whether the observed activity of nuclei can be explained by known physical effects in a region of high star density.

AMBARTSUMIAN

I agree, but at the same time I say that the only thing that we know about the nuclei is that they are active and we cannot even see the nucleus, the central part of the galaxy. We know that they are very active bodies, and therefore to say that we can explain the nucleus is something that is still beyond us, therefore I agree with you that your work is very important for the problem of the nucleus, but I think it was shown only just as you have said — that the formation of the region of high activity is possible according to mechanisms you described yesterday.

HOYLE

Since this question of conventional physics has been raised, I would like to comment from the point of view that I think it is very unlikely that a creature evolving on this planet, the human being, is likely to possess a brain that is fully capable of understanding physics in its totality. I think this is inherently improbable in the first place, but, even if it should be so, it is surely wildly improbable that this situation should just have been reached in the year 1970. Therefore I conclude that it is almost certain that probably conventional physics is not complete, and that what occurs in the Universe does go beyond the limits of conventional physics. Of course this is not to say that the phenomena we have been dealing with this week go beyond conventional physics, the physics of 1970. However, insofar as astronomy has been in a position to find something basically new, the best hope in a hundred years does lie in these phenomena. My use of the word "hope" indicates the difference between what I might call the unconventional school and the conventional school. The unconventional school doesn't disagree with the conventional school over explicit issues. The difference is that the unconventional school hopes for something new, whereas those with a conventional point of view seem to me to hope that their work will never lead to anything of real importance. This seems to me a truly extraordinary outlook.

WOLTJER

I fully agree with most of what Professor HOYLE has said. I think, however, that it is important to explore the outer limits of conventional theory because only in that way can one make a convincing case that one must go beyond it.

HOYLE

As a general method of procedure I agree, but how long does one continue the exploration? If one insisted on completeness, exploration would last for ever.

AMBARTSUMIAN

I agree with you that it is not necessary to explore, but you know that it is very difficult to say if there will be a moment when all possibilities of conventional physics will be explored. I think it is very important to try to find this explanation on the lines of conventional physics, but to have in mind that there are possible violations.

WHEELER

I don't know anybody who was more conventional than MAX PLANCK, and I don't know anybody who would have had the strength of character to win through to the discovery he made, except somebody who resisted every possible attempt to invent something new except when it was absolutely imperatively forced on him.

SPITZER

Maybe the conventionalists hope to be able to repeat EDDINGTON's famous comment when the predictions were verified for the EINSTEIN deflection by the sun, I believe he is reported to have said "foiled again, we have learned nothing new about nature".

SALPETER

I just have a negative although uncontroversial point. I am surprised that there was little discussion on a point which I think we all agree is rather important, but I guess there is little information on it, namely whether quasars can be just one evolutionary stage in the life of ordinary galaxies, or whether they are quite separate objects. I am surprised that we have not argued about this more.

VAN DER LAAN

Prof. SCHMIDT has shown that for each absolute optical luminosity we have a similar radio luminosity distribution, while the centre of that distribution shifts with increasing optical luminosity. Professor WOLTJER said that something similar was concluded by Dr. SANDAGE concerning the radio luminosity of radio galaxies. I had a different impression, because if that were the case the intention of the search for more distant clusters by means of empty radio source fields is jeopardised. As you go to weaker radio fluxes you automatically, in the mean, go to intrinsically greater radio luminosities. If you were also, statistically, going to intrinsically greater optical luminosities you wouldn't get the handle you want for the determination of q_0.

SANDAGE

No. I do not believe that the optical luminosity of the first ranked cluster is correlated with its radio luminosity.

E. M. BURBIDGE

I'd like to return to the point raised by SALPETER. I think the trend of the discussion and the basis behind most people's arguments has been that the QSOs are at cosmological distances. For those who accept this postulate, the distribution of the QSOs then requires an evolutionary effect of the type discussed by SCHMIDT, perhaps combined with a cosmological model of LEMAÎTRE type for the universe. It then seems to me that, in such a framework, these arguments necessarily imply that the QSOs must represent the early or formation phases of galaxies, rather than the end points of collapse of old galaxies to a high-density state. Is this so, or is it not so? Does not acceptance of the conventional cosmological interpretation of redshifts mean that one must believe the QSO phenomenon to be connected with the formation of galaxies?

McCrea

What Dr. Burbidge has just said is what I should have argued had I developed the papers that are summarized very briefly indeed in the synopsis. I share Salpeter's surprise that we have not gone into this, although obviously in one week we couldn't develop all possible points of view.

Kellermann

I'd like to comment againt on the interpretation of the radio variations. First, there is no need to require that the large energy which is generated in a time scale of a year be produced continuously for 10^6 years. There are something like five or ten objects in the sky which are working at this rate now. The number that's been discussed for the total number of observable quasi-stellar objects is something like 10^6 or 10^7, so an individual source would only have to work at this rate for maybe one to a hundred years. I think what this means is that the total energy requirement of 10^{60} or 10^{61} ergs that we have accepted for a long time, may, at least in some sources, be generated in something like a hundred years, rather than 10^6 or 10^8 years that might have otherwise been supposed. Secondly, neither van der Laan nor I have ever suggested that the very simple mathematical model of a uniform, isotropic, homogeneous, instantaneously created source, which expands with uniform velocity and conservation of flux and has only expansion losses, actually exists in the real world. There is one case, 3C 120, where the data quantitatively agree with this model. For the rest of the sources the data suggest the more general model of a cloud of relativistic particles which is initially optically thick, at some frequencies, and that, due to expansion, the optical depth of the cloud changes, causing the flux density to change, in the qualitative way that you see a burst which propagates towards longer wavelengths and with reduced amplitude. But certainly in a few cases there is direct evidence that the particles are accelerated over a finite period of time, that the expansion rate is not uniform, and the flux is not conserved. The general picture is, however, firmly supported by the data. Further observations of intensity and angular size variations will further specify the details of the expansion and, even more important, the generation process.

CONCLUSIONS

CONCLUSIONS

a) *Observational*

1) It has become increasingly clear that a large fraction of galactic nuclei have various degrees and forms of activity.

2) Matter is ejected from active galactic nuclei and QSOs.

3) There is strong evidence that massive clouds of gas, relativistic particles and perhaps coherent objects are ejected.

4) Very high star density exists in the nucleus of M 31 and probably in the nucleus of our Galaxy (see papers - OORT, SANDAGE).

5) There is increasing evidence that groups of galaxies with positive energy may exists. Their existence would raise problems for which there is at present no understanding.

6) The discovery of strong infrared fluxes has greatly increased estimates of the total power radiated from certain active nuclei.

7) It is now known that in the nuclei of many normal galaxies and strong radio sources and in QSOs there exist small radio components (diameter of the general order of 10^{18} cm).

8) M 87 is an x-ray source, and weaker evidence exists for other extragalactic sources at the present level of detectability.

9) There is extensive evidence of variability over a wide range of the electromagnetic spectrum in most of the active galactic nuclei and QSOs.

10) Galactic nuclei with substantial overabundances of some elements heavier than helium may exist.

b) *Theoretical*

1) Formation of compact condensations in galaxies by interaction of stars and gas is possible, and may play a role in the initiation and development of activity in galactic nuclei.

2) A consistent picture in which nuclei evolve through phases of increasing density and decreasing angular momentum can be constructed.

3) The formation of massive objects with strong gravitational fields ($2\ GM/c^2\ R \approx 1$) is possible in galactic nuclei.

4) The possibility of two opposite approaches is noted:

   a) The nuclei are primary;

   b) They are formed by contractions.

5) Energy and mass are ejected in bursts of various intensities and time scales.

   Energy per year $\sim 10^{52}$ ergs per galaxy, and considerably more in QSOs, if these are at cosmological distances. Total energy up to $10^{60} - 10^{62}$ ergs/object. Typical mass ejection rates are $1\ M_\odot/\mathrm{yr}$.

6) It remains an open question whether in some cases galactic nuclei eject relativistic particles or coherent objects which generate relativistic particles.

7) High efficiencies of conversion into relativistic electrons are possible.

8) Evolutionary effects are important in QSOs.

9) There is no conclusive evidence that the limits of conventional physics have been surpassed; however, many phenomena are still not adequately explained.

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CONCLUSIONS

a) *Relatives à les observations*

1) Il est apparu de plus en plus évident qu'une grande part des noyaux galactiques sont le siège d'activités de forme et d'intensité différentes.

2) Les noyaux galactiques actifs et les QSOs éjectent de la matière.

3) Il est très probable que cette éjection concerne de massifs nuages de gaz, des particules relativistes et peut-être aussi des objects cohérents.

4) Le noyau de M 31 et problablement aussi celui de notre Galaxie possèdent des densités stellaires très élevées (v. articles - Oort, Sandage).

5) Il apparaît de plus en plus probable qu'il existe des groupes de galaxies à énergie positive. Leur existence poserait des problèmes dépassant nos possibilités actuelles du compréhension.

6) La découverte de forts flux infra-rouges a porté à accroître considérablement pour certains noyaux actifs les estimations quant à l'énergie totale irradiée.

7) On sait maintenant que les noyaux de nombreuses galaxies normales et de radiosources fortes, ainsi que les QSOs, contiennent des composants radio de dimensions plus réduites (diamètre de l'ordre de 10^{18} cm).

8) M 87 est une source de rayons X, et nos possibilités actuelles de détection laissent entrevoir la possibilité d'autres sources extragalactiques.

9) La plupart des noyaux galactiques actifs et des QSOs présentent une variabilité manifeste sur une grande partie de leur spectre électromagnétique.

10) Il existe peut-être des noyaux galactiques contenant des quantités anormalement élevées d'éléments plus lourds que l'hélium.

b) *Théoriques*

1) L'interaction entre étoiles et gaz peut donner naissance à des condensations compactes dans les galaxies, ce qui pourrait jouer un rôle dans l'apparition et l'évolution d'activité dans les noyaux galactiques.

3) Il est possible de construire un modèle cohérent dans lequel les noyaux traversent des phases de densité croissante et quantité de mouvement angulaire décroissante.

3) Dans les noyaux galactiques peuvent se former des objets massifs à fort champ gravitationnel ($2\ GM/c^2 R \approx 1$).

4) Quant aux noyaux, deux hypothèses opposées sont possibles:
   a) ils sont primitifs;
   b) ils se forment à la suite de contractions.

5) L'éjection d'énergie et de masse a lieu par « paquets » d'intensité et d'échelle temporelle différentes.
Emission annuelle d'énergie: de l'ordre de 10^{52} ergs par galaxie, beaucoup plus dans les QSOs, s'ils se trouvent à des distances cosmologiques.
Emission totale d'énergie: jusqu'à 10^{60} — 10^{62} ergs par objet.
Rythme d'éjection de la masse: de l'ordre de $1\ M_\odot$/an.

6) On ne sait pas encore si les noyaux galactiques peuvent ou non éjecter dans certains cas des particules relativistes ou des objets cohérents émettant des particules relativistes.

7) De forts rendements de conversion en électrons relativistes sont possibles.

8) Les effets évolutifs jouent un rôle important dans les QSOs.

9) Rien ne permet de conclure que les limites de la physique conventionnelle aient été dépassées; cependant beaucoup de phénomènes n'ont pas encore reçu d'explication adéquate.

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SUGGESTIONS FOR FUTURE WORK

The following list of research problems includes several which seem important for the study of active galactic nuclei and quasars, but which might otherwise be overlooked. Many of the most important areas for future work are not mentioned, since their importance seems clear. In particular, the list makes no reference to the primary observational research programs in radio, infrared, optical and shorter wavelengths, which must evidently be pushed vigorously if our understanding of this important and central field of astronomy is to be increased. Some detailed suggestions for additional work in these and other programs are contained in the individual papers presented during the Study Week.

1. It is desirable to carry out a morphological study of the forms of Seyfert galaxies, N galaxies, compact galaxies, and of supergiant D-galaxies which sometimes are strong radio-sources and whose inner structure suggests inherent instability.

2. The development of spectroscopic classification for the same objects listed above is recommended.

3. The study of the connection between morphological and spectroscopic features and the comparison of the results of the two approaches (form and spectroscopic) seems to indicate fruitful new lines of investigation.

4. Continuing research should be pursued on the role which active galactic nuclei may play in the evolution of the chemical abundance of elements in galaxies.

5. Groups of galaxies with one discrepant redshift should be intensively studied.
6. There are indications that some galaxies may be in the process of formation. Further study of such cases is required.
7. Theoretical study of the evolution of compact rotating systems, with and without magnetic fields, is desirable.
8. More intensive and systematic study of the variability of active objects in optical and radio frequencies is highly desirable.
9. More detailed studies of the size and structure, and of the variations in intensity and size, of the compact radio sources are required in order to understand the process of generation of relativistic particles.

SUGGESTIONS DE TRAVAIL POUR LE FUTUR

Cette liste comprend de nombreux problèmes qui semblent importants aux fins d'une meilleure connaissance des noyaux galactiques et des quasars, et qui auraient autrement couru le risque d'être négligés. Beaucoup de domaines d'importance fondamentale pour les recherches futures ne sont cependant pas mentionnés; tel est en particulier le cas de nombreux programmes de recherches et d'observation en ondes radio, infra-rouge, lumière visible et longueurs d'onde plus courtes encore, où le progrès de la connaissance de secteurs fondamentaux de l'astronomie apparaît nécessiter une vigoureuse impulsion. En outre les articles présentés au cours de la Semaine d'Etude contiennent des suggestions détaillées quant au travail à accomplir dans ces programmes et dans bien d'autres domaines encore.

1. Il apparaît opportun de procéder à une étude morphologique de la forme des galaxies de Seyfert, des galaxies N, des galaxies compactes et des galaxies supergéantes D, qui quelquefois sont d'intenses radio-sources et qui semblent posséder une structure interne dénotant une instabilité inhérente.

2. Une classification spectroscopique des objets en question devrait être élaborée et approfondie.

3. D'intéressantes perspectives semblent être offertes par l'étude des rapports entre les aspects morphologiques et spectroscopiques desdits objets et par la comparaison entre les résultats des études morphologiques et spectroscopiques.

4. Il faudra poursuivre les recherches au sujet du rôle éventuel des noyaux galactiques actifs dans l'évolution de l'abondance des éléments chimiques dans les galaxies.

5. Une attention particulière devra être consacrée aux groupes de galaxies présentant un déplacement anormal vers le rouge.

6. Certains faits semplent indiquer que des galaxies sont peut-être en voie de formation. Ces cas nécessitent un ultérieur approfondissement.

7. Il apparaît opportun de procéder à une étude théorique de l'évolution des systèmes compacts en rotation, pourvus ou non de champ magnétique.

8. Il apparaît opportun de procéder à une étude intensive et systématique de la variabilité des objets actifs, tant en lumière visible qu'aux fréquences radio.

9. La compréhension du processus d'engendrement de particules relativistes nécessite une étude plus approfondie des dimensions, de la structure et des variations d'intensité et de dimensions des radiosources compactes.

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