PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA

16

SEMAINE D'ETUDE

SUR

LE PROBLEME DES POPULATIONS STELLAIRES

(20-28 MAI 1957)

PONTIFICIA
ACADÉMIA
SCIENTIARVM

EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA

MCMLVIII

LE PROBLEME DES POPULATIONS STELLAIRES

ERRATA

Page XII, par. 3, l. 1 : *au lieu de* proceeding *lire* proceedings
» XX, l. 30 : *au lieu de* Warney *lire* Warner
» 76, l. 6 et l. 10 : *au lieu de* M *lire* *M*
» 107, par. 2, l. 10 : *au lieu de* 6000 pc lire 600 pc
» 184, l. 3 : *au lieu de* photoelectrical *lire* photoelectrically
» 195, par. 3, l. 3 : *au lieu de* extragalctic *lire* extragalactic
» 197, l. 3 : *au lieu de* photoeletrically *lire* photoelectrically
» 201, par. 1, l. 7 : *au lieu de* two *lire* too
» 234, par. 2, l. 19 : *au lieu de* assumption *lire* assumptions
» 281, par. 4, l. 1 : *au lieu de* usully *lire* usually
» 282, l. 4 : *au lieu de* It *lire* If
» 310, l. 3 : *au lieu de* degrees *lire* degree
» 325, titre, l. 2 : *au lieu de* determinded *lire* determined
» 327, par. 2, l. 6 : *au lieu de* type *lire* types
» 442, par. 3, l. 2 : *au lieu de* then *lire* than
» 496, par. 2, l. 1 : *au lieu de* form *lire* forms
» 501, l. 10 : *au lieu de* in region *lire* in the region
» 503, l. 2 : *au lieu de* *z*-motion. *lire* *z*-motion).

PONTIFICIA ACADEMIA SCIENTIARVM

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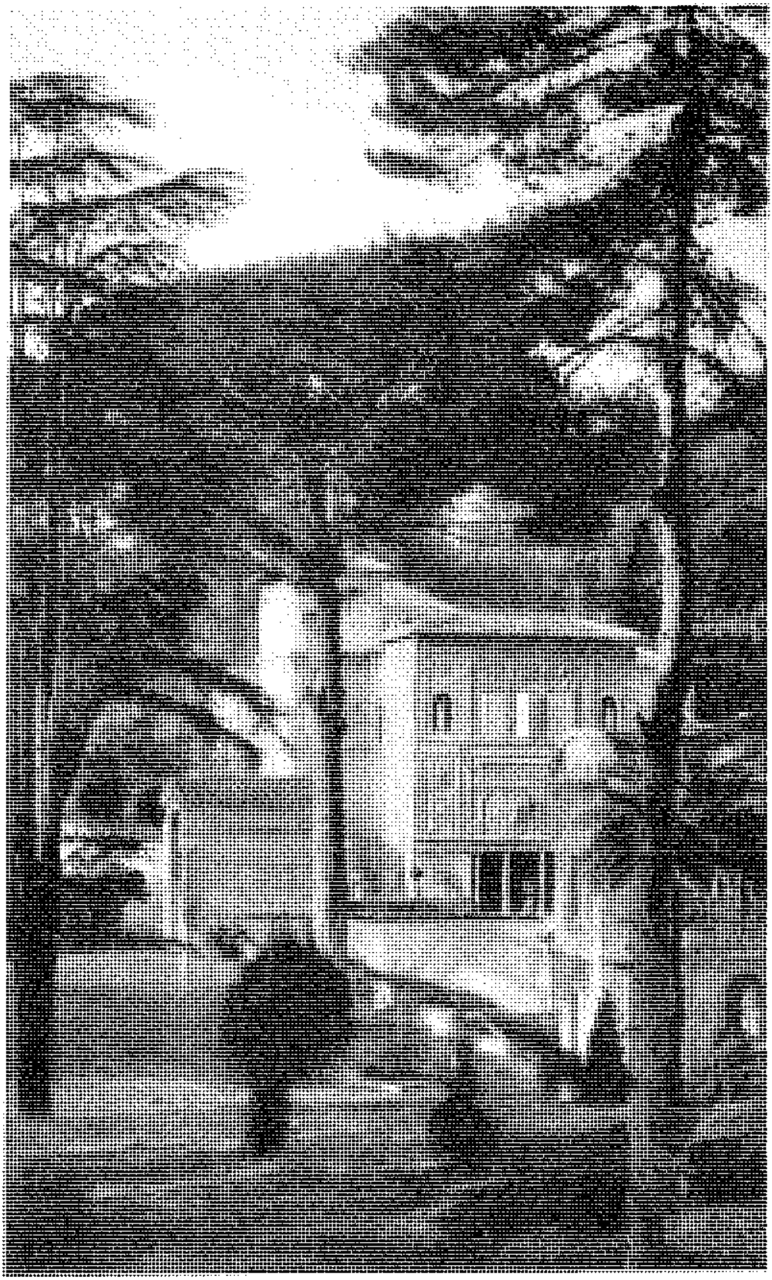

INTRODUCTION

When the Pontifical Academy of Sciences decided to organise from time to time a Semaine d'Étude, it was intended that the first of the series should be on an astronomical theme. The then Director of the Vatican Observatory, Dr. J. STEIN, S.J., was commissioned to organise the Semaine. Not long afterwards the preparations were halted by the outbreak of war. After the war Father STEIN resumed the project, but died before it could be realised. The Chancellor of the Academy asked me, as Father STEIN's successor, to undertake the task.

The General Assembly of the International Astronomical Union held in Dublin in August 1955 provided a good opportunity for discussing the project with other astronomers. Various topics had already been considered and rejected as not suited for the particular type of conference in view, or as not yet ripe for discussion. The topic finally chosen, the Problem of Stellar Populations, first suggested to me by Dr. J.J. NASSAU, proved to be eminently suitable. Ever since BAADE, in his 1944 paper, distinguished two types of stellar populations, the subject has aroused great interest among astronomers and has led to a flood of researches in various branches of astronomy. Nevertheless, up to that time it had not been the subject of any conference or symposium. The time now seemed just right for a thorough discussion of all the problems involved, both observational and theoretical. Those astronomers to whom I proposed it agreed enthusiastically. A small committee was formed to prepare the conference, consisting of W. BAADE, J.J. NASSAU, J.H. OORT, M. SCHWARZSCHILD and D.J.K. O'CONNELL (chairman); later on A. BLAAUW was co-opted as a member. The preliminary meetings of the committee were held in Dublin. The work of organisation was subsequently carried on by correspondence, aided by occasional meetings of some of the committee members. The scientists to be invited were chosen with a view to covering adequately the various aspects of the subject, both in the formal papers and in the discussions. As explained in the Academy's rules for the Semaines d'Étude, the number of participants is strictly limited, in order to ensure freer and more intimate discussions.

The formal opening of the Semaine took place on May 20 in the Consistorial Hall in the Vatican, where Pope PIUS XII received the members in solemn audience, together with the Cardinals present in Rome and the Diplomatic Corps. The subsequent meetings were held in the Academy building, the beautiful 16th century Casino of PIUS IV in the Vatican gardens, on May 21, 22, 24, 25, 27 and 28. There were in all twelve sessions of about three hours each. At each session one or other of the members was asked to preside. The name of the Chairman is given at the beginning of the discussion after each paper. Papers, or abstracts, were reduplicated and distributed to the members beforehand.

The proceeding were taken down on tape-recorders. In addition it was considered advisable to have notes of the discussions taken by astronomers. Father P.J. TREANOR, S.J., of the University Observatory, Oxford, who has had much experience in reporting meetings of the Royal Astronomical Society, was invited to attend the Semaine to take charge of the reporting. At each session he was assisted by a recorder chosen in rotation from the participants. Immediately after each session the recorders' notes were collated and Father TREANOR then dictated them to a typist. The reports were reduplicated and were ready for distribution to the members before the next session. The speakers were asked to correct their remarks as soon as possible, while the matter was still fresh in their minds. These corrections were collated by Father TREANOR and a corrected version of the discussions was prepared. An expert in each particular field was asked to sub-edit this second version. Later on, after the meeting, I checked over the revised versions of the discussions with the tape-recordings and was able thus to correct some points and to amplify some statements. When these edited discussions were in proof, copies were sent to all those who had taken part, and their emendations and additions have been incorporated in the final text.

This scheme worked very well, thanks to the recorders and sub-editors and the secretarial staff, and thanks most particularly to Father TREANOR who shouldered the main burden of this work during the Semaine. Without his expert help and devoted labours it would not have been possible to present so complete and authentic a report. The discussions were in fact very lively and sometimes very prolonged, but it is believed that all important points have been reported.

The Committee felt that it would be a great advantage to prepare a summary of the work of the Semaine that could be submitted to the members before the end of the meeting, so as to clarify ideas and bring the many different approaches to the central theme into relation with each other, and also to facilitate the drawing up of conclusions and recommendations. Mr. HOYLE and Professor OORT kindly consented to undertake this by no means easy task, the former from the physical, and the latter from the astronomical, point of view. The two sessions on the final day of the meeting were devoted to the summaries and their discussion. These masterly summaries form a very important contribution to the work of the Semaine.

The Academy's rules for the conduct of the Semaine provide that at the end of the meeting conclusions be drawn up, present-ing the results of the discussions, as well as proposals for future research. A preliminary statement of the conclusions was issued to the press at the end of the Semaine. The definitive formulation of the conclusions and suggestions for research will be found at the end of this volume.

There remains the pleasant duty of thanking all those colleagues who took part in the Conference and who devoted so much valuable time and took such pains to make it a success. To the Pontifical Academy of Science, especially to the President, Padre AGOSTINO GEMELLI, O.F.M., and the Chancellor, Dr. PIETRO SALVIUCCI, I wish to express, on behalf of all the participants, our heartfelt thanks for the facilities put at our disposal and for the excellent organisation which contributed so much to lighten our labours.

D.J.K. O'CONNELL, S.I.
Académicien Pontifical Surnuméraire

LA SEMAINE D'ETUDE
SUR LE PROBLEME
DES POPULATIONS STELLAIRES

Le but des « Semaines d'Etude » de l'Académie Pontificale des Sciences a été ainsi défini par son 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. 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 procédé pareil semble devoir être particulièrement utile sous ce rapport: 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: « Le Problème des Populations Stellaires » (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 des différentes branches de l'astronomie, spécialistes de la question. Son but était de discuter dans une « Semaine d'Etude » ayant pour titre « Le Problème des Populations Stellaires » de cet important sujet; 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 de photométrie et de spectroscopie stellaire, de dynamique stellaire,

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(1) Cette « Semaine d'Etude » sur « Le Problème des Populations Stellaires » est la quatrième de la série.

La première « Semaine d'Etude » a eu lieu du 6 au 13 juin 1949; elle a été dédiée au « Problème 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 7-ème 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 1951; elle a été dédiée au « Problème des Microséismes », et a été presidée 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 médes spécialistes de la distribution des étoiles dans notre galaxie et dans les autres, des mouvements et de la composition des étoiles, des nuages interstellaires de gaz et de poussière, et même des spécialistes de physique nucléaire.

La présidence de cette « Semaine d'Etude » sur « Le Problème des Populations Stellaires » a été confiée par le Président de l'Académie Pontificale des Sciences, S. E. le Rév.me Père AGOSTINO GEMELLI O.F.M., à l'Academicien Pontifical Surnuméraire le Rév.me Père DANIEL O'CONNELL S.I., Directeur de la « Specola Vaticana » de Castelgandolfo, et l'organisation générale au Chancelier de l'Académie Pontificale des Sciences Dr. PIETRO SALVIUCCI.

Ont été invités à la réunion les savants suivants:

S. E. Prof. Dr. GIUSEPPE ARMELLINI, Académicien Pontifical, Directeur de l'Observatoire Astronomique et Professeur Ordinaire d'Astronomie à l'Université de Rome. - *Rome* (Italie).

Dr. WALTER BAADE, du « Mount Wilson and Palomar Observatories ». - *Pasadena, Calif.* (U.S.A.).

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moires. Les comptes-rendus de la « Semaine d'Etude » ont été publiés dans le 12-ème 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 dédiée au « Problème des Oligoéléments dans la vie végétale et animale », et a été présidée par l'Académicien Pontifical, S. E. JOSÉ 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 14-ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 630 pages.

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

Prof. ADRIAN BLAAUW, Professeur adjoint du « Yerkes Observatory » de l'Université de Chicago et Directeur adjoint des Observatoires Yerkes et McDonald. - *Williams Bay, Wis.* (U.S.A.).

S. E. Prof. Dr. HERMANN ALEXANDER BRÜCK, Académicien Pontifical, Professeur d'Astronomie à l'« Institute for Advanced Studies » et Directeur du « Dunsink Observatory ». - *Dublin* (Irlande).

Dr. DANIEL CHALONGE, de l'Institut d'Astrophysique et Astronome titulaire de l'Observatoire de Paris. - *Paris* (France).

Prof. Dr. WILLIAM A. FOWLER, Professeur de Physique au « California Institute of Technology ». - *Pasadena, Calif.* (U.S.A.).

Prof. Dr. OTTO HECKMANN, Directeur de la « Hamburger Sternwarte » et Professeur Ordinaire d'astronomie à l'Université de Hamburg. - *Hamburg* (Allemagne).

Dr. GEORGE H. HERBIG, du « Lick Observatory ». - *Mount Hamilton, Calif.* (U.S.A.).

Mr. FRED HOYLE, du « St. John's College ». - *Cambridge* (Angleterre).

Rév.me Père JOSEF JUNKES S.I., Préfet du Laboratoire Astrophysique de la « Specola Vaticana » de Castelgandolfo et Académicien Pontifical Surnuméraire. - *Cité du Vatican* (S.C.V.).

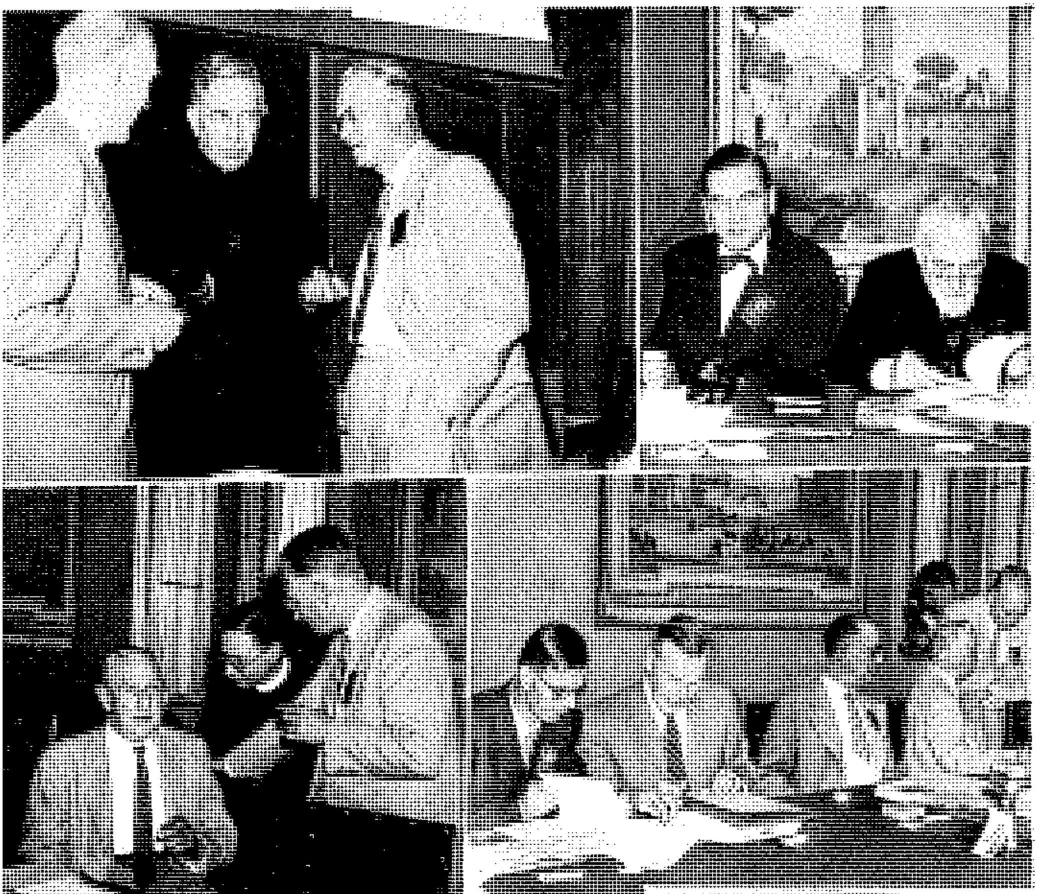
S. E. le Rév. Prof. Dr. GEORGES LEMAITRE, Académicien Pontifical, Professeur de Méthodologie mathématique et d'Histoire des sciences physiques et mathématiques à l'Université Catholique de Louvain. - *Louvain* (Belgique).

Prof. BERTIL LINDBLAD, Directeur du « Stockholms Observatorium » et Professeur titulaire d'astronomie à l'Université de Stockholm. - *Stockholm* (Suède).

Dr. WILLIAM W. MORGAN, Astronome au « Yerkes Observatory » de l'Université de Chicago. - *Williams Bay, Wis.* (U.S.A.).

Prof. Dr. JASON J. NASSAU, Directeur du « Warney and Swasey Observatory ». - *East Cleveland, Ohio* (U.S.A.).

Rév.me Père DANIEL O'CONNELL S.I., Directeur de la « Specola Vaticana » de Castelgandolfo et Académicien Pontifical Surnuméraire. - *Città del Vaticano* (S.C.V.).



Prof. Dr. JAN HENDRIK OORT, Directeur de la « Sterrewacht Leiden ». - *Leiden* (Pays-Bas).

Dr. EDWIN E. SALPETER, du « Laboratory of Nuclear Studies » de l'Université de Cornell. - *Ithaca, N.Y.* (U.S.A.).

Dr. ALLAN R. SANDAGE, du « Mount Wilson and Palomar Observatories ». - *Pasadena, Calif.* (U.S.A.).

Prof. Dr. MARTIN SCHWARZSCHILD, du « Princeton University Observatory » et Professeur d'astronomie à l'Université de Princeton. - *Princeton, N.J.* (U.S.A.).

Prof. Dr. LYMAN SPITZER Jr., Directeur du « Princeton University Observatory ». - *Princeton, N.J.* (U.S.A.).

Prof. Dr. BENGT STRÖMGREN, Directeur du « Yerkes Observatory » de l'Université de Chicago. - *Williams Bay, Wis.* (U.S.A.).

Prof. A. D. THACKERAY, Directeur du « Radcliffe Observatory ». *Pretoria* (Afrique du Sud).

Le Président de la « Semaine d'Etude » a fait appel au Rév.me Père PATRICK TREANOR S.I. de l'« Oxford University Observatory » comme Secrétaire scientifique de la Réunion.

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

Tous les invités, à l'exception du Rév.me Père J. JUNKES S.I., qui n'a pas pu intervenir, ont participé à la Réunion.

Ont aussi participé à la réunion: en qualité d'interprète et chef de secretariat Mme VALENTINE PRÉOBRAJENSKI; en qualité de sténographes polyglottes de séance Mlles JOSÉPHINE LUCAS et HERMIONE MONTANÈR; en qualité de chargé de Procès-verbaux Mr DAVID MONTRESOR; en qualité de dactylographes polyglottes Mme LUCIA STRINGER et Mlle PAULETTE ROSSALDI; en qualité de technicien pour la régistration et la projection Mr MAURO ERCOLE aidé par des operateurs de Radio-Vatican. Le Bureau de Presse était confié au Dr. FRANCESCO SALVIUCCI aidé par le Dr. MAX FINOCCHI.

Le Comité de Réception pour les Dames était composé de Mme HÉLÈNE LOTTI, la Comtesse KARINA CALVI DI COENZO, Mme PAOLINA PUNZI, Mlle GIANNA MICELI, Mlle PAOLA RIOSA.

Le lundi 20 mai, premier jour de la « Semaine d'Etude », tous les Participants ont été reçus en Audience Solennelle par le Souverain Pontife qui leur adressa un savant 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 » (1).

Pendant la Semaine, qui se déroula jusqu'au soir du mardi 28, les travaux scientifiques se poursuivirent sans interruption, sauf le jeudi 24 pour visiter la « Specola Vaticana »; les discussions des differents rapports se déroulèrent groupées selon l'affinité des sujets.

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.; chaque séance était présidée par l'un des Participants à la réunion.

La réussite de la « Semaine d'Etude » a pleinement satisfait les illustres congressistes qui ont voulu envoyer les télégrammes suivantes:

« S. E. AGOSTINO GEMELLI, Président de l'Académie Pontificale des Sciences. Cité du Vatican. — Les participants à la Semaine d'Étude sur les Populations Stellaires expriment leurs sentiments de profonde reconnaissance au Président de l'Académie Pontificale des Sciences pour avoir bien voulu leur donner la possibilité de participer a la Semaine d'Étude dans des conditions idéales de recuillement et d'independance intellectuelle stop. — ARMELLINI, BAADE, BLAAUW, BRÜCK, CHALONGE, FOWLER, HECKMANN, HERBIG, HOYLE, JUNKES, LEMAITRE, LINDBLAD, MORGAN, NASSAU, O'CON-

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(1) Voir aux pages suivantes l'Audience, le Discours du Saint Père et la Séance Ordinaire.

NELL, OORT, SALPETER, SANDAGE, SCHWARZSCHILD, SPITZER, STRÖMGREN, THACKERAY ».

« Dr. PIETRO SALVIUCCI, Chancelier de l'Académie Pontificale des Sciences. Cité du Vatican. — Les participants à la Semaine d'Étude sur les Populations Stellaires expriment au Chancellier de l'Académie Pontificale des Sciences leur reconnaissance la plus sincère pour l'impeccable organisation de la Semaine qui leur a permis de discuter en pleine sérénité et d'atteindre des résultats très importants à la fin de leurs travaux stop. — ARMELLINI, BAADE, BLAAUW, BRÜCK, CHALONGE, FOWLER, HECKMANN, HERBIG, HOYLE, JUNKES, LEMAITRE, LINDBLAD, MORGAN, NASSAU, O'CONNELL, OORT, SALPETER, SANDAGE, SCHWARZSCHILD, SPITZER, STRÖMGREN, THACKERAY ».

En ce qui concerne les résultats de la rencontre, les savants participant à la « Semaine d'Etude » ont préféré rédiger tout de suite une Note Préliminaire.

Dans cette Note, publiée par la Presse, ils ont rendu compte immédiatement des résolutions et des recommandations formulées lors de la clôture des travaux.

Ainsi ils purent procéder par la suite plus commodément et plus pondérément à la rédaction définitive de la « Note Collective Finale » prévue par le « Règlement des Semaines d'Etude » et où sont consignées les « Conclusions » tirées des discussions.

Dans les pages qui suivent, après le compte-rendu de l'Audience du Saint-Père et de « Règlement des Semaines d'Etude », sont imprimés les rapports originaux présentés à la Réunion, et les discussions qui les ont suivis.

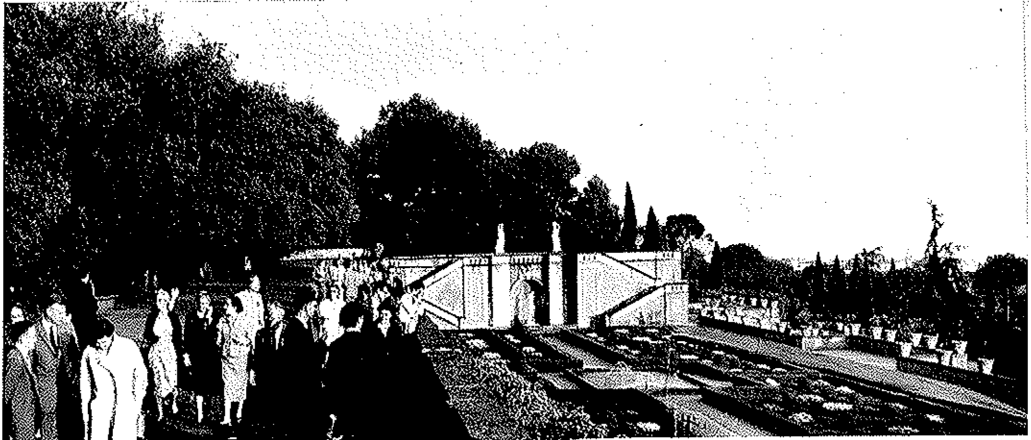
Les « Conclusions » de la « Semaine d'Etude » se trouvent à la fin du présent volume.

A la fin des leurs travaux les Participants à la « Semaine d'Etude » 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 PIE XII. Cité du Vatican. — Les participants à la Semaine d'Etude sur les populations stellaires expriment à Sa Sainteté leur profond respect et leur profonde gratitude. Ils sont particulièrement reconnaissants à Sa Sainteté de ce que, grâce à l'organisation particulière des Semaines d'Etudes, l'Académie Pontificale des Sciences est en état d'offrir aux savants des differents Pays la possibilité de donner à leurs travaux un caractère strictement privé sans intervention de personnes étrangères. Ils ont pu ainsi discuter dans un milieu idéal de paix et de sérénité les importants problèmes mis à l'ordre du jour, ce qui a facilité grandement leur tâche et leur a permis d'atteindre avec moins de difficulté des résultats tangibles. Ils renouvellent au Souverain Pontife l'assurance de leur reconnaissance émue pour l'honneur que Sa Sainteté leur a accordé en les invitant à venir travailler à Son Académie. — ARMELLINI, BAADE, BLAAUW, BRÜCK, CHALOGNE, FOWLER, HECKMANN, HERBIG, HOYLE, JUNKES, LEMAÎTRE, LINBLAD, MORGAN, NASSAU, O'CONNELL, OORT, SALPETER, SANDAGE, SCHWARZSCHILD, SPITZER, STRÖMGREN, THACKERAY ».

A ce télégramme d'hommage et de remerciement, le Saint Père a daigné répondre par le message suivant, envoyé à Son Exc. le Rév.me P. AGOSTINO GEMELLI O.F.M., Président de l'Académie, et signé par Son Exc. Mgr ANGELO DELL'ACQUA, Substitut de la Secrétairerie d'Etat.

« *Sa Sainteté particulièrement touchée noble message distingués savants ayant pris part Semaine Etudes sur Populations Stellaires organisée par l'Académie Pontificale des Sciences, agrée avec satisfaction assurance fructueux résultats session, renouvelle expression haute estime pour illustres chercheurs adonnés étude problèmes de grande portée scientifique et invoque sur leurs personnes et sur continuation de leurs travaux abondantes faveurs divines.* — DELL'ACQUA, *Substitut* ».



Jeudi 24 mai dans l'après-midi le Rév.me Père DANIEL O'CONNELL S.I., Directeur de la « Specola Vaticana » de Castelgandolfo, invita les Participants à une visite détaillée de l'Observatoire Astronomique tandis que le Laboratoire d'Astrophysique leur fut presenté par le Préfet, le Rév.me Père JOSEF JUNKES S.I. Les Participants visitèrent aussi les travaux en cours pour l'installation d'un nouveau réflecteur puissant du type Schmidt spécialement adapté à la résolution des problèmes relatifs à l'évolution stellaire.

A cette occasion ils ont visité aussi les Catacombes de Saint Callixte sur la « Via Appia Antiqua » et l'Abbaye de Sainte Marie de Grottaferrata ou ils ont été reçus par le Rév.me P. Archimandrite ISIDORO CROCE, Supérieur Général de la Congrégation d'Italie des Moines Basiliens.

À Castelgandolfo les savants étaient attendus par le Dr. Gr. Off. EMILIO BONOMELLI, Directeur des Villas Pontificales qui leur a fait visiter en détails le Palais des Papes, les jardins, les ruines de la villa romaine de Domitien, l'ex-Palais des Barberini, et les autres dépendances.

Au cours de leurs travaux les savants ont eu également la possibilité de visiter les Musées Pio-Clementino, Chiaramonti, Etrusque, Egyptien; le Braccio Nuovo; les Galeries des tapisseries, des cartes geographiques; les Stances et la Loggia de Raphaël; la Chapelle de Fra Angelico, la Chapelle Sixtine, l'Appartement Borgia et la Pinacothèque Vaticane avec l'assistance du Prof. Comm. FILIPPO MAGI et du Dr. DEOCLECIO REDIG DE CAMPOS de la Direction Générale des Monuments de la Cité du Vatican.

Ils ont aussi visité la Bibliothèque Apostolique Vaticane et les Archives Secrètes Vaticanes sous la conduite des Rév.mes Préfets Mons. MARTINO GIUSTI et Père Abbé ANSELMO ALBAREDA, O.S.B.; et la Station de Radio-Vatican qui leur fut présentée par le Directeur, le Rév.me P. ANTONIO STEFANIZZI S.I.

Dans l'après-midi du dimanche 26 mai les Participants à la « Semaine d'Etude » ont assisté de la tribune réservée à l'Academie Pontificale des Sciences à la cérémonie qui eut lieu à l'occasion de la Béatification solennelle de la Servante de Dieu MARIE DE LA PROVIDENCE, dans la siècle MARIE SMET, fondatrice des « Religieuses Auxiliatrices des âmes du Purgatoire »; cérémonie au cours de laquelle le Saint-Père vint vénérer la nouvelle Bienheureuse.

Enfin, le mardi 28 mai, un diner d'adieu a été offert, selon la coutûme, aux savants participant a la « Semaine d'Etude ». En fin de repas Mr le Prof. Dr. JAN HENDRIK OORT, s'adressa au Chancelier de l'Académie dans les termes suivants:

« C'est un plaisir très spécial de vous dire combien nous avons tous apprécié la grande bienveillance avec laquelle nous avons été reçus à Rome. Nous tous sommes confus d'une hospitalité plus royale et plus complète que toutes celles rencontrées jusqu'ici.

Au nom de tous les participants à cette « Semaine d'Etude » je voudrais remercier très chaleureusement l'Académie Pontificale des Sciences de l'accueil si grandiose qu'elle nous a réservé.

Sans aucun doute, la conférence a eu le plus grand succès. Nous nous étions réunis pleins de confiance; mais j'ai l'impression que en réalité nous avons appris les uns des autres beaucoup plus que nous ne pouvions l'espérer.

Nous voulons exprimer notre profonde gratitude pour tous les soins dont nous-mêmes et nos dames avons été l'objet; pour l'organisation des nombreuses excursions avec de si excellentes guides; pour l'organisation si parfaite de notre logement à l'Albergo Reale, et des transports journaliers à travers Rome.

Nous avons aussi apprécié beaucoup le travail des membres de votre Secrétariat et l'excellente organisation de votre Bureau.

Quand je vous ai dit ce matin combien nous étions confus de cette hospitalité vous m'avez répondu que c'était simplement le devoir de l'Académie Pontificale des Sciences et qu'elle voulait nous persuader que Rome n'appartient pas seulement aux Romains mais qu'elle nous appartient aussi.

C'est là la plus parfaite expression d'une hospitalité, une expression que nous nous rappellerons pendant toute notre vie.

En vous offrant en souvenir de cette réunion un très petit témoignage de reconnaissance, je veux exprimer l'espérance que, de votre côté, Mr le Chancelier, vous avez ressenti pendant cette réunion que l'Univers et les étoiles, dont nous sommes un peu les habitants, appartiennent non seulement aux astronomes mais aussi bien à vous-même et à vos collaborateurs ».

L'AUDIENCE
ET LE DISCOURS DU SAINT-PERE

Le matin du lundi 20 mai, le Saint Père a accordé dans la Salle du Consistoire du Palais Apostolique Vatican, une Audience Solennelle à l'Académie Pontificale des Sciences à l'occasion de la « Semaine d'Etude » sur « Le problème des Populations Stellaires » tenue par l'Académie même. Ont participé aussi à l'Audience de nombreux hauts personnages.

Etaient présents Leurs Eminences les Cardinaux: EUGÈNE TISSERANT, GIUSEPPE PIZZARDO Académicien Honoraire, BENEDETTO ALOISI MASELLA, GREGOIRE PIERRE XV AGAGIANIAN, CELSO COSTANTINI, GAETANO CICOGNANI e NICOLA CANALI.

De nombreux Académiciens Pontificaux sont intervenus, et spécialement Leurs Excellences: le Rév.me Père AGOSTINO GEMELLI O.F.M. Président, UGO AMALDI, GIUSEPPE ARMELLINI, MARCELLO BOLDRINI, HERMANN ALEXANDER BRÜCK, F.J.J. BUYTENDIJK, ALDO CASTELLANI, GUSTAVO COLONNETTI, GAETANO ARTURO CROCCO, JOSÉ GARCIA SIÑERIZ, ALESSANDRO GHIGI, FRANCESCO GIORDANI, OTTO HAHN, WALTER RUDOLF HESS, CORNEILLE HEYMANS, GASTON JULIA, GEORGES LEMAITRE, LUIGI LOMBARDI, ALBERT MICHOTTE VAN DEN BERCK, PAUL NIEHANS, ENRICO PISTOLESI, GAETANO QUAGLIARIELLO;

les Académiciens Pontificaux Surnuméraires Rèv. P. Abbé ANSELMO ALBAREDA O.S.B., P. DANIEL O'CONNELL S.I., P. JOSEF JUNKES S.I., Mgr MARTINO GIUSTI; l'Académicien Honoraire Nob. Prof. Cav. di Gr. Cr. RICCARDO GALEAZZI LISI, et le Chancelier de l'Académie Dr. Gr. Off. PIETRO SALVIUCCI.

Parmi le groupe des Académiciens assistaient les savants spécialistes « Participants » à la « Semaine d'Etude » sur « Le Problème des Populations Stellaires » MM. les Professeurs: WALTER BAADE, ADRIAN BLAAUW, DANIEL CHALONGE, WILLIAM A. FOWLER, OTTO HECKMANN, GEORGE H. HERBIG, FRED HOYLE, BERTIL LINDBLAD, WILLIAM W. MORGAN, JASON J. NASSAU, JAN H. OORT, EDWIN E. SALPETER, A. R. SANDAGE, MARTIN SCHWARZSCHILD, LYMAN SPITZER Jr., BENGT STRÖMGREN, A. D. THACKERAY et le Rév. Père PATRICK TREANOR S.I.

Etaient également présents leurs Excellences les Neveux de Sa Sainteté Princes Don CARLO, Don MARCANTONIO et Don GIULIO PACELLI; S. E. Rév.me Monseigneur DOMENICO TARDINI, Pro-Secrétaire d'Etat; les hauts Prélats de la Sécrétairerie d'Etat, LL.EE. Rév.mes Nosseigneurs ANTONIO SAMORÉ, CARLO GRANO et ANGELO DELL'ACQUA; un groupe d'Assesseurs et de Secrétaires des Sacrées Congrégations, ainsi qu'un groupe d'Archevêques et d'Evêques, parmi lesquels LL.EE. Rév.mes Nosseigneurs DIEGO VENINI, PIETRO CANISIO VAN LIERDE, ALFONSO M. UNGARELLI, CARLO CONFALONIERI, FRANCESCO ROBERTI, PIETRO SIGISMONDI, DOMENICO BRACCI, PRIMO PRINCIPI, BENIAMINO NARDONE, et autres personnages de la Curie et de l'Etat de la Cité du Vatican.

Parmi les membres du Corps Diplomatique près le Saint-Siège étaient présents: Leurs Excellences les Ambassadeurs de Pologne, d'Autriche, du Portugal, du Venezuela, d'Uruguay, du Panama, d'Argentine, de la République de Saint Domingue, du Guatemala, de Bolivia, de Cuba, du Paraguay, d'Haïti, d'Irlande, de Costa Rica, de l'Equateur, de la Belgique, et d'Honduras; les Ministres de l'Ordre Militaire Souverain de Malte, de Syrie, de Chine, du Japon, et de Hollande; les Chargés d'Affaires du Pérou, d'Espagne, d'Allemagne, de France et d'Italie et de nombreux autres Conseillers, Secrétaires et Conseillers Ecclésiastiques.

Le Saint Père a fait son entrée dans la salle à 10 heures, accompagné par sa Noble Antichambre avec S. E. Rév.me Monseigneur FEDERICO CALLORI DI VIGNALE Maître de Chambre, Nosseigneurs CARLO EMANUELE TORALDO et MARIO NASALLI ROCCA DI CORNELIANO Camériers Secrets Participants, et sa Garde Noble.

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

Après avoir gagné le trône, le Saint Père adressa en français à l'assemblée le savant discours qui suit.

A l'égal des autres sciences physiques dont l'époque présente admire le prodigieux développement, l'astronomie traverse maintenant une période de recherches et de découvertes des plus fécondes. Aussi Nous agrée-t-il particulièrement d'accueillir aujourd'hui, avec le groupe choisi d'astronomes qui participent à la conférence réunie à l'Observatoire du Vatican, les membres de Notre Académie Pontificale des Sciences. Au milieu de cette assemblée de savants insignes et d'infatigables investigateurs des merveilles de la création, Nous éprouvons l'ardent désir de redire l'hymne que le Seigneur met sur les lèvres de tous ceux qui reçoivent de lui avec reconnaissance le don de la vie, de l'intelligence et de l'amour: « Caeli enarrant gloriam Dei et opus manuum eius annuntiat firmamentum » (Ps. 18, 2).

Like the other physical sciences, whose prodigious development we of the present day contemplate with admiration, astronomy is now passing through a period of extremely fruitful researches and discoveries. Thus We are particularly glad to welcome to-day, with the elect group of astronomers taking part in the conference convened at the Vatican Observatory, also the members of Our Pontifical Academy of Sciences. In the midst of this assembly of distinguished scientists and tireless investigators of the wonders of creation We feel an ardent desire to repeat the hymn that the Creator puts on the lips of all those who receive gratefully from Him the

Pour connaître mieux encore ce ciel étoilé qui vous parle, par son immensité et son ordonnance, de la puissance et de la sagesse de son Auteur, la conférence convoquée sous Nos auspices se propose d'aborder en un débat libre et familier les questions les plus actuelles, qui préoccupent les spécialistes, et même tous ceux qui s'intéressent de près ou de loin à la connaissance de l'univers physique. Lorsque le Congrès de l'Union Astronomique Internationale se réunit à Rome en 1952, Nous en profitâmes pour féliciter ses membres des conquêtes merveilleuses, que leur science avait accomplies au cours des dernières années. Nous avons alors retracé les étapes marquantes, qui avaient permis de se former une idée plus précise du système galactique et de la position que le soleil y occupe; puis d'établir la nature véritable des nébuleuses spirales, en reconnaissant en elles d'autres galaxies analogues à la nôtre et peuplées de milliards d'étoiles. Au delà des mondes connus, on pouvait dès lors en soupçonner d'autres, qui se révèleraient bientôt au regard pénétrant d'un télescope géant.

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gift of life, of intelligence and of love: « Caeli enarrant gloriam Dei et opus manuum eius annuntiat firmamentum » (Psalm 18).

In order to know better this starry firmament which speaks to you, by its immensity and its order, of the power and the wisdom of its Author, the conference convened under Our auspices proposes to debate in free and friendly discussion questions of great interest, which are absorbing the attention of specialists, and also of all those who are interested in one way or another in our knowledge of the physical universe. When the Congress of the International Astronomical Union was held in Rome in 1952, We took the opportunity of congratulating its members on the marvellous conquests that their science had accomplished during recent years. We then retraced the salient steps which enabled astronomers to form a more precise idea of the galactic system and of the position that the Sun occupies within it; and then to determine the real nature of spiral nebulae, recognizing in them other galaxies analogous to ours and peopled by thousands of millions of stars. Beyond the worlds already known, *A ce moment d'ailleurs on publiait la découverte faite par Baade, selon laquelle l'échelle communément admise des dimensions de l'univers devait être doublée, ou même multipliée par un facteur plus grand encore.*

C'est à ce même astronome que l'on doit aussi la première mention du thème central de vos présents colloques, l'existence de deux types de populations stellaires. L'article de Baade, paru en 1944, signalait d'abord que des photographies prises sur des plaques sensibles au rouge avec le télescope de 2 m 50 du Mont Wilson avaient pour la première fois résolu en étoiles distinctes les deux compagnons de la nébuleuse d'Andromède et la région centrale de cette même nébuleuse. Heureux coup de hasard? Non point, mais plutôt le fruit d'une recherche longue et ardue. De puissants télescopes permettaient déjà de résoudre en étoiles individuelles les parties extérieures de la nébuleuse, mais le noyau central restait complètement amorphe, même sur les photographies prises avec les meilleurs instruments.

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one could suspect the existence of others, which would soon reveal themselves with the aid of giant telescopes. At this very time moreover there was published Baade's discovery that the hitherto accepted scale of the universe had to be multiplied by a factor of two or even more.

To the same astronomer we owe the first mention of the central theme of your present discussions, the existence of two types of stellar populations. Baade's paper, published in 1944, starts with the statement that recent photographs on red-sensitive plates, taken with the 100-inch telescope at Mount Wilson, for the first time resolved into stars the two companions of the Andromeda nebula and the central region of the Andromeda nebula itself. This was no chance discovery, it was the fruit of long and painstaking research. With giant modern telescopes it was possible to resolve the outer parts of the nebula and to photograph individual stars, but the central nucleus remained completely amorphous, even when photographed with the most powerful instruments. Finally skill and

Finalement l'habileté et la patience eurent raison de la difficulté; pour divers motifs, on pouvait supposer que le noyau de la nébuleuse contenait réellement des étoiles distinctes, mais trop faibles pour apparaître comme telles sur les clichés. On pouvait aussi présumer que les plus brillantes d'entre elles seraient les géantes rouges. Baade pensa qu'en utilisant des plaques sensibles au rouge, on réussirait à les fixer. Poussant à la limite des possibilités les moyens dont on disposait alors, il prolongea le temps de pose jusqu'à neuf heures, et réussit à photographier un bon nombre d'etoiles dans le noyau de la nébuleuse d'Andromède et dans ses deux compagnons.

Il démontra ensuite que les astres nouvellement découverts étaient moins lumineux et plus froids que les géantes bleues qui peuplaient les bras de la spirale, et arriva à la conclusion que les populations stellaires des galaxies se divisent en deux groupes: l'un représenté par les géantes bleues et les étoiles des amas galactiques (Type I), l'autre par les étoiles du noyau, les amas globulaires et les Céphéides

patience overcame the difficulty. On various grounds it seemed reasonable to suppose that the nucleus really contained individual stars, but that these stars were too faint to appear as such on the plates. It also seemed likely that the brightest stars in the nucleus would be red giant stars. Baade thought that it should be possible, by using red sensitive plates, to pick up at least these red giants. By taking every precaution and using very long exposures (of up to nine hours) Baade reached the very limit of what was possible with the means then available and succeeded in photographing great numbers of stars in the nucleus of the Andromeda nebula and in its two companions.

Baade then showed that these newly discovered stars are cooler and less luminous than the blue giants in the spiral arms of the nebula and came to the conclusion that the stellar populations of the galaxies can be divided into two groups, one represented by the blue giants and the stars in galactic clusters (Type I), the other by the stars in the nucleus, those in globular clusters and short period *variables à courte période (Type II). Les deux types diffèrent non seulement en éclat et en couleur, mais en âge, situation, composition chimique, mode et quantité de la production d'énergie.*

Dans le même article, Baade note que, dès 1926, Oort avait découvert dans notre galaxie deux catégories d'étoiles aux caractères différents: les unes douées d'un mouvement rapide par rapport au soleil, les autres se déplaçant plus lentement. Ces deux catégories, qui se distinguaient aussi par la fréquence de leurs types spectraux et par la concentration galactique, correspondent respectivement au Type II et au Type I de Baade. Ainsi les découvertes de Baade et de Oort se complétaient mutuellement et ouvraient la voie à toute une série de théories et de recherches, dont vous traiterez dans cette conférence.

Un simple regard sur le programme, que vous vous êtes fixé, dévoile, même à qui n'est pas spécialiste en la matière, la complexité des questions qui s'offrent à vous et des lignes d'approche que né-

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Cepheid variables (Type II). The two types of stars differ not only in brightness and colour, but in age, location, chemical composition, and in the mode and rate of energy production.

In the same paper Baade points out that, as early as 1926, Oort had distinguished in our Galaxy two groups of stars, a group of stars moving with high velocity relative to the Sun, as contrasted with the stars moving more slowly. These two classes, which differ also in frequency of their spectral types and in galactic concentration, correspond to Baade's type II and type I respectively. Thus these discoveries of Baade and Oort supplement each other. They opened the way to a flood of theories and researches, with which you will deal in this conference.

A glance at the programme that you have prepared shows, even to one who is not a specialist in these matters, the complexity of the topics that bear on your problem and the many different lines of approach that are needed for a thorough examination of the subject. You commence with a study of external galaxies and proceed later *cessite une investigation complète du sujet. Vous commencez par l'étude des galaxies extérieures et procédez ensuite à la discussion détaillée du système de la Voie Lactée. Tel est en effet le processus logique pour aborder la question des populations stellaires et ce fut la marche suivie en réalité par les progrès de la science, car il a été extrêmement difficile de déterminer les détails de notre Galaxie du fait que la terre elle-même y est incluse. Les premiers éléments de solution de votre problème furent donc trouvés dans les galaxies extérieures, bien que tout récemment on ait appris beaucoup au sujet de notre propre Galaxie. Ainsi les astronomes hollandais ont réussi à localiser les bras de la spirale, grâce à l'observation des ondes radio-électriques émises par l'hydrogène qui s'y trouve. Puisque les étoiles de notre système sont beaucoup moins lointaines que celles des galaxies extérieures, l'astronome aborde plus aisément leur étude et s'applique à déterminer leur éclat, leurs spectres, leurs mouvements et leur distribution dans l'espace.*

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to a detailed discussion of our own Milky Way system. This is indeed the logical approach to a study of the question of stellar populations, and the line which advance in knowledge has in fact taken, for it has been extremely difficult to chart the details of our own Galaxy, owing to the fact that our own solar system is embedded in it. The first indications of your problem were found in external galaxies, although in the meantime a great deal has been learnt about our own Galaxy. The Dutch astronomers, for instance, have succeeded in tracing the spiral arms of the Galaxy by means of their observations of radio waves emitted by the hydrogen in the arms. Since the stars of our system are much less distant than those in external galaxies, the astronomer can learn a great deal more about them, by studying their brightness, their spectra, their motions and distribution in space.

Much of this knowledge could be acquired only with the aid of the most powerful means available. Thus the study of globular clusters, which has proved so fruitful in providing information about

Une grande part de ces connaissances ne put être acquise qu'à l'aide des moyens les plus puissants, dont on disposait. Ainsi par exemple, l'étude des amas globulaires, si féconde en renseignements sur les populations de Type II, a profité des services du réflecteur de 5 m du Mont Palomar. Néanmoins on accomplit aussi d'excellente besogne avec des instruments plus modestes, notamment pour l'étude des étoiles variables, à laquelle l'Observatoire du Vatican, Nous sommes heureux de le souligner, apporte une utile contribution. Sur les Céphéides, qui constituent une source précieuse d'information pour le problème des populations stellaires, on attend encore une estimation plus précise de leur nombre dans les diverses parties de la Galaxie, ainsi que de leurs spectres, de leurs mouvements et du mécanisme de leurs variations. Quant aux étoiles éclair, ces astres étonnants, que l'on voit soudain croître pour briller intensément pendant un temps plus ou moins bref, puis revenir à leur éclat primitif, sans doute en découvrira-t-on de nouvelles et parviendra-t-on à mieux expliquer leur comportement et leur distribution.

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stars of population II, has been carried out with the 200-inch telescope at Mount Palomar. Nevertheless much excellent work can be done with more modest instruments, notably in the study of variable stars, to which, we are happy to note, the Vatican Observatory is bringing a useful contribution. For the Cepheid variables, which constitute a precious source of information for the problem of stellar populations, one needs a more precise estimate of their distribution in the Galaxy, as well as more information about their spectra and their motions and about the mechanism which is responsible for their variability. As for the flare stars, those remarkable objects that flare up suddenly, remaining bright for a short time and then fading more slowly to their original brightness, no doubt more of them will be discovered and more will be learned about their behaviour and their distribution.

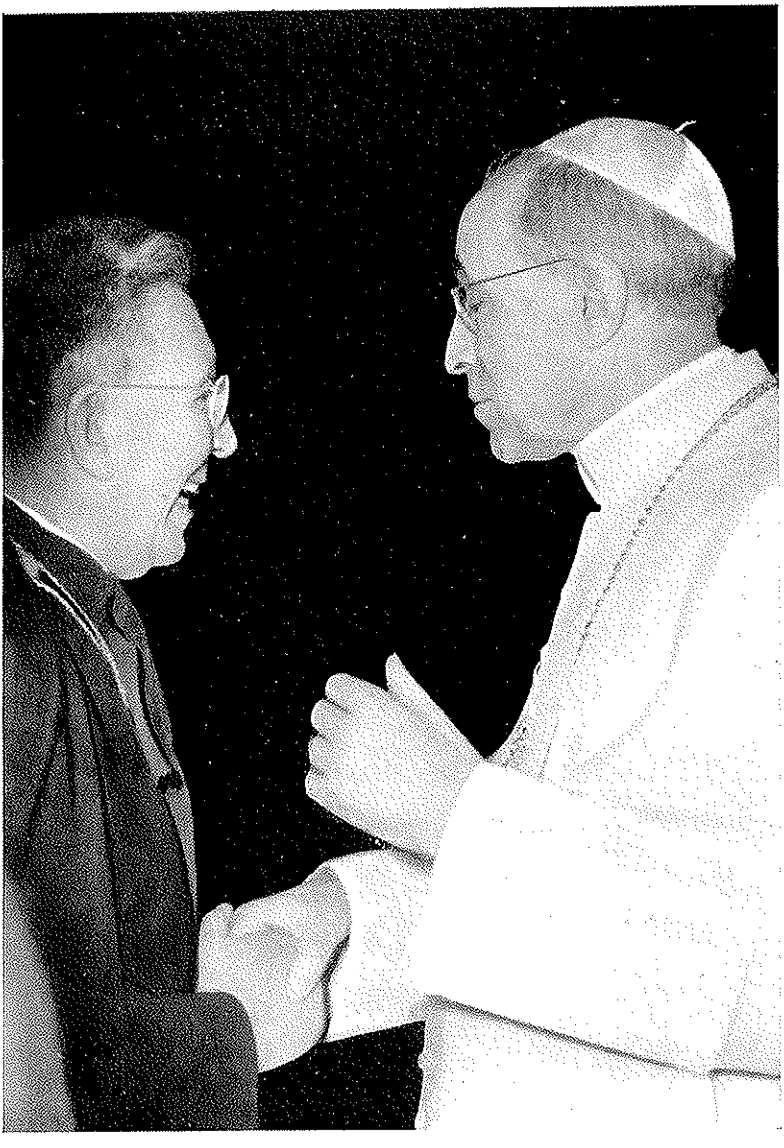
You will give much attention to problems connected with the evolution of the stars, the production of energy in their interior, the formation of atoms and the transmutations which they undergo.

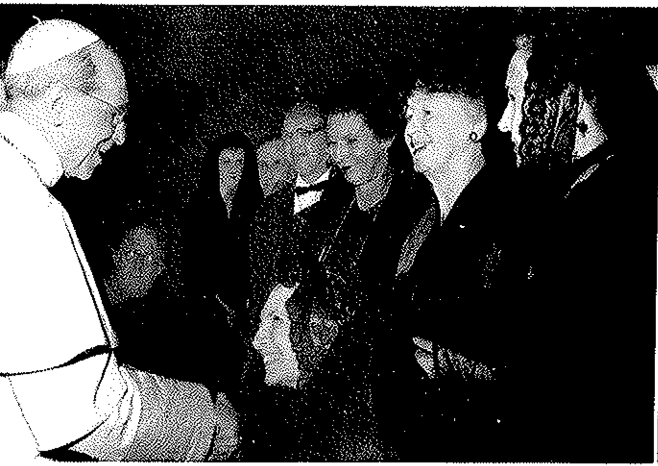
Vous accorderez une attention particulière aux problèmes, qui concernent l'évolution des étoiles, la production d'énergie à leur intérieur, la formation des atomes et les transformations qu'ils subissent. La collaboration du spécialiste en physique nucléaire et de l'expert en statistiques s'impose ici pour compléter ce que l'on sait déjà sur les modifications subies par les noyaux atomiques soumis à des températures élevées, sur les cycles qui se succèdent dans le développement d'une étoile individuelle et les différences de comportement qui caractérisent sur ce point les divers types d'étoiles. Vous vous efforcerez de préciser le rôle de la composition chimique dans la genèse des différents types et les changements qu'elle subit ensuite, de même que les effets exercés par le milieu interstellaire, poussière ou gaz, sur les astres qui le traversent, les échanges de matière entre le milieu et l'étoile, et les conséquences qui s'ensuivent pour l'un et pour l'autre.

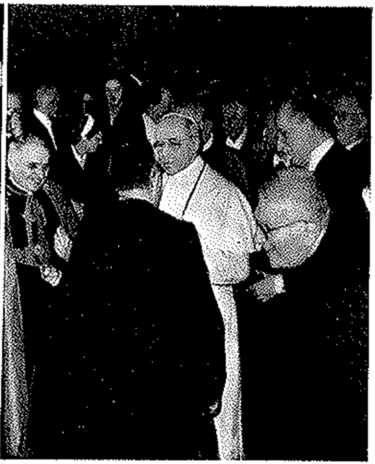
L'écart d'âge, que vous assignez aux divers types, recèle aussi

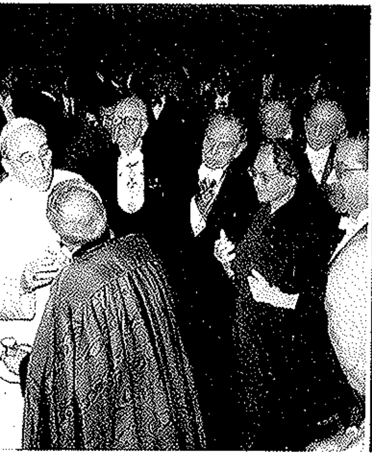
Here you need the aid of nuclear physicists and of experts in statistics, in order to learn more about the nuclear changes in the intensely hot interior of a star, the different cycles that may succeed one another in the development of an individual star and the differences in this respect between the various types of stars. You will try to determine how the development of the different types is affected by their original chemical composition, and the subsequent changes it undergoes. You will want to know what effect the interstellar medium, dust or gas, has on the stars which pass through it, what exchange of matter there is between medium and star, and what effect these processes have on both.

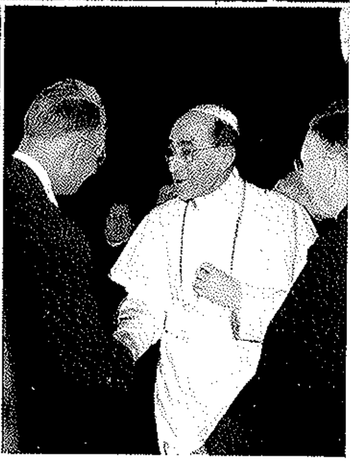
Of very great interest is the enormous difference in the ages that you now assign to various types of stars. Whereas you believe that stars of population II are about 5,000 million years old, about as old as the universe itself, the age of population I stars seems to be at most some tens of millions of years. It is understandable that the blue supergiants, which emit continuously such a vast quantity











une signification du plus haut intérêt. Tandis que les étoiles de population II comptent environ 5.000 millions d'années, c'est-à-dire à peu près l'âge de l'univers lui-même, la population I semble vieille tout au plus de quelques dizaines de millions d'années. Il est naturel que les supergéantes bleues, qui émettent constamment une quantité considérable d'énergie sous forme de chaleur et de lumière, payent cette prodigalité par l'épuisement relativement rapide de leurs réserves, tandis que les étoiles anciennes, comme le soleil, ménagent davantage leurs ressources, encore que la quantité d'énergie émise continuellement par le soleil paraisse énorme. Vous réussirez peut-être à découvrir des étoiles plus jeunes encore que celles que l'on connaît, ou même — qui sait? — à en observer la genèse.

La formation et l'évolution des étoiles les plus anciennes de la population II, requerra une bonne part de votre attention, malgré l'intérêt bien compréhensible que s'attirent leurs compagnes plus jeunes à cause de leurs transformations spectaculaires. Le soleil mé-

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of energy in the form of heat and light, are so spendthrift of their store that they must burn themselves out comparatively quickly, whereas such ancient stars as our Sun husband their resources better, though even the Sun pours out what seems to us enormous quantities of energy. You may succeed in discovering stars more youthful still, or even perhaps in observing the very birth of a star.

The formation and evolution of the older stars of population II will also demand much of your attention, in spite of the interest naturally evoked by the spectacular transformations of their younger companions. Our Sun in particular cannot be neglected, for, apart from the direct influence it has on the earth and its inhabitants, it is so much nearer to us than any other star that we can learn far more about its secrets, and its study must ever remain an essential department of astronomy.

No one would think, on that account, of neglecting the external galaxies, the importance of which for astronomical research We have already emphasized. The Magellanic Clouds in particular have the *rite bien qu'on ne le néglige pas, car, outre l'influence directe qu'il exerce sur la terre et ses habitants, il consent aussi plus facilement, en raison de son voisinage, à révéler les secrets de son comportement; son étude ne cessera donc jamais de constituer un secteur essentiel de l'astronomie.*

Nul ne pensera cependant à négliger pour cela les galaxies extérieures, dont Nous avons souligné plus haut l'importance pour les recherches astronomiques. Les Nuages de Magellan en particulier ont l'avantage d'être les deux systèmes stellaires les plus proches de notre Galaxie et de fournir des renseignements qu'on demanderait en vain aux systèmes plus distants. Aussi avez-vous invité à votre conférence le représentant d'un grand Observatoire de l'hémisphère Sud, qui leur a consacré une part notable de ses efforts.

Les galaxies elliptiques, qui contiennent surtout des étoiles de population II, ressemblent un peu aux amas globulaires, mais s'en distinguent certainement par les dimensions et l'origine. Les amas

advantage of being the two stellar systems nearest of all to our Galaxy, and information can be obtained from them that cannot be obtained from more distant systems. You have therefore invited to your conference the representative of a great observatory in the Southern hemisphere, who has devoted much of his labours to these systems.

The elliptical galaxies, which contain mainly stars of population II, bear some resemblance to globular clusters, but differ from them certainly in size and origin. The globular clusters themselves, when subjected to precise examination, show certain differences from one to another. Thus the Hertzsprung-Russell diagram in one cluster does not correspond precisely to that in another. It is even possible that the types of stellar population are not limited to two. It is now your task to debate among yourselves and to communicate on this point, as on the other topics which We have mentioned, the facts that you have gathered and the conclusions to which you have been led.

globulaires eux-mêmes, quand on les soumet à un examen approfondi, révèlent entre eux certaines discordances. Ainsi le diagramme de Hertzsprung-Russell de l'un ne correspond pas exactement à celui d'un autre. Peut-être même en conclura-t-on que les types de populations stellaires ne sont pas limités à deux. Il vous appartient d'en débattre et de vous communiquer mutuellement sur ce point, comme sur tous ceux que Nous avons évoqués, les informations que vous avez recueillies et les conclusions, auxquelles vous conduit votre expérience personnelle.

Chercher inlassablement des faits précis, élaborer des théories pour les expliquer, vérifier la théorie par de nouvelles observations, la corriger au besoin, la remplacer par une autre plus parfaite, qui tienne compte davantage des données acquises, tel est le labeur incessant de l'astronome, labeur qui, même aux yeux des profanes, apparaît titanesque. Quel que soit le stade atteint par son enquête, l'astronome ne peut se passer d'une image d'ensemble de l'univers,

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The tireless search for precise facts, the development of theories to explain the facts, the verification of theory by new observations, the modification of a theory when necessary, its replacement by another more perfect theory which fits better the data acquired, such is the incessant labour of the astronomer, a labour which appears titanic even to the uninitiated. Whatever stage the astronomer has reached by his researches, he cannot dispense with a general picture of that universe, whose minutest details he is scrutinising. Even if awkward gaps in his knowledge cause some of his constructions to break down, he cannot lose the exciting conviction that by thought he is lord of the cosmos, and will sooner or later tear from it new secrets.

But even when he holds in his hands the keys which will open to him doors yet closed, his task will still be far from finished; not only because the evolution of stellar worlds constantly renews the object of his interest, but also because the truth which will satisfy his urge is in reality on a higher plane than that of scientific *dont il scrute les plus minutieux détails. Même si de lourdes inconnues rendent caduques certaines de ses constructions, il ne se défend pas de l'impression si exaltante qu'il domine le cosmos par la pensée et lui arrachera tôt ou tard de nouveaux secrets.*

Mais alors même qu'il tiendra en main les clefs qui lui ouvriront les portes closes, sa tâche sera encore loin d'être terminée. Non seulement parce que l'évolution des mondes stellaires renouvelle sans répit l'objet de son intérêt, mais parce que la vérité qui mettra le terme à son élan occupe en réalité un plan supérieur à celui de la recherche scientifique. La connaissance de l'univers physique, de l'infiniment petit à l'infiniment grand, grise l'intelligence humaine par ses enigmes déconcertantes et attirantes à la fois, mais elle ne dissipe pas son véritable tourment. Comme tous les autres savants, comme l'ingénieur aux prises avec les applications modernes de l'électronique ou de l'énergie nucléaire, mais aussi comme le plus humble des travailleurs intellectuels ou manuels, l'astronome cherche une vérité qui dépasse de loin celle du calcul mathématique, des lois

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research. The knowledge of the physical universe, from the infinitely small to the infinitely great, intoxicates the mind of man, by its tantalizing, but alluring riddles; yet it does not free him from his unease. Like all other scientists, like the engineer at grips with modern applications of electronics or of nuclear energy, but also like the humblest of intellectual or manual workers, the astronomer seeks a truth which far surpasses that of mathematics, or of general laws of physics, or of material objects which he can measure, move, or control. What would the immensity of the cosmos, its splendour, its organization be, without the intelligence which discovers itself in contemplating the cosmos and which sees in it as it were its own image? Is not what man reads in the stars a symbol of his own greatness, a symbol which invites him to mount higher, to seek elsewhere the meaning of his existence? Contemporary scientific *générales de la physique, ou de quantités matérielles à mesurer, à déplacer, à dominer. L'immensité du cosmos, sa splendeur, son organisation, que seraient-elles sans l'intelligence, qui s'y découvre en le contemplant et qui y voit comme un reflet d'elle-même? Ce que l'homme lit dans les étoiles, n'est-ce pas le symbole de sa propre grandeur, mais un symbole qui l'invite à monter plus haut, à chercher ailleurs le sens de son existence? La pensée scientifique contemporaine s'habitue à ne reculer devant aucun problème, et c'est légitime aussi longtemps qu'elle reste dans son ordre propre. Mais, comme l'univers moral transcende le monde physique, toute acquisition de la science se situe sur un plan inférieur aux fins absolues de la destinée personnelle de l'homme et aux relations qui l'unissent à Dieu. La vérité scientifique devient un leurre à partir de l'instant, où elle croit suffire à tout expliquer, sans se rattacher aux autres vérités et surtout à la vérité subsistante, qui est un Etre Vivant et librement Créateur. L'effort du savant, si désintéressé et courageux soit-il, perd sa raison dernière, s'il renonce a voir, au delà des fins*

thought is accustomed not to retreat before any problem, and that is legitimate so long as it remains within its own domain. But, since the moral universe transcends the physical world, every gain made by science is on a lower plane than that of man's personal destiny — the ultimate aim and purpose of his existence — and of the relations which unite him to God. Scientific truth becomes a decoy from the moment when it is considered adequate to explain everything, without being linked up with other truths and above all with subsistent truth, which is a living and freely creative Being. The labour of the scientist, however disinterested and courageous, loses its ultimate motive if he refuses to see, beyond purely intellectual ends, those proposed to him by conscience, the decisive choice between good and evil, the profound orientation of his life towards the acquisition of spiritual values, of justice and of charity;

purement intellectuelles, celles que lui propose sa conscience, le choix décisif entre le bien et le mal, l'orientation profonde de sa vie à la conquête des valeurs spirituelles, de la justice et de la charité, de cette charité surtout qui n'est point simple philantropie ou sentiment de la solidarité humaine, mais qui procède d'une source divine, de la Révélation de Jésus-Christ.

Heureux qui peut lire dans les étoiles le message qu'elles renferment, un message d'une autorité à la mesure de qui l'a écrit, digne de récompenser le chercheur de sa ténacité et de son habileté, mais l'invitant aussi à reconnaître Celui, qui donne la vérité et la vie et établit sa demeure dans le coeur de ceux qui l'adorent et qui l'aiment. En formant des voeux sincères pour que ces échanges de vues répondent à votre attente et vous procurent les vives satisfactions d'un labeur plus fructueux, Nous prions l'Auteur de tout bien de vous accorder son aide et sa protection, en gage desquelles Nous vous donnons de tout coeur Notre Bénédiction Apostolique.

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above all of that charity which is not merely philanthropy or a feeling of human solidarity, but which proceeds from a divine source, from the revelation of Jesus Christ.

Happy is he who can read in the stars the message which they contain, a message worthy of its author, and capable of recompensing the seeker for his tenacity and his ability, but inviting him also to recognize Him who gives truth and life and who establishes His dwelling in the heart of those who adore and love Him. While expressing the sincere wish that your discussions will come up to your expectations and will bring you the lively satisfaction of having accomplished a most fruitful task, We beg the Author of all good to grant you His aid and protection, in pledge of which We give you with all Our heart Our Apostolic Benediction.

A la fin du discours, suivi avec une attention recueillie par tous les assistants, le Souverain Pontife a donné la Bénédiction Apostolique et des applaudissements nourris lui dit la réponse fervente et la gratitude sincère de toute l'assemblée.

Après être descendu de son trône, le Saint Père s'est entretenu d'abord avec les Cardinaux puis avec les Prélats présents à l'audience. Sa Sainteté passa ensuite parmi les Académiciens et les savants participants à la « Semaine d'Etude », trouvant pour chacun d'aimables paroles de félicitations et de souhaits, usant dans la conversation des différentes langues suivant les aptitudes de chacun.

Le plus chaleureux hommage se manifesta de nouveau au moment où, l'Audience terminée, le Saint Père quitta la Salle du Consistoire.

LA SEANCE ORDINAIRE
DE L'ACADEMIE

La « Semaine d'Etude » a coïncidé — comme d'habitude — avec la « Session Plénaire » de l'Académie Pontificale des Sciences, au cours de laquelle les Académiciens Pontificaux présents à Rome se réunissent pour la présentation de travaux scientifiques originaux et pour tout ce qui concerne la vie intérieure de l'Académie.

A cette occasion une Séance Ordinaire a eu lieu, au Siège de l'Académie à la « Casina Pio IV » dans les Jardins du Vatican, le matin du lundi 20 mai, tout de suite après l'Audience Pontificale Solennelle. En voilà le procès verbal.

Etaient présents Leurs Excellences les Académiciens Pontificaux: AGOSTINO GEMELLI Président, UGO AMALDI, GIUSEPPE ARMELLINI, MARCELLO BOLDRINI, HERMANN ALEXANDER BRÜCK, F.J.J. BUYTENDIJK, ALDO CASTELLANI, GUSTAVO COLONNETTI, GAETANO ARTURO CROCCO, JOSÉ GARCIA SIÑERIZ, ALESSANDRO GHIGI, FRANCESCO GIORDANI, OTTO HAHN, WALTER RUDOLF HESS, CORNEILLE HEYMANS, GASTON JULIA, GEORGES LEMAITRE, LUIGI LOMBARDI, ALBERT MICHOTTE VAN DEN BERCK, PAUL NIEHANS, ENRICO PISTOLESI, GAETANO QUAGLIARIELLO; les Académiciens Pontificaux Surnuméraires Rév. P. Abbé ANSELMO ALBAREDA, P. DANIEL O'CONNELL S.I., Mons. MARTINO GIUSTI; l'Académicien Honoraire Nob. Prof. Cav. de Gr. Cr. RICCARDO GALEAZZI LISI, et le Chancelier de l'Académie Dr. Gr. Off. PIETRO SALVIUCCI.

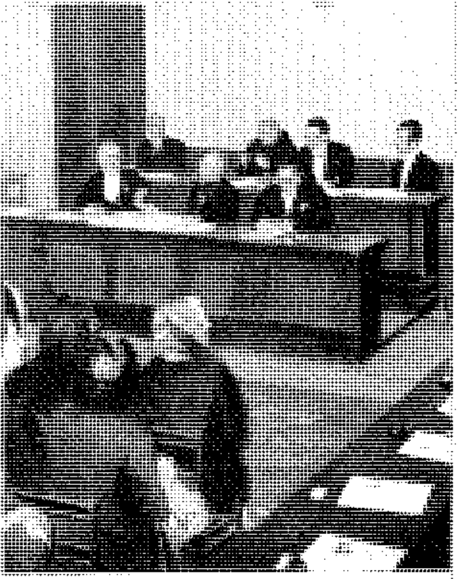
A la séance prirent part naturellement les savants participants à la « Semaine d'Etude » sur « Le Problème des Populations Stellaires »; accueillis avec une chaleureuse cordialité par les Académiciens Pontificaux, ils furent invités à prendre place au milieu de ces derniers sur les mêmes fauteuils académiques.

Ils étaient MM. les Professeurs: WALTER BAADE, ADRIAN BLAAUW, DANIEL CHALONGE, WILLIAM A. FOWLER, OTTO HECKMANN, GEORGE H. HERBIG, FRED HOYLE, BERTIL LINDBLAD, WILLIAM W. MORGAN, JASON J. NASSAU, JAN H. OORT, EDWIN E. SALPETER, A. R. SANDAGE, MARTIN SCHWARZSCHILD, LYMAN SPITZER Jr., BENGT STRÖMGREN, A. D. THACKERAY et le Rév. Père PATRICK TREANOR S.I.

A l'ouverture de la séance, S. E. le Rév.me Père AGOSTINO GEMELLI O.F.M., Président de l'Académie, proposa à l'assemblée de manifester ses sentiments d'hommage et de remerciement à Sa Sainteté qui avait daigné les éclairer de Son Auguste enseignement. L'assemblée répondit par des applaudissements unanimes, tandis que les assistants se levaient pour exprimer, eux aussi, leur respectueux hommage filial.

Soudain les Académiciens CROCCO, LOMBARDI et GEMELLI commémorerent respectivement les Académiciens défunts MODESTO PANETTI, Professeur de Mécanique appliqué aux machines et de Constructions aeronautiques à l'Ecole Politechnique de Turin; GIANCARLO VALLAURI, Professeur d'Electrotechnique à l'Institut Supérieur d'Ingénierie de Turin; PIETRO RONDONI, Professeur de Pathologie générale et experimentale à l'Université de Milan; tandis que le Chancelier SALVIUCCI lit la commemoration de l'Académicien défunt HERMANN WEYL, Professeur de Mathématique à l'Université de Zürich, qui avait été envoyé par l'Académicien SEVERI, absent.

Le Chancelier SALVIUCCI remettait ensuite officiellement le « Collier » de l'Académie aux nouveaux Académiciens Pontificaux qui



étaient présents pour la première fois à une Séance Ordinaire. Ils étaient Leurs Excellences: HERMANN BRÜCK, Directeur de l'Observatoire de Dublin; OTTO HAHN, Prix Nobel et Président de la « Max-Planck-Gesellschaft » de Göttingen; WALTER RUDOLF HESS, Prix Nobel et Professeur de Physiologie à l'Université de Zürich; GASTON MAURICE JULIA, Professeur d'Analyse supérieure à la Sorbonne et de Géométrie à l'Ecole Polytechnique de Paris; Mons. MARTINO GIUSTI qui, appelé par le Saint Père à succéder au feu Mons. ANGELO MERCATI comme Préfet des Archives Secrètes Vaticanes, prenait sa place parmi les Académiciens Pontificaux Surnuméraires.

Le président GEMELLI exprimait alors sa satisfaction de les voir pour la première fois à une réunion académique et, au nom de tous ses collègues, leur souhaitait la bienvenue au Siège de l'Académie et leur exprimait tous ses voeux pour leurs personnes et pour le meilleur succès des leurs études.

Le Président GEMELLI s'adressait ensuite à l'Assemblée dans les termes suivantes:

« Ainsi qu'en ont déjà été informés les Académiciens Pontificaux présents, le but principal de notre réunion est de souhaiter amicalement et fraternellement la bienvenue aux illustres confrères et aux éminents savants venus de toutes les parties du monde pour participer à la « Semaine d'Etude » sur « Le Problème des Populations Stellaires ».

Je dois tout d'abord les remercier d'avoir accepté notre invitation, de l'avoir même acceptée avec enthousiasme. au point d'abandonner pour une brève période leurs Instituts scientifiques pour se réunir au Siège de l'Académie afin de discuter et de coordonner les résultats des recherches pour obtenir une vision toujours plus unitaire du problème.

Je formule le voeu qui naît spontanément dans nos coeurs, et qui est le désir de tous, que notre réunion soit véritablement fructueuse pour le progrès de la science et pour la plus grande connaissance de ce magnifique Univers où nous a placés le Créateur pour L'honorer et Le bénir, comme l'a dit ce matin le Saint Père.

Je ne terminerai pas sans remercier tout spécialement notre cher Père O'CONNELL, Académicien Surnuméraire, qui a travaillé de tout son zèle avec notre actif Chancelier, le Dr. SALVIUCCI, à la réalisation de cette « Semaine d'Etude » sur « Le Problème des Populations Stellaires ». Ils ont formé, à eux deux, un binôme de labeur et de préparation dont nous recueillerons certainement les magnifiques fruits ».

Enfin plusieurs Académiciens Pontificaux ont fait leurs communications scientifiques et présenté des Notes et des Mémoires originaux. Pour cela prirent la parole les Academiciens: ARMELLINI, BUYTENDIJK, CASTELLANI, CROCCO, GEMELLI, GHIGI, MICHOTTE VAN DER BERCK, ALBAREDA.

Après avoir remercié tous les orateurs de leurs déclarations et renouvelé à tous les Participants ses voeux pour eux-mêmes et pour leurs études, le Président GEMELLI leva la Séance.

LES "SEMAINES D'ETUDE"
ET LEUR REGLEMENT

Lorsque l'Académie Pontificale des Sciences fut fondée en 1936 par le Saint-Père 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 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

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A general movement of sympathy and admiration was aroused in scientific circles when, in 1936, the Pontifical Academy of Science 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, on the contrary, solemnly proclaimed the dignity of the search for truth 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 Notre 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 ».

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.

(*) « 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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for its own sake (*) and, raising his thoughts above all preoccupations of a utilitarian nature, asserted that all he 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 ».

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

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 à 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.

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 s'est pas borné 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.

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Les sciences posent chaque jour des problèmes nouveaux qui donnent lieu d'ordinaire à divers essais de solution, souvent contra-

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the lofty place reserved for purely intellectual values in the Catholic Church.

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

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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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 dictoires. 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 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 d'organiser de pareilles rencontres scientifiques. L'organisation de ces ren-

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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 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 Science decided to organize scientific meetings of this description. These meetings, known as « Study Weeks », were planned on the following lines:

contres qu'on a appelées « Semaines d'Etude » a été établie 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 « 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 discussions 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 d'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.

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 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;

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

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

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 parmi les personnalités étrangères à l'Académie, auxquels se joindront, dans la discussion, les Académiciens versés dans la même discipline. Cette invitation, de plus, ne se rapportera qu'à l'étude d'une question déterminée, pour chaque science.

5. - Les discussions auront un caractère strictement privé; elles prendront la forme de conversations particulières, sans autre assistance que celle de quelques membres de l'Académie Pontificale des Sciences particulièrement compétents dans la matière.

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

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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 selected from amongst those who are not connected with the Academy. They will be joined during the discussions by Academicians versed in the same discipline. This invitation, moreover, will apply only to the study of one precise problem in each branch of science.

5. - The debates will be strictly private and will take the form of personal talks, in the presence only of a few members of the Pontifical Academy of Science with special knowledge of the subject under discussion.

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;

forme d'une « Note Collective Finale » (à laquelle pourront éventuellement être jointes des annotations individuelles), mentionant:

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

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 aussitôt imprimées et communiquées, par le soins de l'Académie Pontificale des Sciences, à tous les centres scientifiques qu'elles seraient de nature à intéresser.

8. - 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.

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

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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 Science, to all the scientific centres which might be interested therein.

8. - 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 Science.

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

TRAVAUX SCIENTIFIQUES

I.

LES GALAXIES
ET LEURS POPULATIONS STELLAIRES

GALAXIES AND THEIR STELLAR POPULATIONS

A REVIEW OF THE PRESENT STATE OF AFFAIRS

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When I succeeded in 1943 in resolving the central region of the Andromeda nebula and its two companions NGC 205 and NGC 221, it became clear that in dealing with galaxies we have to distinguish two different kinds of stellar populations, which I called the population I and II [1].

Of these two the population I represented nothing new. It is the population of the spiral arms of galaxies and we are well acquainted with it because our sun is located in a spiral arm of our galaxy. In fact, we can use the color-magnitude diagram of the solar neighborhood, at least down to absolute magnitude +3, as a definition of the population I. Its outstanding feature is the main sequence which in some cases may include stars of the absolute magnitude −8 and even brighter. Typical objects of the population I are, besides O- and B-stars of high luminosity, type I cepheids, galactic star clusters and stellar associations.

Prototype of the population II are the stars in globular clusters. Their color-magnitude diagram, entirely different from that of the population I, has been known for more than a quarter of a century and again represented nothing new. But new was the realization that the globular clusters are the representatives of a second widespread stellar population which had remained unrecognized because its brightest members are a hundred times fainter than the brightest stars of the population I. Typical objects of the population II are the cluster-type variables, the novae and the planetary nebulae.

Two points I would like to stress here. Since the two populations are defined by their color-magnitude diagrams, and since for stars of a common origin the color-magnitude diagram describes the physical state of the stars (their masses, age and original chemical composition), the populations are defined in a physical sense. This is my first point. The second is that in dividing the stellar populations into two main groups we use the same dividing line by which we assign the star clusters to either the galactic or the globular group, depending upon the topology of their color-magnitude diagrams. The division of the stars into two main populations is, therefore, by no means as naive as some critics have claimed.

On this two-population picture the elliptical galaxies would be pure population II systems. In the Sa- and Sb-spirals both populations are present but differentiated by their spatial distributions — the population I being restricted to the spiral arms. In the Sc-spirals and the Magellanic Cloud-type galaxies the population II is as a rule completely drowned in the magnificent display of population I supergiants. There are, however, good reasons to believe that in these galaxies too the population II is present although it may be quite inconspicuous and not easily detectable.

A very striking feature is the correlation between dust and gas and stellar population. Galaxies containing only population II stars are free from dust and gas or contain at best insignificant amounts. In contrast, the population I is found only in the presence of dust and gas. These striking relationships are another very strong indication that the two stellar populations order the stars in a physically significant manner. They also provided the first hint that the two populations differ in age. The lifetimes of the brightest population I are so short (of the order of 10^7 to 10^8 years) that they must be continuously replaced in order to explain their presence in the spiral arms of galaxies. Since they occur only where dust and gas is present, one had to assume that they are continuously formed in the dust and gas. All this implied that the population I stars are young stars. Similarly, one had to conclude that in the absence of dust and gas star formation in the ellipsoidal galaxies had come to an end, possibly long ago, and that therefore their population II is older than the population I.

When I presented in 1944 the concept of two basic stellar populations I had at my disposal only rough and often scanty data. Today we are in a much better position, thanks to the rapid advances of the past ten years. It will simplify things later on if we discuss briefly the most relevant results. They all concern the population II of which we knew very little previously.

The Color-Magnitude Diagram of the Population II

As a result of the investigations of ARP, BAUM, JOHNSON, SANDAGE, SAVEDOFF and WALKER we have today color-magnitude diagrams of high precision for 8 globular clusters. All are members of the galactic halo. Although there are differences from cluster to cluster in the inclination of the giant-subgiant branch and in the strength of the horizontal branch and its continuation — differences which are not yet understood — the topology of the color-magnitude diagram is the same for all 8 clusters. A glance at the color-magnitude diagram is therefore usually sufficient when we have to decide whether a given cluster belongs to the globular group (type II) or not.

The diagrams of the 8 globular clusters to which we referred above cover only the brighter part of the color-magnitude diagram. It had been suspected for a long time that the subgiant branch of the globular clusters in its sweep downward would lead somewhere into the main sequence and that the localization of this sequence might provide the key to the understanding of the population II. One of the first programs for the new 200-inch telescope was therefore the determination of the color-magnitude diagram of the globular cluster M 3 down to absolute magnitude + 5. It was carried out by A. SANDAGE as his thesis [2]. For the understanding of the color-magnitude diagrams of the globular clusters this diagram of M 3 has been of fundamental importance because it showed that the main sequence in globular clusters begins at about the absolute magnitude + 3.5 and that at this point the cluster stars turn off in large numbers into the subgiant branch. In a detailed discussion SANDAGE [3] showed that the data provided by the color-magnitude diagram of M 3 are compatible with the evolutionary interpretation first proposed by GAMOW and SCHWARZSCHILD, and he concluded from the fact that the main sequence above $+3^{M}_{\cdot}5$ has disappeared in M 3 that the cluster is about 5×10^{9} years old. This semi-empirical interpretation was put on a solid foundation when HOYLE and SCHWARZSCHILD [4] succeeded a year ago in computing the evolutionary path of a star having 1.2 solar masses from the time it leaves the main sequence until it reaches the top of the giant branch. Since the original chemical composition plays a role, HOYLE and SCHWARZSCHILD computed the evolutionary path for two different cases; one in which the ratio of the metals to hydrogen is about the same as in the sun, and the other in which this ratio is 17 times smaller. As expected (see next paragraph), the computed evolutionary path of the star with the low content of metals represents the subgiant-giant branch in globular clusters. Considering the difficulties which had to be overcome, the agreement between computed and observed subgiant-giant branches is truly remarkable. For the age of the stars in a globular cluster like M 3 HOYLE and SCHWARZSCHILD found a value around 6×10^{9} years. Population II stars are therefore old stars. We shall see later that they are in fact the oldest stars which we know in galaxies at present.

The first indications that the metal content of the population II stars is lower than that of the population I stars came from spectroscopic observations. When a few years ago the first spectra of stars in globular clusters were obtained at the coudé spectrograph of the 200-inch, the observers noted at once that compared to "normal" stars their metallic lines are abnormally weak, the degree of this weakening varying from cluster to cluster [5]. More recently W. W. MORGAN [6] has studied this anomaly in the integrated slit spectra of a number of globular clusters by determining the spectral type *a*) from the strength of the hydrogen lines, *b*) from the strength of the metallic lines. He finds that for the globular clusters of the galactic halo the two spectral types differ systematically — the spectral type from the strength of the metal lines being about three quarters of a spectral class earlier than that inferred from the hydrogen lines. For "normal" stars the two spectral types would be of course in agreement. Although it is almost certain that the anomaly has to be interpreted as low abundance of the metals in globular cluster stars, this interpretation should be confirmed by a quantitative analysis of the spectra of one or two K giants in a globular cluster. Equally important would be a check of how much the metals to hydrogen ratio varies among the globular clusters of the halo.

That great age of a cluster and a low metals-to-hydrogen ratio do not necessarily go together is strikingly demonstrated by the M 67 case. In contrast to the globular clusters which we have so far discussed and which are members of the galactic halo, M 67 is a member of the galactic disk and it has always been classified as a galactic (population I) cluster. But it has a very remarkable color-magnitude diagram as JOHNSON and SANDAGE [7] showed two years ago. Just as in the globular clusters, the main sequence begins at about $+3^{\mathrm{M}}\!.5$ and a subgiant-giant branch turns off to the left at this point. But the giant branch ends not, as in the globular clusters, at $M_v = -3.0$ but at $M_v \cong 0.0$. From the fact that in M 67 the turn off from the main sequence is at the same point ($M = +3.5$) as in globular clusters we must conclude that M 67 is as old as the globular clusters, i.e., 6×10^9 years. The difference in the run of the subgiant-giant branch compared to that of the globular clusters must be ascribed to a difference in chemical composition, and since the stars of M 67 show no anomaly in the strength of the metals, JOHNSON and SANDAGE concluded that the color-magnitude diagram of M 67 represents that of a cluster just as old as the globular clusters but with a normal metals-to-hydrogen ratio. This conclusion is supported by the calculations of HOYLE and SCHWARZSCHILD [4] who showed that stars as old as those in globular clusters but with a normal abundance of metals can reach as giants only an absolute magnitude around $M = 0$, in agreement with the observations in M 67. In my later discussions I shall again and again return to the M 67 case. Here I would like to raise only briefly the question: how should we classify this cluster? In view of its age and the topology of its color-magnitude diagram one could assign it to the population II (a population II cluster with normal metal content), while its chemical composition might induce us to assign it to the population I (an old population I cluster). I believe that the time has not yet arrived to decide on this question of terminology and that important gaps in our present knowledge must be filled before we can answer it intelligently.

The Population of Elliptical Galaxies

With our present telescopes we can actually resolve into stars only those elliptical galaxies which are within a radius of about 750 kpc. Our main source of information about the stellar composition are therefore the E-galaxies of the local group. They are listed in Table 1 with HOLMBERG's [8] magnitudes and colors when available. Although important data are still lacking I have tried to arrange the galaxies according to their absolute integrated magnitudes. Figures which are still provisional are given in brackets. There is probably very little change in absolute magnitude among the last four members of the list. Table 1 reflects the well-known fact that our local group contains only E-galaxies of intermediate and low luminosities.

TABLE 1

NGC	m_{pg}	*C*	*m – M*	M_{pg}	*Remarks*
	m	m		m	
205	8.89	+0.72	24.25	– 15.4	Contains several glob. clusters
221	9.06	0.90	»	– 15.1	
185	10.29	0.86	(23.9)	– 13.6	Contains 2 glob. clusters
147	10.57	0.84	(»)	– 13.3	» 2 » »
Fornax System	. . .	. . . .	(21.4)	. . . .	» 4 » »
Leo I »	11.27	0.87	(23.3)	– 12.0	
Sculptor System	. . .	. . . .	(19.6)	– 10 to – 11	
Draco »	. . .	. . . .	20.3		
Leo II »	12.85	0.81	(22.5)		
UMi »	. . .	. . . .	(19.9)		

It will be recalled that the findings in the Sculptor system, in particular the occurrence of cluster type variables in large numbers, led me in 1944 to the conclusion that the E-galaxies are made up of pure populations II. In order to get additional confirmation, I have investigated during the past few years at the 200-inch telescope the Draco, Leo II and UMi systems. All three are close enough to observe the cluster-type variables. It would have been desirable to include the Fornax system but it is too far south for an extended series of observations from our latitude. Although the search for variable stars has not yet been completed in the Leo II and UMi systems, it can be stated already now that in all three systems the cluster-type variables are present in large numbers. The Draco system contains more than 250, the Leo II system more than 200, and a similar figure is indicated for the UMi system. In addition to the numerous cluster-type variables a few type II cepheids are usually present. These data thoroughly confirm the earlier findings in the Sculptor system. Judged by the kind of variable stars which we find in them, the population of the E-galaxies must be a pure population II.

More detailed data are available for the Draco system for which Miss Swope, my collaborator, has just finished the study of the variable stars. This dwarf galaxy is at a distance of 114 kpc and has a linear diameter of 1.6 kpc. The 200-inch plates used in this investigation cover only the central region of the Draco system and Miss Swope has derived periods and light curves for 134 variables. Two are type II cepheids with periods larger than a day, the rest cluster-type variables. The latter have a remarkable period-frequency curve, 86% of the periods lie in the narrow interval from 0.55 to 0.70 days. In the light curves only Bailey's type *a* and *b* seem to be represented. There are a few variables with small amplitudes among the shortest and the longest periods but they are not true *c* types because their light curves are quite asymmetric.

NOTE ADDED MARCH 1958:

Since the Rome conference the measures for the color-magnitude diagram of the Draco system have been finished. In its overall features the Draco diagram is the typical population II diagram as we know it from the globular clusters. But it has a striking peculiarity. Instead of turning sharply to the right and approaching $M_{pv} = -3.0$ asymptotically at color indices between $+1^{\mathrm{m}}.4$ and $+1^{\mathrm{m}}.6$ the giant branch in the Draco diagram turns to the right only slightly and reaches $M_{pv} = -3.0$ at the color index $+1^{\mathrm{m}}.2$ where it ends. According to Hoyle, with whom we discussed this peculiarity, the position of the giant branch in the Draco system indicates a metal-to-hydrogen ratio still smaller than that in the globular clusters. It will be interesting to see whether the color-magnitude diagrams of the Leo II and UMi systems show this same peculiarity.

Because the dwarf E-galaxies of Table 1 are still relatively small samples of the population II — they surpass the brightest globular clusters of our galaxy in luminosity only by factors of the order 5 to 10 — we must turn to one of the larger E-galaxies if we want to get information on the rarer types of variable stars which are members of the population II. Since the 200-inch telescope came into operation I have photographed on every suitable occasion NGC 185 on red-sensitive or photovisual plates. This E-galaxy is too far away to observe the cluster-type variables and the series of red-sensitive and photovisual plates will provide information mostly on red variables But more information on the red variables in E-galaxies is badly needed because it is not yet quite clear which of the long-period variables should be assigned to the population II. The investigation of the numerous red variables of NGC 185 should answer this question.

The Populations of the Andromeda Nebula

In contrast to the simple situation in the elliptical galaxies with their pure populations II, things are more varied in the spirals because, besides the population II, the population I now appears. As an example of a spiral galaxy I would like to discuss the Andromeda nebula for several reasons. It is near enough to reach at least the brightest stars of the population II. It has a rather uncomplicated spiral structure because there is little branching of the spiral arms, which particularly in Sc spirals clutters up the spaces between the spiral arms. Finally it is an Sb spiral like our own galaxy. Since it is notoriously difficult to see in our galaxy the forest for the trees, the overall picture of an Sb spiral should be a useful guide when we try to understand the bewildering details which we encounter in our galaxy. We shall discuss the spiral structure of the Andromeda nebula with its population I first.

a) *The Spiral Arms and the Population I of the Andromeda Nebula*

In Table 2 I give a brief description of the spiral arms of M 31 at their crossings with the major axis of the nebula. Arms crossing the north-following half of the major axis are

TABLE 2

Spiral Arms in M 31

Spiral Arm	*Distance from Center*		*Spiral Arm*	*Distance from Center*		*Remarks*
		Kpc			*Kpc*	
N1	3′.4	0.6	S1	1′.7	0.3	Dust arm. No supergiants or H II regions visible.
N2	8′.0	1.5	S2	10′.5	1.9	Dust arms with sprinkling of pop. I supergiants. The first supergiants appear in N2-S2, the first H II regions in N3-S3.
N3	25′	4.6	S3	30′	5.5	
N4	50′	9.2	S4	47′	8.6	Maximum display of pop. I. Spiral arms now represented by abundance of supergiants while dust becomes more and more inconspicuous.
N5	70′	12.9	S5	66′	12.1	
N6	91′	16.7	S6	95′	17.4	These faint outer arms are defined by scattered groupings of blue supergiants. No immediately obvious signs of dust are visible.
N7	110′	20.2	S7	116′	21.3	

designed by N; those crossing the south-preceding half by S. Arms with the same number, e.g., N1 and S1, represent north and south crossings of the same arm. The distances of the arms from the center of M 31 are based on the modulus $m\text{-}M = 24.0$, which should be correct within ±.15 of a magnitude.

The descriptions given in Table 2 reflect the dual nature of the spiral arms:

1) As concentrations of the dust and gas.
2) As locations of the population I with its bright supergiants.

As I have pointed out on another occasion [9], this association of dust and gas and population I stars is most strikingly revealed by the H II regions of the Andromeda nebula which are strung out like pearls along the spiral arms. That these H II regions and with them their exciting O- and B-stars of high luminosity are deeply imbedded in the dust of the spiral arms is shown by their strong reddening. It will be recalled that HUBBLE in his survey of the Andromeda nebula, which covered on blue-sensitive plates the central region inside the arm N5-S5, was unable to find a single emission nebula, and that it required a search on red-sensitive plates (Hα region) to bring out the H II regions by the hundreds. The reasons for this abnormally strong reddening are perfectly clear today. A plot of the measured positions of the H II regions shows that the angle between the main plane of the Andromeda nebula and the line of sight is only 12°, so that large absorption and reddening effects in the dust-filled spiral arms are to be expected.

Outside the spiral arms the density of the dust must be quite low because the globular clusters of the Andromeda nebula do not show the general strong reddening exhibited by the H II regions. They are scattered all through the nebula with a marked concentration toward the center and their distribution is clearly unrelated to the spiral structure. Since the globular clusters on the average have much larger distances from the main plane of the Andromeda nebula than the dust and gas of the spiral structure, the light of half of them on the way to us will have to pass through this plane. The fact that no strong reddening comparable to that of the H II regions is observed in the globular clusters, except in the relatively few cases where they happen to shine through a spiral arm, clearly indicates that the density of the dust outside the arms must be very low indeed. These findings have been thoroughly confirmed by ARP [10] in his recent study of the novae of the Andromeda nebula. Like the globular clusters, the novae are representatives of the population II in the Andromeda nebula and unrelated in their distribution to the spiral structure. ARP concluded that for 24 of the 25 novae which he investigated the absorption was negligible (not exceeding 0.2 mag.). For only one (No. 4 of his list) he found an absorption of about 2.2 magnitudes and a reddening of 0.5 magnitudes, but this nova appeared in the arm N5-S5 of Table 2 and obviously shone through it! Altogether we have good reasons to believe that the distribution of the dust and gas in the Andromeda nebula is the same as that inferred from the recent measures of the 21-cm line of hydrogen in our own galaxy: high density of dust and gas in the spiral arms and very low or negligible density outside the arms.

We have today convincing reasons to believe that dust and gas are the primary constituents of the spiral structure and that the associated stellar population I represents a secondary phenomenon, its stars being formed up to the present day in the dust and gas clouds of the spiral arms. This conclusion, originally solely based on observations in other galaxies, has been in recent years confirmed by investigations in our own galaxy which showed that dust and gas clouds like the Orion nebula and IC 5146 are the breeding places of young population I stars.

From the descriptions given in Table 2 we must conclude that star formation is going on in all spiral arms of the Andromeda nebula with the exception perhaps of the innermost. Most of it is hidden by heavy absorption in the inner arms N2-S2 and N3-S3 in which the sprinklings of blue population I supergiants probably represent stars near the surface of the dust and gas arms. Only the numerous heavily reddened H II regions indicate that star formation is also going on in the deeper interiors of these spiral arms. We see the population I in its full display in the arms N4-S4 and N5-S5. Judged from what we see, most of the dust and gas in these arms seems to have been converted into stars. Located in the arm N4 is one of the regions which have been investigated at the 200-inch for variable stars. The abundance of the population I in this arm is illustrated by the fact that in an area covering only 0.1 square degrees 350 variables stars were discovered, of which 230 turned out to be type I cepheids, the eclipsing systems ranging next in frequency. Compared with the inner arms, the absorption in this field is quite low. Judged by the scatter of the cepheids around the period-luminosity relation the mean absorption for the field is close to 0.8 magnitudes. As we pass to the outermost arms N6-S6 and N7-S7, the most pronounced feature is the rapid numerical decline of the population I. It leads to a very patchy appearance of the arms which for long stretches are difficult to trace. The average density of the dust in these arms must be quite low because neither the stars nor the few H II regions exhibit signs of much reddening. Altogether one gets the impression that star formation has reached its peak in the intermediate arms N4-S4 and N5-S5 of the Andromeda nebula and that it is definitely on the decline in the outermost arms N6-S6 and N7-S7.

It is well known that in spite of their spectacular population I the spiral arms contribute less than 20% of the total light in Sb galaxies [11]. This figure implies that the population I stars of the spiral arms represent only a negligible fraction of the total mass of an Sb galaxy. But how much gas and dust is still available in Sb galaxies for future star formation? This important question has recently been answered by VAN DE

HULST [12], who showed as a result of his 21-cm surveys of neutral hydrogen in the Andromeda nebula and in our Galaxy that in both systems the still available amount of gas represents only 1 to 2 per cent of the total masses. This figure leaves no doubt that the phase of star formation in Sb galaxies is nearly over and that the bulk of the stars in these systems was formed in the past. We shall come back to this point at the end of the next section.

b) *The Disk Population of the Andromeda Nebula*

Soon after the resolution of the central region of the Andromeda nebula into stars, it became obvious that the population II is not restricted to the central lens but extends through the whole nebula. Its density, as we go outwards from the center along the major axis, decreases in about the same ratio as the brightness of the nebula if we disregard the spiral arms.

Because of the foreshortening effect of the projection, the extent of the population II is most easily determined along the minor axis. On the south preceding side the stars of the companion NGC 205 interfere, but on the north following — which is entirely free — the population II can be traced outward to a distance of 45 minutes of arc from the center. This is about the same limit to which STEBBINS and WHITFORD [13] with their photocell were able to trace the light of the Andromeda nebula in the direction of the minor axis. To establish the corresponding limit along the major axis is much more difficult and I do not yet possess the necessary place material. All I can state at present is that the population II has been traced along the major axis up to 2 degrees from the center and that it probably extends still farther. It has been occasionally suggested that these population II stars are the representatives of a large halo surrounding the Andromeda nebula. This interpretation is impossible because suitably located check fields show that the system of population II stars is quite elongated in projection and that it must be identified with the disk of the Andromeda nebula.

We have also convincing evidence that the stars which suddenly appear in such large numbers at photovisual magnitude 21.2 and fainter are really the brightest members of the population II. The evidence is as direct as one could wish. On plates taken with the 200-inch the globular clusters of the Andromeda nebula show clear signs of resolution whenever the exposure times are sufficient to bring out the population II stars in the surrounding field. We are, therefore, on safe grounds when we state that the brightest disk stars in the Andromeda nebula are the red giants of the population II.

But we have good reasons to doubt that with this statement the question of the general composition of the disk of the Andromeda nebula is already settled. These doubts arise because we are quite certain that in the disk of our own galaxy, at least in the surroundings of the sun, the overwhelming majority of the giants are ordinary red giants of the visual absolute magnitude 0 and not population II giants of the absolute magnitude -3. That the composition of the disk of the Andromeda nebula must be indeed very similar to that of the disk of our own galaxy has recently been demonstrated by W. W. MORGAN [6] [14]. MORGAN showed that the main contributors to the integrated spectrum of the central region of the Andromeda nebula are ordinary giants with strong CN bands and metallic lines of normal strength, and not population II giants in which both the CN bands and metallic lines are weak. Most of the light of the Andromeda nebula comes, therefore, from ordinary giants.

But we can go still a step farther. We know that stars can reach the giant region at $M \cong 0$ by two evolutionary routes. The first of these turns off the main sequence at $M \sim 0$ and leads on a practically horizontal line in the color-magnitude diagram into the giant region. Representative star clusters for this route into the giant region are the Hyades, Praesepe and

M 11. The second route turns off the main sequence at about $+3^{M}.5$ and leads through the subgiants into the giant region. The representative star cluster for this route is M 67. It is obvious that the giants which emit the bulk of the light of the disk of the Andromeda nebula cannot have arrived by the first route because in this case the main sequence itself just below the turn off point would be so filled with A-type stars that the latter would outshine the giants. The resulting integrated spectral type in the blue region of the spectrum would be probably a late A or early F and the corresponding color index would be around $+0^{m}.3$, in contradiction with the observations. We can therefore rule out the first route. The second route on the other hand fits perfectly. There are no main-sequence stars brighter than $+3^{M}.5$ or earlier than spectral type F5, and the integrated color of a galaxy made up of stars of the M 67 diagram should be about the same as that of an E-galaxy. We must conclude, therefore, that most of the light from the disk of the Andromeda nebula comes from stars which are similar to those found in M 67, which means old stars comparable in age to those of the population II in globular clusters but differing from them in chemical composition (higher abundance of metals).

We are thus led to the following picture of the Andromeda nebula. The brightest observable stars of the disk, if we disregard for the moment the spiral structure with its population I, are the red giants of the population II. But this population II, which is poor in metals, represents only a fraction of the disk stars. Most of the light of the disk comes from M 67 type stars which are as old as the population II stars but which are much richer in metals. Imbedded in the disk is the thin layer of gas and dust which exhibits the spiral structure. Star formation (population I stars) is still going on in the dust and gas clouds of the spiral arms, but the quantity of gas available for star formation has become very small since it amounts to only 1% of the total mass of the Andromeda nebula. We shall see later that the disk of our own galaxy is made up in the same manner.

The Population of Sc Spirals and Irregular Galaxies

Sc spirals and irregular galaxies are in many ways so similar that they can be discussed together. In our local group of galaxies the Sc spirals are represented by M 33, the irregular galaxies by the Magellanic Clouds and the 3 dwarf systems IC 1613, IC 5152 and NGC 6822. Their outstanding characteristic is the overwhelming strength of the population I. Nevertheless, the population II must be present too since novae, typical population II objects, have been found in the Magellanic Clouds, M 33 and IC 1613. For the Magellanic Clouds this question was finally settled in a decisive manner when THACKERAY and WESSELINK [15] discovered cluster-type variables in three globular clusters of the Clouds. We have therefore good reason to believe that star formation in the Sc spirals and the Magellanic Cloud-type systems started at the same epoch as in the E-galaxies and the Sa and Sb spirals.

However, the rate of star formation in the Sc spirals and the Magellanic Cloud-type systems must have been much slower, because a considerable fraction of their masses is still present in the form of gas. According to KERR, HINDMAN and ROBINSON [16], the neutral hydrogen present in both Clouds accounts for about 40% of their masses and Professor OORT informs me that in M 33 about 10% of the mass is neutral hydrogen. Both figures may be somewhat changed in the future, but there are good reasons to believe that they are at least of the right order.

CONCLUSIONS

Summing up, we can draw the following conclusions:

a) Star formation began in all galaxies about 6×10^9 years ago. The sequence of nebular types has therefore nothing to do with evolution.

b) The rate at which star formation proceeded depended on the type of the galaxy.

In the E-galaxies it is best described as one big burst of star formation at the very beginning. It produced the population II with a low content of metals which we observe today in the elliptical galaxies and the spherical halo of our Galaxy.

There must have been a similar big burst of early star formation in the disks of the Sb and the Sa spirals. But it produced, for reasons which are not yet clear, both stars with a low content of metals and stars with a "normal" content of the metals. The present color-magnitude diagram of the first group is that of the globular clusters; that of the second group, the M 67 diagram. Star formation continued afterwards in the dust and gas clouds of the spiral structure of these galaxies, but it was apparently a trickle compared with the big burst of star formation at the beginning. Today star formation in these galaxies is nearing its end since only one to two percent of their total masses consists of gas.

Judged by the much larger percentage of mass which is still present in the form of gas, star formation in the Sc spirals and the irregular galaxies of the Magellanic Cloud-type must have proceeded at a lower and probably more uniform rate.

We also understand now why the two stellar populations, either singly or combined, are such conspicuous features in most galaxies. They are age groups which represent two significant phases of the star formation in galaxies.

REFERENCES

[1] W. Baade, Ap. J., *100*, 79, 1944.

[2] A. R. Sandage, Ap. J., *58*, 61, 1953 and with H. L. Johnson, Ap. J., *124*, 379, 1956.

[3] A. R. Sandage, Mem. Soc. R. d. Sc. d. Liège, série 4, t. *14*, fasc. unique, 254, 1953.

[4] F. Hoyle and M. Schwarzschild, Ap. J., Suppl. No. 13, 1955.

[5] W. A. Baum, A. J., *57*, 222, 1952.

[6] W. W. Morgan, P.A.S.P., *68*, 509, 1956.

[7] H. L. Johnson and A. R. Sandage, Ap. J., *121*, 616, 1955.

[8] E. Holmberg, Medd. Lund's Astr. Obs., Ser. II, Nr. 136, 1957.

[9] W. Baade, Proc. Paris Symposium on Problems of Cosm. Aerodynamics, 166, 1951, and
W. Baade, Pub. Michigan Obs., *10*, 7, 1951.

[10] H. C. Arp, A. J., *61*, 15, 1956.

[11] E. Holmberg, Medd. Lund's Astr. Obs., Ser. II, Nr. 128, 41, 1950.

[12] H. C. van de Hulst et al., BAN *14*, 1, 1957.

[13] J. Stebbins and A. E. Whitford, Proc. N.A.S. Wash., *20*, 93, 1934.

[14] W. W. Morgan and N. U. Mayall, P.A.S.P., *69*, 291, 1957.

[15] A. D. Thackeray, Trans. I.A.U., *8*, 397, 1952, and A. D. Thackeray and A. J. Wesselink, Nature, *171*, 693, 1953.

[16] F. J. Kerr, J. V. Hindman and B. J. Robinson, Aust. J. Phys., 7, 297, 1954.

DISCUSSION

CHAIRMAN: D. J. K. O'CONNELL

HECKMANN

Several fields in Cygnus have been searched by Father MILLER and WACHMANN for cluster variables.

BAADE

We need searches for RR Lyrae variables in low latitude fields distributed in different directions, especially in longitudes, say, within 45° of the galactic nucleus.

HERBIG

The existence of the Aquila rift explains why there is a shortage of observations in the direction of longitudes less than 30°, which BAADE has mentioned.

HOYLE

Are the stars of elliptical nebulae similar in their composition to stars in the halo, or to type II stars in the disk?

MORGAN

From integrated spectra there is no doubt that the principal source of luminosity in the inner part of M 31 and in the giant E0-E5 systems in the Virgo cloud is due to K and M giants with normal metal content. The contribution of the halo stars to the total luminosity is probably minor.

SCHWARZSCHILD

Would the integrated spectral type of the brighter stars of M 67 give an Sb nebula spectrum?

MORGAN

M 67 is a cluster without late K-M giants; some clusters show later K giants. This may be a richness effect. The same is true of the giant ellipticals. The main contribution comes from normal giants.

HERBIG

Has SANDAGE any information on the colours or other properties of the very faint globular clusters found by ABELL in high galactic latitudes?

SANDAGE

One near the galactic pole has a normal colour-magnitude diagram. Of those in ABELL's list only two of six are normal. The four abnormal ones have no horizontal branch according to the measures of E. M. BURBIDGE.

SPITZER

What is the magnitude of the brightest giants in the late type globular clusters investigated by MORGAN?

SANDAGE

This matter is under investigation. The giants in M 67 are of visual magnitude zero, while those in normal globular clusters are of magnitude –3. A decision on this matter in MORGAN's clusters would seem to be critical.

SPITZER

What is the difference in colour index between elliptical nebulae and normal globular clusters?

BAADE

0.85 for elliptical galaxies and 0.58 for globular clusters.

NEUTRAL HYDROGEN IN GALAXIES

J. H. Oort
Leiden Observatory

At the time when I suggested this item I had hoped to be in a position at the Semaine d'Etude to report on observations of the 21-cm line in a number of external galaxies. Progress has, however, been somewhat slower than foreseen, so that the only external galaxies for which reliable data are available are the Andromeda nebula and the Magellanic Clouds.

On the assumption that in these three galaxies the hydrogen is optically thin in the radiation of the 21-cm line, we can easily determine the total amounts of atomic hydrogen. These quantities, in units of the solar mass, are shown in Table 1. For comparison the quantity of hydrogen in the Galactic System is given in the fourth line. The second column shows the total mass of each system, in the same units. Except for M 32 these masses were derived from rotational velocities measured by means of the 21-cm line. The last column gives the ratio of mass to photographic luminosity, both expressed in the sun as unit. These ratios refer to the entire system, except in the case of the Galactic System where it was estimated for a cylinder with axis perpendicular to the galactic plane and passing through the sun. The sources from which the various quantities were taken are given at the end of this contribution.

TABLE I

Comparison of Total Amount of Interstellar Neutral Hydrogen with Total Mass.

System	*Total Mass*	*Mass H I*	*Fraction H I*	*Mass* / *luminosity*
Large Mag. Cl.	1 $\times 10^9$ [1]	0.7 $\times 10^9$ [1]	$\simeq$ 0.5	0.4 [1]
Small Mag. Cl.	1.3 » [1]	0.5 » [1]		2.6 [1]
M 31	270 » [2]	2.5 » [3]	0.009	29 [2]
Galactic System	70 » [4]	1.5 » [3]	0.02	4.2 [5]
M 32.	16 » [6]	$<$0.01 » [7]	$<$ 0.0006	100 [6]

A very preliminary measurement of M 33 by E. RAIMOND and Miss L.M.J.S. VOLDERS [8] shows that the amount of hydrogen is between 0.2 and 0.9 $\times 10^9$ solar masses (*). With a total mass of 4×10^9, the fraction of the mass which is in the form of hydrogen atoms would lie between 0.05 and 0.2.

Although the estimates of the total masses of the Magellanic Clouds are still uncertain by factors of at least 1.5, these rough data suffice to show that something of the order of half of their masses are still interstellar. It is not clear why this fraction is so much smaller in the spirals like the Galactic System and the Andromeda nebula.

It would be of great interest to have some data on the interstellar-matter content of elliptical galaxies. However, this is a very difficult observational problem. The radiation to be expected from isolated elliptical galaxies or from those in the Virgo cluster is extremely small. By far the largest intensity

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(*) *Note added in proof.* Since the above was written the observations on M 33 were completed. From these observations Miss VOLDERS has derived 4.4×10^8 solar masses for the total quantity of hydrogen.

should be found in the elliptical companions to the Andromeda nebula, which are some ten times closer than the brightest other elliptical systems. But in this case it is extremely difficult, if not impossible, with existing instruments, to disentangle it from the relatively strong radiation emitted by the main spiral. An attempt has been made by HEESCHEN [7] with the 60-foot Harvard radio telescope. He kindly informed me that he found a temperature of 0°6, which may be estimated to correspond to a total mass of 0.02×10^9 $\mathfrak{M}_\odot$ of neutral hydrogen. It is unknown how much of the observed radiation comes from M 31, so that we can only give an upper limit for the fraction of interstellar hydrogen. This upper limit is 0.001. The true fraction might well be considerably smaller.

The 21-cm observations in the Galactic System and M 31 give also some information on the manner in which the hydrogen is distributed. The distributions for the two galaxies are shown in Figure 1. For the Galactic System the data are by WESTERHOUT [9], for the Andromeda nebula by VAN DE HULST et al. [3]. An interesting feature in the latter is the high maximum at 1°, or 8.7 kpc from the centre. This maximum is shown equally in the two halves of the nebula. In neither of the systems does the hydrogen in the plane of the spiral appear to extend much beyond the region where OB stars and emission nebulae are observed.

In most systems where hydrogen is abundant it is concentrated in spiral arms. A general discussion of these spiral structures would carry us too far from the main topic of the Semaine. I should only like to mention a curious phenomenon connected with this structure, which was recently discovered from observations with the 25-metre radio telescope in Dwingeloo. It was found that the gas in spiral-like structures within about 3 kpc from the centre of the Galactic System is moving away from the centre with velocities ranging from roughly 50 to 200 km/sec. [10]. The expanding arms take

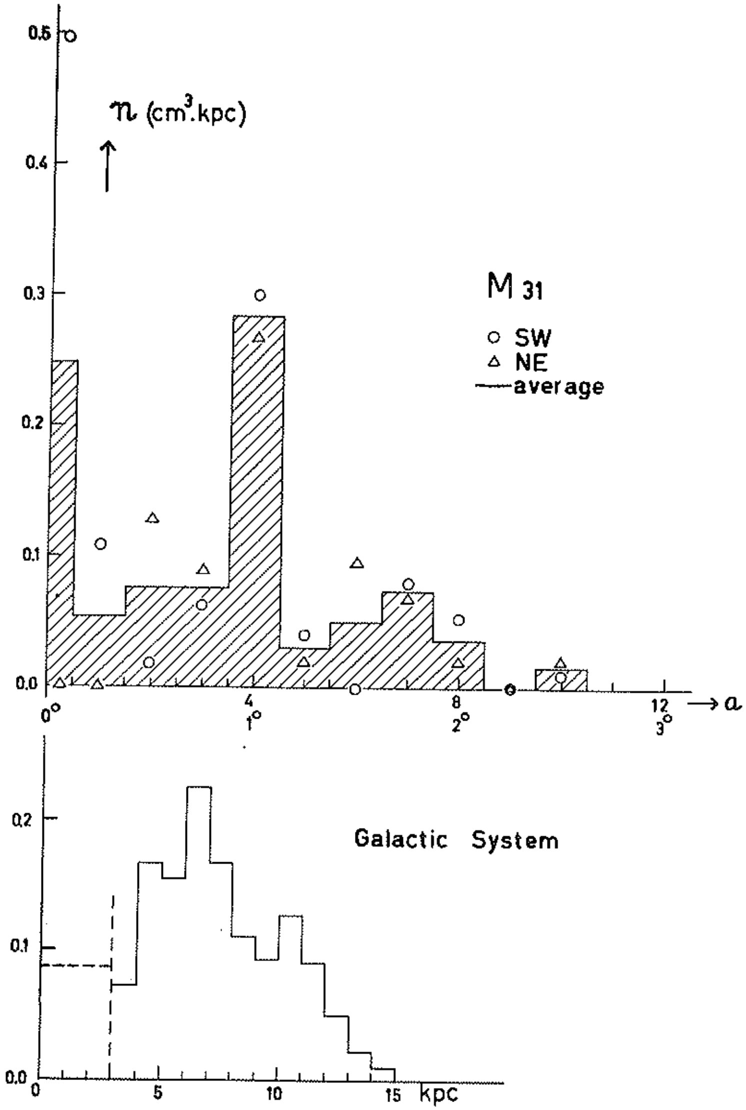

FIG. 1 — Variation of hydrogen density in the Andromeda nebula and the Galactic System with distance from the centre. Abscissae are distances from the centre measured in the plane of the spiral (in the Andromeda nebula $1_0 = 8.7$ kpc). If the equivalent thickness of the layer is *d* kpc the density in this layer may be obtained by dividing the ordinates by *d*.

part in the rotation of the system and are confined to a very thin layer around the galactic plane. The speed with which the gas moves away from the centre is so high, and so much mass is involved in the expansional motion, that the whole part of the disk within 2 kpc from the centre would be emptied in some 50 million years if there would be no replenishment. It appears highly probable that replenishment is effected by a continuous stream of hydrogen falling in towards the centre from regions outside the galactic plane. This gas may come from a large halo of rarefied gas surrounding the disk with its spiral structure. The presence of such a halo has also been indicated by other observations. The 21-cm observations have given some evidence to show that the halo contains likewise clouds of neutral hydrogen; these appear as long tails to the emission lines observed in high latitudes. Up to the present, however, only fragmentary observations have been made. Better measurements must be awaited before it is possible to give estimates of the extent and total mass of the halo.

REFERENCES

[1] F.J. Kerr and G. de Vaucouleurs, Austr. J. Phys., *9*, 90, 1956. For the Large Cloud the mass is based on the assumption of a moderate inclination i of the plane of the nebula to the line of sight. The authors themselves favour a very large value of i (65°) and their mass estimate is accordingly a factor 3 higher. The evidence for such a large inclination does not appear convincing.

[2] Computed by M. Schmidt, B.A.N., *14*, 17, 1957, from the rotational velocities of neutral hydrogen as measured by van de Hulst a. o. (reduced to an assumed distance of 0.5×10^6 pc for M 31).

[3] H. C. van de Hulst, E. Raimond and H. van Woerden, B.A.N., *14*, 1, 1957. The distance of M 31 has been taken as 0.5×10^6 pc.

[4] M. Schmidt, B.A.N., *13*, 15, 1956.

[5] J. H. Oort, to appear in the B.A.N.

[6] The $\mathfrak{M}/L$ ratio was estimated to be similar to that in the elliptical galaxy NGC 3115, in which values between 100 and 200 were found for this ratio depending on the assumptions made. The mass was computed from the luminosity.

Note added in proof. By measuring line widths in M 32 Minkowski has found the velocity dispersion to be 100 km/sec. Using this result Poveda has recently derived a much smaller value of the mass and, therefore, of the ratio of mass to luminosity in this galaxy (unpublished).

[7] D. Heeschen, unpublished.

[8] E. Raimond and L.M.J.S. Volders, B.A.N., *14*, 19, 1957.

[9] G. Westerhout, B.A.N., *13*, 151, 1957.

[10] H. van Woerden, W. Rougoor et J. H. Oort, C. R., *244*, 1691, 1957.

DISCUSSION

CHAIRMAN: D. J. K. O'CONNELL

SPITZER

What is the total mass of hydrogen in the halo?

OORT

This has not been estimated. The brightness temperature measured in the halo may be about 2 degrees.

STRÖMGREN

How far is the assumption that the hydrogen is optically thin justified?

OORT

The assumption had to be made for the Magellanic Clouds. In the Andromeda nebula and the galactic system optical thickness was allowed for in a way, but recent observations of the 21-cm absorption lines in the Cassiopeia A and the Taurus A radio sources suggest that interstellar matter may largely be concentrated in optically thick clouds. To take this into account we must know more about the individual clouds. There may be a factor of one and a half or two to be applied to all hydrogen densities when this effect is taken into account.

POPULATION TYPES AND THE EVOLUTION OF BARRED SPIRALS

BERTIL LINDBLAD
Stockholm Observatory

In the case of the barred galaxies several interesting problems present themselves concerning the relation between the population types and the structural details. At least from a superficial examination of some typical cases regarding structure and colour it seems probable that the bar, as well as the central condensation, are in general mainly made up of population type II. From typical examples of barred spirals it is evident that there is a continuous transition from barred to ordinary spirals. It is even possible that practically every spiral nebula has a trace of a barred structure.

However, a contention that central system plus bar contains only type II stars would be incorrect. There is certainly in many cases a mixture of types I and II towards the ends of the bar, at the transition to the main ring of the system, from which the spiral arms extend. Very often the part of the spiral structure close to the end of the bar is particularly strong. But if we look closer at the centre there is often a small very red central nucleus, surrounded by a formation which is sometimes an irregular ring, but sometimes has a plain spiral structure. From this small ring, or spiral, presumably of population type I, clouds of dark matter proceed outwards, symmetrically on one side only of the half-bar.

A quantitative theoretical explanation of this phenomenon has been given by LANGEBARTEL [1]. For a certain prescribed density-distribution in the density wave defining the bar we can obtain the potential of the wave and can compute the internal motions on the assumption that the bar follows nearly the circular motion in the undisturbed system.

The theory is consistent, because it has been shown [2] that just the prescribed form of the density function follows by the equation of continuity from the computed internal motions. The optical phenomenon of the bar is created by two eccentric density maxima situated on one and the same diameter and on either side of the central condensation. These density maxima correspond to local whorl motions, which occur in the same direction as the angular velocity of the system. On the diameter at right angles to that of the density maxima there is a thinning out of matter with local whorl motions in the opposite sense. There are streamings from the central region outwards in the two quadrants which follow the diameter of the bar in the rotation, and it is readily seen how local streams of matter can proceed from the region about the centre outwards along the bar in these quadrants.

We may illustrate the conditions by two typical cases. In the nebula NGC 3992 (Fig. 1) the two whorls of strong density are plainly shown, and also the regions of minimum density. The spiral arms are fairly tightly wound.

In NGC 1365 (Fig. 2) the arm system has opened up widely. It is plain that the bar contains in this case a considerable amount of population type I. The motion of matter along the bar is well developed. If this motion occurs from the centre outward, and is interpreted on the basis of a purely gravitational theory, the direction of rotation should be counter-clockwise, so that the spiral arms open up in the direction of rotation. The shape of the arms can then be understood as a consequence of the outward motion in the two quadrants following the bar in the rotation, in conjunction with a differential rotation lead-

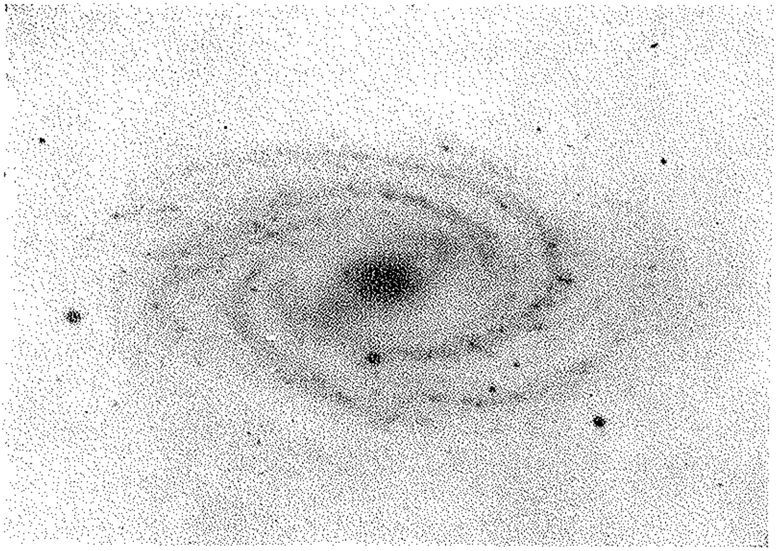

FIG. 1 — NGC 3992.

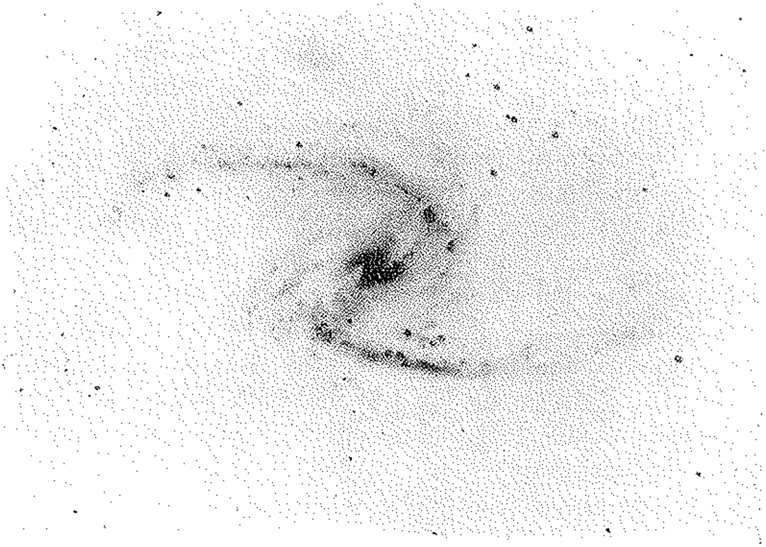

FIG. 2 — NGC 1365

ing to a steep run of the arms outwards and a strong concentration of matter in the inner parts of the arms close to the bar. If, on the other hand, the direction of the rotation is in reality the opposite one, and the arms are trailing, either the motion along the bar occurs inwards, from the spiral structure to the centre, or in the case of an outward motion, when account is taken of the Coriolis force, there should be an exceedingly high speed of the emerging matter and perhaps a force of repulsion from the bar rather than a force of attraction on the matter in question.

In the case of the Andromeda nebula, M 31, there appear rather plainly traces of a bar structure in the intermediate region between the nucleus and the strong outer arms [3]. The general similarity between the Andromeda nebula and the barred spiral NGC 7723, type SBb, is quite striking. In M 31 the bar is probably mainly built of population type II. Traces of an interior structure of population I may be identified in the dust clouds emerging from the central region.

The conclusion of what has been said may be that the bar, together with the central system, as a rule contains mainly population II, but that population I sometimes partakes considerably in the bar structure, depending on the general type of the nebula. In the very "late" types population I may dominate. This agrees with the opinion that the bar depends on a general density wave in the system, and not primarily on the kind of matter prevailing in the system. In barred spirals of intermediate type matter of population I occurs not only in the outer spiral structure but also in the central regions, often in the shape of a small spiral. From this small spiral matter is presumably transported along the bar out to the main spiral structure, perhaps until the population I at the centre will be exhausted. It seems probable that the velocity with which this transport occurs is considerable.

I should like to point out in this connection the importance of observations of internal motions in barred spirals for solving

[3] I, 3 - *Lindblad I* - p. 4

the physical and dynamical problems of the galaxies. If we observe in detail motions in tilted barred spirals with the bar along the apparent major axis, as well as in spirals with the bar along the apparent minor axis, we should get a good idea of the systematic motions and an extremely important check on any dynamical theory. At the same time we should get a starting point for more definite conclusions as to the development of the population types in the galaxies of the barred type.

REFERENCES

[1] R. G. Langebartel, Stockholm Annals, *17*, No. 3, 1951.

[2] B. Lindblad and R. G. Langebartel, Stockholm Annals, *17*, No. 6, 1953.

[3] B. Lindblad, Stockholm Annals, *19*, No. 2, 1956.

DISCUSSION

CHAIRMAN: D. J. K. O'CONNELL

HECKMANN

Are there any independent observations confirming that in barred spirals the ring is composed of population I and the centre of population II?

LINDBLAD

In 1950 I took some plates at Mount Wilson in blue and yellow which show the differences of colour qualitatively.

BAADE

Where you have spiral arms containing H II regions there is normally dark matter in the bars, but there are some cases of bars containing population II and no dust, according to HUBBLE. Have there been spectroscopic observations along the bar?

LINDBLAD

The condition for dust in bars is probably that there should be a small spiral of type I in the centre.

II.

AMAS STELLAIRES DE NOTRE GALAXIE COMME REPRESENTANTS DES POPULATIONS STELLAIRES

THE COLOR-MAGNITUDE DIAGRAMS OF GALACTIC AND GLOBULAR CLUSTERS AND THEIR INTERPRETATION AS AGE GROUPS

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology

I. *Open Clusters*

Much of the observational evidence for the evolution of the stars comes from color-magnitude diagrams of star clusters. The modern observational era begins with O. J. EGGEN's photoelectric studies of bright galactic clusters such as Pleiades, Hyades and Praesepe. EGGEN's work was followed by H. L. JOHNSON's three color studies of these and other open clusters. The principle results were; (1) evidence that in any one cluster the cosmic scatter of stars around the main sequence was very small or even zero, (2) the bright end of the main sequence terminates at different absolute magnitudes in different clusters, (3) in clusters where yellow giants occur, the position of the giant sequence is systematically related to the turn-off point of the main sequence.

The observational data relevant to the evolutionary problem is summarized in a composite color-magnitude diagram of ten galactic clusters and one globular cluster shown in Figure 1. Here the absolute visual magnitude M_v is plotted against the normal unreddened $B - V$ color on the JOHNSON and MORGAN UBV photometric system. The same data are displayed in the more useful M_{bol}, log T_e plane in Figure 2 which was obtained

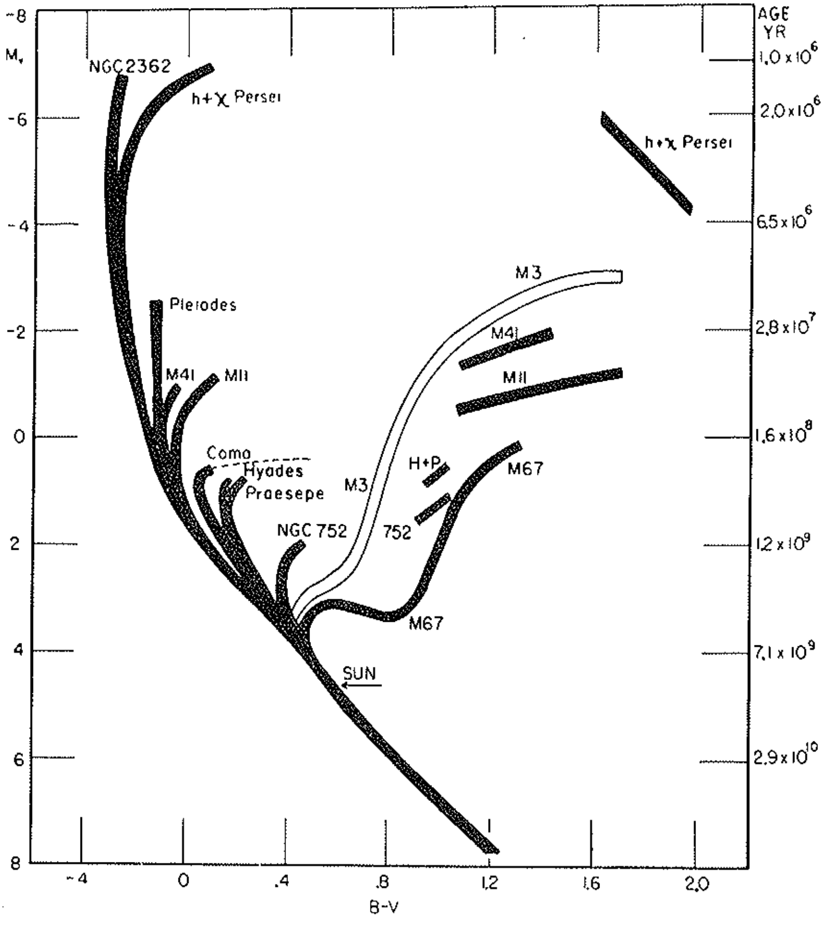

FIGURE 1 — A composite color-magnitude diagram of ten galactic clusters and one globular cluster. Ages corresponding to the various main sequence termination points are given along the right hand ordinate.

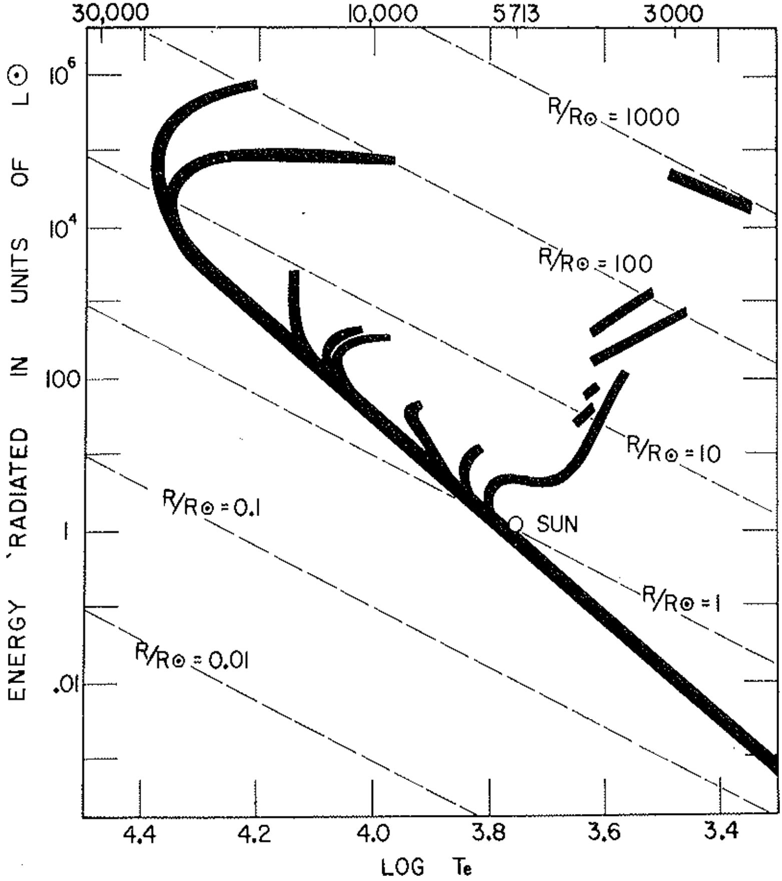

FIGURE 2 — A composite H-R diagram in the M_{bol}, log T_e plane for the same ten galactic clusters shown in Figure 1. The ordinate gives luminosity in terms of the sun. Temperature is in °K. Lines of constant radii are dashed.

from Figure 1 by the usual $B\text{-}V=f(T_e)$ and $\Delta M_{bol}=f(B\text{-}V)$ relations. The dashed lines of Figure 2 show the lines of constant radii.

Is there evidence from these data for a spread of ages among the galactic clusters? The most striking feature of Figures 1 and 2 is the range in absolute magnitude for the main sequence termination points in the various clusters. No main sequence stars are present in h and χ Persei brighter than $M_v = -7$; in the Pleiades brighter than $M_v = -3$; in Hyades and Praesepe brighter than $M_v = +0.5$; and in M 67 brighter than $M_v = +3.5$. Furthermore, near the termination points, the slope of the main sequence in each cluster steepens from the next brighter cluster. These results, which have been known in preliminary form since the time of R. J. TRUMPLER's work, are interpreted as the result of stellar evolution and are the evidence for age differences among the clusters.

Current ideas of star formation and subsequent evolution (due principally to early work by ÖPIK, SCHÖNBERG and CHANDRASEKHAR, GAMOW, and later by SCHWARZSCHILD and his school) require that stars are formed from the interstellar medium and contract toward the main sequence with a Helmholtz contraction time scale. The central temperature rises during contraction, until, at a certain critical value, thermonuclear reactions begin, contraction stops, and a stable star is born. The luminosity of the stable star depends upon the mass of the initial condensation. Because there is a mass distribution function for the initial condensation, stars are spread continuously along the main sequence at the time of stellar birth.

The first result of the nuclear reactions is to convert hydrogen into helium in the central regions of the star. This causes a readjustment of the stellar structure so as to compensate for the increase in the mean molecular weight. Detailed computations of this structural change were first made by SCHÖNBERG and CHANDRASEKHAR [1] and later by many other authors. The general result is that the evolving star remains close to the main sequence until a critical fraction, q_c, of its mass has been exhausted of hydrogen, at which time the star rapidly expands and moves redward in the color-magnitude diagram into the region of the yellow giants.

These theoretical expectations find direct support in Figures 1 and 2. When a cluster has been in existence for a time T, all stars brighter than a certain luminosity will have exhausted the critical mass q_c and will have left the main sequence. Stars only slightly fainter than this limit will have exhausted a smaller fraction $q_i < q_c$ and will have evolved only slightly from their initial stellar structure on the main sequence. The details of the theoretical evolution explain rather well the observed change of slope of each galactic cluster main sequence near its termination point.

The age of each cluster follows immediately if we identify the main sequence termination point with the stage when a star has exhausted q_c of its mass of hydrogen. In exhausting q_c, the star has released an amount of nuclear energy

$$E_n = \Delta Mc^2 = .007\,\mathfrak{M}\,Xq_c\,c^2 \tag{1}$$

where X is the fractional hydrogen abundance by mass. The star releases this energy at a rate L_i ergs/sec which varies with q_i. The function $L_i = f(q_i)$ is given by the various theories. The total time required to burn $Xq_c\,\mathfrak{M}$ grams of hydrogen is

$$\tau = .007\,\mathfrak{M}\,c^2\,X \int_{q_i=0}^{q_i=q_c} \frac{d\,q_i}{f(q_i)} \ . \tag{2}$$

Let L_T be the luminosity of the main sequence termination point. The function $L_i = f(q_i)$ may be written as $L_i = L_T h(qi/q_c)$. The age of a cluster whose luminosity at the main sequence termination is L_T is then

$$\tau = \frac{.007\,\mathfrak{M}\,c^2}{L_T} \int_{Xq_i=0}^{Xq_i=Xq_c} \frac{X\,dq_i}{h(q_i/q_c)}\,. \tag{3}$$

If we adopt the SCHÖNBERG-CHANDRASEKHAR evolution, $Xq_c = 0.07$ and $h(q_i/q_c)$ is known. Equation (3) becomes

$$\tau = 1.10 \times 10^{10} \frac{\mathfrak{M}}{L_T} \text{ years} \tag{4}$$

where $\mathfrak{M}$ and L_T are in solar units. L_T is known from observations and $\mathfrak{M}$ is given by the mass-luminosity relation.

The ages of the clusters shown in Figure 1 have been computed from equation 4 and are given in Table 1. These ages are not precise because in equation 4 we have assumed that $Xq_c = 0.07$ independent of the mass. This requires homologous models from $\mathfrak{M} = \mathfrak{M}_\odot$ to $\mathfrak{M} = 30\,\mathfrak{M}_\odot$ which is probably not strictly true.

TABLE 1

Cluster	$M_{v,T}$	τ (*years*)
NGC 2362	< -7.0	$< 1 \times 10^6$
h + χ Per	-7.0	1×10^9
Pleiades	-2.5	2×10^7
M 41	-1.5	6×10^7
M 11	-1.3	6×10^7
Coma	$+0.5$	3×10^8
Hyades	$+0.8$	4×10^8
Praesepe	$+0.8$	4×10^8
NGC 752	$+1.9$	1×10^6
M 67	$+3.5$	5×10^9

The stages of the evolution after the star has left the main sequence are not adequately accounted for by present theoretical stellar models for masses greater than 2 $\mathfrak{M}_\odot$. But

Figures 1 and 2 show certain aspects of the history. For clusters brighter than M 67 (mass $>1.2\ \mathfrak{M}_\odot$) a distinctive Hertzsprung gap appears between the termination of the main sequence and the beginning of the giant sequence. This suggests that for $q_i > q_c$ the increase in the radius of the evolving star is very rapid until a $B-V$ of about 1.0 is reached. Here the rate of expansion slows down and stars spend appreciable time in the giant region of the M_v, $B-V$ plane. The observational manifestation of this change in rate is the appearance of giant sequences in most clusters. The width of the Hertzsprung gap appears to be a function of mass. It goes to zero in M 67 where the mass of an individual giant star is about $1.2\ \mathfrak{M}_\odot$. It widens to about $\Delta(B-V)=0.7$ magnitude at Hyades and finally to about 1.6 magnitute for h and χ Persei. The presence or absence of the gap may be connected with the presence or absence of a convective core. It is perhaps significant that the p - p thermonuclear reactions probably give way to the C - N cycle with the consequent onset of convection at masses of about $1.5\ \mathfrak{M}_\odot$ (absolute magnitude $\approx +3$). This is close to where the Hertzsprung gap begins.

Figures 1 and 2 suggest that the shape of the evolutionary tracks are dependent upon mass. For stars as massive as those in the Hyades, the tracks in the M_v, $B-V$ plane are nearly horizontal. Younger clusters such as M 11, M 41, and h and χ Persei, also suggest nearly horizontal tracks. For masses less than $3\ \mathfrak{M}_\odot$, the tracks from the main sequence bend upward like in NGC 752 and M 67. Because of this change of shape of the tracks with mass, all clusters older than Hyades ($\tau = 4 \times 10^8$ years) have the property of funnelling their stars into a narrow band in the giant region between $M_v = +2$ to $M_v = 0$. Consequently, stars of different mass and different ages end up in the same region of the H-R diagram along what appears to be a sequence when data for the field stars are plotted. But actually, because of the funnel effect, this is no sequence at all but rather a region of the diagram which contains stars whose ages range from $\tau = 4 \times 10^8$ years to 5×10^9 years, whose masses range from $\mathfrak{M} = 3\ \mathfrak{M}_\odot$ to about $\mathfrak{M} = 1.2\ \mathfrak{M}_\odot$, and whose original spectral class along the main sequence ranged from B7 to F7 with the consequent change of kinematical properties. Computation of the luminosity function for K0 - K2 stars from $M_v = +5$ to $M_v = -4.5$ using the tracks suggested by Figures 1 and 2, indicate that the observed luminosity class III giant "sequence" can be explained in this way. Good agreement is obtained between the observed and the predicted luminosity functions [2].

II. *Globular Clusters*

Color-magnitude diagrams for globular clusters were first obtained by SHAPLEY around 1915. These early diagrams showed clearly that the brightest stars were red in contrast to the situation in normal galactic clusters. In the 1930's and early 1940's SHAPLEY's early work was extended to other clusters by several workers, but no study went faint enough to locate the connection of the observed sequences with the main sequence. Post-war work with the large reflectors on Mount Wilson and Palomar has located the main sequences in M 3, M 13, and M 92, although there still remain unsolved photometric problems at very faint light levels. Agreement between the various observers has not yet been reached for stars fainter than $V = +20$, so, although the main sequences have been found in the three clusters, their exact positions in the M_v, $B - V$ plane are not yet known.

The location of the main sequences and, in particular, their exact termination point, is fundamental for the problem of finding age differences among globular clusters. However, use of this method is quite unsatisfactory at present not only because of the current observational uncertainty but also because of the lack of precision of the method at $M_v = +3.5$. A difference of only 0.3 magnitude in the main sequence termination point corresponds to the large age difference of 10^9 years at $M_v = +3.5$. We are therefore compelled to look at the more easily accessible, brighter parts of color-magnitude diagrams for globular clusters to see if differences here can be interpreted as age parameters.

Since the time of S. BAILEY's discovery of RR Lyrae stars in globular clusters, much work has gone into obtaining periods and light curves for these stars. Although most RR Lyrae variables have periods between 0.3 and 0.8 days, it is a curious fact that the distribution of periods from one globular cluster to another is not the same. OOSTERHOFF pointed out in 1939 [3] and 1944 [4] that the mean period of the type *a* and *b* RR Lyrae stars in any cluster was either near 0.54 days or 0.64 days and the separation of clusters into two groups seemed definite. Further work by Dr. HELEN HOGG has confirmed this conclusion. It was further shown that the mean period of the type *c* variables was divided in the same ratio with values of either near 0.31 days or 0.37 days. The data upon which these conclusions rest are shown in Tables 2 and 3 and are taken from the compilation of OOSTERHOFF. Table 2 contains data for both the *a, b* type and the *c* type variables in clusters which have been well observed. Table 3 gives less complete data for only the *a, b* variables in a number of clusters. This table is divided into two sections, one for the short period group, and the other for the longer period group. When more clusters are observed, it may be that the period difference will form a continuum rather than two separate groups.

We now seek an explanation for this phenomenon and ask if these differences can be a possible age parameter.

RR Lyrae stars are found only along the horizontal branch of color-magnitude diagrams of globular clusters in a discrete region of instability extending from $B-V=0.17$ to $B-V=0.39$ from which non-variable stars are excluded. Suppose there is an absolute magnitude difference in the horizontal

TABLE 2

Cluster	$\overline{P}_{a,b}$	*No.*	$\overline{P}_c$	*No.*
ω Cen	$0^{\rm d}.65$	77	$0^{\rm d}.37$	58
M 15	.65	31	.38	28
M 53	.62	17	.37	15
M 92	.63	9	.37	3
M 3	.55	124	.32	27
M 4	.55	31	.29	9
M 5	.54	63	.32	13

TABLE 3

NGC	*M*	$P_{a,b}$	*No.*	*NGC*	*M*	$P_{a,b}$	*No.*
362		$0^{\rm d}.54$	7	5024	53	$0^{\rm d}.62$	17
3201		.56	55	5139	ω Cen	.65	77
5272	3	.55	124	6341	92	.63	9
5904	5	.54	63	6656	22	.63	7
6121	4	.51	17	7078	15	.65	31
6723		.51	17	7089	2	.63	11
6981	72	.55	21				
		.545	304			.643	152

branch between two clusters A and B, with A the brighter. If RR Lyrae stars occur in both clusters, the period distribution of those in A will not be the same as in B because the horizontal branch of each cluster cuts the domain of instability at different levels. Figure 3 illustrates the situation where two hypothetical horizontal branches are drawn. The domain of instability is

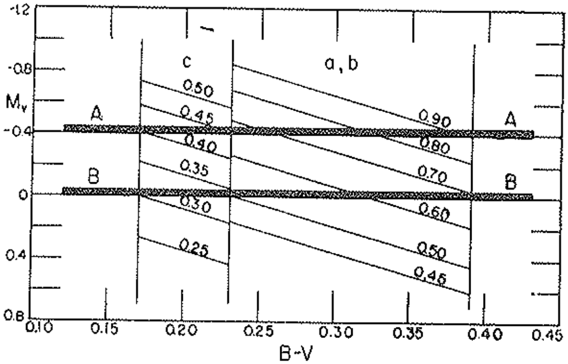

FIGURE 3 — A section of the color-magnitude diagram for globular clusters showing the domain of the RR Lyrae stars along the horizontal branch. Lines of constant period slant from the upper left. Sections of two horizontal branches of hypothetical clusters A and B are drawn.

shown with a range of M_v ±0.8 magnitude and with color boundaries which do not change with M_v. Lines of constant period are drawn separately for the *a, b* stars and the *c* stars. These lines satisfy $P\sqrt{\bar{\rho}} = Q$ where $Q_{a,b}/Q_c = 1.5$ (see ROBERTS and SANDAGE [5]). Figure 3 shows that the mean period for variables in cluster A will be longer than in cluster B. Furthermore, this model predicts that in cluster A and B the ratio $P_{a,b}/P_c$ will be the same. And this is true from the observational data.

If this is a reasonable explanation for the period differences between clusters, then the difference in absolute magnitude,

M_v, of the horizontal branches must be small enough so as not to conflict with other data for RR Lyrae stars in the general field. An estimate of $\Delta M_v = f(\Delta P)$ can be made.

It has been shown by SCHWARZSCHILD [6] and by ROBERTS and SANDAGE [5] that variables in M 3 satisfy the pulsation criterion $P\sqrt{\rho} = Q$. This equation can be expressed in the observable quantities by use of the $B - V = f(T_e)$ and the $M_{bol} = h(B - V)$ relations with the result that

$$(5) \quad \log P + 0.3 M_v = 0.840 (B - V) + \log Q - \frac{1}{2} \log \mathfrak{M}/\mathfrak{M}_\odot + \text{const.}$$

(Equation 5 was used to compute the lines of constant P in Figure 3). If the magnitude differences between clusters A and B are small, we can, to a first approximation, neglect the slight variation of $\mathfrak{M}/\mathfrak{M}_\odot$ between the clusters. If we further assume that the color boundary of the unstable region is vertical, equation 5 predicts

$$(6) \qquad \Delta M_v = -3.3 \, \Delta \log P$$

If we do *not* neglect the variation of $\mathfrak{M}/\mathfrak{M}_\odot$ with a change ΔM_v but assume that $\Delta\, \mathfrak{M}/\mathfrak{M}_\odot = g(\Delta M_v)$ as given by the main sequence mass-luminosity relation (this assumes that the difference in magnitude of the main sequence termination points between cluster A and B is the same as the ΔM_v of the horizontal branch), then

$$(7) \qquad \Delta M_v = -2.8 \, \Delta \log P$$

The ratios of the mean periods for the two groups of clusters in Table 3 requires that the absolute magnitude of the horizontal branches differ by $\Delta M_v \approx 0.2$ magnitude. This is small enough to be reasonable from other considerations.

Do these results imply an age difference? If the magnitude difference of $\Delta M_v = 0.2$ continues to the main sequence termination point we predict an age difference of

$$(8) \qquad \Delta\tau/\tau = 0.7 \, \Delta M_v \quad \text{or} \quad \Delta\tau = 7 \times 10^8 \text{ years} .$$

The assumptions made in deriving equations 6, 7 and 8, are:

1) The color boundaries of the domain of instability for RR Lyrae stars do not differ between the clusters.

2) The pulsation constant does not differ between the clusters.

3) The magnitude difference computed from equation (6) or (7) is the same as that of the main sequence termination points.

The validity of these assumptions is unknown at present. The present hypothesis predicts certain consequences for the period-amplitude relation, the period-color relation, and the color-amplitude relation among the RR Lyrae stars. These are discussed in detail in a forthcoming paper in the *Ap. J.* The predictions can be checked observationally and will help to test assumption 1. But as yet the required data are too meagre for a test. Check of assumption 2 will eventually come from theory. Assumption 3 will be checked observationally only when the photometry at low light levels is perfected.

The present discussion should be considered only as suggestive that differences in the properties of RR Lyrae stars can be considered as age parameters. The discussion does suggest that there may be age differences among the globular clusters but that these differences are small. Our present estimate gives $\Delta\tau < 10^9$ years for globular clusters, while Figures 1 and 2 show a continuous age distribution from 10^6 to 5×10^9 years for galactic clusters. This confirms current ideas that globular clusters were formed in our galaxy at nearly the same epoch, 5×10^9 years ago (with a possible spread of 10^9 years), while galactic clusters have been formed continuously.

III. *Comparison between Globular Cluster and Galactic Cluster Color-Magnitude Diagrams*

Figures 1 and 2 show that the shape and position of the various evolutionary tracks in the M_{bol}, $\log_{T_e}$ plane depend not only upon the mass of the stars but also on a second parameter.

The case in point is the M 3 - M 67 difference. M 67 is an old galactic cluster located close to the galactic plane. M 3 is a globular cluster in the halo. Both are about the same age because their main sequence termination points occur at about the same absolute magnitude. Consequently, the mass of the stars along the evolving sequences in both clusters are nearly the same ($1.2\ \mathfrak{M}_\odot$). But the tracks of evolution differ. Stars in M 3 reach $M_v \approx -3$ while those in M 67 brighten only to $M_v \approx 0.0$. For two reasons, the second parameter responsible for the difference is believed to be chemical composition.

1) The theoretical models of HOYLE and SCHWARZSCHILD [7] predict a difference similar to that observed between M 3 and M 67 if M 67 has a higher metal abundance by about a factor of 15.

2) *UBV* photometry of individual stars in both clusters shows a great difference in the energy distribution curves. Stars in M 3 show an ultraviolet excess of $\Delta\ (B\text{-}V) \approx 0.3$ magnitude compared with stars in M 67. Following STRÖMGREN, this is interpreted as a difference in the blanketing of the absorption lines which would result from a low heavy element content in M 3. Stars in all other globular clusters tested (M 3, M 13, M 92, NGC 4147) show the $\Delta\ (U - B)$ excess.

If M 3 and M 67 are exactly the same age, then present ideas of an enrichment of the heavy element abundauce of our galaxy as a unique function of time are untenable because here are two clusters of the same age but with greatly different chemical composition. In this case, one must postulate that a chemical separation existed between the disk and the halo 5×10^9 years ago, with the disk having the higher metal abundance. However, we are not yet forced to this conclusion with the present data. Inaccuracy of the distances to M 3 and M 67 permit some difference in the absolute magnitude of the main sequence termination points with a resulting difference in the ages. The modulus of M 3 depends upon the assumption that $M_v = 0.00$ for the RR Lyrae stars. For this case, the main sequence break point is at $M_v = +3.3$ (JOHNSON and SANDAGE [8]. But if the RR Lyrae stars have $M_v \approx +0.5$ — as the results of P. P. PARENAGO [9] and of E. D. PAVLOVSKAYA [10] suggest, and as the M 3 data require when the main sequence is fitted to an age zero sequence taking into account the $\Delta\,(U-B)$ — then the break point is at $M_v = +3.8$ which is about 0.3 magnitude fainter than M 67. In this case, a spread in age of about 10^9 years between M 3 and M 67 is possible, which may be sufficient for enrichment to occur according to current ideas of element synthesis (BURBIDGE, et al. [11]. Thus, the observations do not contradict the enrichment hypothesis. They do, however, put an upper limit of about 10^9 years for the time available to achieve an enrichment factor of ~ 15 at an epoch 5×10^9 years ago, unless we assume a chemical separation between disk and halo.

IV. *Summary*

1. Evidence is presented for assigning different ages to galactic clusters ranging from 10^6 to 5×10^9 years.

2. Age differences among globular clusters are not well established but interpretation of the differences in the mean periods of RR Lyrae variables from cluster to cluster may suggest age differences of the order of 10^9 years, centered about a creation epoch about 5×10^9 years ago.

3. Evidence from the M 3 - M 67 case suggest that differences in chemical composition greatly affect the shapes of the evolutionary tracks in the M_{bol}, $\log_{T_e}$ plane. A time difference of the order of 10^9 years is required to achieve an enrichment factor of ~ 15 at an epoch about 5×10^9 years ago, unless a chemical separation existed between disk and halo.

REFERENCES

[1] M. Schönberg and S. Chandrasekhar, Ap. J., *96*, 161, 1942.

[2] A. R. Sandage, Ap. J., *125*, 435, 1957.

[3] P. T. Oosterhoff, Observatory, *62*, 104, 1939.

[4] — B.A.N., *10*, 55, 1944.

[5] M. Roberts and A. Sandage, A. J., *60*, 185, 1955.

[6] M. Schwarzschild, Harvard Obs. Circ., No. 437, 1940.

[7] F. Hoyle and M. Schwarzschild, Ap. J. Supp. Ser., *2*, 1, 1955.

[8] H. L. Johnson and A. R. Sandage, Ap. J., *124*, 379, 1956.

[9] P. P. Parenago, Per. Zvezd., *10*, 193, 1954.

[10] E. D. Pavlovskaya, Per. Zvezd., *9*, 349, 1954.

[11] E. M. Burbidge, G. R. Burbidge, W. A. Fowler and F. Hoyle Rev. Mod. Phys., *29*, 547, 1957.

DISCUSSION

CHAIRMAN: J. H. OORT

SCHWARZSCHILD

Should theoreticians take small differences in the colour-magnitude diagrams of open clusters of the same age seriously?

SANDAGE

Some of the differences are probably not significant but it seems that the Pleiades main sequence near the breakoff point has a significantly different shape than the main sequences of say Hyades or Praesepe near their breakoff points.

HECKMANN

The alpha Persei cluster has the same main sequence as the Pleiades. Alpha Persei itself very probably belongs to the cluster and would lie in the Hertzsprung gap.

SANDAGE

There are other examples of stars in the gap also. This must mean that the gap is not a region which is completely devoid of stars but rather a region of faster evolution where occasionally a star may be found.

MORGAN

Observations of NGC 6231 confirm the presence of stars of very high luminosity of types earlier than in *h* and χ Persei. This suggests that the observed differences in the HR diagram of *h* and χ Persei compared with NGC 2362 are due principally to the fact that the number of stars created of very large mass is much greater for the former cluster than for the latter. The main sequence turn-off occurs at the same spectral type (B1) for both clusters.

BAADE

Are the M-type supergiants of *h* and χ Persei members of the clusters or of the surrounding association?

SANDAGE

They are spread over a wider region than the clusters proper, but probably have had the same evolutionary history as the cluster stars.

SANDAGE

The differences in the colour-magnitude diagrams of M 67 and M 3 which have about the same age should be emphasized. We have here a clear indication of some sort of chemical difference between disk and halo at nearly the same cosmic time.

OORT

Is M 67 not a disk globular cluster?

SANDAGE

It looks more like a dense open cluster.

HOYLE

It is interesting that the beginning of the Hertzsprung gap occurs at absolute magnitude +2. This is just where the carbon nitrogen cycle should become effective.

SCHWARZSCHILD

A lot of other things happen in this region, e.g. degeneracy becomes unimportant in the exhausted cores of the brighter stars, while it is important for stars fainter than $+2^{m}$.

SALPETER

Is the horizontal branch absent in M 67?

SANDAGE

We think it is present, but the numbers are certainly small. There are not more than ten possible cases.

SALPETER

How accurately do we know the breakoff points of the main sequence in M 3 and M 67?

SANDAGE

The determination involves fitting to a standard main sequence for M 67 and the assumption of absolute magnitude zero for RR Lyrae variables for M 3. There is an uncertainty therefore of at least half a magnitude, because each of these assumptions is uncertain.

BAADE

How close do the RR Lyrae variable gaps in globular clusters coincide in colour? If, for example, one attrihutes the shifts in colour to reddening one finds occasionally a value for the absorption not consistent with the high galactic latitudes.

SANDAGE

But is this not a statistical relation, which, in any individual case, might give quite incorrect results?

SCHWARZSCHILD

Since there is no unreddened case observed in the second group of clusters on SANDAGE's list it appears that there is no observational answer to BAADE's question.

SCHWARZSCHILD

How much colour shift would be needed to explain the difference in period between the two groups of globulars?

Sandage

About $0^{\mathrm{m}}.09$, too small to observe, without some independent estimate of the reddening.

Spitzer

Is there a slight progressive colour difference in the vertical branches of the different groups?

Sandage

Yes. In addition, there appears also to be a difference between the energy distribution of individual stars in globular clusters and stars of high metal content. Strömgren has suggested a blanketing effect. In a star like the sun this would make the *B-V* colour bluer by $0^{\mathrm{m}}.2$, and the *U-B* colour bluer by $0^{\mathrm{m}}.6$.

Strömgren

This mechanism of blanketing could explain the difference between F subdwarfs and normal main sequence stars.

Sandage

Three-colour photography should make it possible to identify stars like the globular cluster stars in the general field.

Hoyle

If the objects of the halo condensed at an early stage, when matter occupied a volume somewhat greater than the galactic system as it is at present, the density must have been about 10^{-25} grams per cc and the time scale for gravitational contraction about 10^{9} years. This is the order of age differences which have been suggested for globular clusters.

Oort

The local density might be much higher.

Schwarzschild

Sandage's proposed interpretation of the period distribution of RR Lyrae variables indicates only one possibility. He assumes homology for small ranges of mass and age. One could, for example, just as well assume that the luminosities are essentially the same, but that the depth of the convection zone critically depends on differences of chemical composition in the photosphere. Variations in the depth of the convection zone might seriously affect the period-density relation.

With regard to Baade's stars of period 0.3 days near the galactic nucleus, for which Sandage quotes a possible magnitude difference of $0^{\mathrm{m}}.7$ from variables in our surroundings, could this indicate a possible alteration in the distance of the galactic centre? If Baade's absorption is right, this correction brings us to about 5 kpc from the centre.

Oort

That I think would be very objectionable. I would not mind putting the centre a little further out.

Schwarzschild

That means that Baade has to subtract from his absorptiom something like $0^{\mathrm{m}}.7$.

Baade

I should feel uncomfortable about a change of $0^{\mathrm{m}}.7$. I feel more certain about the value of the absorption, which was derived from NGC 6522, the globular cluster in the centre. I feel more certain because Morgan has checked the integrated spectrum of this cluster and it belongs to the weak-line globular clusters. It was assumed that it was comparable to those clusters for which we know the integrated spectrum, i.e. those in the halo. Stebbins made measures in four colours for a number of globular clusters in the halo and for 6522, and this led to an absorption of $2^{\mathrm{m}}.75$. But there is a second argument. This field was at latitude $-4^{\circ}.5$. Shapley's field, which he investigated carefully, was at latitude -20°. He selected a field as high as that in order to escape the effects of heavy absorption, because at -20° latitude the extragalactic nebulae appear to be there in normal numbers. SHAPLEY checked a large field and came to the conclusion that a small correction for absorption was still necessary. My corrected distance modulus of $14^{\mathrm{m}}.56$ for the galactic centre is very close to the value of $14^{\mathrm{m}}.43$ which I derived from SHAPLEY's data, and the small discrepancy can be accounted for by the assumption of spherical equidensity surfaces.

SANDAGE

What was the apparent magnitude scale for the distribution of RR Lyrae variables in the galactic nucleus and how secure do you consider the magnitude scale to be?

BAADE

The peak occurs near $m_{pg} = 17.5$. To this limit the scale seems to be secure because WHITFORD's photoelectric scale in S.A. 68, which was used for the photometric transfer, extends to magnitude 19.

SPITZER

I would like to ask SANDAGE about the correlation between the spectra of globular clusters and characteristics of the RR Lyrae variables present.

SANDAGE

ARP concluded that those clusters containing the shortest periods showed the more nearly normal spectra.

MORGAN

ARP has recently compared my recent results with his and he finds good agreement, except for ω Centauri.

SANDAGE

One would expect the globular clusters with the weakest lines to be the oldest from the enrichment ideas of FOWLER, HOYLE and others. If the clusters with the shortest period variables are older, then this expectation would not be realised, because the clusters with short-period variables have the more normal spectra. This may argue against the interpretation of period differences as due to age differences.

OORT

Disintegration of Galactic Clusters and Statistics of Their Ages

The assumption that the age of a cluster is given by the brightest main-sequence stars, as indicated by SANDAGE, and that the colour-magnitude diagram of a cluster corresponds to stars having all approximately the same age, appears very plausible. The evidence in favour of the theory of evolution of galactic clusters as summarized by SANDAGE is very convincing.

There is, however, one piece of information which does not seem to fit into this picture, and which has worried me for some time. Why don't we observe more old clusters? The difficulty may be illustrated by the following table, in which the observed numbers of clusters are given for which the earliest stars have spectral types in the limits shown in the first column. The table was compiled from the catalogue published by TRUMPLER (1930). The statistics will have been influenced by selection effects, because the clusters with early-type stars will be discovered more readily and up to greater distances. We have therefore confined ourselves to clusters whose distances according to TRUMPLER are less than 1000 pc, and have divided these again into two groups, with distances less than 500 pc and between 500 and 1000 pc, respectively. There appears to be no conspicuous difference between the results for these two distance groups. It seems safe to assume that the shortage of clusters with main sequences beginning with types later than A0 is a real phenomenon.

[4] II, 1 - *Sandage I* - p. 23

TABLE I.

Spectrum earliest stars	*Observed numbers*		T (10^6 *years*)	ΔT (10^6 *years*)
	$r < 500$	$500 < r < 1000$		
O	1	3	10	10
B0	3	1	60	50
B1-2	1	1	150	90
B3-5	8	10	290	140
B6-8	5	10	400	110
B9-A0	8	10	540	140
A1-8	1	5	1800	1260
F0 and later . . .	1	1	long	(1200)

This lack of later-type clusters would seem to indicate that clusters generally disintegrate before they attain ages corresponding to a main-series beginning with A1 or later. The approximate ages computed on the assumption that all main-sequence stars brighter than the earliest stars observed in a cluster have transformed the hydrogen in the convective core into helium and have moved off the main sequence, while the earliest stars present are on the verge of this condition, are given in the next to last column. They refer to the latest spectral type indicated for each line. They were estimated from data given by STRÖMGREN (1952); complete rotational mixing was assumed to have taken place in the core. The last column gives the time, ΔT, during which a cluster would have its earliest stars in the spectral interval concerned.

Should we suppose that clusters have been formed at the same rate during the last 3×10^9 years, that they do not disintegrate to an appreciable extent and that all of them had originally contained O or B0 stars, the numbers of clusters in different spectral stages should be proportional to ΔT. Should some of them not have contained such very-early-type stars at their birth, the relative numbers in the last part of the table would be still higher.

It is evident that the observed distribution does not conform with these expectations. The numbers in the last two lines are about 50 times too low. We must conclude either that the clusters do not live longer than about 500 million years, or that the lives of A0 stars have been underestimated by a factor of 5 or more. The latter appears improbable, for we have already assumed that there would be complete mixing in the nuclear part. It is conceivable that new stars are continually formed in clusters, and that they would thus conserve their young appearance. But the available data on interstellar matter in clusters give no indication that such a rejuvenating process would be in progress. If we discard this possibility, we appear to be forced to the conclusion that in general the clusters do not live longer than about 500 million years.

A cluster can dissolve in two ways. Either it is unstable, like an expanding association, or it is semi-stable, being only gradually disrupted by mutual encounters between its members. In the first case the internal velocities must generally exceed the velocity of escape from the cluster. For a typical specimen like the Pleiades the velocity of escape is about 0.8 km/sec at a distance of 1.7 pc from the centre. This means that the cluster would double its radius in 2 million years and would have become unrecognizable as a galactic cluster in 10 or 20 million years. Ages of the same order would result for most clusters. It should be mentioned that DIECKVOSS (1) has suggested that observations would indicate an expansion of the Pleiades. From an analysis of HERTZSPRUNG's proper motions he found a coefficient of expansion of 4.0×10^{-7} year^{-1}, with a mean error of $\pm 1.4 \times 10^{-7}$, the coefficient of expansion being defined as the fraction by which the distance to the centre increases per year. As the Pleiades move away from the sun with a velocity of about 6 km/sec, they must show a geometrical shrinking of 0.4×10^{-7} year^{-1}. The true expansion coefficient would therefore be 4.4×10^{-7} year^{-1}, corresponding to an age of 2.3 million years. The corresponding velocity of expansion at 1.7 pc from the centre would be 0.8 km/sec, of the same order as the velocity of escape.

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(1) *Naturwissensch.* 40, 505 (1953).

The indication should be considered as quite uncertain and, moreover, concerns only one cluster (2). The ages that can be attributed to expanding clusters are from 10 to 100 times lower than those derived on the evolutionary theories that have been outlined. Acceptance of the idea that clusters are expanding groups would, therefore, mean that we would have to reject the notion of appreciable evolution in any cluster, except in the very youngest ones.

The evidence for evolution in clusters is so convincing that we seem to be forced to accept the other alternative, viz: that clusters are being dissolved by internal encounters. Extensive calculations about this process have been made by CHANDRASEKHAR (3). If due account is taken of the phenomenon which he calls dynamical friction, the disintegration time of a cluster like the Pleiades is found to be 3×10^9 years. This is incompatible with the statistical data shown in Table 1. It would, therefore, appear to be desirable to reconsider CHANDRASEKHAR's calculations and the effects of dynamical friction, taking into account the fact that clusters are not homogeneous bodies as was assumed in these investigations. A reduction factor of at least 5 would be needed to bridge the discrepancy.

Note added October 1957.

Prof. SCHWARZSCHILD has drawn my attention to a recent computation by IVAN KING (4) who has shown that the shrinking of a cluster caused by the "evaporation" of members causes a decrease in the relaxation time. As a consequence, the time needed for total disintegration is shortened by a factor of about 2.5. It was further pointed out to me by SPITZER that the rate of ejection of stars may be larger than estimated by CHANDRASEKHAR because of the influence of tidal forces due to large agglomerations of interstellar clouds.

It appears likely that these and other effects may bring the

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(2) DIECKVOSS himself now considers his discovery of the expansion of the Pleiades to be inconclusive (comment made to W. W. MORGAN June, 1957).

(3) *Ap. J. 98*, 54, (1943).

(4) *A. J. 62*, 144 (1957), abstract.

theoretical disintegration times into accordance with the value of about 0.5×10^9 years suggested by the table given above.

HOYLE

One interesting possibility is that open clusters that start by having O and B type stars would presumably lose mass, due to the O and B type stars losing mass during their evolution. If this were to go on in a more or less gentle fashion, by some spherically symmetrical emission from the surface of the stars at quite low speeds, it would presumably not have disastrous effects on the stability of the clusters, but if at a certain stage the stars began to lose their mass by violent emission then the remaining nuclei after a star had emitted material with violence would presumably get a very considerable recoil from the explosion and this could have the effect of greatly increasing the effective temperature of the cluster and increase the rate of escape.

OORT

I would like to comment on the consequences of accepting that open clusters are expanding objects. If their lives were really as short as ten million years, the number of stars poured into the galactic system from the galactic clusters would be enormous and for the A type stars would be about of the same order as all the A type stars that are now present. One would come to the conclusion that all the stars may have been formed originally in dense galactic clusters, instead of having been formed singly or in associations. But that is pure speculation. I repeat that in my mind the evidence for the evolution of the clusters, and for the halfway long ages of the order of 5×10^8 years, is very strong.

SPITZER

One process that would reproduce the observed distribution would be to evaporate preferentially stars of small mass.

OORT

It would still take rather long.

SPITZER

If the mass of the clusters is rather high a few relaxation times would be enough.

STRÖMGREN

The fact that we are in the neighbourhood of a spiral arm may affect the ratio between the numbers of young and old galactic clusters observed within 1000 pc.

HECKMANN

Furthermore, there is a strong observational selective effect. Only about half of the clusters in TRUMPLER's list have been studied and the loose clusters have been ignored.

MORGAN

We may be missing many F-type clusters in the galactic plane because they are difficult to distinguish from the field stars, due to the absolute faintness of the brightest stars.

NASSAU

STOCK has found some twenty such clusters of this type.

47 TUCANAE — AN INTERIM REPORT

A. D. THACKERAY
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During the last five years considerable observational material on 47 Tucanae has been gathered at the Radcliffe Observatory. Comparison of this famous globular cluster with other northern objects which have been so extensively studied in recent years is of obvious importance to general problems of Stellar Populations. It is of peculiar interest for various reasons. SHAPLEY [1] finds it intrinsically the most luminous of globular clusters with $M_{pg} = -10.2$; it contains three very bright long-period variables with periods of about 200 days and several other red variables. No cluster types have been proved as members.

Material: Spectra at 49 Å/mm and 86 Å/mm have been obtained for 28 stars in the cluster, of which only 2 are certainly foreground.

Photographs in two colours down to about 20^m are being measured for the colour-magnitude array; a photoelectric sequence down to about 15^m has been set up by WESSELINK and this is being extended (with assistance from H. C. ARP) down to 18 m. WESSELINK has measured a great many stars in the iris photometer at the Leiden Observatory down to 16^m or 17^m. Much of this material is still in an incompletely reduced state and therefore this report has very much an interim character.

Spectra. Of the 26 member stars we find

19	red giants
6	red variables
1	bright blue star (probable member)

(a) *Red Giants.* These show a continuous range in spectral types from G8 to M2, while the luminosity classes are estimated as II to III. As compared with M 92, line-ratios are found to be far "more normal" in 47 Tuc. The weakening of CN in 47 Tuc corresponds to that found in high-velocity stars.

DEUTSCH [2] finds "more normal" spectra for clusters such as M 3 in which the giant branch of the c-m array lies to the red side of the position in the "abnormal" clusters.

The existence of several M giants in 47 Tuc is of special importance. As far as we are aware, non-variable stars of this type have not been found in any other cluster.

(b) *Variable Stars.* The 6 variables studied are nos. 1, 2, 3 with known periods about 200 days, nos. 5, 7 irregular, and no. 8 semi-regular ($P \sim 150$ days). All 6 variables have TiO bands somewhat stronger than in the non-variable M stars and are classified as M2 to M3. Nos. 1, 2, 3 have luminosity classes Ib - II at maximum, the others are classed II-III.

Nos. 1 - 3 show emission lines due to H alone, and resemble normal Me variables of comparable period. Hγ and Hδ emission have also been found in no. 8.

No certain distinctive peculiarities have been detected in any of these variables to distinguish them spectroscopically from Me variables outside clusters.

(c) *The Blue Star* is easily the brightest star photographically. WESSELINK finds its visual magnitude to be 10.3. FEAST classifies it as B8III (lines present are due to H, He I, Mg II, Si II, Ca II. Its radial velocity agrees well with that of the red stars and we regard its membership as established with a fairly high degree of probability. Unfortunately the radial velocity of 47 Tuc is low. JOHN HERSCHEL included this star with a red companion as a double star in his catalogue and regarded it as foreground; unfortunately he did not measure it for separation and position angle.

c-m Array. WESSELINK's available material does not extend appreciably below $14^{\mathrm{m}}.1$. It shows a well-defined red giant branch as usual, and at its brighter end it does appear to lie somewhat below and to the red of that for M 3, i.e. decidedly to the red of the most "abnormal" cluster M 92. This agrees with the spectroscopic proof of the presence of non-variable M giants.

Both spectroscopic and photoelectric evidence therefore point to new characteristics which mark 47 Tuc as unusually removed from Population II towards Population I. We have M stars, we have an apparently depressed red giant branch, we have a probable B-type member as the brightest star; even the low radial velocity might be a pointer in this direction.

Distance Modulus. FEAST, from various spectroscopic arguments chiefly depending on the calibration of luminosities on the MK system, and without any access to the photoelectric results, deduced a distance modulus of about 13.5, i.e. 1.2 mag. nearer than SHAPLEY's distance. This would give for the cluster $M_{pg} = -8.8$ and an absolute magnitude (visual) for the bright long-period variables at maximum a little brighter than -3. This is not seriously discordant with the expected absolute magnitudes for long period variables of 200 days.

FEAST points out that with his distance modulus the two Harvard variables 810, 814 of RR Lyrae type might well be members. This possibility was rejected by SHAPLEY and NAIL [3] in view of their greater distance modulus.

WESSELINK's c-m array shows fairly convincing signs of an incipient horizontal branch at $13^{\mathrm{m}}.9$ to $14^{\mathrm{m}}.1$.

It therefore appears that we must regard the most probable distance modulus of 47 Tuc as between 13.5 and 14.0. This still leaves the red variables as rather bright, but not so surprisingly as SHAPLEY's estimate. Moreover, the blue star's luminosity becomes that of class II-III rather than III if it is to be retained as a member.

We cannot escape from the conclusion that 47 Tuc is an exceptional cluster, but its abnormality is of the opposite type to M 92. If the latter is regarded as extreme Population II, then 47 Tuc might be termed Population II tending towards I.

REFERENCES

[1] H. SHAPLEY, Harvard Reprint 228, P.N.A.S., 27, 440, 1941.
[2] A. N. DEUTSCH, *Principes Fondamentaux de Classification Stellaire*, p. 25, C.N.R.S. Colloquium, 1955.
[3] H. SHAPLEY and V. McK. NAIL, H. B., 920, 1951.

DISCUSSION

CHAIRMAN: J. H. OORT

OORT

This is a welcome contribution about an important southern cluster.

BAADE

Has THACKERAY found any cluster variables in 47 Tuc?

THACKERAY

SHAPLEY and NAIL found two with magnitudes 13.5 which they dismissed as foreground stars. With the new modulus for 47 Tuc FEAST suggested that they may be cluster members after all and we are investigating them.

SPITZER

Could 47 Tuc have escaped from the Magellanic Clouds?

THACKERAY

No. Its velocity is very low — a possible population I characteristic.

BLAAUW

How did FEAST obtain the distance modulus of 47 Tucanae?

THACKERAY

From spectroscopic luminosity classification of the red giants and from the long period variables.

LUMINOSITY FUNCTIONS OF GALACTIC CLUSTERS, GLOBULAR CLUSTERS, AND ELLIPTICAL GALAXIES

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I. *Introduction*

The stellar luminosity function is important not only for the classical problems of statistical astronomy but also for modern problems of star formation and stellar evolution. In this report we are concerned with the general luminosity function in the field and in three classes of stellar objects; (1) galactic clusters, (2) globular clusters, and (3) elliptical galaxies.

The luminosity function in the general field has been the subject of nearly continuous study beginning with SEELIGER's work in the 1890's, continuing with the work of KAPTEYN, VAN RHIJN, LUYTEN, and many others from 1900 to the early 1930's, and culminating in modern times with MCCUSKEY's extensive study using modern spectroscopic techniques. The function is fairly well established from $M_v = -4$ to $M_v = +10$. It is less well known fainter than this.

Direct counts of known members of galactic clusters give information in these aggregates from $M_v = -7$ to $M_v = +8$. In globular clusters the function can be observed only to $M_v = +6$ even with the largest telescopes. The form of the function fainter than $M_v = +6$ must be inferred from such integral properties as the mass to light ratio and the total mass. The luminosity function in elliptical nebulae is almost completely unknown. Here the spectral energy distribution, the color index, the mass to light ratio, and the bright end of the color-magnitude diagram must be used to put limits on $\varphi(M_v)$.

II. *The Luminosity Function in the General Field; the Salpeter Creation Function*

The luminosity function is defined as the number of stars at absolute magnitude M in dM in a unit volume. This number, called $\varphi(M)\,dM$, is obviously related to the rate of stellar birth $dN/dt\ (M, t)$ for stars of absolute magnitude M at time t, and to the total life time of a star at this absolute magnitude. The total number of stars at absolute magnitude M which have been formed in the age of the galaxy is

$$N(M) = \int_{t=0}^{t=T} \frac{dN}{dt}(M, t)\,dt \quad . \tag{1}$$

Of these stars, only those which have formed more recently than the life time of a star of absolute magnitude M will still be around. Equation 4 of the preceeding paper gives this time as

$$\tau = 1.10 \times 10^{10} \frac{\mathfrak{M}}{L_T} \quad \text{years} \quad . \tag{2}$$

Hence the observed luminosity function will be

$$\varphi(M) = \int_{T-\tau(M)}^{T} \frac{dN}{dt}(M, t)\,dt \qquad \text{for} \qquad \tau \leqslant T \tag{3}$$

and

$$\varphi(M) = \int_{0}^{T} \frac{dN}{dt}(M, t)\,dt \qquad \text{for} \qquad \tau \geqslant T . \tag{4}$$

The physical content of equations 1 to 4 is clear. Stars of all ages exist in the galactic system. The general luminosity function $\varphi(M)$ is the *sum* of the distribution functions at the times of star formation but modified to account for the depleting action of evolution. The luminosity function for stars formed at time t in dt is $dN/dt\ (M,\ t)\ dt$. If no evolution of the stars occurred after these stars were born, the $N(M)$ of equation 1 would be the observed luminosity function at the present time. However, evolution does occur such that stars of a given luminosity L cease to exist after a time τ given by equation 2. The only stars presently visible of luminosity L are those which have been formed in the time interval between the present and τ years ago. Equations 3 and 4 follow from this statement.

Equations 1 to 4 were first given implicitly by SALPETER [1] in a fundamental discussion of the luminosity function in terms of stellar evolution. SALPETER wished to obtain the function which describes the initial distribution of luminosities at the time of star formation. The problem can be solved with no additional assumptions only if the shape of the creation function, denoted by $\psi(M_v)$, and if the rate of star formation are both time independent. In this case, $\psi(M) \equiv N(M)$ and equations 1, 2, and 3 give

$$\psi(M) = \frac{dN}{dt}(M)\,T \tag{5}$$

$$\varphi(M) = \frac{dN}{dt}(M)\,\tau \qquad \text{for} \quad \tau \leqslant T \tag{6}$$

$$\varphi(M) = \psi(M) \qquad \text{for} \quad \tau \geqslant T \tag{7}$$

Combining 2, 5, and 6 gives

$$\psi(M) = \varphi(M)\ \frac{\mathfrak{M}_l}{\mathfrak{M}}\ \frac{L}{L_l} \tag{8}$$

where $\mathfrak{M}_l$ and L_l are the mass and luminosity which give $T = \tau$ in equation 2. Equation 8, which was explicitly derived by SALPETER, permits the calculation of the creation function from the observed general luminosity function.

Values of the general luminosity function have been given by many authors. The generally accepted value from $M_v = -6$

to $M_v = +13$ is that given by VAN RHIJN [2] but recently McCUSKEY [3] showed that VAN RHIJN's function should be smoothed slightly from $M_v = -2$ to $M_v = +4$ to better represent data in the solar neighborhood. Two modern studies which go fainter than $M_v = +13$ are by LUYTEN [4] which extends to $M_{pg} = +20$, and by KUIPER [5] which goes to $M_v = +17$. The mean of the values of these two authors has been used in this paper. Table 1 gives the adopted luminosity function for the general field, $\varphi(M)$, together with the resulting SALPETER function computed from equation 8. The two functions refer to main sequence stars only. The unit of volume is one cubic parsec.

TABLE 1

The Adopted General Luminosity Function and the Salpeter Creation Function

M_v	$\log \varphi + 10$	$\log \psi + 10$	M_v	$\log \varphi + 10$	$\log \psi + 10$
−6	1.29	4.71	+8	7.66	7.66
−5	2.43	5.59	+9	7.72	7.72
−4	3.18	6.08	+10	7.81	7.81
−3	3.82	6.41	+11	7.95	7.95
−2	4.42	6.68	+12	8.11	8.11
−1	5.04	6.92	+13	8.22	8.22
0	5.60	7.10	+14	8.21	8.21
+1	6.17	7.26	+15	8.12	8.12
+2	6.60	7.25	+16	7.98	7.98
+3	7.00	7.23	+17	7.76	7.76
+4	7.30	7.30	+18	7.40	7.40
+5	7.45	7.45	+19	6.58	6.58
+6	7.56	7.56	+20	5.28	5.28
+7	7.63	7.63			

It is of interest to compute the mean rate of formation of stars of all absolute magnitudes. From equation 5 it follows that

$$\frac{dN}{dt}(\text{all } M) = \frac{1}{T}\int_{M=-\infty}^{M=+\infty} \psi(M)\,dM\,. \tag{9}$$

Summation of $\varphi(M)$ in Table 1 shows that 0.120 stars/pc^3 have been created in the age of the galaxy in the solar neighborhood. If T is adopted as 6×10^9 years, then $\overline{dN}/dt = 2\times10^{-11}$ stars/pc^3 year. McCUSKEY's results show that $\varphi(M)$ does not change much in a cylindrical volume of about 1000 parsecs in radius centered in the galactic plane and ± 250 parsecs perpendicular to the galactic plane. The volume of this cylinder is 15×10^8 pc^3. We expect that the order of 3×10^{-12} stars per year will be created in this space. The number is far too small to observe and suggests that the recent observations of HERBIG [6] should probably not be interpreted as seeing stars actually in the process of creation.

III. *Luminosity Functions in Galactic Clusters*

Galactic clusters provide a test for SALPETER's ideas because their luminosity functions should be similar to the creation function $\psi(M)$ if the escape of stars is neglected. Membership of galactic clusters is known from proper motion data. Counts in these membership lists provide the luminosity distribution from $M_v = -7$ to $M_v = +2$ in h Persei, from $M_v = -3$ to $M_v = +8.5$ in Pleiades, from $+0.5$ to $+5.5$ in Coma Berenices, from 0 to 6.5 in Hyades, from 0 to $+7.0$ in Praesepe, and from 0 to $+6.5$ in M 67. Both VAN DEN BERGH [2] and SANDAGE [8] find that SALPETER's $\psi(M_v)$ is a good representation of the galactic cluster distributions. This is illustrated for the Pleiades where a detailed comparison between the observed distribution, the normalized Salpeter function, and the normalized standard van Rhijn function is shown in Table 2.

TABLE 2

Luminosity Function for the Pleiades

M_v	*Observed*	$\psi(M_v)$	$\varphi(M_v)$
− 3.00 to − 2.51	1	1.12	0.004
− 2.50 to − 2.01	0	1.40	0.009
− 2.00 to − 1.51	3	1.76	0.017
− 1.50 to − 1.01	2	2.14	0.035
− 1.00 to − 0.51	0	2.56	0.071
− 0.50 to − 0.01	3	2.99	0.141
0.00 to + 0.49	2	3.50	0.257
+ 0.50 to + 0.99	3	3.98	0.467
+ 1.00 to + 1.49	7	4.50	0.850
+ 1.50 to + 1.99	5	5.05	1.41
+ 2.00 to + 2.49	8	5.61	2.29
+ 2.50 to + 2.99	11	6.19	3.54
+ 3.00 to + 3.49	7	6.83	5.12
+ 3.50 to + 3.99	6	7.58	7.07
+ 4.00 to + 4.49	9	8.47	9.53
+ 4.50 to + 4.99	19	9.49	12.01
+ 5.00 to + 5.49	13	10.57	14.10
+ 5.50 to + 5.99	17	11.76	15.82
+ 6.00 to + 6.49	10	13.53	17.76
+ 6.50 to + 6.99	13	14.18	18.59
+ 7.00 to + 7.49	9	14.86	19.47
+ 7.50 to + 7.99	7	15.20	19.92
+ 8.00 to + 8.49	14	15.54	20.39
$\sum_{-3.00}^{8.49}$	169	169	169

The fact, known for many years, that the luminosity function for the general field gives too few stars for the bright end of the galactic cluster distribution is therefore explained by the statement that no evolutionary depletion has occurred in a galactic cluster but has occurred for the brighter stars in the general field. The close fit of $\psi(M_v)$ to the cluster observations is rather significant because the $\varphi(M_v)$, from which $\psi(M_v)$ is derived, refers to stars in the general field and not to those in aggregates. This fact suggests that there is little dependence of the $\psi(M_v)$ creation function on the total mass which condenses into stars in any given region of space. In other words, single stars and stars in large clusters appear to obey the same distribution law for the way the prestellar mass divides itself into stars of different luminosities at the epochs of star formation.

With knowledge that the SALPETER $\psi(M_v)$ fits the cluster data, we can predict the number of bright stars which were originally present in each cluster but which have subsequently disappeared from the main sequence by exhaustion of their energy sources. These stars are presumably still cluster members but appear now as white dwarfs. The predicted numbers of white dwarfs in five clusters with good proper motion data are: h Persei 0; Pleiades 2; Coma Berenices 9; Hyades 23; Praesepe 20; numbers which are in good agreement with the observations when account is taken of the incomplete observational search.

The faint end of the luminosity function of galactic clusters is less well understood. All data show that the cluster function does not rise nearly so steeply as does the van Rhijn function fainter than $M_v = +6$. AMBARTSUMIAN [9], SPITZER [10], CHANDRASEKHAR [11] and others have computed the rate of escape of stars from a cluster in each relaxation time. VAN DEN BERGH [12] has applied the theory with success to the old cluster M 67 and explains the small number of stars fainter than $M_v = +6$. However, the same theory probably cannot explain the few faint stars in very young clusters such as Pleiades because the age of the cluster, compared with its relaxation time, is so small that few stars will have escaped. We must conclude that, as yet, the faint end of the luminosity function of galactic clusters is not completely understood.

IV. *Globular Clusters*

Only the bright end of the luminosity function for globular clusters is available to direct observation. Even with large telescopes we cannot expect to reach fainter than $M_v = +7$ by star counts. The luminosity functions are known to faint light levels for only the two clusters M 3 (SANDAGE [8]) and M 92 (TAYLER [13]) and to brighter levels for five additional clusters (ARP [14]). The M 92 data reach to $M_v = +4.6$; the M 3 data reach to $M_v = +6.0$. The M 3 distribution is shown in Figure 1 as a solid line where the ordinate is the log of the number of stars at M_v in $\Delta M_v = \pm 0.1$ witbin a circular area 8′ arc radius from the nucleus of M 3 on the plane of the sky. The Salpeter creation function is also plotted from Table 1 but normalized to the M 3 data at $M_v = +5.0$. The sharp peak in the M 3 curve at $M_v = 0.0$ is due to stars on the horizontal branch.

To obtain an estimate of $\varphi(M)$ fainter than $M_v = +6$ we require that any trial function give the correct mass to light ratio and the correct total mass as obtained, for example, by WILSON and COFFEEN [15] as rediscussed by SCHWARZSCHILD and BERNSTEIN [16]. As a first guess, the φ function fainter than $M_v = +6$ which is tabulated in Table 1 has been tested. This is plotted as a dotted line in Figure 1. The total mass given by the trial function is $\mathfrak{M}_T = 2.45 \times 10^5 \ \mathfrak{M}_\odot$ which is in excellent agreement with the scaled up dynamical mass of $(2.4 \pm 1.2) \times 10^5 \ \mathfrak{M}_\odot$ obtained by SCHWARZSCHILD and BERNSTEIN. Included in this value of $\mathfrak{M}_T = 2.45 \times 10^5$ is the estimated mass of white dwarf stars. The estimate was obtained from the $\psi(M_v)$ function brighter than $M_v = +3.5$ by the method described for galactic clusters. The white dwarf contribution

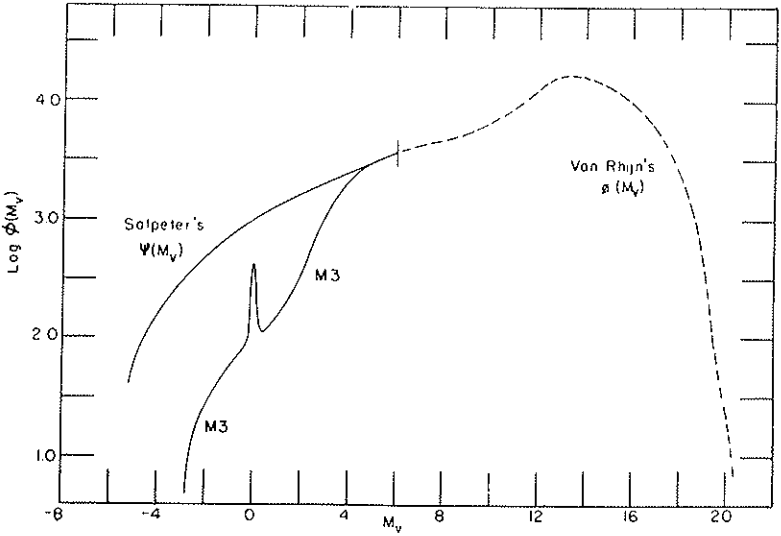

FIGURE 1 — The observed luminosity function for M 3 is shown as the solid line to $M_v = +6.0$. The extension to $M_v = +20$ with the general luminosity for field stars is shown as a dotted line. SALPETER's creation function $\psi(M_v)$ is also shown.

amounts to 4.8×10^4 stars and 6.9×10^4 solar masses if all white dwarfs have the Chandrasekhar mass of $1.44\ \mathfrak{M}_\odot$.

As a final check on the adopted function, we find that the total light computed from the M 3 $\varphi(M)$ is $M_v = -9.00$. The color index of M 3 is about 0.50 which gives $M_{pg} = -8.5$. This is in good agreement with CHRISTIE's observed value of $M_{pg} = -8.42$. The mass to light ratio is 0.70 in solar units (adopting $M_v = 4.84$ for the sun as given by STEBBINS and KRON). From these tests with integral properties we conclude that the faint end of the luminosity function for globular clusters can be represented by the standard van Rhijn function valid for the general field.

It is now of interest to compute the fractional light and the fractional mass contributed by stars brighter than given absolute magnitudes in M 3. Tables 3 and 4 give the results. It is

TABLE 3

Fractional Light for Stars at M_v and Brighter in M 3

M_v	*Fractional Light*	M_v	*Fractional Light*	M_v	*Fractional Light*
−3.0	0.004	+0.6	0.652	+4.2	0.922
−2.6	.046	+1.0	.684	+4.6	.943
−2.2	.123	+1.4	.712	+5.0	.959
−1.8	.203	+1.8	.739	+5.4	.972
−1.4	.282	+2.2	.768	+5.8	.981
−1.0	.353	+2.6	.800	+6.5	.994
−0.6	.416	+3.0	.832	+7.5	.998
−0.2	.480	+3.4	.865	+8.5	.999
+0.2	0.615	+3.8	0.896	+9.5	0.9996

TABLE 4

Fractional Mass Contributed by Stars at M_v and Brighter in M 3

M_v	*Fractional Mass*	M_v	*Fractional Mass*
−3.0	0.000	9.0	0.371
−2.0	.000	10.0	.425
−1.0	.000	11.0	.482
0.0	.005	12.0	.546
1.0	.008	13.0	.614
2.0	.014	14.0	.661
3.0	.030	15.0	.692
4.0	.069	16.0	.706
5.0	.136	17.0	.712
6.0	.196	18.0	.714
7.0	.258	19.0	.715
8.0	0.317	White dwarfs	0.285

seen that stars brighter than $M_v = +6$ contribute more than .90 of the total visual light but less than .15 of the total mass — a fact important in the interpretation of integrated spectra of globular clusters.

V. *Elliptical Galaxies*

BAADE's resolution of M 31 and its companions into stars opened the modern approach to the problem of the stellar content of elliptical galaxies. BAADE concluded that the color index and the absolute magnitude of the brightest stars he resolved were so nearly the same as for globular clusters ($M_v = -3$, $CI = 1.3$) that stars in elliptical galaxies were like those in globular clusters. Further work with the 200-inch telescope seemed to confirm this view because BAADE's 200-inch plates showed that stars in individual globular clusters belonging to M 31 and M 32 resolved at the same apparent magnitude as stars in the general background field. Because of these observations, many workers concluded that the stellar content of elliptical nebulae and of globular clusters was identical. Three observations point against this conclusion. These are: (1) the spectral energy curves for globular clusters and for E nebulae are different over the wavelength range λλ 3000 to 10,000 Å; (2) W. W. MORGAN's integrated spectra of elliptical nebulae and globular clusters are entirely different; and (3) the mass to light ratio for E nebulae is about 100 times that of globular clusters. We shall discuss these points in order.

(1) Figure 2 shows the energy distribution curves for the E galaxy M 32 and for the mean of the globular clusters M 2, M 13, M 15, and M 92 as observed by STEBBINS and WHITFORD with their six color equipment. The curves have been normalized to a relative peak intensity of 1.0. M 32 is a factor 2 brighter in the infrared and about a factor of 1½ fainter in the ultraviolet than the globular clusters. The difference is also evident in two color photometry. Color indices of globular clusters are near B-$V = 0.62$ (international color = 0.50) while B-$V = 0.98$

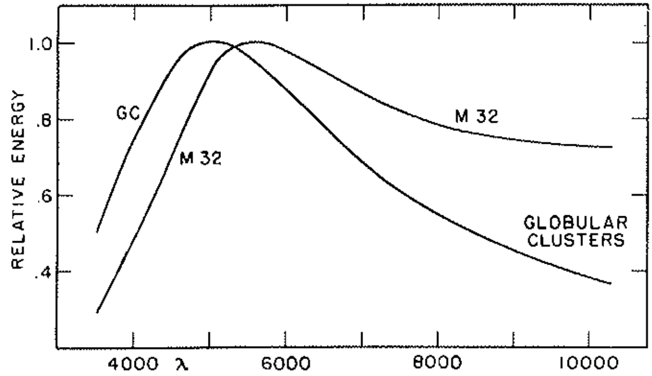

FIGURE 2 — Comparison of the energy distribution curves for the E galaxy M 32 and for the globular clusters M 2, M 13, M 15, and M 92. The data are from STEBBINS and WHITFORD.

(international color = 0.86) for E galaxies. The difference can be explained in two ways; (a) the color-magnitude diagrams for E nebulae and globular clusters are similar but the distribution of stars along the sequences, i.e. the luminosity function, differs; or (b) the color-magnitude diagrams for the two types of objects are different even though the brightest stars have the same M_v and B-V. Recent work by Miss H. SWOPE (unpublished) for the color-magnitude diagram of the dwarf elliptical in Draco suggests that alternative (a) is correct and that the difference in the luminosity function must be fainter than $M_v = +2$. The Draco system is of the Sculptor-Fornax type and is similar to the dwarf ellipticals Leo I and Leo II for which HOLMBERG has measured integrated international colors of 0.87 and 0.81; very close to the colors of normal E galaxies. We would therefore infer that the energy distribution curves for dwarf ellipticals are like M 32 at least in the wavelength range from 3600 Å to 6000 Å. But the color-magnitude diagram for the Draco system is similar to that of a globular cluster to the limit of SWOPE's study at $M_v = +2$. Consequently, the cause of the difference between E galaxies and globular clusters shown in Figure 2 must be fainter than $M_v = +2$.

(2) During this conference, MORGAN will undoubtedly report in detail on his spectrographic work on the differences between E galaxies and globular clusters. The differences are of such a nature to throw some doubt on the interpretation of the above paragraph because spectra of E nebulae appear to have normal metallic line strength unlike the situation in globular clusters. These observations contradict the supposition that the color-magnitude diagrams of E galaxies and globular clusters are alike. We are therefore led to doubt the similarity of the dwarf ellipticals with normal E galaxies despite HOLMBERG's color observations. MORGAN's observations are quite positive in showing that the major contributor to the light in E galaxies comes from non-globular-cluster-like stars.

(3) The mass to light ratio for E galaxies compared with globular clusters imposes a further restriction on the solution to the problem. The difference of luminosity function and/or color-magnitude diagram between E galaxies and globular clusters must not only account for Figure 2 but must also give a mass to light ratio of about 100 for E galaxies compared with about 1 for globular clusters. Two solutions which satisfy both Figure 2 and the $\mathfrak{M}/L$ ratio bave been proposed. One by M. S. ROBERTS [17] adds very red stars fainter than $M_v = +2$ to a globular cluster to produce a synthetic E galaxy. ROBERTS is successful in fulfilling both conditions but the number of dwarf K and M stars which are required seems very high. The other solution by W. A. BAUM [18] supposes that E galaxies are composed of M 67 type stars together with gas. The difference between M 67 and M 3 type stars explains the energy curves of Figure 2 and the large mass of gas gives the correct $\mathfrak{M}/L$ ratio. BAUM's solution has not been published in detail so it cannot be adequately discussed. It does however violate SWOPE's observations of the similarity of color-magnitude diagrams of dwarf ellipticals and globular clusters (but this may not be an essential point as was pointed out in the last paragraph). More serious, however, is that BAUM's solution appears

to require so large a mass of gas that, if this gas is neutral, it should be observed as 21-cm radiation at least in the nearest systems like NGC 205 and M 32, or, if it is ionized, it should be seen as Hα emission. Neither of these predictions are true. The virtue of BAUM's solution is that it is consistent with MORGAN's spectroscopic observations.

We may summarize the present dilemma as follows; ROBERTS' solution explains Figure 2, gives an acceptable $\mathfrak{M}/L$ ratio, but does not explain MORGAN's spectra. BAUM's solution explains Figure 2, gives an acceptable $\mathfrak{M}/L$ ratio, explains MORGAN's spectra, but violates SWOPE's Draco observations, and apparently requires an unacceptable gas density in view of the lack of strong enough radio or Hα radiation. Perhaps a combination of both solutions is necessary where the main contributor to the total light are M 67 type stars but where many faint stars are added to provide the $\mathfrak{M}/L$ ratio. In any case there must be a sprinkling of globular-cluster-like stars at $M_v = -3$, $B\text{-}V = +1.6$ to explain BAADE's resolution data. It is clear that the problem of the luminosity function and color-magnitude diagram for E nebulae has not yet been solved.

VI. *Summary*

(1) A time independent function, $\psi(M_v)$, which describes the distribution of luminosity at the time of star formation, has been derived by SALPETER from the general luminosity function, $\varphi(M_v)$.

(2) SALPETER's function gives an average rate of star formation in the solar neighborhood of 2×10^{-11} star/pc^3 year.

(3) The SALPETER $\psi(M_v)$ fits the observed luminosity function in galactic clusters at the bright end.

(4) The luminosity function in globular clusters is observed to $M_v = +6$. Fainter than $M_v = +6$, the VAN RHIJN luminosity function seems to provide an adequate fit as judged from the agreement of the predicted mass with that obtained from the observations of the velocity dispersion.

(5) The stellar content of E nebulae differs from that of globular clusters because (a), the energy distribution curves differ and (b), the mass to light ratios are different. The reason for the difference lies either in the character of the color-magnitude diagram or in the luminosity function or in both. An adequate solution has not yet been found.

Note added March 15, 1958:

A recent conversation with W. A. BAUM showed that the above discussion of E nebulae does not completely represent BAUM'*s* point of view. In the work cited [18] BAUM considered both cases mentioned here i.e. (1) The adding of faint main-sequence stars to a globular clnster to reproduce the I (λ) curve of Figure 2 and at the same time to give a mass-to-light ratio of about 100 (this is the model also considered by ROBERTS), and (2) the M 67 case (old population I) with the addition of either very faint stars or non-luminous matter to account for the large mass-to-light ratio. The intercomparison of these two models for I (λ), $\mathfrak{M}/L$, and spectroscopic characteristics led BAUM to conclude that case 2 gave the better fit to all data. It was primarily the integrated spectroscopic differences between globular clusters and E nebulae which favored the M 67 case. Although BAUM's quoted abstract suggested that large quantities of gas might exist in E nebulae to account for the high $\mathfrak{M}/L$, he now believes this to be less likely than the addition of other non-luminous matter, perhaps in the form of rather large particles. He favors the addition of non-luminous matter rather than very faint stars because of the radical departure from the van Rhijn luminosity function which would result by the addition of enough stars.

REFERENCES

[1] E. E. SALPETER, Ap. J., *121*, 161, 1955.

[2] P. J. VAN RHIJN, Groningen Pub., No. 47, 1936.

[3] S. W. McCUSKEY, Ap. J., *123*, 458, 1956.

[4] W. LUYTEN, Pub. Astr. Obs. U. Minnesota, *2*, No. 7, 1939.

[5] G. P. KUIPER, Ap. J., *95*, 201, 1942.

[6] G. HERBIG, I.A.U. Symposium Volume. *Non-Stable Stars*. 1957.

[7] S. VAN DEN BERGH, Ap. J., *125*, 445, 1957.

[8] A. R. SANDAGE, Ap. J., *125*, 422, 1957.

[9] V. A. AMBARTSUMIAN, Ann. Leningrad State Univ., No. 22, issue 4, p. 19, 1938.

[10] L. SPITZER, M.N., *100*, 396, 1940.

[11] S. CHANDRASEKHAR, Ap. J., *98*, 54, 1943.

[12] S. VAN DEN BERGH, A. J., *62*, 100, 1957.

[13] R. J. TAYLER, A. J., *59*, 413, 1954.

[14] H. C. ARP, A. J., *60*, 317, 1955.

[15] O. C. WILSON and M. F. COFFEEN, Ap. J., *119*, 197, 1954.

[16] M. SCHWARZSCHILD and S. BERNSTEIN, Ap. J., *122*, 200, 1955.

[17] M. S. ROBERTS, A. J., *61*, 195, 1956.

[18] W. A. BAUM, A. J., *60*, 153, 1955.

DISCUSSION

CHAIRMAN: J. H. OORT

BLAAUW

The procedure of obtaining the initial luminosity function starts from the Van Rhijn and Luyten luminosity function for the solar region. This includes high-velocity stars originating at large distances from the plane, where no high-luminosity stars are formed at present. If we want a luminosity function for a volume of space we should exclude this high-velocity component. This would mean a correction of a factor of about 3 to the faint end of the luminosity functions used and a corresponding correction to the initial luminosity function. We also should be aware that the assumption that stars are produced at a uniform rate is implied in the result.

SALPETER

In extrapolating the luminosity function to the faintest stars one starts from old stars anyway, so the assumptions about the rate of formation is irrelevant to the faint part of the diagram.

BLAAUW

It comes in when discussing the ratio of the number of high and low luminosity stars, because for the high-luminosity stars one can see only the result of the present rate of formation, and, if that is extrapolated to the initial luminosity function, one assumes that there has been the same rate of formation during all the history of the galaxy.

SALPETER

How certain is the luminosity function for M 3 at the faint end as determined from counts?

SANDAGE

Very rough, because of the impossibility of counting to the center of M 3 for the faint end. There might be a factor of three uncertainty.

SPITZER

There is some uncertainty about the luminosity functions of the large elliptical galaxies which MORGAN's observations will unravel. It seems definite that they contain K and M giants.

BAADE

I should like to ask MORGAN how sure he is about his luminosity classification. The integrated spectrum of the nuclear region of the Andromeda nebula was originally classed as dG5 at Mount Wilson and that was a terrific puzzle. It was cleared up finally when it was seen that the lines were so blended and confused, due to velocity dispersion, that the spectrum was thought to be dG5 when it should have been gG5. Are you certain in your case that the velocity dispersion does not interfere?

MORGAN

The main luminosity criterion used by me has been the CN bands and the whole process is quite different from that used in the earlier work at Mt. Wilson. As far as the earlier Mt. Wilson determination of the dwarf nature of the spectrum of the nucleus of the Andromeda nebula is concerned, I doubt if that is the complete explanation. In my interpretation it is due to a combination of two factors. First the lines are broad and, when one uses relatively high dispersion, this makes the lines look faint. This resulted in a spectral type of G5, solar type. When one gets into the K type stars the low-level iron arc lines are greatly enhanced in intensity. They are near their maximum intensity in the temperature sequence. In the line ratios which were used for luminosities with the higher dispersion one component is usually a low level metallic line, the other being a line which is enhanced in giant stars, so that you have a ratio of an iron line versus, say, an ionised strontium line. The stronger the iron line is, relative to the strontium line, the lower the luminosity. If you make a mistake in your spectral type and you are really working with a K star, when you think it is a G star, you will get a ratio which indicates a dwarf, when what you have is a combination of temperature effects. Now I did not use these ratios. I did not use a single criterion which was used by Mt. Wilson Observatory.

OORT

This subject will be pursued further in a later session, when MORGAN presents his paper on integrated spectra.

At Leiden VAN HERK has computed the number of faint stars which must be added to those observed by SANDAGE in M 3, assuming equipartition of energy. From SANDAGE's counts of stars we can essentially determine the potential field as well as the velocity distribution in the central part of the cluster. The amount of mass in the form of stars fainter than the limit of SANDAGE's count (about +6 absolute magnitude) that can be added at the centre is fixed very critically and amounts to about one fifth of the mass of stars of absolute magnitude brighter than +6 on SANDAGE's list. From the calculations, which show that the faint stars greatly outnumber the brighter ones in the outer parts of the cluster, we have an independent mass determination of about 3×10^5 $\mathfrak{M}_\odot$. This is somewhat larger than SANDAGE's value of 2.4×10^5 $\mathfrak{M}_\odot$. The total mass is, however, very sensitive to the structure in the parts beyond 30 pc from the centre, where the densities are very uncertain.

NOTE ON BINARIES AND THEORIES OF STELLAR EVOLUTION

D.J.K. O'CONNELL, S.J.
Vatican Observatory, Castel Gandolfo

We hoped that STRUVE would have been here to deal with this topic. That would have been particularly fitting, since important work in this field is being done by him and his collaborators at Berkeley.

I intend to indicate very briefly certain lines of research now being pursued which may produce results of great importance for theories of stellar evolution.

No hard and fast boundary can be drawn between very wide binaries and star clusters or associations. From proper motions obtained by LUYTEN and others, VAN BIESBROECK [1] has found binaries with (projected) separations of the order of 40,000 A.U. The chance of such very wide systems long surviving perturbations due to stellar encounters must be small, so that they would seem to be comparatively young systems, presumably owing their origin to some form of capture. There may be a regular exchange between such systems and individual stars, in other words they may be continually forming and disappearing.

I would be inclined to consider such very wide binaries in a class by themselves. All other binaries may be considered together, to this extent that there seem to be no sharply defined boundaries between visual double stars, spectroscopic binaries and eclipsing binaries of various types. If we have to seek a common origin for all these types of binaries, it is clear that no capture theory will suffice, for stellar approaches that could lead to capture must be far too few to account for the observed number of binaries, at least as long as the space density of stars is anything like what is now observed (HUANG [8]).

The classical fission theory of binary formation, developed in the elegant analysis of DARWIN, JEANS, POINCARÉ, was based on assumptions which are very remote from reality, i.e. uniform density and rotation as a solid body with uniform angular velocity. Subsequent studies on the stability of systems formed in this way have shown that they would be unstable [2], so that on this ground alone the theory would be untenable.

There remains the possibility that binary or multiple stars were formed from condensations in a turbulent gaseous medium undergoing gravitational contraction. This theory is discussed in a recent paper by ODGERS and STEWART [2]. There is evidently room for further theoretical studies on these lines.

Supposing that the components of a binary system were formed together, then anything that throws light on the evolution of such a system should provide valuable information about stellar evolution in general and about stellar population types in particular. Some recent researches do indicate that we are on the way to learning something about such evolution. The theoretical and observational work on β Lyrae by KUIPER and STRUVE at Yerkes showed that matter is being expelled from one component and is spread in the form of a ring or shell around the system, giving rise to the emission lines observed in the spectrum. STRUVE and his school at Berkeley are now actively prosecuting similar researches on other binaries.

Theoretical considerations show that ejection of mass from a component of a binary system can occur in different ways. Mass may be transferred to the other component, or it may form a stream around the system and perhaps eventually be lost to the system altogether. Spectroscopic observations have shown conclusively the existence of such gaseous streams, causing bright lines to appear in the spectrum. The analysis of the effects of such a transfer of matter in the system, or of loss of matter to outer space, is by no means easy. At any rate the orbital elements of an eclipsing binary should be affected, so that continued observations of such binaries are needed to detect, e.g., changes in the period. It has long been known that the period of β Lyrae is increasing. Similar studies of other eclipsing binaries are badly needed. Particularly valuable would be simultaneous photometric and spectroscopic observations. Some of us have been organising cooperative research on these lines. SAHADE and STRUVE are observing certain promising eclipsing binaries spectroscopically at Mt. Wilson, while a number of observatories, separated in longitude, are making photoelectric observations of the same stars, so far as possible simultaneous with the spectroscopic observations. This programme, although started only very recently, is already beginning to pay off. I will take one example — a piece of work just completed, but not yet published.

Many years ago A. H. JOY called my attention to the very peculiar spectrum of W Serpentis and suggested that I observe the light curve, which indeed proved to be very peculiar, indeed unique [3] [4]. It is now clear that we have here an eclipsing binary with unusual features. Recent spectroscopic observations by SAHADE and STRUVE [5] suggest that the primary component, apparently a late A type star, ejects matter at high velocity which forms an expanding shell. Gas is also streaming from the secondary component towards the following hemisphere of the primary star and the whole system is surrounded by a very extended atmosphere. FRESA is observing the variable photoelectrically at Capodimonte and finds that the period is definitely increasing [6]. It would seem that W Serpentis is a close binary in rapid evolution.

I can do no more than draw attention to recent theoretical studies by HUANG and STRUVE [7] [8] [9] and by KOPAL [10] on the evolution of binary systems in which the components are gaining or losing mass. It seems that we have here a promising approach to problems of stellar evolution. What we need now are more observations, photometric and spectroscopic, especially of certain eclipsing binaries showing bright-line spectra or with changing periods.

Note added in proof:

Much that is relevant to the above discussion is contained in papers on "*Instability in Binary Systems*" by Z. KOPAL, V. A. KRAT, D. J. MARTYNOV, and F. B. WOOD, contributed to the I.A.U. Symposium on *Non-Stable Stars* (edited by GEORGE H. HERBIG, Cambridge, 1957). This volume was not received until after the Semaine.

REFERENCES

[1] G. van Biesbroeck, J. R. Ast. Soc. Canada, *51*, 39, 1957.

[2] G. J. Odgers and R. W. Stewart, J. R. Ast. Soc. Canada, *51*, 97, 1957.

[3] D. J. K. O'Connell, Lembang Ann., *8*, 22, 1937.

[4] S. Gaposchkin, Harvard Ann., *105*, 539, 1937.

[5] J. Sahade and O. Struve, Ap. J., *126*, 87, 1957.

[6] A. Fresa, A. J., (in press).

[7] S. S. Huang, A. J., *61*, 48, 1956.

[8] — J. R. Ast. Soc. Canada, *51*, 91, 1957.

[9] O. Struve and S. S. Huang, R.A.S. Occasional Notes, *3*, No. 19, 1957.

[10] Z. Kopal, Ann. d'Ast., *19*, 287-335, 1956.

DISCUSSION

CHAIRMAN: A. BLAAUW

MORGAN

What is the spectral type of the secondary of W Ser?

O'CONNELL

The spectrum of the secondary has not been detected even at primary minimum.

MORGAN

Is SX Cas a similar case?

O'CONNELL

In some respects, but W Ser has some unique complications.

HERBIG

It is odd that, as far as I am aware, very few of the massive eclipsing systems of the types of β Lyr, SX Cas, and others studied by STRUVE are members of stellar associations. But perhaps this has not been studied adequately.

O'CONNELL

They are sometimes difficult to detect. W Ser was long thought to be a Cepheid; only after a long series of observations was it found to be an eclipsing binary. There may be many more such systems.

HECKMANN

Could one component of W Ser be a Cepheid? THIESSEN has analysed BM Cas for resonance between the periods of revolution and the pulsation of one component.

O'CONNELL

This is a real possibility. There is certainly at least one other type of variation present in addition to that due to eclipse.

SCHWARZSCHILD

Perhaps one may divide doubles into three groups:

1) Widely separated pairs which presumably evolve like single stars. 2) Intermediate cases where perturbation by the companions already has noticeable effects, but is not yet fundamentally altering the evolution of the individual stars. This group should in principle be a wonderful tool to test our ideas for individual stars, e.g. the stability of photospheric layers. However, as far as I know, up to now we have not found a good application of this intermediate group. 3) Very close pairs, whose evolution is fundamentally affected by mass exchange and must be completely separated from that of normal stars.

O'CONNELL

How do you define the intermediate group?

SCHWARZSCHILD

Those with radii a good deal smaller than their separations.

O'CONNELL

Eclipsing binaries with apsidal rotation would fall in that group and may provide useful information.

HERBIG

Upsilon Sgr is an extraordinarily interesting helium-rich spectroscopic binary badly needing photometric observation; the spectroscopic observations are very extensive.

III.

ETOILES JEUNES DE LA POPULATION I DANS LES BRAS SPIRAUX DE NOTRE GALAXIE

STELLAR ASSOCIATIONS

A. Blaauw (*)
Yerkes Observatory

ABSTRACT

Evidence is given in favor of the hypothesis that most stars are formed in associations or clusters. The question is discussed whether the rate of formation of stars in the early stages of the Galaxy may have been very different than it is now. Our meager present observational data can be reconciled with the assumption of a uniform rate of formation. The use of the Van Rhijn - Luyten luminosity function in the Salpeter-Sandage procedure for the reconstruction of the Initial Luminosity Function is criticized. The initial velocity distribution of the stars is derived; it probably is independent of the stellar masses except for the very massive stars which have a higher percentage of high velocities. These stars with high initial velocities are discussed in some detail. They are mostly O to Bo stars and represent an injection of massive stars into the halo at the rate of about 10^8 solar masses per 5×10^9 years.

Introduction

The term "stellar association" was introduced by Ambartsumian [1] in his description of loose groups of stars, containing as their brightest members either stars of spectral type O or early B (O-associations) or T Tauri variables (T-associations). Both these types of stars have a strong clustering tendency; only few objects are observed outside the associations.

The occurrence of such groups had been known since spectral classifications were available for the naked eye stars and

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(*) Now at the Kapteyn Laboratory, Groningen.

their distributions on the sky had been studied. Thus, KAPTEYN [2] studied in considerable detail the group motions of several of the nearest groups of O and B stars, including those in Orion and Scorpio-Centaurus. It had also been realized that the dynamics of the internal motions in these groups is basically different from that of galactic clusters, in that these motions are not governed primarily by the mutual attraction of the members of the association, but rather by the general galactic field of force and occasional encounters with field stars. Thus, in a study [3] of the kinematics and the development of the Scorpio-Centaurus group, it appeared sufficient as a first approximation to analyse the orbits of the individual members in the general galactic field of force characterized by the constants A and B of differential galactic rotation.

The importance of the associations for the study of star formation and stellar evolution was for the first time properly evaluated by AMBARTSUMIAN [1]. He stressed the fact that we are dealing with unstable groups of stars which cannot have existed in their present form during an interval of more than a few tens of millions of years, or one percent of the age of the galaxy. The inference was that the stars constituting the associations have been formed only recently. It is now generally assumed that star formation has taken place in the Galaxy from its earliest stage up to the present, and is still going on.

In present research on associations we may distinguish two types of investigations: those dealing with the large scale distribution in the Galaxy and those dealing with the properties of the individual associations and their stellar contents. The first category is of great significance for the study of the spiral structure and the distance scale of our Galaxy. The second category offers possibilities for the study of the circumstances under which star formation takes place, and provides information on the properties of stars in the early stage immediately after their formation, including the last phases of the contractional stage.

In the present account we shall be concerned mainly with the significance of the O-associations for the study of the stellar populations. We shall consider the present rate of formation of stars, the distribution of masses and luminosities of newly formed stars, their kinematical properties and their duplicity characteristics.

Associations as the Origin of O- and B-type Stars

There is strong evidence that the majority of the stars are formed in associations or clusters, and seldom or not at all in the general field. For the O and B-type stars this has most recently been discussed by ROBERTS [4]. ROBERTS assumed that all clusters and associations initially contain O stars, and explained the number of O- and B-type stars in the Galaxy by taking into account the number of O clusters and O associations, their mean stellar contents and their mean life times. More direct evidence may be given by means of Table 1, which refers to the stars within 6000 pc from the sun and north of − 20° declination [5]. The upper division of the table shows the numbers of stars of spectral types O5 to B3 and luminosity classes I to V in the three associations I Lac, I Ori and II Per. The second division refers to the stars in an old association, Cas-Tau (age about 50×10^6 yrs), and the lowest one to the field stars. Outside of the lower right division of the diagram, outlined by the dashed line, we only find stars in the associations or stars which originated in associations according to the direction of their space motion. This dashed line roughly divides the diagram into stars with bolometric absolute magnitudes brighter and fainter than − 7.0. Assuming for such stars a mass of 22 solar masses and an upper limit of 12% for the amount of hydrogen converted into helium, we find an upper limit for their age of 5.5×10^6 yrs. As the space motions of these stars are of the order of 13 km/sec only (see below), stars more luminous than $M_{bol} = -7$ will in general not be found at a distance of more than 70 pc from their origin. This is confirmed

TABLE I

Distribution of Spectral Types for Stars Within 600 pc and North of −20° Declination, Inside and Outside Associations.

	O5	*O6*	*O7*	*O8*	*O9*	*O9.5*	*B0*	*B0.5*	*B1*	*B1.5*	*B2*	*B2.5*	*B3*
							Associations I Lac, I Ori, II Per						
I *a,b*						1	2	1	1				
II						1							
III									1		4		2
IV											7		4
V		1	1		1	3	2	1	13	2	32	2	23
							Cassiopeia-Taurus Group						
I *a,b*													
II													
III											1		
IV							1				3		4
V								1			13	1	16
							Field Stars within 600 pc, Decl. > −20°						
I *a,b*									(1)				
II											(1)		
III								1	(1)		2		2
IV							(1)	5	2		8		9
V							(1)	1	13	2	63	2	62

by Table 1. The few stars found at large distances from associations are indeed the ones with high space velocities which can be traced to an association as their origin.

For B1V stars the 12% conversion limit is reached after 27×10^6 yrs, and distances of a few hundred parsecs from the origin should be quite common, as indeed they are observed to be. If a larger volume of space than that represented by Table 1 could be accurately surveyed for the numbers of field stars and association members, it would be possible to derive independent information on the limiting ages for the various sub-types from the ratio of the numbers outside and in the associations, the velocity distribution, and the assumption that all stars have their origin in an association.

The Problem of the Present and the Past Rate of Formation of Stars

In connection with the present discussion of the galactic population it is of interest to consider the rate of formation of stars in the associations and to investigate whether the present rate of formation is much different from that in the past. In particular it will be interesting to know whether star formation may have taken place at a more or less uniform rate since the early stage when the Galaxy had assumed its flat shape, or whether an appreciably higher rate of formation has occurred in the early stage.

Even for the region of the Galaxy near the sun, where our present knowledge of the population is the least incomplete, only a rough guess can be made. In doing so, it seems reasonable as a first step to assume that, wherever star formation takes place, there is a uniform initial mass distribution and hence also a uniform distribution of luminosities when the stars are on the main sequence. The notion of this Initial Luminosity Function, denoted by $\psi(M)$, has recently been introduced by SALPETER [6]. SALPETER approached the problem just mentioned in a somewhat different way, namely by postulating an Initial

Luminosity Function and a uniform rate of production of stars in the general solar neighbourhood, and attempting by means of these to explain the general luminosity function as determined by VAN RHIJN, LUYTEN and others, taking into account the evolutionary changes in the stars as they are understood at present. The Initial Luminosity Function thus determined by SALPETER was, after some modifications, tested by SANDAGE [7] who found its shape for M brighter than $+7$ to agree within the limits of uncertainty with the luminosity function of young galactic clusters, the evolutionary changes of which since their formation can be supposed to be small.

In the following we shall show that the bright end of this Initial Luminosity Function agrees well with data derived from the nearest and most completely known associations. The comparison of the Salpeter-Sandage luminosity function with the data from the associations will be limited to stars with absolute magnitudes brighter than -1, i.e. types B5 and earlier, because the data are too incomplete beyond this value. Table 2 shows the total numbers of stars in the associations II Per, I Lac, I Ori and Sco-Cen, in four intervals of M brighter than -1.0. In all these associations the presence of a number of stars fainter than $M = -1$ indicates that no serious incompleteness is to be feared from the fact that these associations are partly very young and part of the stars still must be in the contraction stage. The third column shows the numbers predicted by SANDAGE's modified $\psi(M)$ and reduced to the same total for the three divisions brighter than $M = -2.0$. The good agreement between the observed and predicted numbers in the first three lines, although perhaps fortuitous, shows at least that the chosen $\varphi(M)$ is satisfactory. A deficiency of observed numbers in the fourth line was to be expected since we know that in some of the associations incompleteness of our data on membership sets in at this luminosity. For comparison the numbers of stars according to VAN RHIJN's luminosity function, $\varphi(M)$, normalized in the same way are shown in the last column.

TABLE 2

Numbers of Stars, Brighter Than $M = -1.0$ in the Associations II Per, I Lac, I Ori and Sco-Cen.

M	*Observed number*	*Predicted with* $\psi(M)$	*According to* $\varphi(M)$
Br. than − 4.0	17	16	4
− 3.0 to − 3.9	24	27	16
− 2.0 to − 2.9	49	47	70
− 1.0 to − 1.9	46	73	282

TABLE 3

Predicted Numbers of Stars Fainter than $M = -1$ in Some of the Nearest Associations According to $\psi(M)$.

Spectral Type	*Scorpio - Cen*		*II Per*	*I Lac*	*Orion*	
	Upper Sco.	*Centaurus*			*Nebula region*	*ε Ori region*
Observed brighter than $M = -2.0$	11	18	8	18	18	17
B8 to B9 . .	20	33	15	33	33	31
A0 to A2 . .	18	30	13	30	30	28
A3 to A5 . .	13	21	9	21	21	20
F0 to F2 . .	26	42	19	42	42	40
All $M < +11.0$.	660	1090	480	1080	1080	1030
All $M < +16.0$.	1580	2570	1140	2600	2600	2400

In the region of the Galaxy within 1000 pc from the sun the number of stars present in associations and brighter than $M = -1$ is larger than the corresponding number in open clusters. Since, moreover, the rate of disintegration of the associations is much faster than that of the clusters, we may conclude that many more stars are formed in associations than in clusters. We found that the Initial Luminosity Function is the same in the associations as in the clusters as far as our meager data can tell us, and in reasonable agreement with the $\psi(M)$ as derived by SALPETER and SANDAGE. Taking further into account the basic assumption of SALPETER's and SANDAGE's procedure, we may provisionally infer that formation of stars has taken place mainly in the associations and at a more or less uniform rate since the beginning of the Galaxy. It should be born in mind that this statement applies to the population I stars which constitute the majority of the stars in the van Rhijn-Luyten luminosity function.

Adoption of the Salpeter-Sandage Initial Luminosity Function provides a basis for estimating the numbers of stars of fainter absolute magnitudes which should occur in the associations, or will appear in them in the future in so far as they are still in the contraction stage. These numbers are shown in Table 3. They are based on the total number of members observed brighter than $M = -2.0$. At present very little observational material is available to test these predictions but work in several associations is in progress. In the Upper Scorpio region there seem to be at least 20 B8-B9 stars according to provisional work by BERTIAU [8]. Further work on the stellar content of the associations is much desired in order to settle the uncertainty in the initial luminosity function.

While, according to this initial luminosity function, the total number of faint stars which will eventually be formed in the associations is of the order of at least one hundred times the number brighter than -2.0, the mass represented by these faint stars is relatively small. The total mass of all stars is

[8] III, 1 - *Blaauw I* - p. 8

only six times the mass represented by stars brighter than -2.0.

It is probably superfluous to say that the above considerations merely represent a first attempt to throw some light on the question of the rate of formation of the population I stars. In this connection we should like to point out that the Salpeter-Sandage procedure in deriving $\psi(M)$ is liable to the following criticism. The Van Rhijn-Luyten luminosity function, which is used by SALPETER and SANDAGE as the observed quantity from which $\psi(M)$ is reconstructed, represents the distribution of absolute magnitudes per volume of space in the solar neighbourhood and is for low luminosities ($M > +5$) based on stars within 50 parsecs from the sun. The low luminosity stars are different from the early type stars in some important respects: they have larger peculiar motions and reach correspondingly larger distances from the galactic plane. Therefore one cannot assume that star formation from the interstellar matter within a certain volume of space and the subsequent stellar evolution — regardless whether or not this formation took place at a uniform rate — will lead to the van Rhijn - Luyten luminosity function for the element of volume. It may be that the low luminosity stars, among which we find the oldest population, have partly escaped from an originally thin layer of interstellar matter due to encounters with interstellar clouds; this would require increasing the ratio of the numbers of low luminosity stars with respect to those of high luminosity in the van Rhijn-Luyten luminosity function before using it in the Salpeter-Sandage procedure. If we assume that the layer of interstellar matter has not been much thicker in the past than it is now, the ratio between the number of G to M dwarfs and the number of B stars would first have to be increased by a factor of 4.

On the other hand, if we assume the layer of interstellar matter to have extended in the past to greater heights and star formation took place at distances z where no interstellar matter occurs now any more, then the van Rhijn - Luyten luminosity function should first be freed from the contribution of low luminosity stars originated at large distances z, and the ratio between the G to M dwarfs and the B stars will have to be reduced.

These considerations may serve to illustrate the large uncertainty still present in the procedure applied in reconstructing $\psi(M)$.

The Initial Velocity Distribution

Since the O and early B type stars are too young to have experienced appreciable velocity changes due to the general gravitational field or as a consequence of close encounters, their velocity distribution may be regarded as the initial velocity distribution, i.e. the one determined by the process of formation. We have derived this velocity distribution from the O to B3 stars within 600 pc and north of − 20° declination. It is represented in Figure 1. The drawn line refers to the space velocities; the dashed one has been derived from it for the velocities in one component. The latter can be represented by the frequency formula

$$N(v)\,dv = \frac{1}{2\eta}\,e^{-|v|/\eta}\,dv \tag{1}$$

with $\eta = 6.8$ km/sec. Evidently this initial velocity distribution is very different from the gaussian shape which fits the observed velocities of later type stars. This is probably due to the fact that the shape of the initial distribution of the lowest velocities is markedly changed in the course of 10^9 years by encounters with interstellar clouds and cloud complexes, smoothing out the sharp peak at the very low values.

The question whether the initial velocity distribution is the same for stars of various masses cannot yet be quite satisfactorily answered. In the following section evidence will be presented in favor of larger velocities for the stars of very large masses. The small velocities of the A type stars in general, whose masses are about two solar masses or one tenth of that

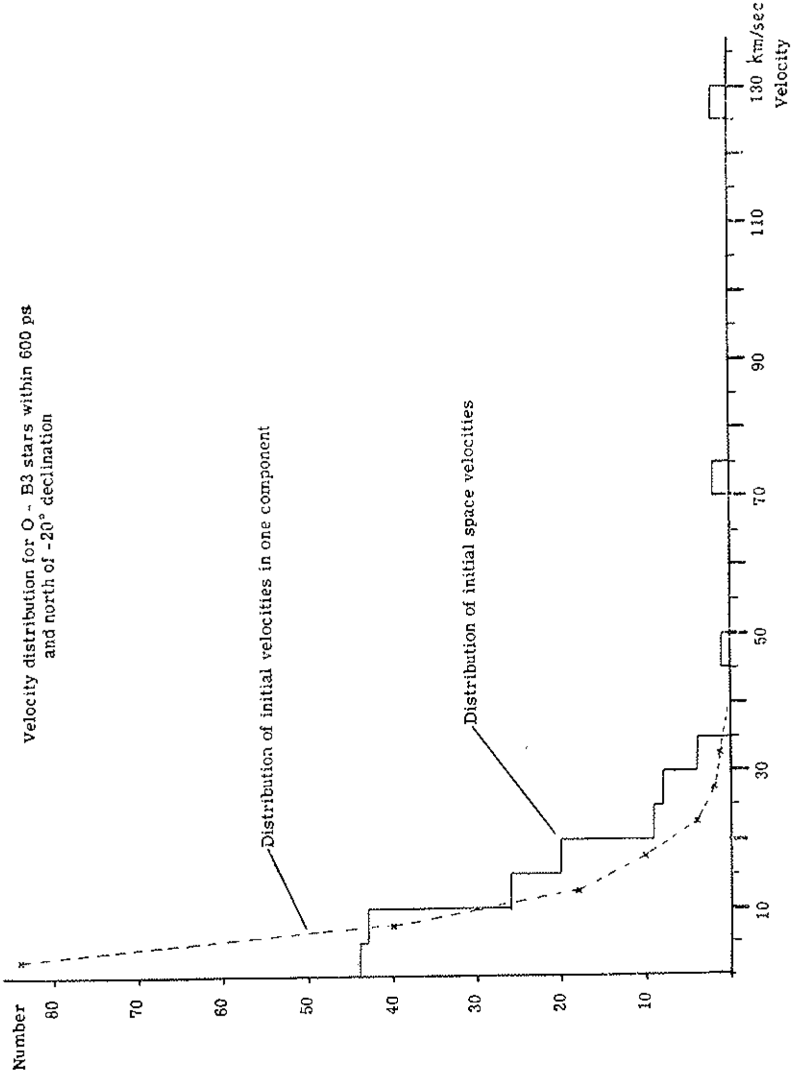
Velocity distribution for O - B3 stars within 600 ps
and north of -20° declination
Distribution of initial velocities in one component
Distribution of initial space velocities
Number
80
70
60
50
40
30
20
10
10
30
50
70
90
110
130 km/sec
Velocity

FIG. 1.

of a Bo star, probably represent approximately the initial velocity distribution [1]. The velocities of emission M dwarfs, probably also very young stars, but of much smaller mass, are of the same order as those of the A type stars [10]. Hence it appears safest to assume that the initial velocity distribution is independent of mass except for the very massive stars.

This conclusion has an important bearing on the theory of star formation, for it would then seem to be likely that the initial velocity distribution of the stars is that of the interstellar medium in which star formation takes place, and that the mass distribution of the stars which are being formed in a cloud is independent of the velocity of the cloud except for the very massive stars.

In this connection it is important to notice that the initial velocity distribution (1) is very similar to that found from Ca II lines [11] in interstellar clouds and from 21-cm measurements of neutral H in the region around the sun [12].

Except for a small percentage of the stars, to be discussed in the next section, the initial velocities are below 30 km/sec. This means that *a*) the initial velocities are in general too small to carry the newly formed stars more than 500 pc away from the galactic plane [13]; the majority will remain within 200 pc from the plane, and *b*) the newly formed stars will only slightly deviate from circular orbits around the galactic center. The majority of the stars produced will remain confined within a range from 0.7 to 1.5 times their present distance from the galactic center [14].

Stars with High Initial Velocities

It is interesting to notice that a few very high values occur among the initial velocities. A sample of such stars has been given elsewhere [5]. They deserve special attention in the present context, for they represent a category of young stars which may be encountered in regions of the Galaxy largely populated by old stars. The frequency of these high-velocity stars has been determined from a survey of the O to B0.5 stars within 1000 pc and the B1 to B5 stars within 600 pc (the limits for sufficiently accurate determinations of the velocities). Velocities exceeding 30 km/sec are included. The highest well determined values encountered are about 130 km/sec, and 75% of them exceed 60 km/sec. Table 4 shows the results of the survey. We notice that among the O to B0 stars, about one in four has a high velocity. This frequency rapidly decreases toward the later spectral types and is only about 1% for B1 to B5. At distances from the galactic center equal to that of the sun, stars with velocities of 60 km/sec may reach distances up to 1500 pc from the galactic plane, i.e. well in the region of the halo.

The rate at which such high-velocity stars are injected into the halo can be estimated from the data in Table 4, taking into account the difference in the life times of the various spectral types. Table 5 gives, for the three spectral divisions, the number of such events per 10^7 yrs within 1000 pc from the sun; allowance has been made for the incomplete coverage of the sky and for some incompleteness of the survey in Table 4. The number of such events for later spectral types is unknown but the trend in Table 4 indicates that it may well be less than double the number occurring among O5 to B5.

It is interesting to notice that the O to B0 stars provide the majority of these events. As the period of oscillation of the motion perpendicular to the galaxy is of the order of 10^8 years, we should expect these stars to display their subsequent evolutionary stages at large distances from the galactic plane. If the present statistics is extended over the whole volume of the Galaxy with a radius of 14 kpc and everywhere the same production rate, the total supply per 10^7 years will be 200 times that of Table 5, of which perhaps 10% are observable. A number of high luminosity supergiants in the halo have indeed been detected [15], which may well be the later stages of these early type high-velocity stars.

TABLE 4

Frequency of High-Velocity Stars (Velocities > 30 km/sec) Among Early Spectral Types (only declinations > −20° surveyed).

Type	*Total number of stars*	*Number of high velocities*		*Percentage high velocities*
O5 to O9.5	30	8	within 1000 pc	27 %
B0	20	5		25
B0.5	19	3		16
B1V	31	0	within 600 pc	0
B2V	133	1		1
B3V	122	2		2
B5V		1		1

TABLE 5

Number of High-Velocity Early Type Stars (Velocities > 30 km/sec) Formed Within 1000 pc per 10^7 Years.

Type	*Adopted life time*	*Number per 10^7 yrs within 1000 pc.*
O5 to B0	3×10^6 yrs	70
B0.5	6×10^6	8
B1 to B5	23×10^6	8

The total production of this component of the Halo population over a period of 5×10^9 years would be of the order of 10^7 stars. The mass contribution would be of the order of 10^8 solar masses if all mass is retained in the halo. A considerably larger amount of mass may, moreover, be fed into the halo in the form of high-velocity interstellar clouds, for the high-velocity young stars may represent only the small fraction of the mass of such clouds which was able to condense into stars.

The high-velocity early type stars differ from the low-velocity stars also in their duplicity properties. As has been pointed out elsewhere [5], these high-velocity stars are almost without exception single stars. On the other hand, of the O to B3 stars with space velocities below 20 km/sec, only one third are single and the majority double or multiple. The samples on which these results are based are sufficiently large to warrant the conclusion that we are dealing with a well established phenomenon. The young component of the halo population will therefore contain few double or multiple stars. The fact that the high-velocity early type stars differ from the low-velocity ones both in their spectral distribution (i.e. their mass distribution) and in their duplicity properties, indicates that they are the result of a process of formation which favors the formation of massive systems with low angular momentum.

REFERENCES

[1] W. A. AMBARTSUMIAN, Astr. Journal U.S.S.R., *26*, 3, 1949. (German translation in *Abhandlungen aus der Sowjetischen Astronomie*, Folge 1, Berlin 1951).

[2] J. C. KAPTEYN, Ap. J., *40*, 43, 1914 and *47*, 104, 146 and 255, 1918; Mt. Wilson Contr. Nos 82 and 147.

[3] A. BLAAUW, Groningen Publ., No. 52, 1946.

[4] M. S. ROBERTS, Publ. Astr. Soc. Pac., *69*, 59, 1957.

[5] Presented previously at the Symposium on "Evolution in the Galaxy", Berkeley 1956; Publ. Astr. Soc. Pac., *68*, 495, 1956.

[6] E. E. SALPETER, Ap. J., *121*, 161, 1955.

[7] A. SANDAGE, Ap. J., *125*, 422, 1957.

[8] F. C. BERTIAU, *The Absolute Magnitudes of the B stars in the Scorpio-Centaurus Cluster*, thesis. Louvain, 1956. Ap. J., (in press).

[9] L. SPITZER and M. SCHWARZSCHILD, Ap. J., *114*, 385, 1951 and *118*, 106, 1953; D. E. OSTERBROCK, Ap. J., *116*, 164, 1952 and *117*, 471, 1953.

[10] J. DELHAYE, Comptes Rendus Ac. Sc., *237*, 294, 1953.

[11] A. BLAAUW, B.A.N., *11*, 459, 1952.

[12] H. C. VAN DE HULST, C. A. MULLER and J. H. OORT, B.A.N., *12*, 117, 1954.

[13] J. H. OORT, B.A.N., *6*, 249, 1932, Table 31.

[14] M. SCHWARZSCHILD, A.J., *57*, 57, 1952.

[15] J. L. GREENSTEIN, D. A. MACRAE and R. FLEISCHER, Publ. Astr. Soc. Pac., *68*, 242, 1956; W. K. BONSACK and J. L. GREENSTEIN, Publ. Astr. Soc. Pac., *68*, 249, 1956; G. MÜNCH, Publ. Astr. Soc. Pac., *68*, 351, 1956.

DISCUSSION

CHAIRMAN: J. J. NASSAU

BAADE

It should be emphasized that the O associations are not disk but spiral structure features.

BLAAUW

Yes, they originate in spiral arms and are therefore very young type I objects.

OORT

Only a small fraction of the known high-velocity objects can have originated in this manner.

BLAAUW

Yes.

HERBIG

High-velocity early-type stars ejected at right angles to the galactic plane will return, but not as O or B stars, after perhaps many millions of years. BIDELMAN called attention to some middle-type supergiants having high z values; their distribution is very different from those in the galactic plane. A star which may be one of the returning stars is the remarkable F2 Ia-type object 89 Herculis, at a moderately high galactic latitude, and with variable light and radial velocity.

BLAAUW

It seems very reasonable to assume that the high-velocity O stars are the early stage of these high latitude supergiants.

FOWLER

Can you estimate the total mass of all the stars formed in the associations?

BLAAUW

This estimate is uncertain because we have no direct information on the initial luminosity function fainter than $M = -1$. But for the bright part it is similar to that in open clusters and the open cluster luminosity function is rather similar to that derived by SALPETER's procedure in explaining population I by uniform rate of formation. It is, therefore, quite possible that all stars were formed in associations and clusters.

LINDBLAD

The ejection of high-velocity stars might have been of great importance in a primitive state of the system — perhaps ejection from a compact layer. The process may have been more intense at that time.

BLAAUW

We should like to know what the process of formation of these objects is.

SPITZER

Does the fractional decrease of the number of high-velocity objects, with spectral type, persist beyond O and B type stars?

BLAAUW

The numbers are too small to be sure.

NASSAU

Are there not blue stars in the Andromeda galaxy away from the disk?

BAADE

B stars of high luminosity are occasionally observed beyond the spiral structure. I interpret them as part of the spiral structure that has completely broken up.

THACKERAY

There is a small group of high-velocity helium-rich stars (e.g. HD 168476) at galactic latitude 10-15°. Are they related to BLAAUW's high-velocity group?

BLAAUW

One would need to know their age.

OORT

At what stage of evolution is a helium-rich star?

HOYLE

It would be an advanced stage.

SCHWARZSCHILD

The difficulty is that there are two types of O and B stars — those absolutely bright of population I and those of magnitude near zero on the horizontal branch of population II.

THACKERAY

The absolute magnitude of HD 168476-like stars is not known but cannot be much fainter than -2.

OORT

The total mass poured into the halo in the manner suggested by BLAAUW (10^8 solar masses) must not be assumed to be present now in the halo. It will come back into the disk, or into nuclear parts, if clouds collide and this may perhaps supply the gas which according to the 21-cm observations is leaving the nucleus. In connection with BLAAUW's observation that there are hardly any binaries among the high-velocity OB stars, it is worth remarking that the percentage of doubles among ordinary high-velocity stars, compared with low-velocity stars, shows a similar effect though not so strongly. (Cf. an article by WOLTERBEEK MULLER soon to appear in the B.A.N.).

HOYLE

The existence of the high-velocity early-type stars described by BLAAUW suggest that a release of nuclear energy may be involved in their origin. This feature reminded me of EDDINGTON's idea that stars might become unstable due to radiation pressure. To test this idea Miss BLACKLER, Dr. HASELGROVE and I performed integrations for stars of very large mass and we did not find that such stars would be unstable, if uniformly mixed.

SPITZER

Is this not a test of equilibrium rather than stability?

HOYLE

It tests at least some form of instability, since one does not start with the final stellar model — one has to converge on to the correct solution by an iterative process. The fact that this process does converge supplies one test of stability, although of course it does not test all possible modes of instability.

HERBIG

I should like to ask BLAAUW about the apparent conflict of the time scales. Is it true that the existence of Beta Canis Majoris stars in associations and the central concentration of the eclipsing binary AG Persei require a greater age than the expansion rates of the associations indicate?

BLAAUW

The Beta Canis Majoris stars have small motions and are in parts of the associations where individual stars may be somewhat older than the association as a whole. The association has not a sharply defined age. With regard to AG Persei in the Zeta Persei association, the evidence that it is older is uncertain. Its age as derived from the proper motion is well determined.

SCHWARZSCHILD

KUSHWAHA computed the rate of apsidal motion for this type of star, not only for the initial state, but also for all the main-sequence phases. The difference between the observed and predicted apsidal motion of this star can only be partly accounted for (about one third) by assuming an advanced evolutionary phase. Hence this assumption does not solve the difficulty and may be wrong. As another difficulty I would like to point to the single star in BLAAUW's list (68 Cygni) whose distance from the centre of the association indicated a life longer than the life indicated by its absolute magnitude. Perhaps the velocity is already acquired by the cloud.

BLAAUW

Indeed this may be so.

SPITZER

OORT and I have considered an acceleration process for interstellar clouds. One observational fact against this is μ Columbae and AE Aurigae, a pair of stars with identical high velocities in opposite directions, suggesting stellar fission.

BLAAUW

Can one get in this way clouds with velocities of 100 km per second?

SPITZER

It might not be impossible. But it would be difficult for a star to form from clouds moving as fast as this. Are there any other cases of twins?

BLAAUW

Certainly many of these high velocity stars are not twins. If one takes a star like ζ Oph, which runs away from the Scorpio association, there can be no doubt about its origin. There certainly is not a star like that on the other side of the association. The same is true for ξ Per, which has a very high radial velocity compared to the ζ Per association. If it had a counterpart on the other side, it would be a star moving towards us. We simply don't see a star like that.

HOYLE

Some caution is necessary in assessing discrepancies between dynamical ages and those derived from luminosity, since the mass-luminosity relation increases more slowly with mass at high luminosities than might be expected. This could lead to an under-estimation of mass and therefore an under-estimation of physical ages. However, this effect could not be important in the case of stars with masses as low as ten times the solar mass.

BLAAUW

If one looks at the differential effects in some of the associations like those in Scorpio, Orion and Lacerta, then one can see that the one part must be older than the other just from the shift of the main sequence. If one compares that shift with the age of the association derived from the motions, one gets the impression that the evolution of the star seems to be somewhat faster than what is predicted from stellar model calculations. It seems that the age found from the motions is somewhat shorter than that obtained from the shift — if that is interpreted as an age effect. This applies mainly to stars of type B1 to B5, which of course have smaller masses than those referred to by HOYLE.

T TAURI STARS, FLARE STARS, AND RELATED OBJECTS AS MEMBERS OF STELLAR ASSOCIATIONS

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Lick Observatory, University of California

The "T Tauri stars" are a group of emission-line stars of moderate to low luminosity that are found solely in association with nebulosity. It is the writer's view that assignment to this group is entirely a spectroscopic problem, and given adequate spectroscopic material, classification on the basis of the emission line spectrum is ambiguous only in certain objects of late type where the spectra resemble those of normal dKe or dMe stars. In many nebulous regions, such as that around the Orion Nebula, one finds also many irregular variable stars without bright hydrogen lines; under the present usage, these are not T Tauri stars. Neither are a number of peculiar emission-line stars of early spectral type or of rather high luminosity that are occasionally found in the nebulae. These variables and peculiar stars are of considerable interest for their own sake, but it is advantageous to consider them separately from the T Tauri group.

In the advanced T Tauri stars — those with very strong emission lines — the spectrum is crowded with bright lines and no stellar absorption features can be seen. In some of these objects, the bright line spectrum on occasion "clears up", and features become visible that look like an approximately normal stellar absorption spectrum. In less advanced examples of the class, an absorption spectrum is permanently visible. The earliest type that has been assigned to any of these absorption spectra is F8, while the latest is M2. We shall consider later the stars lying outside these limits.

We now possess a multitude of observational data regarding the T Tauri stars. I believe that the totality of evidence now points strongly to the conclusion that the T Tauri stars are the counterparts, in the low to moderate mass range, of the O- and early B-type stars that have been born rather recently in the nebulae. Let us review this evidence briefly.

1. The Taurus-Auriga dark clouds have been rather well surveyed for bright-line stars. The data show that, per unit volume, there are from 5 to 15 times as many T Tauri stars in these dark clouds as there are in the same absolute magnitude interval near the sun. (These factors would perhaps be doubled if all the irregular variables without emission lines were to be included as well). It therefore seems very improbable that the T Tauri stars are field stars that have accidentally wandered into the nebulae, unless they have thereby been modified to a major extent.

2. Several star clusters are known that are still imbedded in nebulosity and whose brightest members are of very early type; these clusters must be quite young. In and around these young clusters are found large numbers of T Tauri stars. Although the "ages" of the two kinds of star may not be the same, they probably are not greatly different.

3. There are about 20 T Tauri stars in the region of the Zeta Persei association that can, to a considerable degree of probability, be shown to be members of the association along with the bright O- and B-type stars. According to Blaauw, the expansion age of the association is only one or two million years.

4. A number of examples are known where a bright early-type star, imbedded in nebulosity and hence presumably of

rather recent origin, has very close around it several faint T Tauri stars. This suggests that the faint stars are approximately of the same age as the bright one.

If the T Tauri stars are newly-formed objects, as the foregoing evidence indicates, then two otherwise puzzling observational results make sense if these stars are still contracting toward the main sequence. It was not mentioned, in connection with the absorption spectra of the T Tauri stars, that the absorption lines (in those objects bright enough to be observed with high dispersion) are rather wide and diffuse. If this broadening is interpreted as axial rotation, then the rotational velocities are abnormally high for normal main-sequence stars of these spectral types. But if these T Tauri stars lie on contractive evolutionary tracks such as those recently computed by HENYEY and his associates for masses of 0.65 to 2.3 solar masses, then these stars will arive at the main sequence at points where the final rotational velocities will be entirely normal, if angular momentum is conserved, for normal dwarfs of their terminal spectral types. Second, although the absorption spectra of the T Tauri stars correspond approximately to main-sequence luminosities, those of K- and M-type lie several magnitudes above the main sequence. We should expect just this effect if these stars are moving toward main-sequence types F and G, along evolutionary tracks that are, bolometrically, approximately horizontal.

There are many things yet to explain, but some suggestions can be advanced as to the general outline of the T Tauri process, under the fundamental assumption that the foregoing point of view is correct. Star formation takes place in the nebulae, and sometimes we are able to observe stars lying over the whole mass spectrum, as in the Orion Nebula. But in systems like the Taurus clouds, there are no very early-type stars. Whether the stars of large mass will appear later, or whether they will not be produced at all in these particular clouds, is unknown. The fact that the T Tauri stars are conspicuously confined to the clouds and their fringes, and are not found against clear star fields far outside the obscuration, indicates that the duration of the emission-line phase of their careers is comparable with, or shorter than, the time that their motions allow them to remain in the vicinity of the clouds. The irregular nebular variables without bright lines might be stars that have evolved beyond the emission-line stage, but they may be something else altogether.

Determination of accurate proper motions and radial velocities of T Tauri stars should make possible an estimate of the time scale of the association of these stars and the clouds. This datum is of the greatest importance, and a considerable effort would be justified in its determination. The very scanty data available at the present time suggest that a time scale of the order of magnitude of 10^6 years may not be too far from the truth.

The variations with time in the light, radial velocity, and spectral characteristics of the T Tauri stars show that the road of Kelvin contraction is not a smooth one, at least in its earlier stages. Although considerable information is on hand regarding the details of these fluctuations, we are still in darkness as far as any general understanding of the time-dependent phenomena are concerned. If a thorough and well-planned observational attack on the problem were made, something significant might emerge.

One fact is clearly visible in the mass of detail now on hand: the bulk of the spectroscopic data shows that the upper layers of the atmospheres of the T Tauri stars are *rising* with respect to the layers where the absorption-line spectra are produced. There is no spectroscopic evidence that the T Tauri stars, as a class, are collecting material. Whatever the source of the activity of these stars, the immediate origin of the disturbances must be within rather than outside the photosphere.

The role played by the end products of the T Tauri process is a legitimate subject for speculation. If these stars do move along contractive evolutionary tracks and in time arrive at the main sequence, then the associations and the dark nebulae must continually be feeding stars of moderate to small mass into space. The question is whether the production rate of dwarf stars by the T Tauri process is sufficiently large to make the mechanism of practical importance. The surveys are now sufficiently complete that a preliminary estimate may be made of the number of T Tauri stars in the solar neighborhood. Between M_{pg} values of $+4$ and $+11$, it is estimated that there are at least 3×10^3 T Tauri stars within 1 kiloparsec of the sun; this is a lower limit that may have to be increased substantially. Consideration of the relative volumes then gives a minimum T Tauri popnlation of 5×10^5 for the whole galactic system. In the present picture, the T Tauri stage is a transient one, but how long does it last? That is, what is the time interval required for the production of another generation of T Tauri stars by the nebulae? An interval of the order of 10^6 years has already been mentioned, from what little is known of the velocity dispersion. To be conservative, let us assume a value of 5×10^6 years. On the basis of this figure, some 10^3 generations of T Tauri stars have been born during the lifetime of the Galaxy, giving a total number of at least 5×10^8 stars that have been produced in this way. Presumably the majority of these are by now main-sequence stars of types F through K. If they are now scattered fairly uniformly throughout the Galaxy, one would expect about 30 of these relics of T Tauri stars to lie within 10.5 parsecs of the sun. This is about one-third of the number of stars actually found in this volume and in this absolute magnitude interval, according to KUIPER. Of course, the data and the assumptions that went into this calculation are far too uncertain for any significance to be placed on the difference between the observed and computed numbers of stars; the point is that the estimated production rate of main-sequence stars by the T Tauri process seems to be galactically significant. A more thorough study of the problem sometime in the future when better basic data are available should make it possible to sharpen this conclusion.

The time interval that measures the duration of the association of a T Tauri star with a nebula has been estimated to be of the order of magnitude of a million years. But this is very much shorter than the Kelvin contraction time scale for stars of small mass, as is shown by the following rough compilation:

Spectral type	*Mass (in solar units)*	*Kelvin time scale*
Bo	16.	0.03×10^6 years
Ao	3.	2×10^6 »
dG2	1.	50×10^6 »
dK5	0.6	200×10^6 »
dM5	0.2	700×10^6 »

Since T Tauri stars are not found except in association with nebulae, it seems evident from these figures that the T Tauri phenomenon must be confined to the early stages of the contractive process. Once this early stage has passed, its key characteristics will weaken or disappear: the distinctive emission spectrum, the irregular variability, the association with nebulosity. It is difficult to avoid the conclusion that, either because of the movement of the stars out of the clouds, or because of the dissipation of the clouds themselves, many stars must exist that are still in process of contraction but that are no longer marked by the T Tauri characteristics. In general, the consequences should be most conspicuous in the stars of smaller mass and lower luminosity. Stars that find themselves in this predicament should, in principle, be recognizable by their location above the main sequence as defined by the old stars. Their space motions probably would be rather small:

one would expect them to be comparable with, but greater than, the motions of the O- and B-type stars, which also were formed in such clouds. It would be difficult to say how long traces of other characteristics, such as variability and the presence of the strongest emission lines, would survive. But it is not unreasonable to suspect that these characteristics would persist longer in stars with long contraction times than in those of larger mass having short Kelvin time scales. To repeat, if we wish to find those stars that have recently emerged from the clouds and are still contracting toward the main sequence, the effects that we expect to appear should be most conspicuous among objects of low luminosity.

It is interesting to speculate that the low-luminosity M-type dwarfs with bright hydrogen lines in the solar neighborhood might be identified with the old T Tauri stars of small mass. Following the initial work of DELHAYE and BAADE, it is now known that the velocity dispersion of the dMe stars is only about one-half as large as that of the M dwarfs without bright hydrogen lines. (It should be understood that we are using the definition of a dMe star employed by the Mount Wilson observers — i.e., a star having bright *hydrogen* lines — and not that sometimes seen, where *either* hydrogen or calcium is meant). If the dMe stars were born not far from the neighborhood of the sun, then their motions would contain the velocity dispersion of the nearby gas clouds plus a component reflecting the conditions under which the stars themselves were formed. The M dwarfs without hydrogen emission would then be pictured as older objects that owe their larger velocity dispersion to the same effects plus an origin in more distant parts of the Galaxy.

This idea is supported to a certain extent by another fact: it was noticed by KUIPER fifteen years ago that the M dwarfs with emission lines tend to lie above the main sequence, and that those with the stronger emission lines were displaced the most. This result is confirmed by modern photoelectric data, and may mean that the dMe stars have not yet had time to reach the main sequence, as defined by the older non-emission objects. But caution is necessary here: there is reason to suspect that emission lines occur more frequently in close binaries than in single stars. Variation of radial velocity seems to be about twice as frequent among the dMe stars as in non-emission M dwarfs. Consequently, a part of the systematic upward shift of the dMe's with respect to the dM's in the H-R Diagram may be due to the greater fraction of binaries among the dMe stars.

Some support for this idea can be found in an appeal to galactic clusters. In old clusters, if this hypothesis is correct, one would expect to find only dM, and not dMe, stars. Unfortunately, only the very nearest clusters are amenable to this test on account of both the absolute faintness of M dwarf members, and the difficulty in picking out the physical members of distant clusters of small proper motion. The Hyades is the best case; its age has been estimated as about 10^9 years from the turning-off point of the upper end of the main sequence. Recent spectroscopic observations with very low dispersion of ten of the faintest red dwarfs known in the Hyades have not revealed any with bright hydrogen lines, although a few have bright Ca II. It is highly desirable that search be made for still fainter Hyades members so that these studies can be extended to stars of yet lower luminosity.

Of course, all the foregoing evidence indicates only that the dMe stars may be relatively yonng objects, not that they are necessarily the "decaying" T Tauri stars of small mass, for which we are looking. But it is difficult to think of an alternate source of dMe stars in the quantities required to explain their frequency in the solar neighborhood. Also, a connection of the dMe's with T Tauri stars is suggested by the fact that, as already mentioned, the spectra of advanced dMe stars look in some respects quite like the spectra of some late-type T Tauri stars.

So much for speculation on where the T Tauri stars go.

What can we guess about the other end of their evolutionary tracks? One assumes that stars of small to intermediate mass must become luminous somewhere on the right of the H-R Diagram, and above the main sequence; other characteristics such as variability and spectroscopic details would be difficult to predict. Now, a number of faint red variable stars are known in the Taurus clouds and in the Orion Nebula; these are the so-called "flash variables" found by HARO. They exhibit quick, flarelike outbursts of light separated by long intervals of quiescence. Their spectra are those of late-type dwarfs, but emission lines are generally weak or absent at minimum light. They do not fit the definition of a T Tauri star used here, nor are they "flare stars" in the precise sense of the variable Me dwarfs in the solar neighborhood. The fact that the fainter "flash stars" even at minimum light are considerably more luminous than main sequence stars of their spectral types suggests that, like the T Tauri stars, they are probably relatively young objects. But there is no certainty that they are the youngest members of that class; they may be something else altogether.

Of course, when one looks for faint red stars in nebulae, the most famous examples are the low luminosity members of the Trapezium cluster in the Orion Nebula. This is certainly a region where one feels that star formation must be active, if anywhere. Unfortunately we know very little about the Trapezium cluster stars because of the interference by the brilliant nebulosity in that region. Many are said to be variable in light, but nothing is known of their spectra. A real effort to learn more about these objects is long overdue.

Finally, let us consider the so-called Herbig-Haro Objects and the possibility of their being connected with the origin of the T Tauri stars. The Herbig-Haro Objects are very small clots of emission nebulosity, often with a star-like nucleus. The smallest of these Objects appear as no more than fuzzy, semi-stellar spots, while the largest and brightest may be as much as 15″ in diameter, and show considerable structure. Spectroscopically, the H-H Objects are unmistakable: the bright lines of hydrogen, [O I], [O II], and [S II] are very strong. The Objects can be picked out very easily on objective prism or slitless spectrograms because the [O I] and [S II] lines flanking Hα are very intense. About fifteen Herbig-Haro Objects have been found to date, all in regions of very heavy obscuration. The major part of the energy in the accessible portion of the spectrum is in the emission lines. Photographed in the continuum between lines, the brightness of the Objects decreases by 2 or 3 magnitudes. Direct photographs show that small variations in the appearance of some Herbig-Haro Objects take place from time to time. But the most surprising event was the appearance in one Herbig-Haro Object, on plates taken in 1954, of two new nuclei which were not present on photographs exposed in 1946 and 1947. Observations over the past two years have shown no further change or variability. The only information on the rate of brightening of these two new nuclei comes from a plate exposed one year before the discovery photograph. The Object in question lies very near the edge of this exposure, so the definition is poor, but one of the new nuclei appears faintly, while the other has already attained the brightness which it had when it was noticed a year later.

It is obvious that both in structure and in spectrum, the Herbig-Haro Objects and the T Tauri stars are very dissimilar. Except for the fact that both occur in the nebulae, what reason is there to think that they are related at all? The reason is as follows. One of the most characteristic features of the T Tauri stars, which sets them apart from other late-type emission-line stars of similar luminosity, is the presence of lines of [S II], often in some strength. In T Tauri and RY Tauri, the best observed stars, [O I] is also present, as is [O II] in T Tauri. It is clear that these forbidden lines originate somewhere very near the star, but in a region of much lower density than that in which the general emission-line spectrum is produced. That this region is to some extent independent of the ordinary fluctuations in strength of the emission spectrum is indicated by the relative stability of the intensity of the [S II] lines. In T Tauri, part of the region in which the forbidden line spectrum originates can actually be seen and photographed in the form of a nebulous shell that extends only a few seconds of arc out from the star image. When the spectrum of this nebulosity is observed, free from interference by T Tauri itself, it is found to possess, in the great strength of [O II] and [S II], the same peculiarities as are observed in the H-H Objects. As already mentioned, the continuous spectrum of a Herbig-Haro Object is very weak, but one does exist; in the brightest Objects, one finds in addition to the forbidden lines, the H and K lines of Ca II and Mg I λ 4571. The presence of the permitted Ca II lines is quite surprising in view of the nature of the rest of the spectrum, but H and K occur in great strength in the T Tauri stars, where λ 4571 also is sometimes prominent. One has the impression that the continuous spectrum and permitted lines of the Herbig-Haro Objects originate in some kind of stellar or semi-stellar nucleus, while the forbidden lines are formed in the low-density envelope that is so prominent on the direct photographs. If the continuum and permitted-line spectrum of the brightest Herbig-Haro Objects would increase in brightness by a factor of a few hundred times, the result would probably look very much like what we actually see at T Tauri at the present time.

This analogy is the basis for the speculation that the two new nuclei which appeared in the Herbig-Haro Object in Orion might have represented a very early stage in the development of a T Tauri star. This stage may be one in which a very faint star spasmodically emits bursts of radiation that ionize the immediately surrounding gas. Since the ionization would subsequently decay, with a time scale measured in tens of years under the conditions likely in such a Herbig-Haro Object, one would expect there to be a gradual fading-away of these nuclei as observed in the forbidden line radiation. But the source of the continuous spectrum, presumably the star in which the ionizing radiation originated, might behave quite differently. (This suggestion in based on a remark by SOBOLEV). Obviously, such questions are amenable to observational attack, but the angular sizes of the Herbig-Haro Objects are so small that major advances are to be expected only if the work can be taken over by the very largest telescopes. It is hoped that the availability of the 120-inch telescope in the near future will result in an improvement of the observational situation.

All the foregoing is interesting and suggestive, but we still do not know for certain how a T Tauri star looks at the beginning of its career. The nuclei of the Herbig-Haro Objects are the best-known of the candidates for this role, but the exploration of the nebulae with large telescopes has revealed other peculiar objects, both stellar and non-stellar, whose position in this picture is entirely unknown. Until we know more about these other inhabitants of the clouds, the ideas advanced here regarding the origin of the T Tauri stars must be regarded as only the most preliminary of speculations.

Consider now the observational situation for stars more luminous than about $M_{bol} \sim +3$ or $+4$, which seems to be about the upper limit for objects that meet the spectroscopic criteria for membership in the T Tauri class. There are in the nebulae a considerable number of still brighter emission-line stars with spectral types between A and G and luminosities ranging up to $M_{bol} \sim 0$. Many of these stars are variable, have peculiar spectra, and illuminate local reflection nebulae. But without knowing what to expect of stars evolving towards the main sequence through this region of the H-R Diagram, it is hardly possible to decide whether these are the young stars that we seek. There are peculiar stars in the sky whose characteristics cannot be blamed on youthful instability, but the likelihood of more than a very few such objects being associated with nebulae by chance involves a double improbability. On the other hand, why should young stars in this region of the

H-R Diagram look peculiar at all? The A-type stars that WALKER has observed in the "hump" on the main-sequence of NGC 2264, and which presumably are still contracting, are not known to possess emission lines, variability, or conspicuously peculiar spectra. (Of course, the same situation may exist among the stars of low luminosity as well: the variables and T Tauri emission-line stars may not constitute the entire stellar population of the nebulae in that absolute magnitude range). It is possible that the situation will be clarified by work now in progress.

There is little substantial information on the beginning stages of stars of still larger mass, brighter than $M_{bol} \sim 0$. O- and B-type stars must form, and, despite their relative rarity per volume of space and the rapidity of their passage through the contractive stage, one would expect that in some of the accessible, very young associations a few stars might exist that are still midway in the contractive process. Since the bolometric correction passes through a minimum midway in this stage, such early-type-stars-to-be should appear as high luminosity objects of types A to K. Supergiants of these types are known in a number of associations. Unfortunately, the old O- and B-type stars that have departed from the main sequence as a result of hydrogen exhaustion in their cores probably pass back through this same region of the H-R Diagram. There seems no obvious manner in which these two classes of stars can be distinguished from one another, except that the stars evolving to the left in the H-R Diagram will probably be more closely associated with nebulosity than the older ones moving to the right. Of course, if star formation begins in a certain association at the same time for all masses, then the nature of the H-R Diagram should indicate whether the high luminosity stars of intermediate spectral type have had time to reach the main sequence or not, but the condition of simultaneous starting may not be realized over such large volumes of space. In the Orion Nebula, a few G- and K-type giants exist that are 5 magnitudes fainter than the brightest O-type star. This fact is most readily understandable if all the stars in this Nebula did not start their evolution together, as has been suggested by BLAAUW on the basis of the spread in "departure times" of the O- and B-type stars that have apparently been ejected from the Nebula with high velocities.

In this introduction to the subject, little or no acknowledgement has been made to the investigators responsible for the results quoted in the text. I wish to make it clear that many of the ideas, and much of the observational work discussed here, are not mine. This report owes more than I can acknowledge to the work of, and conversations with, Drs. BAADE, HARO, JOY, MORGAN, and STRUVE.

REFERENCES

The original paper which opened the study of the T Tauri stars was by

A. H. Joy, Ap. J., *102*, 168, 1945.

Further studies that provided basic observational data were those of

A. H. Joy, Ap. J., *110*, 424, 1949; J. L. Greenstein, Centennial Symposia (Harvard Observatory Monograph, No. 7), p. 19, 1948; Ap. J., *107*, 375, 1948.

Since 1949, a considerable number of papers, both observational and theoretical, have appeared on various aspects of the problem of the T Tauri stars. Recent discussions of the subject that present the point of view held by Soviet investigators, together with references to their earlier papers, will be found in:

P. Kholopov, Variable Stars, *8*, 83, 1951; V. Ambartsumian, Comm. Burakan Obs., No. 13, 1954; P. Kholopov, *Non-Stable Stars*, ed. G. H. Herbig (I.A.U. Symposium, No. 3, Cambridge 1957), p. 11.

Recent presentations of the views held by the writer are:

G. H. Herbig, Jour. Roy. Astr. Soc. Canada, *46*, 222, 1952; *Non-Stable Stars*, p. 3; and in a paper dealing mainly with the spectra of the T Tauri stars communicated to the 1957 Liège Astrophysical Colloquium.

Papers dealing with the search for T Tauri stars, containing also references to older work, are:

G. Haro et al., Bol. Obs. Tonantzintla y Tacubaya, No. 8, 3, 1953; Ap. J., *117*, 73, 1953; G. H. Herbig, Ap. J., *119*, 483, 1954, and *125*, 654, 1957.

The observational data published thus far on the Herbig-Haro Objects are given in

G. H. Herbig, Ap. J., *113*, 697, 1951; and *Non-Stable Stars*, p. 3; G. Haro, Ap. J., *115*, 572, 1952, and *117*, 73, 1953; K. H. Böhm, Ap. J., *123*, 379, 1956.

The kinematic properties of the M-type dwarfs have been studied by

W. Baade (unpublished); J. Delhaye, Comptes Rendus, *237*, 294, 1953; W. Gliese, Zs. f. Ap., *39*, 1, 1956; E. R. Dyer, A. J., *61*, 228, 1956; A. N. Vyssotsky and E. R. Dyer, Ap. J., *125*, 297, 1957.

Speculations on the relationship between the "flash" and flare variables and the T Tauri stars will be found in papers by

G. Haro, Bol. Obs. Tonantzintla y Tacubaya, No. 11, 11, 1954; No. 12, 3, 1955; No. 14, 3, 1956; the writer's work in the field is unpublished.

Observations of the magnitudes and colors in clusters containing T Tauri stars are in:

P. Parenago, Variable Stars, 7, 169, 1950, and Pub. Sternberg Astr. Inst., *25*, 1954; M. F. Walker, Ap. J. Suppl., *2*, 365, 1956 (No. 23); Ap. J., *125*, 636, 1957.

Physical mechanisms to explain the T Tauri phenomenon are discussed by

J. L. Greenstein, Pub. A.S.P., *62*, 156, 1950, and in a paper presented at the Burakan Conference on Non-Stable Stars, 1956; G. R. and E. M. Burbidge, Observatory, *75*, 212, 1955; V. Ambartsumian, Comm. Burakan Obs., No. 13, 1954, and in *Non-Stable Stars*, p. 177; a review of the 1954 paper, by V. Kourganoff, appears in Supp. Nuovo Cimento, *1*, 273, 1955.

Calculations of the evolutionary tracks of stars evolving toward the main sequence have been published by

L. G. Henyey, R. LeLevier, R. D. Levée, Pub. A.S.P., *67*, 154, 1955.

DISCUSSION

CHAIRMAN: J. J. NASSAU

STRÖMGREN

Are the data on masses, radii and luminosities sufficient to compute the Kelvin contraction time of T Tauri stars to their present state? I should also like to know what data are available about fainter T Tauri stars.

HERBIG

On the last question: their spectral types are late K and early M. The average absolute magnitude can be obtained without difficulty, but to determine the radius we need colours and these are difficult to obtain.

STRÖMGREN

Even a rough estimate of radii would be valuable.

HERBIG

These stars are generally bluer than JOY's spectral type indicates. It is hard to allow for this in getting the surface brightness.

BLAAUW

The star 19 Scorpii, classified by MORGAN as A5II, is in the most condensed part of the Scorpius association. Could this be a star on its way to the main sequence?

Morgan

I do not know what a star of that spectral class would look like on its way to the main sequence. In the case of K dwarfs in the Orion nebula region, there is a large excess of apparent brightness.

Blaauw

Were suitable spectral standards available for the A5II star?

Morgan

Yes, it happened that there were two good standard stars. It was a good observation.

Hoyle

In view of Herbig's suggestion that the nebulosity associated with T Tauri stars is not concerned physically in the T Tauri phenomenon but that the association is due to the fact the nebulosity and the T Tauri stars are contemporaneous, it would be interesting to look for T Tauri stars in regions blown free from gas and dust by neighbouring O stars.

Baade

NGC 2264 is perhaps a case in point.

Herbig

It would be difficult to be sure that such apparently associated O and T Tauri stars are not merely aligned by projection.

Morgan

In NGC 2264, while there is a considerable amount of gas around the association, the dust density is relatively low. There is a rather dense dust cloud, which does not surround it but is displaced by around 3°. It looks as though one has a somewhat later situation in which perhaps the gas and dust may be beginning to separate out.

Spitzer

One should not conclude from the spectrum of T Tauri stars that interaction between the surrounding gas and the stars has no effect on the spectra of the stars.

HERBIG

True, but there *is* direct evidence of material rising, and no substantial indication of any falling in.

SANDAGE

In NGC 2264 the colour excess is small, but the cluster seems to sit in front of an opaque cloud. Could this be the region in which your T Tauri stars occur?

HERBIG

The T Tauri stars are very conspicuously confined to the dark lane which runs past S Mon, the O7 star, and HD 47887, which is a B2 or B3 star, about 1° away. In the lane there are 80 or so T Tauri stars.

THACKERAY

I am circulating a picture of R and T CrA and associated reflection nebulae, another good example of T Tauri stars at the end of a dark lane. (These were R and T CrA, and NGC 6726-7, 6729).

SCHWARZSCHILD

Are T Tauri stars ever surrounded by roundish nebulae?

HERBIG

Yes, there are many examples.

SCHWARZSCHILD

Do the spectra show evidences of expansion?

HERBIG

This is not known, since the nebulae are very faint for observations with adequate dispersion.

HERBIG

It might be of interest to mention that at Lick Dr. HUNGER from Kiel has analyzed some 100-inch coudé spectra of T Tauri and RY Tauri and found the lithium line at λ 6707 to be present in considerable strength.

FOWLER

HERBIG and BLAAUW's results are both significant for the problem of the formation of the elements. I got the impression that the value of 10^8 solar masses ejected into the halo, together with OORT's value for the amount of neutral hydrogen observed at present, suggests that all population I stars must go through a period of stellar formation and evolution of this kind.

BLAAUW

The value of 10^8 solar masses referred to high-velocity stars only. At the same time stars of low velocities with a larger total mass were formed which do not enter the halo.

SALPETER

Yes, but it is an upper limit, for two reasons — (1) it was assumed that they were formed over the whole sky, whereas they might form only in the spiral arms; and (2) the majority of the stuff would not have returned to the disk, but would be spread over the halo.

FOWLER

I had the impression from OORT that most of this material would return into the disk.

OORT

Yes, so far as it gets back into the interstellar gas, but the total mass remaining in the halo might be perhaps not more than 10% of this. That could easily be present in the halo, but there is much more mass in the halo than that.

HOYLE

Would not this be a very welcome point of view, that something like 10^9 solar masses have been circulated, because we know that the He at present in population I material is something like 25%, and if this has been made in the stars, it would involve a circulation of exactly this order?

SALPETER

If I understand correctly, we really do have evidence that there are some associations which are just a few million years old and we see in them some T Tauri stars whose luminosity is sufficiently low so that the Kelvin time scale is appreciably longer. In other words they were formed a short time ago, so that at the time of formation their radius was not much bigger than it is now. Thus they must have been formed quite rapidly into an almost fully grown stage of fairly high density.

HERBIG

I think that this is correct in general. However, BLAAUW mentioned that the nuclei of some of these associations might have ages quite different from those indicated by the expansion time.

NGC 2264 AND M 8 AS EXAMPLES OF VERY YOUNG STELLAR ASSOCIATIONS WHICH ARE STILL PARTLY IN THE STAGE OF KELVIN CONTRACTION

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I. *Introduction*

In 1953, E. E. SALPETER [1] [2] proposed a direct observational test for the hypothesis that stars are formed from the interstellar medium by contraction to the main sequence. Because the time to contract from infinity to the dimensions of main sequence radii is shorter for stars of higher mass, SALPETER suggested that the color-magnitude diagram for an extremely young cluster should consist of a normal main sequence which terminates at the faint end at a critical luminosity whose value depends on the age of the cluster. Stars which will eventually populate the sequence fainter than the critical value are still in the process of contraction and should be observed as red stars. Later, detailed calculations of contracting stars by HENYEY, LELEVIER, and LEVÉE [3] carried the theoretical problem further and reached the same conclusions.

Early observational work by P.P. PARENAGO [4] on the I Orionis association suggested that main sequence stars did exist only to a certain luminosity, fainter than which non-main sequence subgiants appeared. PARENAGO's results were sug-

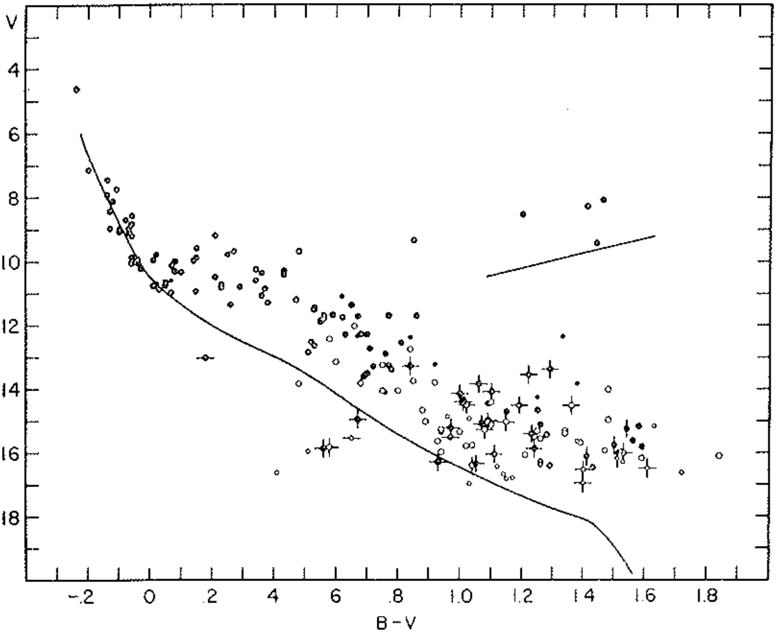

FIG. 1. — WALKER'S color-magnitude diagram of NGC 2264. Dots represent photoelectric observations, circles photographic observations, vertical lines known T Tauri variables, horizontal lines are stars with bright Hα. The solid line is the age zero main sequence. The apparent modulus of this cluster is 9.7 and the reddening is $E_{B-V} = 0.082$.

gestive but were open to some objection because of the inadequate observational material which was at his disposal for stars fainter than $m_{pg} = 10$. MERLE WALKER [5] [6] has provided the modern observational solution to the problem in his very beautiful results for NGC 2264 and M 8. WALKER'S observations consist of photoelectric and photographic observations on the three color *UBV* system for about 250 stars in NGC 2264 and 120 stars in M 8. Figures 1 and 2 show WALKER'S color-magnitude diagrams for NGC 2264 and for M 8. The data are plotted as observed with no correction for interstellar reddening. Using the B-$V = f(U$-$B)$ diagram, WALKER shows that the

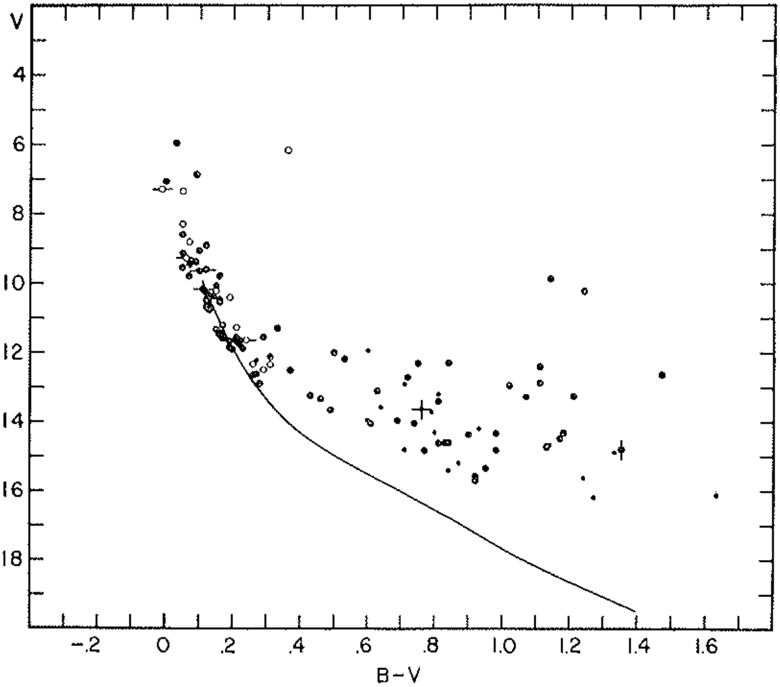

FIG. 2. — WALKER's color-magnitude diagram for M 8. The symbols are the same as in Figure 2. The apparent modulus of the cluster is probably 11.7 and the reddening is probably $E_{B-V}=0.332$. These values are uncertain for observational reasons.

reddening is small and uniform over the field of both aggregates. The unevolved, age zero, main sequence is drawn as a solid line in both diagrams.

These diagrams prove that both clusters have a normal main sequence which covers a spectral range from O5 to A0. In both clusters this sequence ends abruptly at A0. Many subgiants are present fainter than this. They lie from 0.5 to 5 magnitudes above the normal main sequence. WALKER has suggested that these stars are the ones predicted by SALPETER to be still in the process of gravitational contraction. Thermonuclear reactions have not yet begun. The energy which is radiated has been released from the gravitational field. Satisfactory as this interpretation seems, detailed comparison between theory and observation shows a difficulty concerning the time scale.

II. *Theory*

The calculations of HENYEY, et al., give the tracks followed by contracting stars in the M_{bol}, log T_e diagram. They also give the Helmholtz time scale. With certain assumptions, their results can be produced by dimensional arguments from the equations for the structure of stable stars.

In contracting from the interstellar medium to a radius R on the main sequence, the star must radiate part of the energy contained in the gravitational field (computed later on). The rate of liberation is determined by the opacity. If we assume an opacity law

$$\varkappa = \varkappa_0 \rho T^{-3.5} \tag{1}$$

then the luminosity of the star is

$$L = \frac{\text{Const.}\ \mathfrak{M}^{5.5} (\mu\beta)^{7.5}}{R^{0.5}} \ . \tag{2}$$

For constant chemical composition and mass equation 2 becomes

$$L = \text{Const.}\ R^{-0.5} \ . \tag{3}$$

Equation 3 defines the contraction path in the M_{bol}, log T_e plane through the relation

$$L = 4\pi R^2 \sigma T_e^4 \ . \tag{4}$$

Combination of (3) and (4) gives the required answer of

$$\Delta M_{bol} = -2 \Delta \log T_e \ , \tag{5}$$

which is very close to the tracks computed by HENYEY, LE LEVIER, and LEVÉE. The crux of the above argument is in the form of equation 1. The computations of HENYEY et al were based on detailed opacity tables and it would not have been surprising if equation 5 did not fit their accurate tracks. But because equation 5 does fit we shall use it to extend the HENYEY tracks to lower values of log T_e than these authors tabulate.

The only remaining datum necessary to construct a theoretical color-magnitude diagram is the contractional time scale — a problem first solved by HELMHOLTZ. By conventional arguments it can be shown that, if the *only* energy source is that contained in the gravitational field, then the time Δt for a star to contract from a radius R_1 to R_2 is

$$(6) \qquad \Delta t = 3.16 \times 10^7 \frac{\mathfrak{M}^2}{L_{12}} \left[\frac{1}{R_1} - \frac{1}{R_2} \right] \text{ years}$$

where $\mathfrak{M}$ is the mass and L_{12} is the mean luminosity between stage 1 and 2, both expressed in solar units. The total time $T_{g.c.}$, to contact from infinity to a radius R on the main sequence works out to be

$$(7) \qquad T_{g.c.} = 6.32 \times 10^7 \frac{\mathfrak{M}^2}{L_{m.s} R} \text{ years}$$

where $L_{m.s}$ is the main sequence luminosity. It should be noted that this is *minimum* time required for any star of given L, $\mathfrak{M}$, and R to reach the main sequence. If there are additional energy sources in this evolutionary phase such as nuclear energy, E_n, from the burning of Li, Be, or B, then the time will be *increased* by the order of E_n/L seconds. The only way $T_{g.c.}$ can be made smaller than that given by equation 7 is for the contracting mass to have been larger at an early stage and then fragment before reaching the main sequence. (To show this, substitute the approximate mass-luminosity relation $L \propto \mathfrak{M}^{3.5}$ in equation 7 giving $T_{g.c.} = \text{Const } \mathfrak{M}^{-1.5} \; R^{-1}$).

Equation 3 for the tracks and equation 6 for the time along these tracks now permit us to compute a theoretical color-magnitude diagram for any cluster of a given age τ. To be specific, let us assume $\tau = 3 \times 10^6$ years. We suppose in this example that all stars in the cluster were born and started contracting from the interstellar medium at the same time.

Stars whose masses and luminosities are large enough to give $T_{g.c.}$ less than 3×10^6 years will have reached the main sequence. But the very brightest of these will not have remained on the main sequence for the entire time τ because they will have had time to consume $Xq = 0.07$ of their nuclear fuel and will have evolved away. Stars in this category are the brightest in the cluster and are such that the nuclear time scale of

$$T_N = 1.10 \times 10^{10} \frac{\mathfrak{M}}{L_T} \text{ years} \tag{8}$$

(see the third paper of the conference) is less than 3×10^6 years. These considerations show that the main sequence will be present in the cluster, but bounded at the bright end by stars whose mass and luminosity satisfy $1.10 \times 10^{10}\ \mathfrak{M}/L_T = 3 \times 10^6$, and at the faint end by stars whose parameters satisfy $6.32 \times 10^7\ \mathfrak{M}^2/LR = 3 \times 10^6$. These termination luminosities are about $M_{bol} = -7.6$ at the bright end, and $M_{bol} = -0.4$ at the faint end. Fainter than $M_{bol} = -0.4$, $T_{g.c.} > 3 \times 10^6$ years and stars are still contracting along tracks given by equation 5. By successive application of equation 6, we can compute the radius R_2 which stars have reached in 3×10^6 years along each track. The lines of constant time (3×10^6 years) crossing these tracks can then be drawn in the M_{bol}, log T_e plane and this is the theoretical color-magnitude diagram. The computations show that the time scale is so rapid that the contracting stars should all lie very close to the line $\Delta M_{bol} = -2\ \Delta \log T_e$, and further, that there should be no stars in the diagram fainter than $M_{bol} = 0$ for $\log T_e > 2.8$.

III. *Comparison of Theory and Observation*

These theoretical results fainter than $M_{bol}=0$ are in direct conflict with the observations. Subgiant stars exist close to the main-sequence from $M_{bol}=0$ to the limit of WALKER's data at $M_{bol}=+7$. The situation is shown in Figure 3. Here the evolutionary tracks given by equation 5 are drawn as solid lines. The gravitational contraction times required to travel from infinity to the main sequence are written on each track. WALKER's observations of 2264 are drawn in a striped area. Here the usual bolometric corrections and temperature scale have been used to convert from the M_v, B-V plane to the M_{bol}, $\log T_e$ plane. We shall return to the validity of these corrections later. The time scale, T_N, for remaining on the main sequence is given on the right hand ordinate. We can date the cluster in two ways; either (1) by T_N or (2) by $T_{g.c.}$. The star S Mon is the brightest star in NGC 2264. It is still on the main sequence. S Mon has an apparent visual magnitude of $V=4.62$ and a color, corrected for reddening, of $(B\text{-}V)_0=-0.32$. WALKER gives an apparent modulus of 9.7 for NGC 2264. Consequently, the parameters for S Mon are $M_v=-5.08$, $\Delta M_{bol}=-2.67$, and $M_{bol}=-7.75$. At this luminosity, the mass is 26.3 $\mathfrak{M}_\odot$. Equation 8 gives $T_N < 2.8 \times 10^6$ years. The age is less than this because S Mon is still on the main sequence. Presumably it is not much less. The other method of dating is from the faint end of the main sequence break point. The main sequence terminates at about $M_v=+1.0$ (the exact value is defined to only about ± 0.3 magnitude from the observations). This corresponds to $M_{bol}=0$, a mass of 3.2 solar masses, and a radius of 2.12 $R_\odot$. These values in equation 7 give 3.6×10^6 years. Thus the bright and faint termination points give about the same age to the cluster. This is significant because it means that *there is nothing wrong with the contraction times given by equation 7 at the faint main-sequence termination point.* Figure 3 then poses the following question. If equation 7 is correct, how can stars at

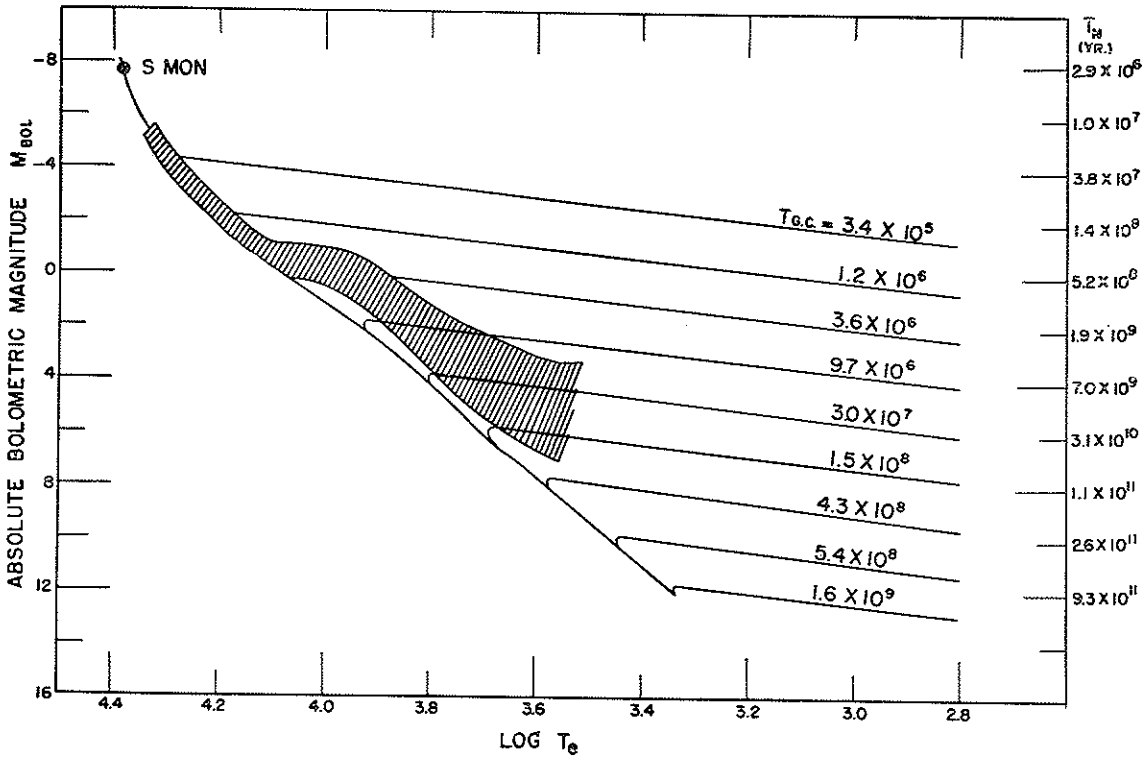

FIG. 3. — The contraction paths in the M_{bol}, log T_e plane as computed from equation 5. Contraction times $T_{g.c.}$ to reach the main sequence are written on the tracks. Times for the stars to remain on the main sequence at the given M_{bol} are on the right hand ordinate. WALKER's data for NGC 2264 are in the shaded area.

$M_v = +6$ be as close to the main sequence as they are observed. These stars can reach their observed M_{bol}, log T_e values only after 1.5×10^8 years, yet the cluster is only 3×10^6 years old. If all stars in the cluster started to condense at the same time, then equation 7 cannot be correct and still fit the observations. We have seen that the only way to get a shorter contraction time than 7 predicts is to have the contracting stars fragment. This would solve the dilemma. But the observations militate against this because, if this were the case, the times computed from T_N and $T_{g.c.}$ at the bright and faint ends of the main sequence would disagree in the sense that ($T_{g.c.}$ computed) $>$ (T_N computed). Three examples of young clusters give $T_{g.c.} \approx T_N$. These are 2264 (WALKER [5])]), M 8 (WALKER [6]), and I Orionis (JOHNSON [7]).

Because $T_{g.c.} \approx T_N$, the only other possibilities which I can see to explain Figure 3 are (a) that there has been a real spread in the times at which stars began to contract, in the sense that the least massive stars began their contraction as long ago as 2×10^8 years while the most massive stars were not formed more than 3×10^6 years ago or (b) that there is a very large error in the bolometric corrections and $B\text{-}V = f(T_e)$ relations used to convert WALKER's data into Figure 3. Neither of these explanations sound plausible, because for case (a) one would not *a priori* expect $T_N = T_{g.c.}$ unless the stars of mass 3.2 $\mathfrak{M}_\odot$ $M_{bol} = 0$) began to contract at just the correct time of 3×10^6 years ago. And for case (b), errors in ΔM_{bol} and $B\text{-}V = f(T_e)$ probably can not be made large enough to explain the difficulty because both WALKER's spectra and his $U\text{-}B = f(B\text{-}V)$ data for a number of the stars in question seem quite normal.

There is no doubt that WALKER's observations in NGC 2264 and M 8 are of the greatest importance for knowledge of the early phases of the formation of the stars. But it appears that the data cannot be understood in detail in terms of present models for contracting stars.

REFERENCES

[1] E. E. SALPETER, Symposium on Astrophysics (Ann. Arbor: Univ. of Michigan), 1953.

[2] E. E. SALPETER, Liège Symposium Volume. *Les Processus nucleaires dans les astres*, p. 116, 1954.

[3] L. G. HENYEY, R. LELEVIER and R. D. LEVÉE, Pub. A.S.P., *67*, 154, 1955.

[4] P. P. PARENAGO, Astr. J. Soviet Union, *30*, 249, 1953.

[5] M. F. WALKER, Ap. J. Suppl. Ser., *2*, 365, 1956.

[6] — Ap. J., *125*, 636, 1957.

[7] H. L. JOHNSON, Ap. J., *126*, 134, 1957.

DISCUSSION

CHAIRMAN: J. J. NASSAU

HERBIG

Another way in which WALKER's anomaly might be explained is the following: T Tauri-like stars, even those with quite weak emission, often seem to be too blue for their spectral types. Since WALKER observed U, B, V and not log T_e, a conversion of the former to the latter by the ordinary relationships might introduce just such an effect as is observed.

SANDAGE

Though normal stars were used for the transformation from the B-V, V plane to the log T_e, M_{bol} plane this point must be checked rather carefully.

HERBIG

On a point of history: although, as SANDAGE has stated, SALPETER called attention to this possibility in 1952, the elevation of the main sequence was present already in the magnitudes and spectral types published by JOY in 1945 and 1949. That is, JOY's data showed clearly that the late-type T Tauri stars in the Taurus clouds were too bright for their main-sequence spectral types by several magnitudes. This effect was confirmed in 1949-50 by EGGEN and HERBIG by photoelectric observations. It is precisely the effect found later by WALKER in the colour-magnitude diagram of NGC 2264 and Messier 8.

HOYLE

The evolutionary tracks assume almost constant energy emission which is likely to be a good approximation near the main sequence, but we do not know enough about surface opacity below 2000° to guarantee its correctness far to the right in the H-R diagram. To resolve the problem raised by SANDAGE, it is necessary to dissipate gravitational energy rapidly. In this connection it is interesting that the energy loss of the brightest of the Herbig-Haro objects is of the order required to dissipate the right amount of energy in about 3×10^6 years.

SANDAGE

KRAMERS' opacity law was used. The emission effect suggested by HOYLE would show up in the position on the colour-magnitude diagram.

HOYLE

Stars would evolve very quickly through the Herbig-Haro phase, and then they would slow down as they got to the main sequence. The opacity effect alone might not be sufficient, but it might trigger a different mechanism of dissipation.

SCHWARZSCHILD

It looks as though these stars must undergo most of their evolution at larger mass.

The question whether the colours are to be interpreted in terms of effective temperature in the usual relation is very important. Even though SANDAGE's arguments make one feel a little more safe, we need to extend observations to fainter magnitudes, and further to the red, to be sure about the temperatures.

SANDAGE

The fact that the faint main sequence breakoff point gives a contractional time scale which agrees with the nuclear time scale for the brighter stars, makes it artificial to suppose that disagreement sets in immediately below the breakoff point.

SPITZER

They may have evolved at a higher mass and divided before reaching the main sequence. They might have gained velocity at fission, in which case we should look for kinematic differences between the lower and higher parts of the diagram. Have you searched for infra-red stars, which should be particularly numerous in so young a cluster?

THACKERAY

We have met several cases of very strong infra-red stars in M 8.

BAADE

There are very many infra-red stars in the Milky Way regions.

HERBIG

I should like to second SCHWARZSCHILD's suggestions of observations at another wave-length, and suggest a colour system based on infra-red ($\lambda > 7000$) and yellow (λ 5500) measures, carefully filtered to avoid the hydrogen and other emission lines. Such a colour system will become more and more necessary as the observations are extended to heavily nebulous associations (as the Orion Nebula) and to more distant groups.

I should also like to point out, in answer to SPITZER's question, that there are probably many faint low-luminosity red foreground stars and many reddened background stars seen projected upon these obscured regions. Until these can be excluded somehow, it is difficult to see how useful the simple discovery of faint red stars in these regions would be.

IV.

ETOILES VARIABLES PHYSIQUES ET POPULATIONS STELLAIRES

QUELQUES TYPES SPECIAUX D'ETOILES

PHYSICAL VARIABLE STARS AND STELLAR POPULATIONS

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Variable stars, in particular the cepheids and cluster-type variables, have become increasingly important in the exploration of our own and other galaxies. In the present note I want to discuss briefly the question whether we can assign the known types of physical variable stars unambiguously either to the population I or II. To prevent any misunderstandings, I shall adhere strictly to the original definition of the population II in which the globular clusters of the galactic halo served as the prototype.

The physical variables which we can definitely assign today to either the population I or II are listed in the following table.

Population I	*Population II*
Type I cepheids	Type II cepheids
β Can Maj. stars	RV Tauri stars
T Tauri stars (including former RW Aur, Orion-type variables, etc.)	Cluster-type variables
Supernovae II	Long-period variables of small amplitude and periods from 70 to 200 days.
	Ordinary novae
	Supernovae I

I have omitted from the table the irregular and semiregular variables since it would be impossible to distinguish the members of the two populations by their light curves. An exception are the T Tauri stars which are listed as members of the population I. Although their light variations are irregular, they usually stand out in the sky because they happen to appear in groups (T Tauri associations).

Probably the only group in column one which needs some comment are the Supernovae II. It is well known that Supernovae II and I are easily distinguished by their spectra at the time of maximum brightness. While the spectra of the supernovae II at maximum are perfectly understood — they consist of widened emission lines indicating velocities of expansion of the order of 6000 km/sec — those of the Supernovae I have so far defied any interpretation and we must assume that they are of nonthermal origin. The two kinds of supernovae also differ radically with respect to their locations. Whereas Supernovae I have been observed in all types of galaxies from E's to Sc's, Supernovae II have been found only in spirals and there only in the spiral arms (cf. the supernova in the Sb galaxy NGC 4725). This different behaviour of the two kinds of supernovae permits only one explanation, i.e., that the Supernovae II are members of the population I while Supernovae I belong to the population II.

The only groups in column two which may need comment are the RV Tauri variables and the Novae. That the RV Tauri variables are typical members of the population II is well documented by their appearance in globular clusters. In his investigation of the brighter RV Tauri stars of our Galaxy, Joy on the other hand encountered two groups which differed in their kinematical behaviour. Of these he identified the high-velocity group easily enough as belonging to the population II. But he was obviously puzzled when he found that the low-velocity group did not belong to the population I because its mean velocities were too high. Actually there is no difficulty to explain JOY's result. His low-velocity group is representative of the disk stars of our Galaxy, which suggests that his low velocity RV Tauri stars are disk members of the population II.

As far as the novae are concerned, their assignment to the population II rests on the following facts. First, the appearance of a well-observed nova in the globular cluster M 80 which, judged by its integrated spectrum and its variable stars, is undoubtedly a member of the galactic halo. Second, the appearance of novae in dwarf E-galaxies of the local group. During the past 10 years I have found 2 novae in each of E-galaxies NGC 147 and 185 although neither of the two systems was kept under close control. Third, the high number of novae in the center region of our galaxy which has, as I show in my third paper, a predominant population II.

It is a very remarkable fact that the variables which we assigned in our table to either the population I or II represent the numerically strongest and most important types of physical variable stars with which we have become acquainted in our Galaxy, with one exception. These are the variables of the Mira type. It is well known that they represent a composite group but we are not yet able to separate them in a satisfactory manner.

DISCUSSION

CHAIRMAN: A. BLAAUW

FOWLER

If supernovae of type II are glorified novae, have you any idea why they should have this great intensity in population I?

BAADE

No! Glorified novae is of course only a descriptive term. As in ordinary novae matter is ejected, but higher excitation and higher velocities are involved. We are pretty certain that we have an example of a supernova of type II in our galaxy in the radio source Cas A, which has the right velocity of expansion and must have reached absolute magnitude -13 about 350 years ago, though it was not observed, as it is very heavily obscured. The heavy absorption along the plane of the Galaxy explains why so few are observed.

SPITZER

Can you give us some quantitative data about the difference of frequency between the two types of supernovae?

BAADE

The number observed during the same time interval, after allowance for the different luminosities, leads to a factor of about ten.

HECKMANN

Sandage showed some globular clusters (M 13 and M 10 for example) with no, or very few, cluster variables, which you say are characteristic of population II.

BAADE

If I find cluster variables in a given volume of space they indicate as well as a colour-magnitude diagram that stars of population II are present. If there are none the result is inconclusive.

SCHWARZSCHILD

Their absence cannot always be a statistical accident, e.g. in 47 Tuc.

HECKMANN

Consequently the presence of cluster-type variables may be a sufficient, but not a necessary, condition for population II.

MORGAN

Are M-type giant variables common in globular clusters?

BAADE

They are observed in a few cases.

MORGAN

Are most of the brightest globular cluster stars variable?

BAADE

This is true in the sense that the type II Cepheids and RV Tauri variables are the brightest members in globular clusters.

OORT

Everyone would like to see a neat sequence in globular clusters giving the content of variables of different kinds, and the further characteristics of the colour-magnitude diagram and the spectral types, arranged in what might be an age sequence. This has partly been supplied in yesterday's communication by SANDAGE.

SANDAGE

I am not convinced that a correlation exists between the occurrence of M-type and RR Lyrae variables in clusters. For example, in M 10 there are no RR Lyrae stars, 2 globular cluster Cepheids, and one M-type variable, while in M 3 there are about 150 RR Lyrae stars, one globular cluster Cepheid, and one M-type.

Schwarzschild

Long period variables and Cepheids occur in such small numbers, about two or three per cluster, that correlation is difficult to determine.

Strömgren

Can bolometric amplitudes for the M-type variables of small photograpbic amplitude be estimated?

Baade

Code is working on this. Let me add that there is a mild indication that RR Lyrae stars at a later stage of their evolution may become novae. The number of novae in the Galaxy, allowing for absorption, is about 20 per year. The number of cluster variables it about 1.5×10^5. If we knew the interval between nova outbursts we could infer the number of potential novae. Biermann in 1938 in his theory of novae derived a value which would give us 10^5 potential novae, about the same number as RR Lyrae stars.

Oort

We must remember the difference of velocity and space distribution between the RR Lyrae variables and novae.

Baade

That is true. But we must also remember that our present data about the distribution of the RR Lyrae variables through the disk of our Galaxy are very incomplete.

M-TYPE STARS AND RED VARIABLES IN THE DIRECTION OF THE GALACTIC CENTER

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Case Institute of Technology

Introduction

Some eight years ago objective prism plates taken at the Warner and Swasey Observatory indicated that a large number of M-type stars were present in the general direction of the galactic center. Later HARO of the Tonantzintla Observatory took a number of plates for us covering a large part of the Sagittarius Cloud. Among them two plates included the region of the globular cluster NGC 6522 where BAADE had made previously a systematic search for variables. He selected three regions of equal area centered at the cluster, one within 11′.2 from the center, a ring around this with an outer radius of 15′.9 and a third outer ring. Only the region within 15′.9 was used for the search of variables with plates having a limiting photographic magnitude of 20.2. The study of the variables were made by SERGEI GAPOSCHKIN. Some of the results were reported by BAADE [1] at the Symposium on Astrophysics at the University of Michigan. Details concerning the red variables including identification charts were made available to us by BAADE after this meeting. Recently GAPOSCHKIN [2] published all pertinent data concerning all of the variables discovered by BAADE. As far as the red variables are concerned no significant differences between the recently published work and the previous work was noted.

The present summary deals with the M-type stars in this region and their relation to the red variables. The complete study of the area, which was made by BLANCO and the writer, will be presented later.

Data

The search for M stars was made by means of infrared objective prism spectra following our previously established methods (NASSAU and VAN ALBADA [3], CAMERON and NASSAU [4]). The region examined was limited to 11'.2 from the center of the cluster. Two plates were used and the search and classification of M stars was carried out independently by NASSAU and BLANCO. The survey yielded 203 M stars which represents a surface density of 1850 M stars per square degree. Great care was exercised to insure completeness. Within the center region BAADE discovered 36 red variables.

The infrared magnitudes of all the M stars were obtained from films taken by MCCUSKEY with the 18-inch Palomar Schmidt. Each star image was measured with a graduated scale of images on two films. The internal mean error of the final magnitudes was found to be ±0.1 mag.

The blue magnitudes of the same stars were determined from only one plate taken with the 100-inch telescope by BAADE who also furnished us the blue sequence. The blue magnitudes of the variables (Mira stars excluded) so determined were compared with the mean magnitudes of the variables as determined by GAPOSCHKIN from the same sequence. Although the material is very limited the comparison does not seem to show a zero point or scale error.

Spectral Distribution

The spectral distribution of all the M stars within 11'.2 of the center of the cluster is shown in Figure 1a. Here the red variables are excluded. A similar distribution for the red var-

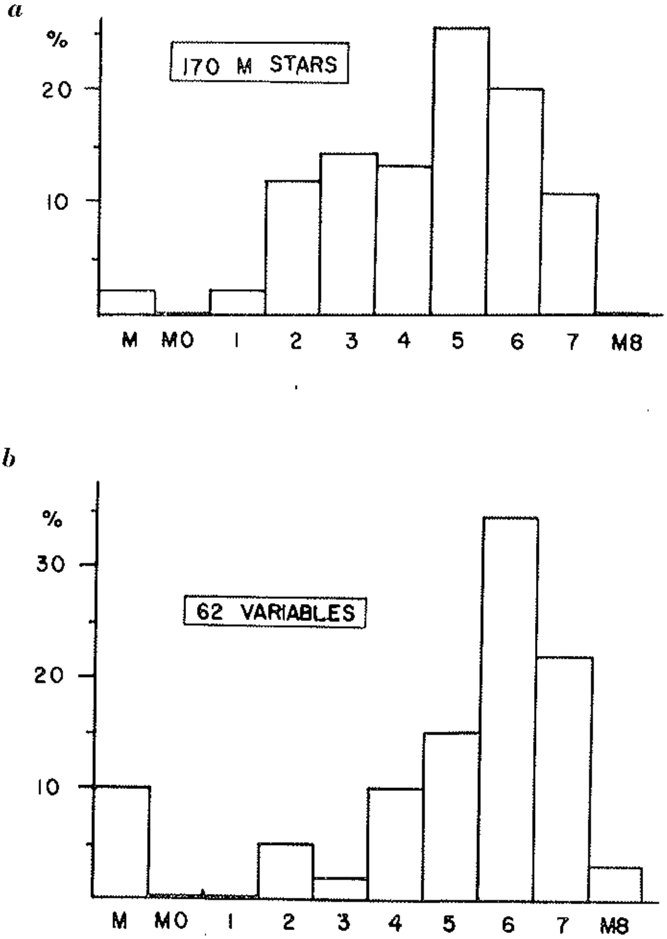

Fig. 1 — (a) Spectral distribution of 170 M stars within a region 11′.2 from the center of NGC 6522. (Red variables excluded). (b) Spectral distribution of 62 red variables within a region 15′.9 from the center of NGC 6522.

iables within 15′.9 for the center of the cluster is shown in Figure 1b. The latter distribution shows a greater number of late type stars in comparison with the distributions observed in four Milky Way regions similarly studied. In these regions the number of stars earlier than M5 were found to be far more numerous (see figure 4). Another dissimilarity in this region is the relatively few variables found among the late M stars. In other regions it is estimated that variables constitute about 50% of the stars at spectral class M5 and nearly 100% for M7 and later stars.

Apparent Magnitude Distribution of M Stars

The frequency distribution of the M stars as a function of the blue magnitude is given in Figure 2a. Here the red variables are excluded. A corresponding distribution for all the red variables within 15′.9 of the center of the cluster exclusive of the Mira variables is given in Figure 2b. The magnitude at maximum light for the variables as given by GAPOSCHKIN is used here. The two distributions show a sharp maximum at about 17.5 mag.

A similar distribution for the same stars was obtained from the observed infrared magnitudes; they are given in Figures 3a and 3b. The maximum for the distribution of the two curves occurs at about $m_i = 11.9$. Actually the maximum for the distribution of the variables should occur at about $m_i = 11.6$ if the distribution is to refer to the light maxima of the variables. This value was obtained from the mean range of the variables.

These results, together with the fact the spectral distribution of the red variables and non-variables are similar, seem to indicate that the two groups of red stars occupy nearly the same volume of space. This will be true provided: *a*) our spectral survey is complete to a magnitude limit such that the maximum of the distribution is reliably determined, *b*) our magnitudes have no serious error in zero point and scale relative to the magnitudes given by BAADE.

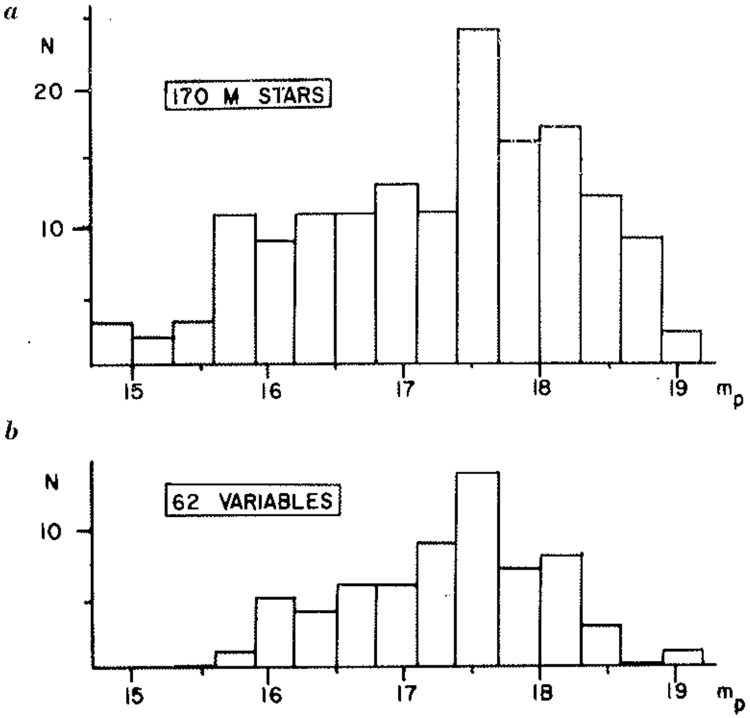

FIG. 2 — (a) Apparent photographic magnitude (m_p) distribution of the M stars within a region $11'.2$ from the center of NGC 6522. (Red variables excluded). (b) Apparent photographic magniture (m_p) distribution at maximum light of all red variables within a region $15'.9$ from the center of NGC 6522.

As stated previously great care was exercised to insure completeness. Spectra for stars brighter than 12.8 infrared magnitude can be detected readily. Separate magnitude distributions made from the data observed on the 15 minute and on the 27 minute plates showed the same maximum. Of the 36 red variables within 11′.2 of the center of the cluster four were undetected on account of faintness or overlapping. One of these was a Mira type.

Our magnitudes are uncertain. In the case of the blue only one plate was available. The infrared magnitudes were determined from two plates but the sequence, in spite of the great care taken in establishing it, was based on a photographic transfer from another part of the sky.

In view of the above and of the many and well known difficulties present in observing such a crowded stellar field, conclusions as given above must be considered most provisional.

Distribution of M-type Stars in the Milky Way

A study of the space distribution of M stars in four regions near the galactic equator, to a limiting infrared magnitude of about 12.5 has been carried out by a number of investigators (see references) at this observatory. These studies differ from our previous surveys in two respects, (1) stars as early as M2 were included and (2) the infrared magnitudes of all the stars classified were determined. The total infrared absorption to about 3 kpc for all the regions was found to be approximately equal to 1.0 magnitude. Similar investigations were carried out in three other regions at galactic latitudes greater than +6°. The present report compares some of the results obtained in these four regions with those obtained in the field around NGC 6522. In addition some tentative conclusions concerning the overall distribution of M stars are drawn.

The density analyses of this material still remain to be completed on a uniform basis, that is, for the same set of absolute magnitudes for the different spectral subgroups. At pres-

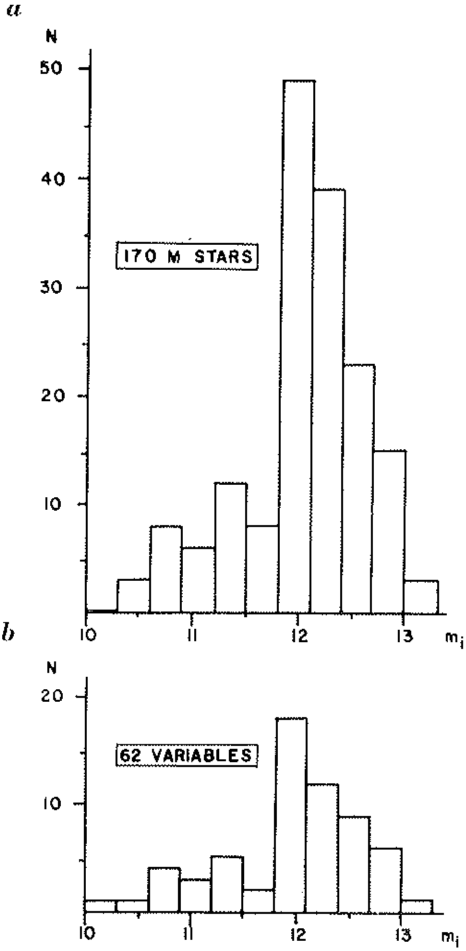

FIG. 3 — (a) Apparent infrared magnitude (m_i) distribution of the M stars within a region of 11′.2 from the center of NGC 6522. (Red variables excluded). (b) Apparent infrared magnitude (m_i) distribution of all red variables within 15′.9 from the center of NGC 6522.

ent our remarks are limited to the surface distribution of M stars as a function of spectral type. Figure 4 gives the distribution in spectral type, the longitude and the number of stars per square degree in each region. Similar data are given for Region 5 which is the field around NGC 6522. The marked increase in the number of stars as the galactic nucleus is approached is evident. The relatively large number of late M stars (M5 to M10) in the direction of the galactic nucleus, referred to previously, is also apparent. The percentage of early M stars in all four Milky Way fields averages 55 while in NGC 6522 it is 37.

Some Concluding Remarks on the Distribution of M Stars

From our studies of the distribution of M stars (M2-M10) the following tentative conclusions may be drawn:

1. Both early and late M stars form a disk distribution. The thickness of the disk decreases with increasing distance from the center of the galaxy.
2. The space density for both groups decreases with increasing distance from the center of the galaxy.
3. Near the galactic nucleus the late M stars (M5-M10) appear to be more numerous than the early types.
4. There are indications that the early type M stars show some concentration toward the spiral arms of the galaxy. Also there is some evidence of clustering.
5. The late type M stars show a more widespread dispersion than the early types. This was observed at longitude 33° and 42°.

The above seems to agree with a suggestion made by Deutsch [5], that is: The M stars are the dying members of population Type I and they have dispersed from the spiral arms.

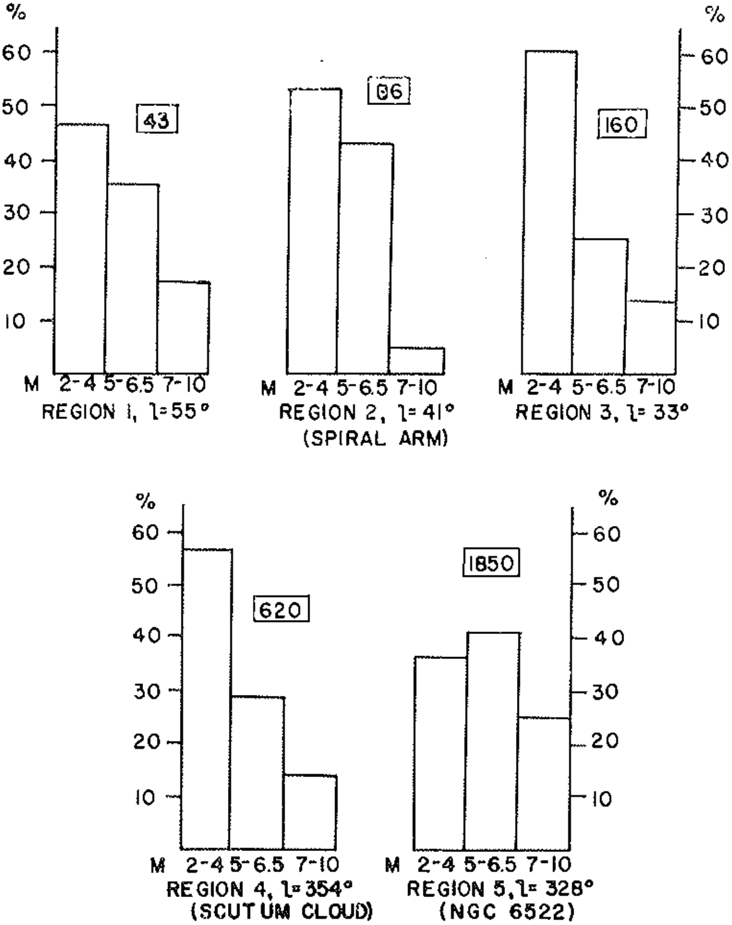

FIG. 4 — The spectral distribution of M-type stars in five Milky Way regions. The stars are divided in three spectral subgroups, M2 - M4, M5 - M6.5 and M7 - M10. The number of M stars per square degree is given in a box for each region.

REFERENCES

[1] W. BAADE, Symposium on Astrophysics, University of Michigan, 1953.

[2] S. GAPOSCHKIN, Variable Stars (U.S.S.R.), *10*, 337, 1956.

[3] J. J. NASSAU and G. B. VAN ALBADA, Ap. J., *109*, 391, 1949.

[4] D. M. CAMERON and J. J. NASSAU, Ap. J., *122*, 177, 1955.

[5] A. J. DEUTSCH, Ap. J., *123*, 210, 1956.

The Study of the Space Distribution of M Stars in the Four Regions near the Galactic Equator was undertaken by the following investigators:

Region 1, $l = 55°$; Father M. F. McCARTHY, S.J.
Region 2, $l = 41°$; J. J. NASSAU and A. G. VELGHE
Region 3, $l = 33°$; B. WESTERLUND
Region 4, $l = 354°$; H. ALBERS

DISCUSSION

Chairman: A. Blaauw

Baade

There seems to be a difference of about $0^{\rm m}.7$ between Nassau's results and mine for the same stars. Mine are brighter.

Nassau

To bring my results into agreement would mean assuming a modulus of $15^{\rm m}.5$ for the galactic nucleus.

Morgan

There may be a differential colour effect.

Sandage

How did Baade get his colour indices?

Baade

I used data from Arp's investigation.

CARBON AND S-TYPE STARS

Jason J. Nassau
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Introduction

This brief report summarizes our recent published results relating to the carbon and S-type stars together with our current activities in this field. Our surveys in the near infrared along the Northern Milky Way in a belt 12° wide from $l = 335°$ to 200° have been completed. In the case of the carbon stars detection was made by means of the CN-bands in the region between λ 6800 and λ 8800. However, when these bands are weak, that is, when the stars are early carbon stars, it is impossible to detect them. In this sense our surveys are incomplete. The S-type stars were detected by means of the LaO-bands. Here again the surveys are not complete because only a fraction of the S stars show the 7400Å and the 7900Å LaO-bands (Keenan [3]) with sufficient intensity for recognition. In nearly all of our lists an estimate of magnitude has been given to assist others in the identification of the carbon and S stars. The limiting infrared magnitude is about 10.2.

Carbon Stars

Our current activities with reference to the carbon stars are concentrated in six Milky Way regions. The limiting infrared magnitude of the stars studied is 12.5, with a number of fainter stars included. The observations of magnitude were based on photoelectrical established sequences of the magnitudes of bright stars in each field. The average interstellar absorption for each region to at least three kiloparsecs was obtained from colors of the early type supergiants and A-type main sequence stars. Provisional results indicate that the distribution of carbon stars in apparent magnitude show discontinuities which may be associated with local and distant spiral arms. This was observed at galactic longitude 66° by NASSAU and BLANCO [4] and more recently by McCARTHY [5] at longitude 55°. The 39 carbon stars found within an area of 20 square degrees at $l=55°$ indicate a grouping of stars between 7.5 and 8.0 infrared magnitude, a gap from 8.0 to 9.0 magnitude and a concentration of 12 carbon stars between 11.5 and 12 magnitude. The M-type stars in the same region do not show such a discontinuous magnitude distribution.

The surveys in the galactic belt include 693 carbon stars. Although some definite groupings are present, in general the overall surface distribution in longitude shows some uniformity, but it is influenced by interstellar absorption. However, there are more than a dozen small conspicuous groups of four and five stars, each group having a diameter of about 1° or less and a number of pairs with a separation of less than 0°.2. Similar grouping were found by BLANCO and MÜNCH [6] between $l=202°.5$ and $l=269°.0$.

In the general direction of the galactic nucleus the number of carbon stars is relatively small, even in regions where the surveys reached stars much fainter than $m_i=12.5$. For example, within an area of 50 square degrees in the Scutum Cloud only four carbon stars brighter than $m_i=13.0$ were detected (ALBERS [7]). Likewise the Sagittarius Cloud yielded only one carhon star in an area of eight square degrees (NASSAU and McCUSKEY [8]). The Tonantzintla infrared surveys in the Southern Milky Way showed the same trend. This was also confirmed by E.v.P. SMITH and H. J. SMITH [8] by means of a survey extending from $l = 180°$ to $360°$ in which they found the greatest concentration of carbon stars not far from the Carina aggregate.

The relative scarcity of carbon stars in the general direction of the galactic nucleus extends to galactic latitudes ±18° where our surveys were carried out in limited regions.

S-type Stars

The infrared surveys in the Northern Milky Way belt 12° wide yielded 68 new S-type stars. A number of fainter S stars were found in regions where the surveys were carried to fainter magnitudes. Although the material is limited, the distribution of the stars in longitude indicates that relatively few are present in the general direction of the anticenter of the galaxy and that they are likely to appear in groups. Such groups often include red supergiants (BLANCO and NASSAU [2]).

Carbon and S-type Stars in Relation to Interstellar Matter

The available charts of the National Geographic-Palomar Survey provide a way of examining the interrelation of carbon and S stars with interstellar clouds. The carbon stars do not show a tendency to appear in or near heavy obscurations, but they do favor semi-obscured regions. Although S stars appear in apparently clear regions, several of them were found imbedded in heavy obscurations or very close to them. Such cases were reported by BLANCO and NASSAU [2]. BLANCO and MÜNCH [6] found two S stars in the densest region of the nebula surrounding Eta Carina.

Carbon and S-type Stars in a Region Near P Cygni

A region of 37 square degrees near P Cygni was examined by NASSAU and VELGHE [10] for faint carbon and S-type stars. Two circular overlapping fields, one centered at $l = 43°$ and

$b=0°$ (Region A) and the other at $l=42°.5$ and $b=1°.9$ (Region B) were chosen. Region A is partly within the Great Rift. In all 38 carbon stars were found, two as faint as 13 infrared magnitude, the limiting magnitude of the survey, and 10 S stars. At approximately the same longitude and at $b=9°$ an area of 21 square degrees was examined yielding three carbon stars and no S stars. An equal area was also examined at $l=45°$ and $b=22°$ where no carbon or S stars were found.

The mosaic of the P Cygni region shown in Figure 1 was made from copies of the red prints of the National Geographic-Palomar Atlas. It shows that the distribution of the carbon stars follows approximately the boundaries of the bright nebulosities. In Region A, which contains the heavy obscuration, 22 carbon stars are present, eight of which are brighter than 8.5 magnitude and the rest are fainter than 10.8 magnitude. Region B does not show such a discontinuity in magnitude. All carbon stars are fainter than 9.7 magnitude.

Of the ten S stars present, eight are within 1°.2 from the galactic equator and close to the Great Rift. No obvious relationship is apparent in the surface distribution of the carbon and S-type stars.

Some of our spectra in the near infrared show abnormally high density near λ 8500 and in a number of cases very narrow bands somewhat like emission features. Their identification is difficult due to the short spectral dispersion available. It is possible that they might be due to Ca II or O I in emission. A number of such cases were also detected by Blanco and Münch [6] and by E. and H. Smith [9]. One of these stars was observed by Herbig, who found no emission. The star was tentatively classified by him as M dwarf.

In examining the P Cygni region ten stars with emission features were found. All but one are within the heavy obscuration and seven of them are grouped within a circle of 0°.7 in radius.

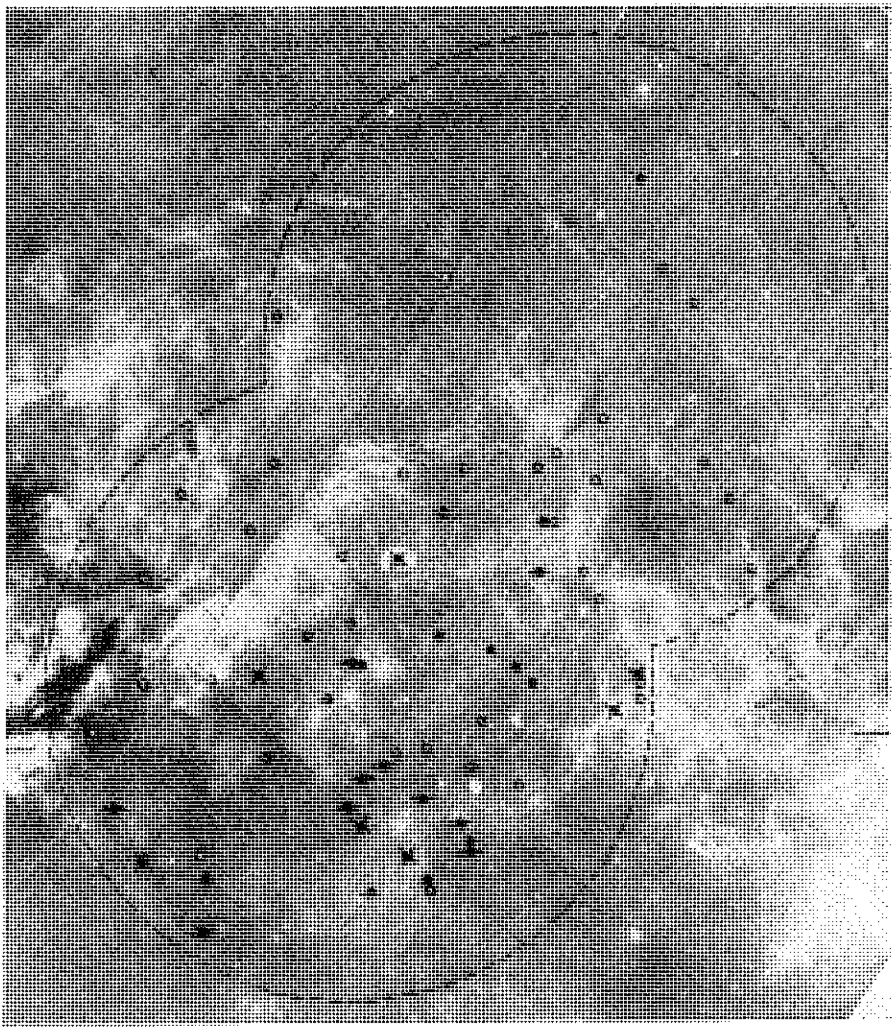

FIG. 1 — The Milky Way Near P. Cygni. - The two circles of radius 2°.6 show the boundaries of the survey. Region A (lower circle) has its center near the galactic equator. The center of Region B is at $b = 1°.9$. Designations: Carbon stars, circles; S stars, dots; stars with probable emission, dots with two bars and W-R stars, dots with four bars.

Carbon and S Stars in Relation to Other Types of Objects

A measure of the degree of concentration in latitude of different types of objects within the 12° latitude belt, may be expressed as follows: For the OB stars (Nassau and Morgan [11]), half are within a zone 5° wide. For the carbon stars (Nassau and Blanco [1]), the corresponding figure is 6°; for the S stars, 5° and for the reddened M stars (mostly red supergiants), 3° (Blanco and Nassau [2]). The corresponding figure for the planetary nebulae derived from the data given by Minkowski [12] is less than 4°. The spread in latitude for the late M-type stars (Nassau, Blanco and Cameron [13]) is definitely much greater than for any of the above groups.

The distribution in longitude of the same objects in the zone 12° wide from $l = 340°$ through zero to $l = 200°$ may be compared by giving their relative numbers within the range $l = 340°$ to $l = 80°$. For the planetary nebulae 83% are within these limits. For the S stars the percentage is 75, for the late M giants (M5 to M10) it is 71, for the F-type supergiants (Nassau and Morgan [14]), 62, and for the carbon stars 41.

The establishment of any spatial relationship or lack of it between the carbon and S-type stars and other objects in the galaxy is impossible with the available data. The limitations of the approach are obvious and need not be enumerated. However, some tentative conclusions may prove useful.

1. Carbon stars are found in spiral arms. Merrill [15] places the N-type stars in spiral arms.
2. Relatively fewer carbon stars are found in the general direction of the galactic nucleus than in other longitudes.
3. In the region of P Cygni the distribution of carbon stars follows approximately bright nebulosities.
4. S-type stars are found in spiral arms. This is supported by the work of Keenan [3].

5. There is some evidence that the surface distribution of early M supergiants and S stars are alike. No such inter-relationships seem to exist between carbon and S stars.
6. More S stars are found close to heavily obscured regions than would seem likely on the basis of chance.

REFERENCES

[1] J. J. NASSAU and V. M. BLANCO, Ap. J., *125*, 195, 1957.
[2] V. M. BLANCO and J. J. NASSAU, Ap. J., *125*, 408, 1957.
[3] P. C. KEENAN, Ap. J., *120*, 484, 1954.
[4] J. J. NASSAU and V. M. BLANCO, unpublished.
[5] M. F. MCCARTHY, unpublished.
[6] V. M. BLANCO and L. MÜNCH, Tonantzintla and Tacubaya Bull., *12*, 17, 1955.
[7] H. ALBERS, unpublished.
[8] J. J. NASSAU and S. W. MCCUSKEY, 1954, unpublished.
[9] E. v. P. SMITH and H. J. SMITH, A. J., *61*, 273, 1956.
[10] J. J. NASSAU and A. G. VELGHE, unpublished.
[11] J. J. NASSAU and W. W. MORGAN, Pub. Obs. University of Michigan, *10*, 43, 1951.
[12] R. MINKOWSKI, Pub. Obs. University of Michigan, *10*, 25, 1951.
[13] J. J. NASSAU, V. M. BLANCO and D. M. CAMERON, Ap. J., *124*, 522, 1956.
[14] J. J. NASSAU and W. W. MORGAN, Ap. J., *115*, 475, 1952.
[15] P. W. MERRILL, P.A.S.P., *67*, 199, 1955.

DISCUSSION

CHAIRMAN: A. BLAAUW

SCHWARZSCHILD

What is the absolute magnitude of Carbon and S stars?

NASSAU

The probable infra-red magnitude of the Carbon stars is about -4; the photovisual -2.5.

MORGAN

It is a difficult problem to tie in the S stars with the spiral arms. In a very nice paper (Ap. J., *120*, 484, 1954) KEENAN gives a plot of the distances of the S stars, showing spiral arms like those found from the O and B stars, but with only 500 pc between the arms, instead of 1500-2000 pc. The trouble apparently arises from the uncertainty in the luminosities of the S stars. The only one for which the luminosity has been determined is π^1 Gruis, with an estimated absolute magnitude (visual) of between 0 and -1.

HERBIG

There are a few composite C-type spectra, as well as some close doubles involving a G star. As I recall, the companions are never earlier than about A0. This indicates a photographic absolute magnitude of these C stars comparable with an A0 star. Selection effects may be important, however.

LINDBLAD

Among R stars there are two velocity dispersion groups.

BLAAUW

Some S stars follow the Gould belt. These must be within 500 parsecs and have absolute magnitudes around zero.

MORGAN

I agree; the Gould belt pattern fades out beyond 500 parsecs.

SCHWARZSCHILD

Do none of these stars occur in clusters?

NASSAU

There is one doubtful case, in NGC 7419, which SANDAGE can tell us about.

SANDAGE

The colour-magnitude diagram shows four early M supergiants, an M7, and a carbon star, forming a sequence, suggesting that the carbon state evolved from the M7 state. It is within the confines of the cluster as determined by the colour-magnitude diagram. If it is really a member, it has an absolute magnitude -5 and provides evolutionary evidence for giants.

SCHWARZSCHILD

What is the brightest star in the cluster?

SANDAGE

One classified by MORGAN as a B supergiant. There is no other galactic cluster with a late M giant. One expects that the absolute magnitude of the brightest main sequence stars are about $M_v = -6$.

HECKMANN

What about the M supergiants in h and χ Persei?

MORGAN

These are the early M stars, stopping sharply at M4. This is the well-defined M supergiant group which has the kinematical properties of the early O and B stars. When you get to the later M stars you get into an entirely different kinematical and luminosity group.

SANDAGE

The colour-magnitude diagram of NGC 7419 gives a gap, 1.6 magnitude wide in colour, so that it should be as bright as the *h* and χ Persei cluster.

OORT

Can't you tell if the carbon star is a member by its radial velocity?

SANDAGE

The photographic magnitude is about 18.5 which is very faint. Observations in the visual region could be made.

HERBIG

I should like to ask SANDAGE about his infra-red material on M 33.

SANDAGE

HUMASON and I blinked red and blue plates of M 33 and found red super giants in the arms along with blue stars. How could we tell if they were carbon stars?

HERBIG

The C and M stars should be separable on plates taken in spectral regions chosen to take advantage of the greater colour indices of the C stars, and the fact that the carbon bands fall in a different spectral region than do those of titanium oxide.

MORGAN

The colour index of some carbon stars is around 3.5 or 4.

SANDAGE

We found about 2000 red stars across M 33. The colour indices are still to be measured.

HERBIG

Are ZWICKY's composite photographs of M 51 to be explained by the concentration of red supergiants in the inner spiral arms?

MORGAN

I think the blue supergiants largely determine these composite pictures.

SCHWARZSCHILD

The data suggest that the C and S stars are a late evolutionary stage, not of very heavy stars, since they do not belong to OB associations; nor of light stars such as the ordinary K and M giants, because of the difference in galactic concentration; but perhaps of intermediate weight, stars originally of late B or early A type.

BLAAUW

They must be young enough to show their grouping characteristics.

MORGAN

They are not a kinematically homogeneous group. These differences ought to be looked at more carefully.

NASSAU

We missed the stars with weak CN bands.

SANDAGE

What is known at present concerning the C^{12} to C^{13} ratio in the carbon stars?

NASSAU

Our dispersion was only 3400 Å/mm! But McKELLAR is working in this field.

HOYLE

Is hydrogen present at the surface of C stars?

MORGAN

There is CH in R stars and in some carbon stars.

HERBIG

There is hydrogen emission in long-period carbon variables.

FOWLER

This is a very great difficulty, if there is carbon mixed very deep with hydrogen, because our most recent measurements would indicate that it all ought to be converted into nitrogen. The only way that one can understand a carbon star is that there is at most a very thin layer of hydrogen on the surface, but not so deep as to become hot enough to burn the carbon.

MORGAN

BIDELMAN has at least one strange star without a G band. This is one star at least whose atmosphere seems to contain no hydrogen

THE MAGELLANIC CLOUDS AND STELLAR POPULATIONS

A. D. Thackeray
Radcliffe Observatory, Pretoria

I need hardly indicate to this audience the vast opportunities offered by the two Magellanic Clouds for the study of Stellar Populations. At a distance which is smaller than that of the Andromeda group by a factor about 10, we can observe a bewildering variety of clusters and associations well resolved, individual stars down to absolute magnitudes of about +1 to +2 and complex regions of bright and dark nebulosity. Although both Clouds have been classified as Irregular in form, the Large Cloud in particular shows some features which have led to its comparison with barred spirals. Recent radio and optical work agree in assigning definite axes of rotation to the two Clouds.

The Large Cloud contains some very bright and extensive diffuse nebulae. Those in the Small Cloud are less prominent, but many are known from the work of Shapley, Henize and others. 21-cm work has shown that the mass of neutral H is as much as 2/3 that in the LMC.

The Large Cloud also contains some very prominent areas of absorption. The smoother structure of the Small Cloud and Shapley's claim to have observed extragalctic nebulae through it, have led to the belief that the Small Cloud is essentially free from dust. Generally speaking the Large Cloud was believed some years ago to be composed of pure Population I, while the supposed absence of dust in the Small Cloud, despite the presence of early type supergiants, led to a belief that the Small Cloud was more closely tending towards Population II. WESSELINK, at the Radcliffe Observatory, has very carefully examined photographs of various regions of the Small Cloud, and while some extragalactic nebulae have been found in the outer less crowded regions, no single case of an extragalactic nebula has been found in the crowded centre. Long exposures in both blue and red in excellent conditions were used for this work. For the centre of the Small Cloud, at least, we may say that the normal ratio of dust to gas is not excluded by the observations.

As regards individual objects which serve as indicators of Population types, we know that, while the most prominent objects in both Clouds are characteristic of Type I, examples of Type II have also been found. Three globular clusters in the Large and one in the Small Cloud are known to contain RR Lyrae type variables; one long-period variable with period 140 days is known in NGC 121 in the SMC; another with period 186 days in or near NGC 1978 in the LMC has almost certainly been established. The work of LINDSAY and KOELBLOED has proved the presence of planetaries in the SMC with a considerable spread in absolute magnitude. The globular clusters still require considerable work for their elucidation, but that some examples of red clusters similar to those in our Galaxy exist can scarcely be doubted. Work on Radcliffe plates of NGC 1866, the best example of a "blue globular cluster", is in progress by SANDAGE. Novae have been found in both Clouds. With all these various examples of Type II, we must regard both Clouds as mixtures of the two main Population types; but the Large Cloud in all probability contains an unusually high proportion of the most luminous examples of Type I.

What I chiefly want to speak about concerns the brightest stars in the Large Cloud. These stars are receiving considerable attention spectroscopically and photoeletrically at the Radcliffe Observatory. A great many blue stars, which must be members because of their high galactic latitude, are known from the Henry Draper Extension. We have found that spectra of stars classified as O, B or Con in the HDE Catalogue in the region of the Cloud show that such stars are almost without exception true Cloud members. This is entirely in accordance with expectations for a Type I system. But, as reported at Dublin in 1955, many of the brightest stars are not in fact O or early B stars, but A or late B types. We can now report the finding of 5 stars which are certainly among the 30 brightest members of the Large Cloud and which have spectral types between F8 and G5. Such stars, with visual absolute magnitudes about -9, we designate super-supergiants [1].

The HR diagram of the brightest stars in the LMC is shown in fig. 1, including the brightest Cepheids observed by FEAST [2] in both Clouds. The visual magnitudes depend on photoelectric measures by WESSELINK, except for the Cepheids for which GASCOIGNE's results have been used. Circles denote P Cyg or emission objects, crosses the Cepheids at maximum. The dashed curve shows the HR diagram of the brightest stars in the *h* and χ Persei cluster, omitting the M supergiants which fall outside the diagram on the right.

Note the group of red super-supergiants and the downward slopes of the plots from A to O types. This slope can be regarded as well established. As will appear later, corrections for absorption are small for these stars, and the measured apparent magnitudes must reflect quite closely the absolute magnitudes. The deficiency in spectral types between A2 and F8 must be regarded with some suspicion; it may easily result from selection effects.

The existence of the red super-supergiants raises the question of how many exist relative to the blue super-supergiants. The

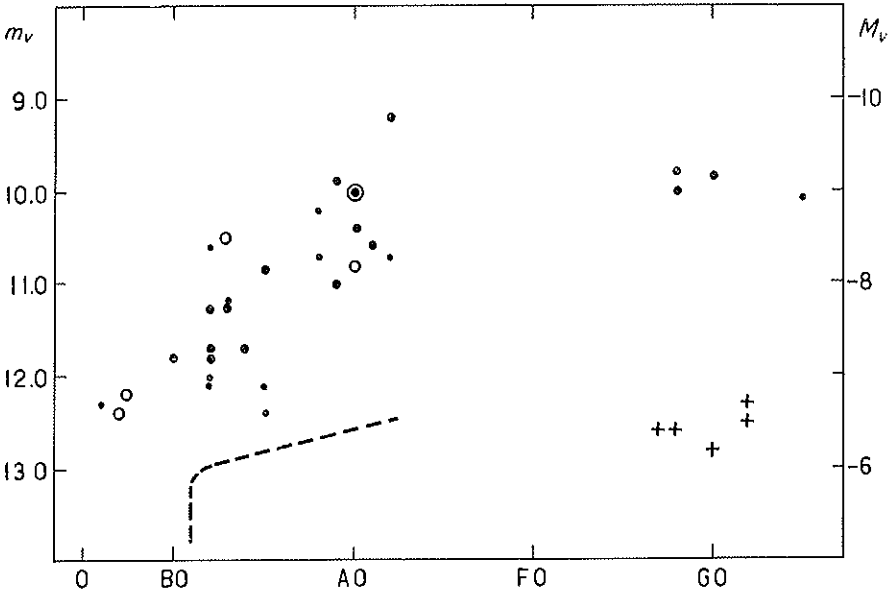

FIG. 1 — HR diagram of brightest stars in Large Magellanic Cloud.
o Emission-line Stars
+ Cepheids

census of the latter may be regarded as reasonably complete down to about $10^{m}.5$ in the HDE stars classified as B etc. However, the difficulty of distinguishing foreground stars is very serious for the red stars, and here the census is probably far from complete. All told we have investigated over 50 red stars down to 12^{m} for membership, and all but these five stars have proved to be foreground. A more economical approach — e.g. through slitless spectra — is urgently required.

Another and much simpler approach to the problem might be through a search for light-variations. If Radcliffe photoelectric magnitudes are compared with HDE magnitudes, the latter appear to be systematically too bright by a quarter-magnitude at 11^{m} with considerable scatter. For the red super-supergiants the scatter is much greater; and there are strong reasons for believing that 269953 has brightened and 271182 has faded since the Harvard observations. There is also evidence that a considerable number of bright blue stars, like S Dor, are varying slowly in light, but the phenomenon does appear to be rather more marked among the few super-supergiants. We would therefore recommend a search for variables in the Cloud region in the magnitude range 10 to 12; a moderately large scale would be of considerable value for the crowded regions. If these super-supergiants are in fact variable, they are either irregular or their periods are very long.

Four of the five red stars known lie within regions of bright nebulosity. The fifth, 271182, lies just outside a region of faint nebulosity discovered by HENIZE.

SHAPLEY has already indicated from star-counts that the Large Cloud must contain red supergiants with absolute magnitudes about −6. Two-colour photographs at the Radcliffe Observatory have shown many apparent members of Cloud clusters or associations to be red, with magnitudes about 13 to 14. For instance, NGC 2004 shows some striking examples; of these stars a spectrum of only one has so far been obtained and this proved to be Eta Carinae type! A promising case in another cluster proved to be foreground.

Colours. — Colours have been measured by WESSELINK for four of the known red super-supergiants. These are shown with some blue stars, compared with the Main Sequence in the Galaxy, in fig. 2.

Not much is known about the intrinsic colours of supergiants in the Galaxy, but it is usually assumed that there is no difference in colour among early types between supergiants and the main sequence. If this is true, then the diagram shows that for the blue stars the colour excess is of the order of $0^{m}.3$ and sometimes considerably less. Of this $0^{m}.1$ can be attributed to reddening within the galactic foreground. Thus we do not derive more than about $0^{m}.2$ reddening, corresponding to $0^{m}.6$ absorption, for these early type super-supergiants in the Clouds. Note

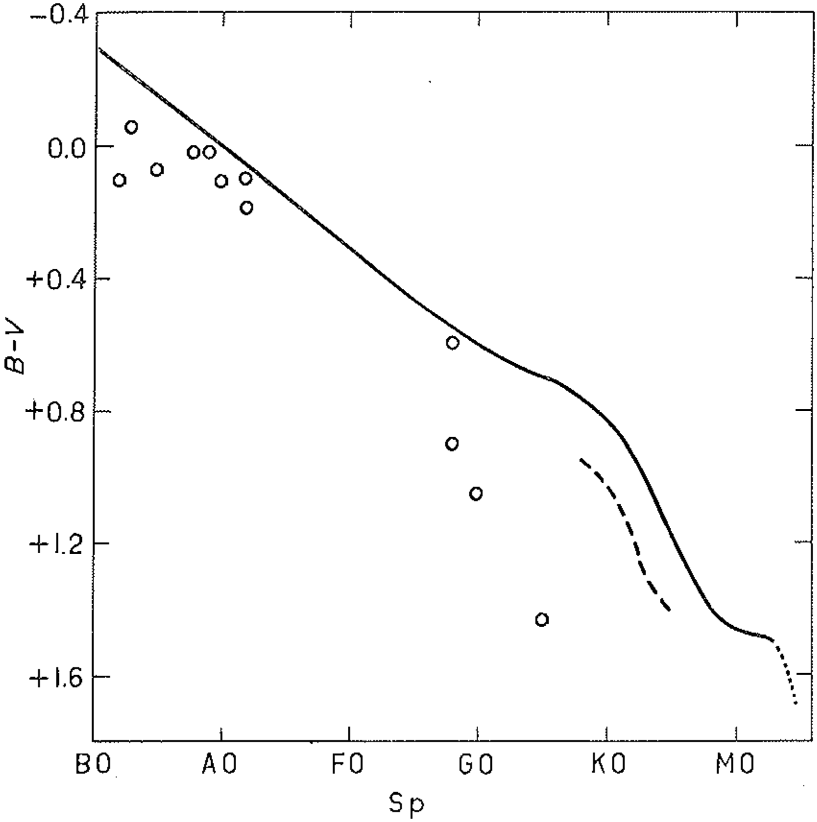

FIG. 2 — Colour-Spectrum for LMC Stars compared with galactic Class V and III.

o	LMC	
———	Main Sequence	(Galaxy)
- - - -	Class III	(Galaxy)

that in selecting the apparently brightest stars we are naturally selecting stars with small absorption.

It will be seen that the colours of the red super-supergiants change from +0.6 to +1.4 while the spectrum only changes from F8 to G5. A similar sensitivity of colour to change in type has been found for the Cepheids [2]. The redness of the

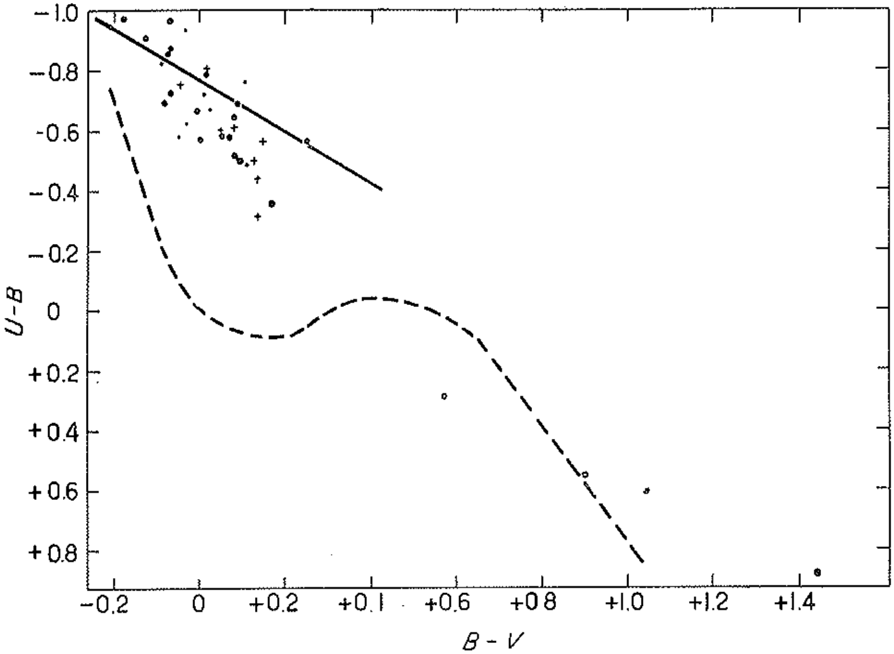

Fig. 3 — *U-B*, *B-V* plot for bright stars in LMC (•) and SMC (+).

Go to G5 super-supergiants is in accordance with extrapolation of the sequence dwarfs - giants; as is well known late-type dwarfs are bluer than giants of the same spectral type, because a higher temperature is required to balance the lower pressure of giant atmospheres in the ionisation equilibrium. For instance, the reddest star, 268757, with colour + 1.4 has an atmospheric pressure far two low for the formation of Ti O molecules. The radius of this star is calculated to be of the order of 2000 solar radii — much the same as VV Cephei.

Finally, we show in fig. 3 a plot of *U-B* and *B-V* colours. Note that the two scales are somewhat different — due to the transformation of the Radcliffe colours into the Johnson-Morgan system. This plot includes some SMC stars as well as LMC stars. While it should be stressed that many of the colours are highly provisional, the most interesting point of the diagram is the suggestion that the red super-supergiants lie on a single smooth curve with the blue stars and that there is *no hydrogen dip*. This is not altogether surprising for such high-luminosity stars. One knows that the spectra among the early type stars show extraordinarily narrow lines — hydrogen included. We must expect the excitation temperatures to be abnormally low and consequently an abnormally high proportion of the atoms to be in the ground state. The opacity is low and the Balmer discontinuity negligible. As is well known, it is the Balmer discontinuity which is responsible for the hydrogen dip in the U-B, B-V plot.

To sum up, both Clouds must be regarded as mixtures of Stellar Population Types. This communication has dealt mainly with the brightest stars in the Large Cloud which seem to exemplify characteristics of extreme Type I population. The HR diagram of these brightest stars shows that O types are not found much brighter than −7 in absolute magnitude; towards the later types there is an increase in the absolute magnitudes of the brightest stars which seem to reach a maximum between −9 and −10 at A0; this maximum seems to be maintained through type F to G in at least five cases, and other cases may still be found. The general shape of the curve seems to parallel nicely the colour-magnitude arrays of young galactic clusters and is thus consistent with the evolutionary tracks of extremely massive stars suggested by current theories.

It will be clear that much of the results described above, like those in my other contribution to this Semaine d'Étude, depend upon the work of my colleagues Drs. FEAST and WESSELINK at the Radcliffe Observatory.

REFERENCES

[1] M. W. FEAST and A. D. THACKERAY, M. N., *116*, 587, 1957.
[2] M. W. FEAST, M. N., *116*, 583, 1957.

DISCUSSION

CHAIRMAN: A. BLAAUW

MORGAN

We must congratulate THACKERAY on providing at last much needed precise data relating to the luminosity function of high luminosity stars. It is interesting to know how bright stars can really be. The stars he has observed seem to be like φ Cas and δ CMa, and possibly ε Aur, so that the luminosity function may be like that of our own Galaxy, where calibration is so difficult, and we can speak with more confidence about absolute magnitudes as bright as -8 or -8.5.

THACKERAY

I should like to stress that this is the work of the Radcliffe team of astronomers. The situation calls for more southern astronomers and telescopes. Is ρ Cas another possible example of a late type super-supergiant?

MORGAN

Yes, but it is a very peculiar star.

SCHWARZSCHILD

The HR diagram showed a fairly sharp upper boundary indicating a reasonably well defined mass limit.

MORGAN

O stars are probably preferentially obscured because they occur near dust clouds, so that there may be a systematic effect of heavy absorption.

BAADE

Have you a value for the difference in the upper limit of brightness between the Large and Small clouds?

THACKERAY

We are handicapped in this by the lack of a finding list for the small cloud.

O'CONNELL

What was the type of the variation in the red stars which you mentioned?

THACKERAY

We found differences between our magnitudes and those of Harvard's of up to one magnitude, suggesting variation over long intervals.

V.

L'EVOLUTION STELLAIRE ET L'ABONDANCE DES ELEMENTS

THEORY OF STELLAR EVOLUTION AND THE AGE SEQUENCE OF STELLAR POPULATIONS

MARTIN SCHWARZSCHILD
Princeton University Observatory

Present Status of Theory of Stellar Evolution

The problem of stellar evolution in its simplest form can be stated as follows. Given a star, i. e. its mass and initial chemical composition, derive the sequence of stellar models which represent the star in its successive evolution phases. This problem has been solved with various degrees of accuracy for a number of stellar masses and initial compositions, largely however only for the earlier evolution phases. In no case this far has the evolution of a star been followed theoretically all the way from the initial main-sequence stage to the final white dwarf state. The great incompleteness of the present theoretical results is caused partly by the amount of numerical work required, which is not small even when large electronic computers are available, and partly by the circumstance that in the most advanced evolutionary phases new physical phenomena such as mass ejection from the surface appear to occur, the causes of which are not yet properly understood.

The results derived from the evolutionary model sequences now available may be summarized as follows. In a star's life the first phase, recently studied in detail by HENYEY and his collaborators, consists of a contraction from the protostar stage.

During this contraction phase the main energy source of the star is provided by gravitational energy release. It appears not implausible that during this phase mass ejection, possibly caused by rotational instability, may play an essential role and may explain the spectroscopic phenomenon of the T Tauri stars. The contraction phase is terminated when the central temperature has become sufficiently high for hydrogen burning to start. The star then settles into the initial main-sequence phase in which the main energy source is nuclear, no longer gravitational, but in which the nuclear processes have not had time to cause any substantial inhomogeneities in the chemical composition. After this initial main-sequence state the star goes through a long evolution phase in which it gradually burns up the hydrogen in its core. This phase lasts for most stars probably a large portion of their entire active life and we should therefore expect to find the majority of the observed stars in this phase.

The evolutionary developments which follow after the hydrogen in the core is exhausted appear to be very different for heavy stars and light stars. After hydrogen exhaustion in the core one should expect an isothermal helium core to form, while hydrogen burning continues further out in a shell surrounding the helium core. But in the heavy stars (say heavier than two solar masses) the isothermal helium cores will be non-degenerate, and SCHÖNBERG and CHANDRASEKHAR have shown that such non-degenerate isothermal cores — except if they contain an extremely small fraction of the stellar mass — will not be able to carry the weight of the outer hydrogen layers. Accordingly in the heavy stars the helium cores must immediately contract and this contraction must continue until the central temperature becomes high enough for helium burning to commence. A star will then enter an evolutionary phase (not yet computed through in detail) with two energy sources, helium burning in the core and hydrogen burning further out in a shell. As SALPETER will show from a statistical discussion, this phase appears not to last long. It might be terminated by a profound mass ejection from the stellar surface as suggested by DEUTSCH from spectroscopic observations.

On the other hand, when the hydrogen is exhausted in the core of a light star (say lighter than 1.5 solar masses) the helium core which forms will be degenerate and such degenerate cores, after some minor contractional adjustments, are found entirely capable of carrying the weight of the overlying hydrogen layers. In a light star therefore the core-burning phases are followed by an extended sequence of shell-burning phases in which the hydrogen burns in a shell surrounding the isothermal degenerate helium core. Eventually, however, even in light stars the core is forced to contract sufficiently fast to cause the central temperature to rise enough for helium burning to begin.

For neither the heavy nor the light stars have the most advanced evolution phases which follow the onset of helium burning in the center been computed through with any consistency. Indeed, present understanding of these most advanced phases of stellar evolution is still so poor that one cannot even say whether the evolution of stars through the horizontal branch, which is observed in the Hertzsprung-Russell diagram of globular clusters and which probably represents these most advanced evolution phases for light stars, takes place from the right to the left or from the left to the right. But in spite of this great hole in the present understanding of stellar evolution it appears fairly probable that the majority of all stars finally reach the white dwarf state in which gravity is permanently counterbalanced by the degenerate pressure of the electrons while the steadily dimming luminosity is fed by the residual thermal energy of the non-degenerate nuclei.

Identification of Observed Star Types with Evolution Phases

Those evolutionary phases for which detailed models have been derived can be identified with fair certainty with observed star types by comparing the luminosities and radii of the theoretical models with those of the observed stars, i. e. by plotting both in the Hertzsprung-Russell diagram. To start with, only an extremely small fraction of all the observed stars (except possibly of the very faintest stars) should be found in the pre-main sequence contraction phase since any one star spends only a very small fraction of its whole life in this phase. In spite of their rarity, however, stars in this phase have been recently identified with the faint red stars in the color-magnitude diagrams determined by WALKER for very young clusters.

Next, the initial main-sequence state in which nuclear burning just starts is not easily isolated from the immediately following phases with hydrogen depletion in the core (since these phases differ only little in luminosity and radius) as long as all the stars in the solar neighborhood are considered. But it has recently been isolated with fine accuracy by JOHNSON and SANDAGE who have used for this purpose nearby well observed galactic clusters. The initial main sequence thus derived from observation is at present probably the most accurate item with which the theory of stellar structure can he checked. Recent models for the initial main-sequence state derived by KUSHWAHA give luminosities and radii in satisfactory agreement with the observed ones.

Models for the subsequent long-lasting phases in which the core hydrogen is more and more depleted give a small but steady increase in luminosity and radius and can be identified with the main-sequence band in which the majority of the stars in the solar neighborhood are observed to lie. For the still later phases when hydrogen is exhausted in the core, all models with helium cores — be they non-degenerate for the heavy stars or degenerate for the light stars — turn out to have extended envelopes with larger radii corresponding clearly to the subgiants and red giants of the solar neighborhood as well as to the bright red giants in globular clusters.

The most advanced evolution phases cannot yet be identified with any certainty with observed star types, since definite models have as yet not been computed for them. It appears likely, however, that among the stars in these late phases are to be counted all pulsating variables, the carbon and S stars, the central stars of planetary nebulae, the novae and even the supernovae. The theoretical interpretation of these rare but important types of stars, presumably all nearing the end of their active lives, appears at present one of the most fascinating unsolved problems of the investigation of stellar evolution.

One more populous type of observed stars needs identification, the subdwarfs. Theoretical considerations make it appear likely that the observed subdwarfs consist of a mixture of two completely separate evolution phases, modified dwarfs and incipient white dwarfs. By modified dwarfs are meant stars in their early main-sequence phases which have hardly started evolving and differ from ordinary main-sequence stars only by having a very low abundance of the heavier elements in their initial composition. By incipient white dwarfs are meant stars which have run through most of their evolution and are approaching the final white dwarf state. It appears plausible that the majority of the high-velocity subdwarfs which lie not more than a magnitude below the main sequence are modified dwarfs, while those high-velocity subdwarfs which lie further away from the main sequence, as well as the suspected subdwarfs in galactic clusters, are incipient white dwarfs. A spectroscopic division of the subdwarfs into these two separate evolutionary types would be of great value to theoretical investigations.

Interpretation of Stellar Populations as Age Sequence

From the theoretical point of view one may expect that all the stars we now observe differ from one another in three basic characteristics, their mass, their initial composition, and their age. If one then classifies all these stars into stellar populations, which of the three basic characteristics is the one in which the stars of one population differ from those of another? It has

TABLE I. - *Age Sequence of Stellar Populations*

Population	*Typical Members*	*Age* (10^9 *yrs*)	*Heavy Elements* Z	*Velocity Dispersion* (*km/sec*)	*Subsystem*
Young Pop. I	young galactic clusters	0 – 1	0.04	10	flat
Intermed. Pop. I . .	"strong-line" stars	1 – 3	0.03	20	intermed.
Old Pop. I	"weak-line" stars	3 – 5.5	0.02	30	
Mild Pop. II	Oort's "high-velocity stars"	5.5 – 6	0.01	50	
Extreme Pop. II . .	globular clusters	6 – 6 5	0.003	130	spherical

long been apparent that it is the age which is the main differentiating characteristic. This interpretation was suggested right away by the eminent occurence of very bright main-sequence stars, which must be very young, in the extreme Population I and their complete absence in the extreme Population II.

However, in addition spectroscopic investigations have shown that the stellar populations differ systematically also in their initial composition. This observation suggests that there exists a close correlation between age and initial composition and thus leads to the assumption that all stars born at one time are born with the same initial composition, an assumption which may not be rigorously true but may be a useful first approximation. This assumption implies that the interstellar medium from which the stars are formed has had a uniform composition throughout the galaxy at any one time, but has changed its composition continuously, presumably in consequence of mass ejection from dying stars.

If one then assumes that age — and correlated with it initial composition — is the basic characteristic which differentiates stellar populations, one should expect to find a continuous sequence of stellar populations. The classification of all stars into a small number of separate populations appears then an artificial but highly useful tool until improved observational techniques permit the classification of stars into a more continuous age sequence.

In Table I it is attempted to summarize the relevant data in terms of five subdivisions of the population sequence. The data regarding the initial composition and the kinematic characteristics of these subdivisions are not the topic of this paper; it is the data regarding the ages of the stellar populations to which the theory of stellar evolution can make a substantial contribution.

It is not yet possible to determine the age of an individual star with the help of the theory of stellar evolution with any certainty. It is possible, however, to determine the age of the stars in a cluster with the help of the model sequences now available representing the early evolutionary phases, if the turnoff from the initial main sequence is observed in the Hertzsprung-Russell diagram of the cluster. By this method the majority of the galactic clusters (excluding such rare cases as M 67), which are representative of the youngest population subdivision of Table 1, are found to be younger than one billion years old. In contrast the globular clusters, which are representative for the oldest subdivision in Table 1, are found to have ages of the order of six billion years.

Between these two extreme age groups determined with the help of the theory of stellar evolution one more datum may be gained by considering the sun. Its age is estimated to be approximately 4.5 billion years, on the basis of geophysical evidence. By indirect spectroscopic observations, VYSSOTSKY and SKUMANICH have classified the sun as belonging to the weak-line stars which are representative of the old Population I subdivision. Thus the sun gives us a hint how to divide among the intermediate population subdivisions the large gap of time left open between the majority of the galactic clusters and the globular clusters.

However uncertain the data given in Table 1 for the ages of the various population subdivisions may be, they should give us a first approximation to the run of ages from the youngest to the oldest stellar population, i.e. to the run of that characteristic of a star which appears to be basic to the observed phenomenon of stellar populations.

DISCUSSION

CHAIRMAN: L. SPITZER

HOYLE

Is the non-degeneracy of the core in stars of large mass a consequence of CHANDRASEKHAR's limit for white dwarfs?

SCHWARZSCHILD

The two phenomena may well be connected. In the construction of the models, however, the connection is not directly apparent.

BAADE

Where in the table would you put M 67?

SCHWARZSCHILD

I should put it towards the bottom of the fairly weak-line stars.

SANDAGE

This would follow from theoretical reasons, but the observations do not show any abnormal blanketing effect in M 67. The $B-V$, $U-B$ plot for M 67 resembles that for strong-line stars. There is no ultraviolet excess.

BAADE

How much weight did you give to the velocity dispersion in arranging the table?

SCHWARZSCHILD

It controlled the order of the five classes, but not the assessment of age.

BAADE

The paper refers only to stars like those in the neighbourhood of the sun. The situation may be quite different in E galaxies. Star formation may there occur all at once, so that Z is not the same function of the time, in fact may be almost independent of the time.

HERBIG

How binding is CHANDRASEKHAR's limit on the masses of stars in the lower left portion of the H-R diagram?

SCHWARZSCHILD

White dwarfs have to obey it very strictly. The limiting mass for white dwarfs is in fact probably below 1.4 solar masses, say 1.2 solar masses, owing to the disappearance of electrons into nuclei at very high densities, as discussed by SCHATZMAN, and owing to an improvement of the equation of state within a white dwarf derived by RUDKJÖBING.

STRÖMGREN

Can you comment on differences in the pattern of evolution of massive and light stars in the early phase after they leave the main sequence? One might expect a difference connected with the existence of mixed convective cores in massive stars and continuous variations of molecular weight in the central regions in lighter ones.

SCHWARZSCHILD

Some work has been done on this by KUSHWAHA for stars of higher mass and by HOYLE for those of lower mass. The differences are of the type you mention. They cause substantial differences in the slope at which the stars leave the main sequence for stars of different masses.

LINDBLAD

Your table suggested that you might have a physical picture of the dependence of the initial composition on age.

SCHWARZSCHILD

The general picture is one in which the percentage of heavy elements in the interstellar gas is steadily increasing by their ejection from massive dying stars.

SPITZER

We could also include in SCHWARSCHILD's table the components of cosmic rays. These have a Z value of 0.1 and support the idea that explosions of stars, observed as supernovae, produce a higher metal content in successive generations.

OORT

What was your precise definition of Z?

SCHWARZSCHILD

It was the fraction of mass in elements other than H and He.

OORT

You asked about the spectral classification of subdwarfs. JOY's list of subdwarfs found spectroscopically were all high-velocity extreme population II objects.

HERBIG

JOY's observing list was based on stars discovered on the basis of their high proper motion, which operates selectively against the inclusion of low-velocity subdwarfs.

SCHWARZSCHILD

I was hoping for a separation of relatively unevolved subdwarfs and those approaching the white dwarf stage.

STRÖMGREN

Miss ROMAN at McDonald took spectra of a few subdwarfs in galactic clusters which do not have the ultraviolet excess characteristic of the extreme population II subdwarfs and could not distinguish them from main-sequence F stars. How sure are we that such stars are actually on their way evolving into the white dwarf stage? They would have to reach a temporary stopping place to appear in a well-defined sequence as they seem to do.

SCHWARZSCHILD

They may well be at a stage where they can stop and burn up their last percent or two of hydrogen.

BAADE

Are the subdwarfs in the Hyades confirmed by radial velocity measurements?

STRÖMGREN

Among these were the stars found by Miss ROMAN to have main-sequence spectra. The spectra were taken for classification and were not suited to check radial velocities.

CHALONGE

It seems perfectly clear from Miss DIVAN's results that the two kinds of subdwarfs (the ordinary subdwarfs and the subdwarf members of the Hyades) have different spectrophotometric characters.

SCHWARZSCHILD

But it is still not settled whether there are two evolutionary phases in subdwarfs of population II.

SPITZER

You mentioned the scatter in the main sequence. I thought this was very small.

SANDAGE

For the stars within 15 parsecs of the sun it is about one magnitude. This scatter appears to be real. There is a correlation between the absolute magnitude of a given star and the ultraviolet excess.

SCHWARZSCHILD

KUIPER found some stars differing by four magnitudes.

SANDAGE

But is this very large scatter real? The spectroscopists in the early days appear to have classified some subdwarfs too early in the spectral class, i.e. the weak lines were confused with a temperature effect. Correcting this classification so as to reproduce a temperature sequence greatly reduces the magnitude difference between the subdwarfs and the normal main sequence.

FOWLER

I was a little surprised to see that you obtained such a good correlation without reference to the helium content.

SCHWARZSCHILD

Unless it were greater than 0.3 it would not make much difference. In fact, I do not know how it could be detected, except in the bright B stars, where it appears in the spectrum.

FOWLER

Then you would have no objection to some helium content?

SCHWARZSCHILD

Not at all.

STRÖMGREN

We may be forced to consider the helium variation pretty soon. The position of the main sequence of different globular clusters may vary. This cannot be explained in terms of differences in Z, and the explanation may be the helium content. In the sun, even a moderate variation of the helium content would produce a shift of this kind. When the data are more secure we shall have more information about helium content. Again, subdwarfs one or two magnitudes below the main sequence with normal spectra, such as those observed by Miss ROMAN, cannot be explained by their low Z value. If the state is stable it may be explained by a high helium content.

HOYLE

Besides the difference in the main sequence, there is a difference in the middle of the rising sequence of different globular clusters, which could hardly be due to the metals.

SPITZER

In principle, it should be possible to compare the helium content in the sun with that of very young stars.

SCHWARZSCHILD

The helium content of very young stars determined spectroscopically appears still rather uncertain.

OORT

What is the situation with regard to the helium content of the interstellar medium as compared to that in the sun?

STRÖMGREN

HUGH M. JOHNSON found helium in an H II region approximately in the solar ratio. This is just a very rough estimate, inaccurate perhaps by a factor of two or three and should be done for a number of H II regions if possible, but the interstellar helium emission lines are very faint.

OORT

Would observations of planetary nebulae be of any use?

SPITZER

This might give a clue to the helium content of very old stars.

STRÖMGREN

Some very interesting and rather accurate work on the helium content of planetary nebulae has recently been carried out by MATHIS.

SCHWARZSCHILD

If the shells of planetaries show high helium content HOYLE will say that it was produced inside the star and came out by mixing, because these stars are in a late stage of their evolution.

REMARKS ON THE COMPUTATION OF EVOLUTIONARY TRACKS

F. Hoyle
St. John's College, Cambridge
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This communication will be very short, because the computing program with which it is concerned fell about two months behind schedule. The program consists in setting up the problem of stellar evolution for an automatic digital computer in such a way that, given the starting composition and the mass of a star, the machine proceeds to work out the evolution with time without any human intervention being necessary.

It was recognized when the program for this conference was being drawn up that to get everything working in a satisfactory way, and to make computations to an advanced stage in the evolution of Type II stars, would be a race against time. In the event the race was lost, I am sorry to report. The satisfactory working of the machine in any complete sense was only achieved about a fortnight ago; and this left much too little time for any extensive calculations to be made. In the short time at my disposal I decided to examine the early phases in the evolution of stars with masses in the range 1 $\mathfrak{M}_\odot$ to 1.4 $\mathfrak{M}_\odot$. This was done using the best present day rate for the C-N cycle. The reasons for this choice were twofold — that some results could be obtained in the time available, and that a determination of the early phases (on the H-R diagram) is crucial to the

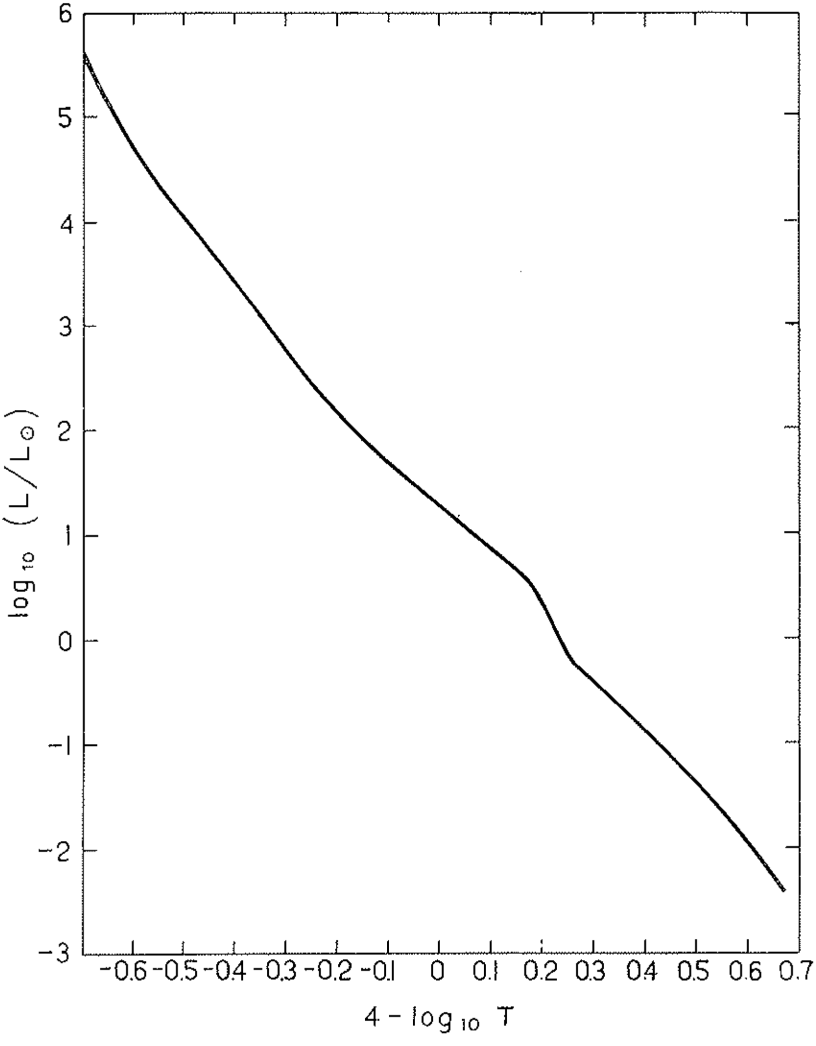

FIG. 1 — Calculated change in bolometric luminosity L (in terms of solar luminosity with effective temperature T, for main sequence stars of Type I ($Z \sim 0.02$). The mass of a star at the low luminosity end of the curve is about $1/5\,\mathfrak{M}_\odot$

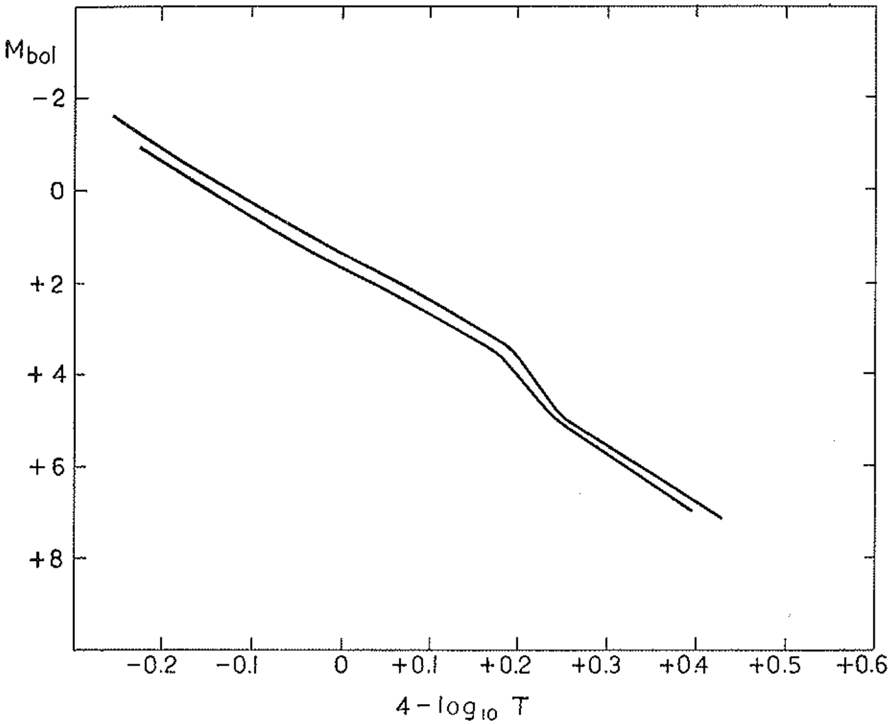

FIG. 2 — Calculated change in absolute bolometric magnitude M_{bol} with effective temperature T for two main sequences: Type I (composition of solar type) above; Type II (metal content and helium content reduced by a factor of 15) below.

estimation of the ages of Type II stars (as SANDAGE has explained in an early paper).

The Type II sequence was followed to approximately the second turning point, the calculations occupying a time of approximately 4 hours on the IBM 704. The calculated points agree well with the observed sequence, and do not show the rapid oscillation on the H-R diagram, as previously reported by HASELGROVE and HOYLE. This difference is almost certainly due to the decreased importance of the C-N cycle in the current calculations.

A rather disturbing feature of the new work is that the evolutionary track does not move immediately away from the main sequence. The track initially moves up the main sequence over a range of approximately 1.5 magnitudes before the "turn-off" point is reached. Most of the lifetime of the star is taken up by this early main sequence phase. This is awkward in the sense that the "turn-off" point no longer seems to give a good indication of age — so much time being spent below the "turn-off" point. This result, it must be emphasized, is very preliminary, and requires confirmation. The effect would be to revise age estimates in an upward direction — by how much it is still too early to say. It may be added that the new calculations treat the development of a burnt-out core in more detail than has been done before — or so I believe. The new result depends on this increased detail.

A similar calculation was performed for the Sun. It turns out that the Sun is following an evolutionary track similar to that just described. It is still moving upwards more or less parallel to the main sequence. After a rise of almost 2 magnitudes, from an initial M_{pv} near $+5{\cdot}0$ it will turn away from the main sequence and move rapidly to the right in the H-R diagram. The results justify a somewhat more detailed representation than is given by the H-R diagram. Thus in Figure 3 the behaviour of the solar luminosity L and radius R are plotted as a function of time. $L_\odot$ and $R_\odot$ refer to present day values. According to the figure the age of the Sun is a little greater than $1{\cdot}5 \times 10^{17}$ sec, i.e. about 5×10^9 years, in excellent agreement with current estimates of the age of the solar system. The figure shows that the Sun was initially about $0^m_.5$ fainter than at present, in agreement with the recent estimate of SCHWARZSCHILD, HOWARD, and HÄRM. The future of the Sun is also clearly shown by the figure. Although the matter falls a little outside the terms of reference of the present conference, the future span available to life on the Earth can be seen to lie in

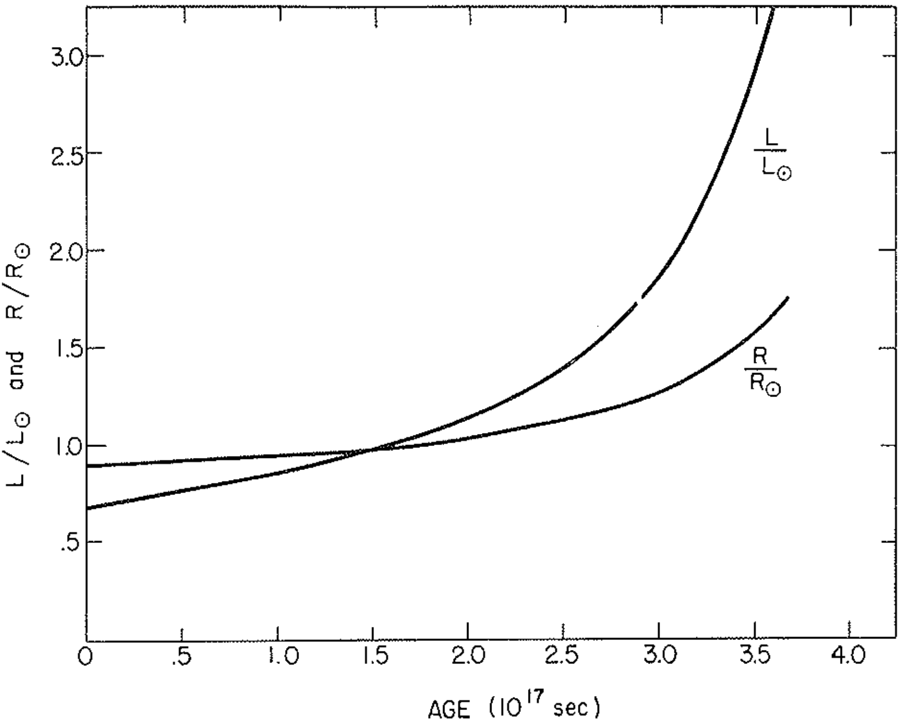

FIG. 3 — Behaviour of the luminosity, L, and radius, R, of the Sun as a function of time. $L_\odot$ and $R_\odot$ refer to present day values.

the region of 2-3 billion years – after a further 5 billion years the oceans will boil and no life will surely persist then.

I would just add that the results shown in Figure 3 were computed in a series of about 30 time steps, occupying the machine for about 2½ hours. The computations were entirely automatic. That is to say, once the machine was started up, there was no further human intervention.

DISCUSSION

CHAIRMAN: L. SPITZER

SALPETER

You said that the stars you calculated increased in luminosity by 1½ magnitudes before turning off the main sequence. Does this tally with KUSHWAHA's results?

HOYLE

His stars were more massive.

SALPETER

KUSHWAHA found that the increase became bigger at higher masses.

SCHWARZSCHILD

I would expect a smooth increase above 2.5 solar masses, but not in the interval 1 to 2.5.

SPITZER

What is the physical reason why a star remains initially on the main sequence for so long an interval?

HOYLE

A star stays near the main sequence if it is of uniform composition and in this respect the proton-proton reaction is much more uniform than the C-N cycle. I can't say anything about stars of high mass as I have not made any computations for them.

STRÖMGREN

Could you comment on the role of the convective zone? Does it play a different part in type I and type II stars?

HOYLE

It makes little difference so long as H supplies the free electrons. Even when the surface temperature falls sufficiently for the metals to provide the free electrons, a small change in surface temperature would have the same effect as a change in the contribution of the metals.

STRÖMGREN

I take it that the outer convective zone was included in these calculations.

HOYLE

Yes. I should point out that on the diagram showing the main sequence of type I and type II, adjacent positions of the two curves correspond to quite different masses.

SALPETER

What is the explanation of the wiggle on the calculated main sequence curves?

HOYLE

The development of a convective zone, the transition from the proton-proton to the C-N reaction and the changing opacity are all contributing. The method of computing leaves one almost helpless to disentangle those factors.

SANDAGE

There is a wiggle in the observed colour-magnitude diagrams about 2 magnitudes brighter than the Sun. The observed shape of the c-m diagram in this region is similar to those shown in HOYLE's computation but the kink occurs at a different absolute magnitude.

HOYLE

My variation is similar in form but about a magnitude fainter.

STATISTICS OF STELLAR EVOLUTION

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I want to review what statistics on the luminosity-spectral type distribution of stars in the solar neighborhood can tell us about stellar evolution and about the stellar population type in our region of the galaxy.

Reasonably detailed observational data are now available on the "total luminosity function" $\varphi(M_v)$, the average number of stars per unit volume within about 500 pc of the sun, per unit range of absolute visual magnitude irrespective of spectral type. Much less detailed information is available on the luminosity-spectral type function $\varphi(M_v, \mathrm{Sp})$, such as the STROMBERG-ÖPIK data [1] on the fraction of stars of different spectral types and given M_v (brighter than apparent visual magnitude $+6$). Although these data are rather coarse they do show that, for each value of M_v brighter than about $+3$, most stars lie either near the main sequence (and slightly redder) or else in the G8-K-M region. For each value of M_v we can thus divide the stars fairly cleanly into a "main sequence (plus some subgiants)" group and a "red giant" group. The spectral type Sp_d for each M_v in the table below gives the (somewhat arbitrary) adopted dividing line between the two groups and f is the fraction of "main sequence" stars at constant M_v, obtained from the STROMBERG-ÖPIK data. This break into two groups, the well-known Hertzsprung gap, is seen even more distinctly in the color-magnitude diagrams of various individual galactic clusters [2], even though the total number of stars involved is rather small. The dividing line Sp_d obtained [2] from the individual galactic clusters is quite similar to ours, adopted directly from the STROMBERG-ÖPIK data.

M_v	+3.5	+2.5	+1.5	+0.5	−0.5	−1.5	−2.5	−3.5	−4.5
Sp_d	G9	G7	G1	F9	F4	A7	A0	A0	A0
f	.93	.79	.71	.44	.55	.61	.55	.45	.43
f'	.89	.70	.68	.45	.67	78	.78	.76	.67

For some purposes we shall be interested not in the ratio $f/(1-f)$ between the *number* of stars in the "main sequence" and "red giant" groups for fixed M_v, but in the ratio $f'/(1-f')$ between the *total bolometric luminosity* in the two groups. f' is obtained by first multiplying the number of stars in each of the various spectral types, all for fixed M_v, by the bolometric luminosity for each spectral type and then using the same Sp_d as before for the dividing line between the two groups. Since the bolometric corrections are smallest near Sp_d, the division into the two groups is even more clearcut for f' than for f. The main uncertainty in the values of f' given in the table above comes from the uncertainty in the bolometric corrections. Note that for the brighter stars, say $M_v \lesssim -1$, f' is appreciably bigger than 0.5. In other words, the total energy radiated by the "red giant" group is appreciably less than that radiated by the "main sequence" group (however, we should remember that the latter group contains besides the "age zero main sequence" also some subgiants on the blue side of the Hertzsprung gap).

With the help of the fraction f, tabulated above, we can then get the observed luminosity function $\varphi_{MS}(M_v)$ for the main sequence [3] [4] (in ref. 3, I had used somewhat different values for f, based on an unsuccessful attempt to separate all subgiants from the main sequence. The numbers given by SANDAGE in ref. 4, based on the natural division line along the Hertzsprung gap as in the table above, should be more meaningful). This luminosity function is a fairly slowly varying function of M_v for stars fainter than about $M_v \sim +3.5$ and then decreases more rapidly with increasing luminosity.

Merely as a basis for further discussion, I derived [3] from this observed function $\varphi_{\mathrm{MS}}(M_v)$ a *hypothetical* "birthrate function" (or "original" luminosity function) $\psi(M_v)$ based on the simplest and crudest possible picture of stellar evolution and of the past history of the galactic region in the solar neighborhood. We make the following drastic assumptions: 1) Each star stays on or *near* the main sequence until it has burned a fraction q_o of its mass from hydrogen into helium; after the fraction of hydrogen burned exceeds q_o, the star moves rapidly across the Hertzsprung gap into the red giant region. In the absence of more detailed evolutionary calculations, I took $q_o = 0.12$, the Schönberg-Chandrasekhar limit, *independent* of the mass of the star. For simplicity I neglected ΔM, the change in magnitude of the star as the fraction q of hydrogen burned increases from zero to q_o. 2) We assume pure Stellar Population I in its most naive form, namely that the birthrate function $\psi(M_v)$ near the sun has been time-independent over the last T years and was zero before that. We take T as 5 or 6×10^9 years, so that the oldest main sequence stars with M_v about $+3.5$ are just beginning to move into the red giant region. 3) We neglect any effects due to the variation of the birthrate function with *position* in the galaxy coupled with the fact that stars move away from their birthplace with time. Under these simple assumptions one obtains [3] uniquely the hypothetical birthrate funcion $\psi(M_v)$ from the observed main sequence luminosity function $\varphi_{\mathrm{MS}}(M_v)$ (improved values for ψ are given in ref. 4). For stars brighter than about $M_v = +3.5$, φ_{MS} represents only those stars which were born recently enough so that the hydrogen fraction q burned is less than q_o and $\varphi_{MS} \propto \psi \mathfrak{M}/L$ ($\mathfrak{M}$ is mass, L is bolometric luminosity). Unlike φ_{MS}, the calculated ψ does *not* decrease more rapidly with increasing L for stars brighter than $M_v = +3.5$.

The observed luminosity function φ_{MS}, discussed above, refers to all nearby stars of all ages. For an individual galactic cluster of much younger age than 5×10^9 years, only the extremely luminous stars have had time to move off the main sequence and the observed main sequence luminosity function for such a cluster should follow the birthrate function ψ up to these high luminosities. SANDAGE [4] and v. D. BERGH [5] *do* indeed find that the observed individual luminosity functions for various young galactic clusters are very much closer to the hypothetical birthrate function ψ, calculated under the above assumptions, than to φ_{MS} for stars of all ages (for luminosities up to a breakoff point which depends on the age of the cluster). Since ψ and φ_{MS} differ by factors of the order of 10^3 at the highest luminosities (when normalized to agree for faint magnitudes), the agreement between ψ and the observed luminosity function for young clusters looks quite spectacular, even though ψ could be uncertain by factors of the order of 2 or 3. This agreement by no means confirms all the drastic assumption made above but it does lead to a few definite, although qualitative, conclusions: (a) The birthrate function in the spiral arm population as a whole is similar to that in individual galactic clusters, which possibly means that a large part of the arm population was originally born in clusters or star associations. (b) This birthrate has been reasonably uniform over the last one or two billion years. The fact that ψ is a reasonably smoothly varying function in the neighborhood of $M_v = +3.5$ (neither ψ nor φ_{MS} have any very pronounced discontinuities there) tells us one more thing: (c) Of the stars (with $M_v \sim +4$, say) in the solar vicinity (we are *not* talking of the galactic disk as a whole) not much more than half, say, could be "really extreme" Population II. In other words, if much more than half of the stars near us *now* had been formed in a very short period of time, say during a less than 1×10^9 year period about 6×10^9 years ago, our φ_{MS} (and the calculated ψ) would have a discontinuity near $M_v = +3.5$ (as the globular clusters *do* have) — which probably would have been observed in spite of the smoothing operations that go into the "observed" φ_{MS}.

There are a number of things which the above results do *not* tell us with any good accuracy: The assumed "age of our part of the galaxy", $T = 6 \times 10^9$ years in assumption 2) above, could be changed by a factor of two either way without any discrepancy showing up. The data are also rough enough, so that the birthrate could have been larger by quite appreciable factors during the first half of this time period T, say, than now. As BLAAUW pointed out a couple of days ago the kinematic effects neglected in assumption 3) above make our conclusions somewhat ill-defined: In fact there is a correlation between magnitude and velocity dispersion, and hence with spatial distribution perpendicular to the galactic plane, and one should really investigate assumptions about the birthrate function as a function of position as well as time. When more detailed calculations on the early evolution of individual stars (q_o and ΔM as a function of mass) and more detailed observational statistics become available, such quantitative investigations should be possible; at present we mainly have the three qualitative conclusions (a) to (c) above.

If we provisionally adopt the hypothetical birthrate function ψ, we can then calculate [3] the mass and the number of stars per unit volume in the solar vicinity which once were on the main sequence but have "moved off" and "burned out" sometime during the last 6×10^9 years. Using the values of f in the table above (see also ref. 4), the number of burned-out stars is about 0.14 times the number of present-day stars brighter than $M_v = 13.5$. This number of burned-out stars is of the same order of magnitude as the observed number of white dwarfs. This agreement further supports our qualitative conclusions above and the simple hypothesis that stars which have moved off the main sequence eventually lose a fair fraction of their mass and end up as white dwarfs. The calculated total *mass* of burned-out stars is roughly equal to the mass of present-day stars with $M_v < 13.5$. The percentages contributed to this mass of burned-out stars by stars of original magnitude M_v are

M_v	+3	+2	+1	0	−1	−2	−3	−4	−5
%	7	11	16	17	16	14	10	6	2

Most of this burned-out mass presumably has been shed into the interstellar gas and should have resulted in a continuous enrichment of elements heavier than hydrogen during the last five billion years or so. Any quantitative estimates are rather precarious at the moment: The calculated *mass* (unlike the *number*) of burned-out stars comes largely from the more luminous and massive stars (as the percentages above show); about the birthrate of these more luminous stars during the earlier stages of the galaxy we have, of course, essentially no information since they burn out so rapidly. Further, the spatial distribution of the stars and the gas is of importance for these considerations and one should probably consider the galactic disk as a whole rather than our immediate vicinity. Finally, as I will suggest in a minute, the fraction of the "burned-out" mass which actually consists of elements heavier than hydrogen is probably rather small and its value somewhat uncertain.

I now want to review briefly some results that can be derived from SANDAGE's "semi-empirical evolutionary tracks": Consider a star of given mass, originally with uniform chemical composition and on the appropriate place of the "zero-age main sequence". As the fraction q of its mass burned from hydrogen into helium increases from zero up, the color and luminosity of the star initially change very slowly. As q reaches a critical value q_o, the "knee" in the evolutionary track, the star's evolution in the color-magnitude diagram begins to speed up appreciably. Purely theoretical calculations on the *early* evolution of the star, in particular the numerical value q_o of q at the "knee" and the change in magnitude ΔM from $q=0$ to q_o, are very much easier and more reliable than calculations on the later and much faster evolution for $q > q_o$. Assume we know ΔM and q_o from theory and that we have the observed frequency distribution or luminosity function for all the stars (all of the same age) in an individual cluster, both on the main sequence and off. Following SANDAGE [6], one can then correct the observed luminosity function for stars that have not yet crossed the "knee" for the effects of the early evolution and extrapolate this corrected "*original* luminosity function" to slightly larger luminosities. By comparing this calculated function with the observed present-day frequency distribution of stars past the "knee", SANDAGE can trace each evolved star back to its original main sequence position and thus find the *later* part (for $q > q_o$) of individual evolutionary tracks. From exactly the *same* data we can also obtain the time spent by a star along the various parts of its evolutionary track past the knee. We thus also obtain values for q, the fractional mass burned, along these later parts of the track - based on theory only for $q < q_o$ and on observation for the rest. From these considerations one also obtains the age of the cluster. These methods are very powerful ones, but one should remember that the numerical values of the results (both for the cluster age and for q along the track) depend quite sensitively on the theoretical ΔM and q_o. As HOYLE and SCHWARZSCHILD will tell us later, accurate enough machine computations which give ΔM and q_o as a function of stellar mass will be available soon; but at the moment determinations of cluster ages cannot claim high absolute accuracy.

For the halo-population globular cluster M 3 a fairly reliable observed luminosity function (up to $M_v = +6$) is now available [4] and one can calculate q along the evolutionary track. Assuming $q_o = 0.12$ and $\Delta M = -1.0$, I find that q has increased to about 0.35 when a globular cluster star has brightened to $M_v = +1.5$ and q has risen to 1.1 after the star has passed right through the horizontal branch. These figures are rough (as our fraction of 110% shows) and the results depend on the assumed q_o and ΔM. But it is evident that stars in halo-type globular clusters burn a large fraction of their mass from H to He during their visible evolution along the cluster diagram, most of this fraction being burned *after* passing through the knee at q_o. [Incidentally, with our assumption of $q_o = 0.12$, $\Delta M = +1.0$, the original luminosity function $\phi(M_v)$, derived from the present observational data, is almost exactly *constant* from $M_v = +6$ to $+4.5$]. The situation is quite different for the (somewhat more massive) stars in the various (younger) galactic clusters: Consider, for instance, the cluster M 11 [*Ap. J. 124*, 81, 1956] where the "knee" in the evolutionary track occurs near $M_v = -1$. This cluster has a fairly impressive giant branch compared with some other galactic clusters. Nevertheless, assuming again $q_o = 0.12$, I find at the very end of its giant branch a value for q of only about 0.20. Although this number is even rougher than for M 3, it is very evident that the brighter stars in galactic clusters burn a *smaller* amount of hydrogen during their travel along the giant branch than during their stay on or near the main sequence. This result, obtained from individual clusters, also tallies with what we saw in our first table (values of $f' > 0.5$) for the solar vicinity, namely that for $M_v \lesssim -1$ the total luminosity in the "main sequence" group is larger than that in the "red giant" group. These results seem to indicate (indirectly) that the more massive stars eject matter continuously at an appreciable rate while they are evolving through the red giant region and before they have burned most of their hydrogen. To digress for a moment to "element-cooking" in stars: Matter ejected in this manner will consist mainly of hydrogen and possibly not carry with it as much heavier stuff produced in the stellar interior as we thought a few years ago. On the other hand, present estimates for the mass ratio of gas to disk-population stars seem to be lower than they were, thus requiring less element-cooking per star. These two changes suggest that we should perhaps look again at the possibility of manufacturing some elements in the *surface* of stars.

Let us finally turn to the luminosity function for red giants as observed in the general field of stars of all ages in our region of the galaxy. The main qualitative fact one has to explain is that most of the red giants fall in a band in the HR diagram which has a wide color range but a narrower luminosity range. In other words, if we plot the observed luminosity function for all stars of a given color or spectral type we seem to find, superimposed on the high-luminosity tail of the main-sequence, another distribution with a moderately sharp maximum (near $M_v \approx +1$) for late G and early K. SANDAGE [2] has made rough calculations for predicted luminosity functions at constant spectral type, which are based on the theoretical birthrate function $\psi(M_v)$ for the general star field plus the semi-empirical evolutionary tracks obtained from individual galactic clusters. These predictions certainly explain the qualitative features of the observations: The low-luminosity edge of the red giant band is due to the fact that only stars more massive than a certain limit have had time to evolve away from the main sequence during the last 5 or 6×10^9 years. The high-luminosity fall-off is simply due to the fact that the more luminous stars burn hydrogen and evolve more rapidly and we only see those born fairly recently. SANDAGE [2] made a more quantitative comparison between his predicted luminosity function for Ko to K2 giants and HALLIDAY'S [*Ap. J. 122*, 222, 1955] observational function. Here the agreement is even good quantitatively, but an equivalent calculation for G8 to G9 does *not* give such good quantitative agreement: The predicted low-luminosity edge of the red giant branch, which is based on the assumption that the evolutionary track for the galactic cluster M 67 (rather than that for globular clusters) is typical of the oldest red giants to be found in our vicinity, lies at lower luminosity than HALLIDAY's observed one. The observational data alone are difficult and uncertain enough so that one need not worry at all about this slight quantitative discrepancy. But I would also like to point out a source of uncertainty in the theoretical predictions about the low-luminosity edge: According to our present views we do not expect a very rapid variation of chemical composition of a star with its time of birth for ages between 10^6 and 3 or 4 × 10^9 years, say. But, for the oldest stars or clusters, chemical composition should depend fairly sensitively on the exact age (as the differences between M 67 and the, not much older, globular clusters show so dramatically). We therefore may have to expect some appreciable spread or deviation in the evolutionary tracks of the least massive red giants in our vicinity from that for the single cluster M 67.

REFERENCES

[1] TRUMPLER and WEAVER, *Statistical Astronomy*, p. 409.
[2] A. SANDAGE, Ap. J., *125*, 435, 1957.
[3] E. SALPETER, Ap. J., *121*, 161, 1955.
[4] A. SANDAGE, Ap. J., *125*, 422, 1957.
[5] S. V. D. BERGH, Ap. J., *125*, 445, 1957.
[6] A. SANDAGE, Liege Symposium Volume, p. 254, 1954

DISCUSSION

CHAIRMAN: L. SPITZER

BLAAUW

HALLIDAY's luminosity function was somewhat uncertain. He made a careful luminosity classification but the calibration of this against luminosity was very difficult.

SALPETER

This means that the quantitative discrepancy I referred to may not be important.

OORT

Another uncertainty in HALLIDAY's work is due to the uncertain mean error in the determination of absolute magnitudes from spectroscopic criteria. This plays a dominant role in determining the luminosity curve, especially for giants.

STRÖMGREN

SANDAGE and SALPETER have indicated that the giant K part of the diagram is a dump containing stars with a fairly large range of mass. Although the spectroscopic criteria can give us the value of the gravity, the radius and hence the luminosity remain uncertain. A thorough comparison of the spectroscopic characteristics of K giants in Praesepe-Hyades and M 67 may help to disentangle this.

BAADE

OLIN C. WILSON can now separate giants using a new criterion, the width of emission in H and especially K. He finds a linear relation between the width of the central emission and absolute magnitude from -7 to $+8$ or 9. He standardised the giants by reference to the Hyades, Praesepe, *h* and χ Persei, and the low luminosity stars from trigonometrical parallaxes. So far he has obtained data for 200 supergiants, giants and subgiants from late F to M. He has plotted these against the Mount Wilson catalogue (Yerkes luminosity classes?) and shown that the giants classified together in the catalogue begin to break up into different groups. The criterion seems to be one of high accuracy.

BLAAUW

WILSON used a dispersion of 10 Å/mm. Could the method be applied without such high dispersion, e.g. photoelectric filtering?

BAADE

He proposed to speed things up by using photoelectric scanning with the same dispersion. With the 200″ he can reach down to 7.5 *M*.

SPITZER

Will he reach a fainter magnitude photoelectrically?

BLAAUW

He is observing at the bottom of an absorption line.

SCHWARZSCHILD

I have been greatly impressed by the presentation of quantitative data — to within factors of two or three —, especially by BLAAUW, HERBIG and SALPETER, regarding some of the key problems for the vital statistics of the stars. It appears now, first, that all stars probably come to birth in clusters and associations; second, that the

T Tauri phenomenon may well be the gateway to the main sequence for the majority of stars; third, that according to SALPETER's and SANDAGE's work the luminosity function of field stars, after correction for star deaths, agrees with that found directly from galactic clusters; and finally, that the rate of star deaths agrees with the number of white dwarfs.

BAADE

These results seem fairly safe, at least if they are restricted to the stage of the galaxy after the appearance of spiral structure. Before that the results are still very uncertain.

COMPOSITION DIFFERENCES BETWEEN STELLAR POPULATIONS

BENGT STRÖMGREN
Yerkes and McDonald Observatories (*)

1. Information regarding composition differences between stellar populations derived from quantitative analysis of high-dispersion spectra is at present not very extensive. However, this information when supplemented with results of a qualitative nature indicates striking differences between populations with regard to chemical composition, particularly with respect to the abundance ratio of heavy elements and hydrogen.

CHAMBERLAIN and ALLER [1] investigated two stars of the class of high-velocity F-type subdwarfs with the help of plates of a dispersion of 10 Å per mm and 20 Å per mm. From an analysis based on model atmosphere calculations they found that the abundances of calcium and iron relative to the hydrogen-abundances is of the order of ten times smaller in these stars than in the sun or in normal population I main-sequence stars.

In continuation of earlier work on subdwarfs by ADAMS and JOY [2], MORGAN and KEENAN [3], and KUIPER [4], Miss ROMAN [5] has shown that there exists in the galactic neighborhood (within 100-200 parsecs) a group of F stars characterized by 1) very high spatial velocities; 2) a spectrum in which the metal lines are very weak considering the effective temperature of the star as indicated by the color and the appearance

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of the Balmer lines; 3) a location in the H-R diagram 1^m-2^m below the population I main sequence. Further investigations by GREENSTEIN [6] have confirmed and extended these results.

The two subdwarfs analyzed by CHAMBERLAIN and ALLER belong to the group of stars in question. It seems certain that we have here a group of extreme population II subdwarfs in which the atmospheric heavy element to hydrogen ratio is very low in comparison with the ratio for population I stars.

UBV photometry by Miss ROMAN [5] indicates that the extreme population II F-type subdwarfs have an ultraviolet excess of about $0^m\!.2$. The effect is so large that the stars in question can easily be segregated from population I stars through *UBV* photometry.

UBV photometry of stars in globular clusters by JOHNSON, SANDAGE and WALKER, ARP and JOHNSON, and SANDAGE and JOHNSON (cf. JOHNSON [7] and SANDAGE, p. 54 of this volume) shows a similar ultraviolet excess for F stars. Although spectra are not available for these faint globular cluster stars, the available information is sufficient to show that they are probably similar in nature to the extreme population II F-type subdwarfs in the galactic neighborhood.

POPPER [8] investigated the brightest stars (red giants) in the globular clusters M 3 and M 13 using slit spectra with a dispersion of 15 Å per mm. He found the *CN* absorptions to be peculiarly weak, in agreement with an early observation by LINDBLAD [9]. Spectra have been studied by BAUM [10] for the brightest stars in M 3 and M 92. KEENAN and KELLER [11] have examined these spectra and found that the *CN* bands and the metallic lines are much weaker than in comparable population I stars. This again indicates a low heavy elements to hydrogen ratio for extreme population II stars.

A large fraction of the high-velocity stars in the galactic neighborhood (defined as having space motions relative to the local centroid larger than 60 km per sec) show deviations in chemical composition from the low-velocity population I stars in the same sense as the extreme population I stars discussed above. However, the deviations are on the average much smaller than for the extreme population II stars. The most striking spectroscopic phenomenon is the weakening of the cyanogen bands for giants and subgiants of classes G6 - K4 described by MORGAN and KEENAN [3]. KEENAN and KELLER [11] have investigated the relation of the *CN* weakening and the space velocity for a number of stars in the galactic neighborhood and found a fairly high correlation.

M. and B. SCHWARZSCHILD [12] have obtained high-dispersion spectra (dispersion 10 Å per mm) of two high-velocity stars typical of the group investigated by KEENAN and KELLER and carried out quantitative line spectrophotometry. From these data SCHWARZSCHILD, SPITZER and WILDT [13] found that the oxygen group content is lower by a factor of about 2 and the iron content lower by a factor of 2-3 in comparison with low-velocity population I stars.

Miss ROMAN [14] classified a number of nearby stars in the spectral range F5 - G5 according to a three-dimensional scheme through visual inspection of slit spectra with a dispersion of 125 Å per mm. The characterization "weak-line star" or "strong-line star" was added to the spectral class and luminosity class according to the MK system. Weak-line stars show a general weakening of the absorption lines relative to strong-line stars which according to the criteria of line ratios belong to the same MK spectral and luminosity class. The spectroscopic effects are much less pronounced, however, for the weak-line stars than for the stars of extreme population II mentioned above. Miss ROMAN found that the stars classified by her as weak-line stars have on the average considerably larger space velocities relative to the local centroid than the strong-line stars.

The investigations of CHALONGE and his collaborators on three-dimensional classifications on the basis of photographic spectrophotometry are described on p. 345 of this volume. Reference is also made to p. 393 of this volume.

The analysis of the spectroscopic results is facilitated through model atmosphere calculations for models with relatively very small metal content. SWIHART [15] computed models for the effective temperatures of the sun and an F5 main-sequence star, respectively, both for the ratio A of hydrogen to metals corresponding to $\log A = 3.8$, and for $\log A = 5.0$, the latter value corresponding to extreme population II subdwarfs. The principal result was that the predicted intensities of the continuous spectrum are quite insensitive to A in the range considered.

Therefore, if an F-type population I main-sequence star and a population II sudwarf have the same spectral distribution of intensity in the continuous spectrum, they must have the same effective temperature, very nearly. A relatively small correction is necessary to allow for the difference in blanketing effect, and for the difference in continuous metal absorption. Also, the difference in gravitational acceleration g in the atmosphere has some effect on the continuous spectrum. If the stellar masses in question can be estimated, or the value of g derived from a spectral analysis, this effect can be allowed for.

2. The internal structure of a star of given mass, its radius and luminosity, depend on the chemical composition. The latter influences the equation of state, the opacity, the energy production, the properties of any outer convective zone, and the age effects produced by non-uniformity of composition through the star. In a general way, it is therefore expected that composition differences between stellar populations will cause corresponding differences in stellar properties as expressed through distribution in the H-R diagram.

REIZ [16] investigated the structure of stars with negligible content of heavy elements, which should represent fairly closely extreme population II stars, and compared the resulting structures with those valid for population I stars in the galactic neighbourhood. The computations were limited to zero-age stars, i.e. stars of uniform compositions. REIZ found the zero-age line in the H-R diagram of the stars of negligible heavy element content to be located about a magnitude below the population I zero-age line in the range of late A and F stars. The location depends on the helium-hydrogen ratio. For pure hydrogen stars (i.e. stars with negligible heavy element and helium content) the zero-age line is close to the population I zero-age line.

HOYLE and SCHWARZSCHILD [17] have found that the evolution tracks in the H-R diagram in the giant region depend in a sensitive way on the heavy element content, because the latter strongly influences the depth of outer convective zones and thereby the internal structure. This is important in discussing the H-R diagrams of population I and II clusters.

3. Analysis of composition differences between stellar populations based on detailed spectrophotometry of the continuous spectrum and the absorption lines and utilizing model atmosphere calculations is, of course, the ultimate goal in the field in question. However, differences in composition can be detected and investigated through photometry in a few properly selected wave-length bands.

An important example is the ultraviolet excess of population II stars discussed above, and the possibility of discrimination between population I and population II stars on the basis of *UBV* photometry. It has been found (cf. p. 393 of this volume) that photoelectric narrow-band photometry of the two hydrogen indices c and l together with *UBV* photometry yields a quantity $\delta\ (U - B)$, i.e. observed U-B minus U-B predicted from c and l, which is an index of chemical composition.

This latter index depends on intensities measured on either side of the Balmer discontinuity. It is however advantageous to obtain an index of chemical composition from photometry of wave-length regions all located above the Balmer discontinuity, since with proper choice of wave lengths such an index would be relatively insensitive to variations in effective temperature and gravity.

In the course of narrow-band photoelectric photometry carried out by the author with the 82-inch reflector of the McDonald Observatory (cf. p. 385 of this volume) an index *m* was measured which has the desired property. The definition of *m* is (cf. p. 394).

$$m = \text{constant} - 2.5\ [\log I(a) + \log I(e) - 2 \log I(d)],$$

where $I\ (a)$, $I\ (d)$ and $I\ (e)$ are intensities measured through interference filters with maximum transmission at 5000Å, 4500Å and 4030Å, respectively. The half-widths of the filters *a, d* and *e* were 90Å, 80Å and 90Å, cf. p. 386.

Since *m* is the difference between two color indices *d-a* and *e-d,* of about equal base line, it is expected that *m* will be insensitive to changes in the energy distribution in the continuous spectrum due to changes in effective temperature and gravity. Also the index *m* should be little affected by interstellar absorption. However, changes in the total strength of absorption lines should influence *m* in the range of F and G stars. For the wave-length regions *a* and *d* the total strengths of absorption lines are about equal, but for that of *e* it is considerably stronger. For the sun this effect of the absorption lines upon *m* is close to $0\overset{m}{.}2$ according to the known total equivalent widths of absorption lines in the wave-length regions in question (cf. e.g. BELL [18]). The effect of difference in continuous metal absorption goes in the same direction, but is probably smaller. It should be emphasized that the effect of absorption lines is smaller for the F stars considered here than for the sun.

The index *m* was determined for a number of bright stars as a by-product of measures of the indices *c* and *l* (cf. p. 387) carried out during three observing periods at McDonald Observatory for the purpose of calibration of *c-l* classification. In addition measures were made with the filters *a, d* and *e* alone for the sole purpose of determinations of *m*-indices during five

[*18*] V, 4 - *Strömgren I* - p. 6

nights (or parts of nights) in March, 1957. We shall refer to these *m*-observations as series A and series B.

The results of the measures of the index *m* for bright F stars observed both in series A and series B are shown in Table 1. The stars are all so close to the sun that interstellar absorption should be negligible.

The differences between the series A and B values of *m* give a p.e. for *m* determined in one series equal to $\pm 0\overset{\mathrm{m}}{.}005$ if the two series are assumed to be of equal accuracy, and a p.e. of $\pm 0\overset{\mathrm{m}}{.}004$ for *m* determined as the mean of series A and series B. The interagreement of *m*-values obtained on different nights of series B indicate a p.e. of one observation of *m* equal to $\pm 0\overset{\mathrm{m}}{.}009$. (This compares with a p.e. for one observation of *c*, an index of the same structure as *m*, cf. p. 391, equal to $\pm 0\overset{\mathrm{m}}{.}008$).

Table 1 gives *B-V*, the distance Δl of the locus of the star in a *c-l* diagram above the zero-age line, cf. p. 391; the values of *m* obtained from the 82-inch measures in series A and B, respectively, and the mean value of *m*; the difference δ (*U-B*) between observed *U-B* and *U-B* predicted from *c* and *l*, cf. p. 392. The values of *B-V* and *U-B* were kindly furnished by Dr. D.L. HARRIS from an unpublished catalogue of *UBV* photometry of bright stars. They are based on measures by JOHNSON, by HARRIS, and by NAUR [19].

The stars are arranged in order of increasing observed *m*. The correlation between *m* and δ (*U-B*) is clearly shown. The correlation coefficient is 0.85. The variation of δ (*U-B*) is 1.6 times the variation of *m* for the regression line considered.

In the range of *B-V* in question, $+0\overset{\mathrm{m}}{.}3$ to $+0\overset{\mathrm{m}}{.}5$, only a small change of *m* with *B-V* is indicated, $\Delta m/\Delta(B\text{-}V)$ being approximately equal to +0.1. A subdivision of the material according to Δl shows no variation of *m* with Δl, i.e. with absolute magnitude for given *B-V*.

TABLE I

Star	*B − V*	Δ *l*	*m* *Series A*	*m* *Series B*	*m* *Mean*	δ(*U*−*B*)	
	m	m	m	m	m	m	
δ Gem	+0.34	+ 0.022	0.099	0.097	0.098	− 0.03	
28 Boo	35	− 1	103	099	101	− 6	
62 Gem	32	+ 8	105	103	104	− 6	
107 Vir	38	+ 16	098	121	110	− 5	
23 UMa	33	+ 34	117	113	115	− 1	
12 CrB	33	+ 16	114	123	118	− 2	
53 Vir	46	+ 19	133	112	122	0	
α Com	45	+ 1	124	124	124	− 2	Binary, nearly equal comp.
37 UMa	32	− 2	124	126	125	− 1	
16 Lep	32	+ 3	131	126	128	0	
18 Boo	38	− 2	120	140	130	− 1	
71 Gem	41	+ 33	136	125	130	+ 1	
89 Tau	31	+ 9	137	131	134	0	In Hyades cluster
22 Lyn	45	+ 4	129	140	134	− 4	
HR 1201	34	+ 2	134	138	136	0	In Hyades cluster
8 Dra	28	+ 5	137	136	136	− 1	
76 Tau	32	+ 6	141	136	138	+ 3	In Hyades cluster
21 Mon	29	+ 34	143	132	138	+ 3	
74 Ori	42	+ 4	142	143	142	0	
45 Boo	42	+ 2	136	148	142	0	
γ Ser	48	+ 5	141	145	143	− 1	High-vel. star
45 Tau	36	+ 8	146	143	144	− 2	In Hyades cluster
31 Gem	43	+ 20	144	144	144	+ 2	
51 Tau	28	− 1	150	143	146	+ 2	In Hyades cluster
45 Aur	43	+ 28	149	156	152	+ 6	
25 Mon	44	+ 35	155	149	152	+ 4	
40 Leo	45	+ 9	150	154	152	+ 2	
78 UMa	36	+ 1	155	151	153	+ 2	
71 Ori	44	+ 4	158	155	156	+ 2	
18 Com	43	+ 28	149	168	158	+ 3	
1 Ori	45	+ 7	165	154	160	0	
20 CVn	29	+ 31	195	175	185	+ 9	
4 Boo	47	+ 1	199	188	194	+ 7	

It should be noted here that when we determine the variation of *m* with *B-V* and absolute magnitude through an empirical calibration, we cannot study systematic variations of chemical composition with age. The average age of the stars considered will vary with position in the H-R diagram, and we cannot without further information distinguish between the effect upon *m* of changes in effective temperature T_e and surface gravity *g* on the one hand, and a systematic change of chemical composition with age. What can be accomplished, however, is a study of the scatter in the chemical-composition parameter for a given small region in the H-R diagram.

When additional information is available the situation changes. Thus, calibration of *m* against *B-V* from the stars of a galactic cluster gives the effect of changes in effective temperature separately from any age effect. Also, if a theoretical evaluation of the effect of changes of T_e and *g* upon *m* becomes available, the systematic variation of chemical composition with age can be evaluated.

In the case of the F subdwarfs of extreme population II the detailed spectroscopic analysis shows that the chemical-composition effect is much larger than the effect of changes in *g* for constant *B-V*, and no great error results when the effect in *m* is all attributed to the change in chemical composition.

The range of variation of *m* for the group of population I F stars considered (cf. Table 1) is much larger than it would be if the variations were due to variation in *B-V* and absolute magnitude alone, so that there is evidence for the influence of a variable third parameter. Referring to the discussion above, we identify the third parameter with the ratio of heavy elements to hydrogen. The correlation between *m* and δ (*U-B*) is just the one expected on this assumption.

If we subdivide the stars in Table 1 in three equal groups according to the observed value of *m* (small, intermediate and large), we find average values of *m*, δ (*U-B*), *B-V* and Δl as given in Table 2.

TABLE 2

	m	$\delta(U-B)$	$B-V$	Δl	m reduced to $B-V=0^{\mathrm{m}}.40$
	m	m	m	m	m
Group of small m (11 stars)	0.116	−0.025	0.36	0.010	0.120
Group of intermediate m (11 stars)	0.138	−0.001	0.36	0.010	0.142
Group of large m (11 stars)	0.159	+0.035	0.41	0.015	0.158

The differences in B-V and l between the groups are small, and the corresponding effect on the average m is very small.

The range of the m-distribution is described by a root mean square deviation of $\pm 0^{\mathrm{m}}.021$. Allowing for the influence of the observational p.e. of $\pm 0^{\mathrm{m}}.004$, we find $\pm 0^{\mathrm{m}}.020$, corresponding to a p.e. of $\pm 0^{\mathrm{m}}.013$. The contribution of the inaccuracies of the photometry to the scatter of the m-values is thus very small.

Binary nature of a star would influence the observed m-value. However, the spectra and radial velocities of the bright stars in Table 1 are well studied, and the probability that any of them is a binary with about equally bright components of unequal color is very small. (A case like α Com, with two practically equal components, is of course uncomplicated). Let us consider the effect of admixture of light from a faint main-sequence component to the light of a typical main sequence F star of photographic absolute magnitude $4^{\mathrm{m}}.0$. If the light of a main-sequence K1 star of photographic absolute magnitude $7^{\mathrm{m}}.0$, with B-$V = 0^{\mathrm{m}}.86$, U-$B = 0^{\mathrm{m}}.54$, $m = 0^{\mathrm{m}}.31$ (according to a separate observation) were added, then B-V would be changed by $+0^{\mathrm{m}}.03$, δ (U-B) by $+0^{\mathrm{m}}.03$, and m by $+0^{\mathrm{m}}.01$. For a difference of 2 magnitudes between the components the effect would be considerably smaller, and the same would be

TABLE 3

Star	*Series*	*B - V*	*U - B*	*m*	*Group*
		m		m	
He 88	B	+0.46		0.155	Pleiades
He 169	B	44		148	
He 227	B	52		162	
He 468	B	47		162	
He 695	B	47		139	
KW 142	B	49		154	Praesepe
KW 155	B	41		127	
KW 268	B	48		141	
KW 271	B	32		138	
KW 292	B	30		148	
KW 295	B	42		166	
KW 350	B	32		151	
KW 370	B	36		134	
Tr 36	B	41		118	Coma Berenices
Tr 49	B	35		125	
Tr 101	B	44		131	
Tr 118	B	45		134	
HD 110 183	A	51		170	North galactic pole
110 297	A	44		145	
110 524	A	37		138	
110 745	A	54		199	
110 963	A	38		145	
111 131	A	42		130	
111 253	A	39		121	
111 271	A	35		150	
111 782	A	41		169	
111 891	A	48		158	
112 031	A	34		171	
112 248	A	41		148	
112 571	A	39		107	
112 886	A	44		146	
112 887	A	43		124	
113 284	A	36		106	
113 468	A, B	57		244	
113 494	A	40		125	
113 562	A	43		165	
113 958	A	54		205	
114 254	A	42		142	
114 311	A	50		186	
			m		
Ro 73	A, B	46	−0.24	016	Subdwarf, HD19445
Ro 189	B	48	− 19	055	Subdwarf
Ro 203	B	30	− 12	063	Subdwarf
Ro 323	B	42	− 21	041	Subdwarf
Ro 342	B	42	− 22	016	Subdwarf
Ro 212	B	50	− 04	131	High. vel. star

The sources of the *B-V* photometry are as follows. Pleiades, H. L. JOHNSON and W. W. MORGAN, Ap. J. *117*, 313, 1953; Praesepe, H. L. JOHNSON, Ap. J. *116*, 640, 1952; Coma Berenices cluster, H. L. JOHNSON and C. F. KNUCKLES, Ap. J. *122*, 209, 1955; North galactic pole, D. L. HARRIS, unpublished; Subdwarfs and high-vel. star (*B-V* and *U-B* photometry), N. G. ROMAN, Ap. J. Supplement Series, No. 18, Vol. 2, 195, 1955.

the case for magnitude differences of 4 magnitudes or larger. It seems unlikely, therefore, that effects caused by possible binary nature of some of the stars in Table 1 should contribute appreciably to the scatter in m and $\delta\ (U\text{-}B)$.

In Table 3 we have collected m-values determined with the McDonald Observatory 82-inch reflector, mostly in series B only, and therefore of somewhat lower accuracy. The measures pertain to stars in the Pleiades, Praesepe, and the Coma Berenices cluster; F stars in a 35 square degree are near the north galactic pole observed by HARRIS and STRÖMGREN, cf. [20]; F-type subdwarfs (and one high-velocity star with about normal spectrum) from Miss ROMAN's catalogue. For the Pleiades and the north galactic pole stars there is noticeable interstellar reddening for at least some of the stars, however the $B\text{-}V$ color excess is not more than a few hundredth of a magnitude, and the effect on m is probably considerably less than $0\overset{m}{.}01$.

The extreme population II subdwarfs stand out in m as expected, as they do in $U\text{-}B$. The difference in m between the average population I main-sequence F star and the extreme F-type subdwarfs is about $0\overset{m}{.}12$. This compares with an ultraviolet excess in $U\text{-}B$ of approximately $0\overset{m}{.}20$. Again the scale ratio $\delta\ (U\text{-}B)$ to $\delta\ m$ is about 1.6.

When the stars within one galactic cluster (Hyades in Table 1, Pleiades, Praesepe and Coma Berenices in Table 3) are intercompared, a scatter in m much smaller than the scatter among the field stars is found. The scatter is in fact so small that it cannot be determined from the present material, but an upper limit given by a root mean square deviation equal to $\pm 0\overset{m}{.}007$ can be derived. This compares with $\pm 0\overset{m}{.}020$, r.m.s. deviation, for the nearby field stars. We interpret this to be the result of greater homogeneity with respect to chemical composition of the stars within one cluster than for the group of nearby field stars.

The m-averages for the Hyades, the Pleiades and Praesepe agree very closely with each other, and closely with the m-

average for the main-sequence field stars, allowing for differences (quite small) caused by differences in average *B*-*V*. The *m*-averages are given in Table 4. The average for the 4 stars observed in the Coma cluster is $0^m.020$ smaller. More observations are needed in order to determine this difference, but it is interesting to note that the difference corresponds in sign, and very nearly in magnitude, to the difference found by JOHNSON and KNUCKLES [21] in the (*B*-*V*), (*U*-*B*) relation.

TABLE 4

	m	$B-V$	m reduced to $B-V = 0^m.40$
	m	m	m
5 Hyades stars	0.139	0.32	0.147
5 Pleiades stars	0.153	0.47	0.146
8 Praesepe stars	0.145	0.39	0.146
4 Coma stars	0.127	0.41	0.126
16 Main-sequences field stars with $\Delta l \leqq 0^m.009$	0.139	0.40	0.139
12 Field stars with $\Delta l \geqq 0^m.016$ . .	0.135	0.36	0.139

The F stars near the north galactic pole listed in Table 3 show about the same *m*-distribution as the bright nearby F stars. Although the *m*-values are less accurate and there is some effect of interstellar absorption on the values of δ (*U*-*B*) it is of interest to compare *m* and δ (*U*-*B*) for the stars in the groups with the smallest and largest *m*-values. Table 5 gives *m*, and δ (*U*-*B*) derived from *c*-*l* classification and *U*-*B* photometry, cf. p. 251.

TABLE 5

	m	$\delta(U-B)$	
HD 113 284	$0^{\mathrm{m}}.106$	$-0^{\mathrm{m}}.04$	
112 571	107	$-$ 07	Binary with nearly equal comp.
111 253	121	$-$ 03	
112 887	124	$-$ 03	
113 494	125	$-$ 01	
110 183	170	$+$ 04	
112 031	171	$+$ 06	
114 311	186	$+$ 05	
110 745	199	$+$ 06	
113 958	205	$+$ 08	
113 468	244	$+$ 15	

The correlation between m and δ $(U\text{-}B)$ is again clearly shown. The large deviation from the $(B\text{-}V)$, $(U\text{-}B)$ relation for the star HD 113 468 = BD 29° 2360 was first noticed by HARRIS. Interstellar reddening could at most explain a few hundredths of a magnitude of the deviation in $U\text{-}B$. The m-value (insensitive to interstellar absorption) is about $0^{\mathrm{m}}.10$ higher than the average for the F stars, however $B\text{-}V$ is $+0^{\mathrm{m}}.57$ and this accounts for a few hundredths of the difference.

It would be expected that the stars in Table 1 with low value of m and significantly negative δ $(U\text{-}B)$ are weak-line stars, and those with high m and significantly positive δ $(U\text{-}B)$ strong-line stars. At present the observational material is too small for a detailed comparison as there are only 9 stars in common between Table 1 and the list by Miss ROMAN [14]. The correlation is however not very good. In 3 cases out of 9 the result of the strong-line classification by visual inspection disagrees with the indication by m and δ $(U\text{-}B)$. For the extreme population II F-type subdwarfs on the other hand there is agreement in every case between the evidence from m, that from δ $(U\text{-}B)$, and Miss ROMAN's classification.

Further investigation of the question would be of interest. As long as the variations of *m* and δ (*U-B*) are only qualitatively understood and have not been analyzed in detail on the basis of the theory of stellar atmospheres, the possibility remains that these quantities and strong-line, weak-line classification indicate variations in different chemical-composition parameters.

The total range of *m* for the F stars observed is over $0^{m}.2$. Recalling that *m* is insensitive to effective temperature and absolute magnitude in the color range $+0^{m}.3$ to $+0^{m}.5$ and for luminosity classes III, IV and V, and that *m* is also insensitive to the effect of interstellar absorption, we conclude that it is a useful index in three-dimensional classification.

It would be desirable to analyze the nature of the *m*-variations further through high-dispersion spectrophotometry. Two approaches appear feasible. For a suitable number of stars the total equivalent widths of the absorption lines in the bands *a*, *d* and *e* could be determined, or the three-band photometry could be carried out in very narrow bands nearly free from absorption lines. By either method the *m*-variations could be broken down into an absorption-line effect and a possible continuous-spectrum effect.

4. We have found that the scatter in *m* among nearby population I F stars is characterized by a root mean square deviation of $\pm 0^{m}.020$ which is about one-sixth of the difference in *m* between population I F stars and extreme population II F-type subdwarfs.

Let us consider the interpretation of the variations within the group of population I F-type stars. If the variations in *m* are caused by variations in the relative abundance of heavy elements Z, as appears likely, then the root mean square deviation of Z from its mean value $\bar{Z}$ must be at least one-sixth of $\bar{Z}$, since the line absorption effects plus any effects of change in continuous absorption vary more slowly than the first power of Z. The difference in *m* between average population I and extreme population II indicates the effect of a reduction in Z from its value for average population I to a value small enough for the effect of line absorption and heavy-element continuous absorption to be almost negligible. A detailed theoretical analysis is required for a better estimate of the magnitude of the chemical-composition variations in question.

As we have seen (cf. p. 253) we cannot by the present type of analysis determine systematic changes of stellar composition at formation with the epoch of formation, but we can investigate the scatter of chemical composition for a given epoch of formation. We ask the question, whether or not the present material is compatible with the assumption of a unique relation between initial chemical composition and epoch of formation of a star (*).

Let us consider, first, the scatter of m for stars near the zero-age line, with $\Delta l \leqslant 0^m.009$, in the range of B-V $+0^m.3$ to $0^m.5$. Since the observational p.e. of the l-values in question is $\pm 0^m.003$, the range of the true l-values is somewhat in excess of $0^m.009$, but not much. The corresponding range in M_v is from the zero-age line to about $0^m.6$ magnitudes above this line (cf. p. 390, Table 1, of this volume). We can roughly estimate the corresponding range in stellar age on the basis of computed evolutionary tracks for population I stars to be from 0 to 2-3×10^9 years, and the root mean square deviation of the age from the average age to be 1×10^9 years. If we now make the assumption that the present rate of change of m with time is equal to that indicated by the differences in m and in age between population I F stars and the extreme population II stars, which is very probably an overestimate, we deduce a root mean square variation in m equal to $\pm 0^m.02$. The observed r.m.s. variation is $\pm 0^m.019$ for these stars. Thus we are not in this way led to a contradiction when we assume a unique relation between initial chemical composition and age. We can sharpen

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(*) The author is much indebted to Dr. MARTIN SCHWARZSCHILD for comments on this question. The following two paragraphs were added to the original paper in order to clarify a point raised by Dr. SCHWARZSCHILD.

the argument somewhat by considering individual stars of low m in our group. As an example take the case of 28 Boo with $\Delta m = -0^{m}.033$ from the normal value for its color. The c-l classification indicates that the star is not likely to be older than 1×10^{9} years, and it is then unlikely that the Δm is accounted for by the age effect. However, with the small number of stars at present available for this type of reasoning the argument is of course not strong.

Let us finally consider the relatively young stars of the Pleiades cluster. These stars have m-indices close to the average for population I (cf. the last column in Table 4). Their age is probably less than 300 million years (perhaps considerably smaller). We now compare the Pleiades stars with the stars of large m (cf. Tables 1, 2 and 5). The latter stars could be younger, but at most, say, 200 million years younger, and the secular increase in m during this time is less than $0^{m}.004$. Probably the age effect is much smaller, or even of opposite sign (if the stars considered are on the average older than the Pleiades). In other words, at most only a small fraction of the excess in m for these stars over that of the Pleiades could be accounted for as an age effect. We are led to the conclusion that there is in the galactic neighbourhood a detectable scatter in initial chemical composition among stars of the same age.

It is hardly necessary to emphasize the tentative nature of this latter conclusion. However, there is hope that further investigations along these lines may lead to more information regarding the correlation between epoch of formation and chemical composition at formation for stars of our galaxy.

REFERENCES

[1] J. W. CHAMBERLAIN and L. H. ALLER, Ap. J., *114*, 52, 1951.

[2] W. S. ADAMS, A. H. JOY, M. L. HUMASON, and A. M. BRAYTON, Ap. J., *81*, 187, 1935.

[3] W. W. MORGAN, P. C. KEENAN and E. KELLMAN, *An Atlas of Stellar Spectra*, University of Chicago Press, 1943.

[4] G. P. KUIPER, Ap. J., *91*, 269, 1940.

[5] N. G. ROMAN, A. J., *59*, 307, 1954.

[6] J. L. GREENSTEIN, Third Berkeley Symposium (Ed. J. NEYMAN), Vol. 3, p. 11, 1956.

[7] H. L. JOHNSON, Third Berkeley Symposium (Ed. J. NEYMAN), Vol. 3, p. 31, 1956.

[8] D. M. POPPER, Ap. J., *105*, 204, 1947.

[9] B. LINDBLAD, Ap. J., 55, 85, 1922.

[10] W. BAUM, A. J., *57*, 222, 1952.

[11] P. C. KEENAN and G. KELLER, Ap. J., *117*, 241, 1953.

[12] M. and B. SCHWARZSCHILD, Ap. J., *112*, 248, 1950.

[13] M. SCHWARZSCHILD, L. SPITZER, Jr. and R. WILDT, Ap. J., *114*, 398, 1951.

[14] N. G. ROMAN, Ap. J., *112*, 554, 1950.

[15] T. L. SWIHART, Ap. J., *123*, 151, 1956.

[16] A. REIZ, Ap. J., *120*, 342, 1954.

[17] F. HOYLE and M. SCHWARZSCHILD, Ap. J. Supplement Series, Vol. 2, No. 13, 1955.

[18] B. BELL, Harvard University, Special Report No. 35, 1951.

[19] P. NAUR, Ap. J., *122*, 182, 1955.

[20] Cf. A. J., *58*, 276, 1953.

[21] H. L. JOHNSON and C. F. KNUCKLES, Ap. J., *122*, 209, 1955.

DISCUSSION

CHAIRMAN: L. SPITZER

MORGAN

I could see no difference at all between the spectrum of BD 29° 2360 and that of a normal star, but the spectrum should be examined in the region in which it was measured. The difference must show up; it could not be a blending effect. I should like to make a general comment about these weak-line stars. RR Lyrae and a very weak-line F star first appeared in the Yerkes Atlas with the designation of weak metallic lines. The spectral classification of RR Lyrae was at first misassessed but moved into the F class, because of the presence of the G band.

With regard to Miss ROMAN's work: the general character of weak-line spectra in the very high-velocity F stars is established. The other category discussed by her in the Astrophysical Journal is a phenomenon of a lower order of obviousness. In all F stars one has a background of arc metallic lines gradually becoming more intense as the spectral type becomes later. If one misclassified an F7 star and called it F8 one might later wrongly classify it as a weak-line star. Some stars of moderate weak-line characteristics there undoubtedly are, but I would not rely absolutely on all of those in Miss ROMAN's list. The kinematic correlation might be explained partly by the presence of a few extreme examples that will affect the mean.

SCHWARZSCHILD

Is the separation of weak-line giant stars easier?

MORGAN

The weak-line stars of type K with weakened CN bands are real. Observations made on bands are much more secure. Miss ROMAN was not satisfied with all the criteria of the Yerkes atlas and her classification was not exactly the same as mine. She used the H lines which are sensitive to changes in luminosity.

LINDBLAD

How does the *m* index vary for later types?

STRÖMGREN

It has not been applied to these because narrow-band photoelectric photometry of the hydrogen indices has not been carried out here, but it should be a useful index.

SPITZER

If the difference of index between the normal and the BD star were due to an effect of the continuum, would this be observable in the spectrum?

MORGAN

It should certainly show up in photometric traces of the appropriate region. I am completely puzzled by this star.

HERBIG

Could the BD star be composite? Say, an F and a G star?

STRÖMGREN

Duplicity does not usually contribute much to variations of the *m* index. In the case of the brighter stars, there would be information regarding duplicity from other investigations but not necessarily for fainter stars like BD +29° 2360. The question should be further investigated for this star.

NASSAU

What was the peculiarity which HARRIS noted in this star?

Strömgren

A large discrepancy in the *U-B* value.

Sandage

Are *l-c* indices available which would place HD 19445 on the absolute magnitude-colour diagram?

Strömgren

They are but, in order to derive an absolute magnitude, one has to use an extrapolated calibration which has not much value, but would place it a little below the main sequence as we should expect.

Sandage

In the *B-V, U-B* diagram, HD 19445 lies almost exactly on the line followed by the F dwarfs in M 3. The absolute magnitude of this star may, therefore, be of interest for the globular cluster problem.

Thackeray

Does your value for cosmical scatter agree with the upper limit you found 2 or 3 years ago?

Strömgren

That upper limit referred to the *B-V* calibration, and it is confirmed by the more recent results. The diagram shows the effects of cosmical scatter for *B-V*. The residuals are only a little greater than the instrumental ones, but there seems to be a small effect present. For the M_v the residuals from the trigonometrical parallaxes are also slightly greater than the photometric error. I might mention the cosmical scatter of B stars obtained by comparing *l-c* classification and absolute magnitudes with those derived by Petrie's photometry. When the best absolute magnitudes available — those of Blaauw — are used, we find a residual scatter of $\pm 0^{\mathrm{m}}.3$ (p.e.) instead of $\pm 0^{\mathrm{m}}.15$ (p.e.). This scatter is of course not attributable to metal content. It might be an indication of a variable H-He ratio, but the evidence is not conclusive. If you take the whole Scorpio Centaurus material you get this scatter. If you narrow the range on the main sequence and so eliminate field stars and spectroscopic binaries, the scatter is $\pm 0^m.22$ (p.e.), not so much greater than the photometric p.e.

SCHWARZSCHILD

If in fact the third parameter is independent we may have to leave the simple picture in which Z is a unique function of age. So it is very important to know if the index m is independent of l and c.

STRÖMGREN

In this range m is very nearly independent of l and c, as far as systematic variations are concerned. The observed variations must be attributed to variations of some parameter that can assume different values when l and c are the same.

SCHWARZSCHILD

If you plot the HR diagram and take age as a third parameter, the stars in question fall in an awkward part of the curve which might make the result less definite.

STRÖMGREN

What is observed is that when l and c are the same m differs, but it may be difficult to pass from l and c to age and mass, as they might not have an unambiguous correspondence.

SANDAGE

Can you comment about M 13, which should be low in metals according to the evolutionary tracks of HOYLE and SCHWARZSCHILD, but has no *U-B* excess? This might suggest that there is not a unique relation between the internal metal content and the *U-B* excess.

STRÖMGREN

The only way to account for a deviation from the standard evolutionary track may be in terms of helium content.

SPITZER

Is the intrinsic scatter greater for weak-line than for strong-line stars?

STRÖMGREN

There is not enough evidence from strong-line stars to be sure.

MORGAN

Is there a systematic variation of spectral type with the value of the index m in your table of faint-line stars?

STRÖMGREN

No, the variation in spectral type is small, and not systematic. The m index does not vary with spectral type.

SPITZER

If there is no further discussion NASSAU has a motion to present to us.

NASSAU

This would perhaps be a good time to present a matter of some importance. I should like to propose that we elect Father O'CONNELL as Editor of the papers and discussions we are having this week.

(This motion was seconded and carried unanimously).

NUCLEAR PROCESSES AND ELEMENT SYNTHESIS IN STARS

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It has become increasingly apparent in recent years that there are serious difficulties in the theory of the origin of the elements in a primeval event in which neutron decay and capture process took place in the early phase of the expansion of the universe. Recent experimental research in nuclear physics has served to confirm in an unequivocal way the long suspected fact that stable isobars do not exist at atomic mass five and atomic mass eight [1]. A simple chain of neutron captures, interspersed with beta decays, is thus not a possible mode of element synthesis.

It was early shown by FERMI and TURKEVITCH [2] that this problem could not be solved by considering processes involving interactions between the isotopes of hydrogen and helium which resulted from the first neutron decays and captures. This failure arose primarily because of the low density of matter (10^{-7} grams per cm^3), assumed by GAMOW and his collaborators [2], at the time of nucleogenesis, some five hundred seconds after the start of the universal expansion. On the other hand, recent experiments on the $3\text{He}^4 \rightarrow \text{C}^{12}$ process [3] have shown that there exists no difficulty in synthesizing the light elements if densities $\geq 10^5$ grams per cubic centimeter and temperatures $\geq 10^8$ degrees are assumed. Recently, HAYASHI and NISHIDA [4], in Japan, have attempted to develop a theory of the synthesis of the light elements in a primeval "matter" universe of high material density (10^6 to 10^7 grams per cm^3) and temperature (10^9 to 10^{10} degrees K) as contrasted to the high radiation density of GAMOW. They and their collaborators are continuing this line of endeavor by following the light element reactions with neutron capture synthesis of the heavy elements. Their assumption of a primeval "matter" universe raises interesting problems in relativistic cosmology.

At the same time it has become clear that the abundance distribution of the heavy elements, which agrees in its general features with the predictions of a neutron capture theory, would seem to require two quite distinct sets of physical conditions and time-scales for the operation of the capture processes. This important feature has been made most strikingly manifest in the remarkable analysis of element abundances by SUESS and UREY [5] who have employed relative isotopic abundances to determine the trend and slope of the universal, cosmic abundance curve as a function of atomic weight. As pointed out by SUESS and UREY [5] and as emphasized by CORYELL and FONG [6], the new curve not only indicates peaks at $A \sim 90$, 139, and 208 corresponding to stable nuclei with the neutron-magic numbers $N = 50$, 82, and 126 but also a set of nearby peaks at $A \sim 80$, 130, and 194. The first set of peaks is expected to be produced in a process of neutron capture at a rate *slow* compared to the intervening beta decays; under this condition the capture path passes through many of the stable nuclei and those especially stable, because of their closed neutron shells and low-neutron capture cross sections, are produced in excess abundance. These nuclei are not produced in neutron capture processes in a primeval event restricted to a short time interval. On the other hand, the displaced peaks correspond to neutron rich, magic-number, beta-unstable nuclei which will be expected to be involved in neutron capture at a *rapid* rate compared to beta decay. Subsequent to the synthesis process these unstable nuclei will beta decay to the stable species with the same mass number. It is not presently known whether even these nuclei can be produced in a primeval event at high matter density.

In spite of the many attractive features of primeval nucleogenesis, the problems just discussed have prompted considerable experimental and theoretical study in the past few years of nuclear reactions in stars which may provide an alternative mode of nucleogenesis. Concurrent with the nuclear research have been numerous related developments in observational and theoretical astronomy and astrophysics. The evolution of stars, the differences in composition between the various stellar populations at least roughly correlated with age of the populations, and the existence of stars with peculiar abundances of certain of the elements, light and heavy, all shed considerable light upon the nuclear reactions which may take place in stars and which may synthesize or destroy elements in stellar interiors. They also pose significant problems concerning the nature of these reactions. A very general approach to the solution of the problem is the attempt to describe quantitatively the manner in which the universal or cosmic abundances of the elements may have been synthesized from hydrogen by stellar nuclear reactions.

Actually, it is well known that the "universal" elemental abundances are largely those of the sun and the solar system. However, it is agreed that the solar system is comparatively rich in the heavy elements and thus that the relative abundances of the elements observed in the system must hold the key to an understanding of at least a majority, if not all, of the nuclear processes which can take place in stars.

A complete quantitative check on the great variety of nuclear reactions which are necessary will be possible only when more exhaustive experimental information is available on nuclear reaction rates, notably those of neutron capture processes, and on nuclear masses and binding energies, particularly of the nuclei in the rare-earth region. Nevertheless it has been possible to make some progress in the past few years. What follows is in the nature of a progress report on the work, during the period, by the author in collaboration with J. L. GREENSTEIN [7], E. M. BURBIDGE, G. R. BURBIDGE, and F. HOYLE [8]. New experimental results obtained in the Kellogg Radiation Laboratory and elsewhere are discussed briefly.

The following stellar nuclear processes are found to be necessary in order to account for the abundances of the elements in the solar system and nearby stars; comments in regard to recent developments in these processes are included:

1) *Hydrogen burning by which hydrogen is converted into helium.*

The recent detection of the free neutrino at Los Alamos [9] leads to increased confidence in the theory of the so far unobserved *pp*-process, which involves neutrino emission. This process makes possible the synthesis of the heavier elements starting with pure primeval hydrogen. New experimental evidence is now available for determining the Gamow-Teller beta-decay constant which occurs in the rate of the $H(p, \beta^+ \nu)D$ reaction. New evidence is also available on reaction rates in the CN-cycle and the NeNa-cycle although it is still only possible to set upper and lower limits on the overall rate of the important CN-cycle. These new hydrogen burning reaction rates are discussed in detail in Ref. 8.

2) *Helium burning by which helium is converted into carbon, oxygen, and neon and by which neutrons are made available in stellar interiors.*

We have been able in our laboratory [3] to demonstrate the existence of an excited state of C^{12} which serves as an intermediate resonance in the conversion of helium into carbon by the Salpeter process, $3He^4 \rightleftarrows C^{12*}(\gamma)C^{12}$. As predicted by HOYLE, this state enhances the rate of the overall process so that it occurs rapidly in the advanced stages of Red Giant evolution when the internal density reached 10^5 grams/cm^3 and the temperature reaches 10^8 degrees. It makes possible in stars the bypassing of the stumbling blocks in element synthesis at mass five and mass eight. Indirect evidence has also been obtained which makes possible the calculation of the reaction rate under stellar conditions of the $C^{12}(\alpha, \gamma)$, $O^{16}(\alpha, \gamma)$, $C^{13}(\alpha, n)$ and $Ne^{21}(\alpha, n)$ processes. The latter two processes are of especial significance in that they are exothermic reactions which supply neutrons for heavy element synthesis in stars and supernovae.

3) *The α-process by which the "alpha-particle" nuclei up to* Ca^{40} *are produced from* C^{12}, O^{16}, *and* Ne^{20}.

As nuclear machines for the acceleration of heavy ions come more and more into use it is expected that experimental evidence will become available on the details of this process. The α-process takes place in the advanced stages of giant evolution [8].

4) *The e-process by which the iron-group nuclei are produced under equilibrium conditions at temperatures near* 4×10^9 *degrees.*

With this temperature and a proton/neutron ratio of 300 as empirically determined parameters, we have been able to account for the relative abundance distributions of sixteen isotopes of V, Cr, Mn, Fe, Co, and Ni with an average deviation of only a factor of two [8]. The high temperature necessary to produce the iron-group nuclei may have occurred in the cores of Type I and Type II supernovae and part of the core material may have been ejected during the explosion of the envelope material.

5) *The s-process by which the abundant light isotopes of the intermediate and heavy elements are built by neutron addition to the iron-group nuclei or the light nuclei at a rate slow compared to the intervening beta decays.*

These isotopes are the well-known "shielded" isotopes which cannot be produced in a rapid neutron-capture process involving neutron-rich nuclei as originally postulated in the primeval theory. The *s*-process we associate with giant stars that evolve in approximately 10^7 years, the individual neutron captures requiring 10 to 10^5 years. We regard the observed presence of technetium, with its longest lived isotope, Tc^{99}, having a half-life of 2.1×10^5 years, in the atmosphere of the giant S-type stars as a demonstration that the building of very heavy elements by neutron addition actually takes place in stars. Giant stars which have mixing between core and envelope will show overabundances of *s*-process elements but not of *r*-process elements discussed in the next paragraph. Overabundances may thus be expected in the elements which have stable isotopes with closed neutron shells such that they are produced abundantly in the *s*-process. These elements are Sr, Y, Zr, Ba, La, Ce, Pr, Nd, Pb and Bi.

6) *The r-process by which the neutron-rich isotopes of the heavy elements are built by neutron addition to the iron-group nuclei at a rapid rate compared to the intervening beta decays.*

The *r*-process we associate with the explosion of supernovae, the time-scale being as short as 10 to 100 seconds. We regard the observed 55-day decay of the light curves of Type I supernovae as giving strong support to this view, for an explanation of this decay seems to demand the building of Cf^{254} in a process of very rapid neutron addition. The 55-day spontaneous fission decay of Cf^{254} in the thermonuclear test at Bikini in November 1952 demonstrates that rapid neutron capture can surmount spontaneous radioactivity [10]. In spite of the extreme provincialism implied, we have been able to find no other nucleus with the unique property of Cf^{254} – a 55-day half-life decay by spontaneous fission in which some 220 million electron volts of energy is released with little or no competition by low-energy alpha-particle decay [11]. A recent determination of the Cf^{254} half-life by Huizenga and Diamond [12] yields the value 56.2±0.7 days. The stable elements produced most abundantly in the *r*-process are Se, Br, Kr, Te, I, Xe, Cs, W, Re, Os, Ir, Pt, Au, and Pb. The parents of the naturally radioactive series, Th^{232}, U^{235}, and U^{238} are produced only in the *r*-process.

7) *The p-process in which the rare, light proton-rich isotopes of the heavy elements are built by modification of a small proportion of the products of the s- and r-processes in a hydrogen-abundant region at high temperature* ($\sim 2.5 \times 10^9$ *degrees*).

With the *p*-process as a rare supplement to the *s*- and the *r*-processes we have found it possible to give a reasonable, quantitative account of all but a few of the many hundreds of isotopes of the heavy elements including the naturally radioactive species [8].

8) *An additional process or processes, not entirely understood, by which D, Li, Be, and B are produced.*

Nuclear reactions at high energy in "hot" spots in the surfaces of magnetic stars have been suggested as a possibility. The bombardment of the expanding, cooling envelope of a supernova by neutrons ejected from the collapsing core is another possibility for deuterium.

ELABORATION OF THE *r*-PROCESS

Because of its special significance in connection with the problem of stellar populations, some elaboration will be made on the *r*-process. There are good reasons to believe that α, n-reactions provide an intense flux of neutrons ($\sim 10^{32}$ per cm^2 sec) in a Type I supernova explosion. Heavy elements ($A > 60$) are synthesized primarily from the iron-group elements in the supernova envelope, by a rapid succession of neutron captures interspersed with negative beta decay. The capture path in the charge-mass (Z-A) plane passes through unstable neutron-rich nuclei whose neutron-binding energies (~ 2 Mev) are such that equilibrium is reached between the (n, γ) and (γ, n) processes involving these nuclei at the temperature ($\sim 10^9$ degrees) and neutron density ($\sim 10^{24}$ per cc) at which synthesis takes place. Abundances have been assumed to be proportional to the beta-decay lifetimes ($\tau_\beta \sim W_\beta^{-5}$) which have been calculated for these nuclei by using extrapolations of empirical beta-decay energies (W_β).

Reasonable agreement is found with the abundances of SUESS and UREY [5] for the neutron-rich stable isobars at a given A which result from the subsequent beta decay of the nuclei produced at A. The abundance peaks at $A \sim 80$, 130, and 194 due to neutron-magic numbers $N = 50$, 82, and 126 are reasonably well reproduced. The critical dependence of the shape of these peaks on the conditions at synthesis raises the question whether the observed neutron-rich heavy nuclei of the solar system might have been produced in a single supernova. If the dilution of the products of a single supernova by mixing with interstellar hydrogen did not exceed 10^4 this hypothesis is capable of accounting for the abundance of the *r*-process elements in the solar system and nearby stars. On the other hand the sharp abundance peaks may also be accounted for by assuming that some mechanism establishes quite similar conditions of temperature and density in all Type I supernovae. In this case the galactic abundance of *r*-process elements would be the same as in the solar system.

It must be emphasized that the *r*-process will most markedly change the abundance in supernova envelopes (e. g. Crab Nebula) of the iron-group elements (partial or total depletion) and of the heavy elements (considerable enhancement). The effect of the r-process on the abundance of the lighter elements from C to Ca is difficult to calculate but in particular the overall abundance of these elements may not be changed.

Supernova synthesis is capable of building radioactive elements and we have calculated the relative abundance of the progenitors which decay to U^{235} and U^{238} by subsequent beta and alpha decay. The production ratio is $U^{235}/U^{238} = 1.64$, assuming spontaneous fission occurs rather than alpha decay for A (odd) ≥ 259, A (even) ≥ 250. From the present U^{235}/U^{238} ratio and the relative decay rates, it is thus possible to calculate the date of a single-event synthesis as 6.6×10^9 years ago. Synthesis in a series of supernovae requires an even longer time-scale ($\sim 10^{10}$ years).

The time-scale for element synthesis suggested by the above considerations concerning the uranium isotopes and, in addition, by the relatively slow rate of at least the early stages of element synthesis in stars, may indicate a somewhat longer time-scale than the presently adopted one for the galaxy. The minimum age of 6.6×10^9 years indicated above is considered to be significantly greater than the age of the solar system, 4.5×10^9 years, and is comparable to the ages assigned to the oldest globular clusters [13].

REFERENCES

[1] F. AJZENBERG and T. LAURITSEN, Revs. Modern Phys., *27*, 77, 1955. This review article includes summaries of all experimental work at mass five and mass eight.

[2] R. A. ALPHER and R. C. HERMAN, Revs. Modern Phys., *22*, 153, 1950. The unpublished results of FERMI and TURKEVITCH are incorporated in this review paper.

[3] COOK, FOWLER, LAURITSEN, and LAURITSEN, Phys. Rev., *107*, 508, 1957.

[4] C. HAYASHI and M. NISHIDA, Prog. Theo. Phys., *16*, 613, 1956.

[5] H. E. SUESS and H. C. UREY, Revs. Modern Phys., *28*, 53, 1956.

[6] C. D. CORYELL and P. FONG, private communications.

[7] W. A. FOWLER and J. L. GREENSTEIN, Proc. Natl. Acad. Sci. U. S., *42*, 173, 1956.

[8] E. M. BURBIDGE, G. R. BURBIDGE, W. A. FOWLER, and F. HOYLE, Revs. Modern Phys., *29*, 547, 1957. For the original, basic studies of stellar nucleogenesis see F. HOYLE, Astrophys. J. Suppl., *1*, 121, 1954.

[9] COWAN, REINES, HARRISON, KRUSE, and MCGUIRE, Sci., *124*, 103, 1956.

[10] FIELDS, et al., Phys. Rev., *102*, 180, 1956.

[11] BURBIDGE, HOYLE, BURBIDGE, CHRISTY, and FOWLER, Phys. Rev., *103*, 1145, 1956.
BAADE, et al., Pub. Astr. Soc. Pac., *68*, 296, 1956.

[12] J. R. HUIZENGA and H. DIAMOND, Phys. Rev., *107*, 1087, 1957.

[13] C. B. HASELGROVE and F. HOYLE, M.N.R.A.S., *116*, 527, 1956.

THE ASTROPHYSICAL IMPLICATIONS OF ELEMENT SYNTHESIS

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Stars act as built-in temperature governors. Gravitational contraction serves to increase the internal temperature. Now gravitational contraction will always take place unless the loss of energy by radiation from the surface is being compensated by the generation of nuclear energy. This means that a star can always adjust itself to bring a nuclear fuel into operation. If the temperature is not high enough for the fuel to be operative, contraction occurs, the temperature is raised, and this continues until the fuel does come into operation.

These are many possible nuclear fuels: hydrogen, helium, carbon, oxygen, nitrogen, neon, . . . Each fuel requires a different temperature for its effective operation. The temperature in the interior of a star is always adjusted to the particular fuel requiring the lowest temperature — the particular fuel that happens to be present, that is to say. This feature allows us to adopt a temperature sequence.

1) Hydrogen-burning, $\sim 10 < T_6 < \sim 50$
2) Helium-burning, $\sim 100 < T_6 < 250$
3) C,N,O,Ne-burning, (α process), $T_6 \sim 1000$
4) All elements to iron group (e process), $T_6 \sim 3000$.

The *s* process is believed to occur at stage (2), the *r* process at and perhaps before stage (4).

I would like to confine my remarks to stages (1), (4), to the two extremes in the temperature sequence. Firstly I would like to show a comparison (Figure 1) between abundances calculated for elements of the iron group and the observed solar abundances (taken together with terrestrial isotopic ratios). The agreement from atomic weight 50 to atomic weight 62 is very good indeed. The data used in the calculations comprise the nuclear masses, and the nuclear spins and energy levels. The nuclear masses are not known to within a precision of more than 200 kv. It is interesting that the mean deviation between

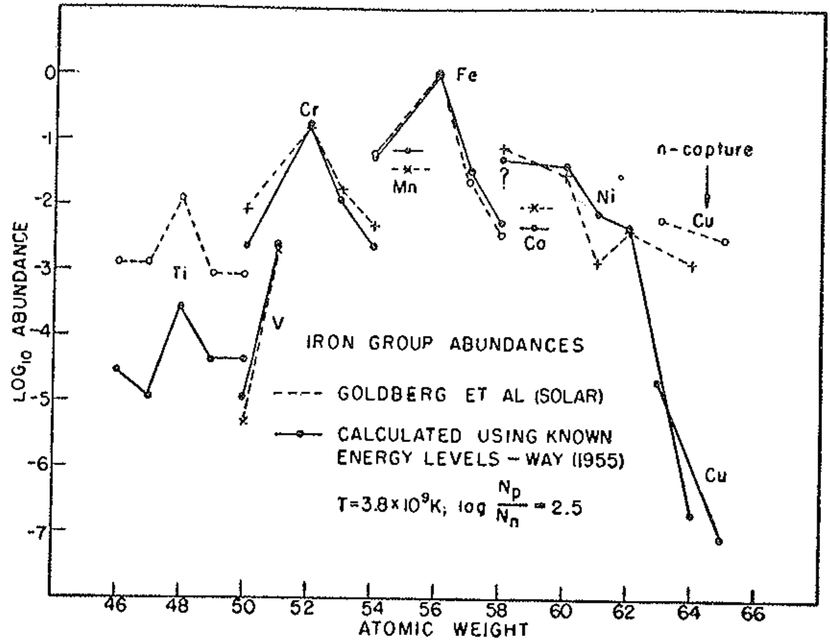

Fig. 1 — Calculated abundances for elements of the iron group compared with the observed solar abundances (taken together with terrestrial isotopic ratios).

calculated and observed values (for $50 \leqslant A \leqslant 62$) corresponds to just what would be expected from an uncertainty of this amount in the nuclear masses.

Figure 1 shows that the *e*-process fails to explain the observed abundances when $A < 50$, $A > 62$. There is no surprise here, for the decline from the peak at $A = 56$ then brings us down to the abundance level of the *s*-process.

Now in what sort of stars does the *e*-process take place? Clearly only in stars at a very advanced evolutionary phase can temperatures exceeding 3×10^9 °K be expected to arise. Tentatively we associate such stars with those that are approaching the supernova state (Type I). Physical reasons can be advanced for this point of view. Here, however, the astronomical rather than the physical implications will be considered.

At the usully accepted rate of 1 supernova of Type I per 300 years, the total number occurring during the lifetime of the Galaxy $\sim 2 \times 10^7$. As a tentative, but entirely feasible, estimate suppose that each supernova yields a mass $\mathfrak{M}_\odot/10$ in the form of *e*-process elements, then the total production of iron group elements comes to $2 \times 10^6\ \mathfrak{M}_\odot$. This is sufficient to produce the degree of contamination found in Population I objects (solar neighbourhood) throughout a total mass of $\sim 2 \times 10^9\ \mathfrak{M}_\odot$, in good agreement with OORT's estimate of the present day mass of the interstellar gas. It is also sufficient to produce extreme Type II contamination (halo population) for a total mass of $\sim 5 \times 10^{10}\ \mathfrak{M}_\odot$, which is comparable with the mass of the whole Galaxy. It is not sufficient, however, to produce the contamination of the disk population II, if the latter stars are taken to possess metal abundances more similar to stars of the solar neighbourhood than to stars of the halo. Our total production in the latter case is too low by a factor ~ 10, and we should then be forced either to accept a higher value for the *e*-process production per supernova ($\geqslant \mathfrak{M}_\odot/10$), or to assume that the incidence of supernovae was appreciably greater in the past than it is at present ($\sim$ 1 supernova per 50 years).

Curiously enough, somewhat similar considerations arise when the initial nuclear stage of hydrogen-burning is considered. Stars of the solar neighbourhood seem to possess about 25% by mass in the form of helium. It this helium abundance is confined to a minor component of the Galaxy, to a component with mass comparable to OORT's value for the present day interstellar gas, the total helium production $\sim 5 \times 10^{8}\ \mathfrak{M}_{\odot}$. Now the total energy given by converting $5 \times 10^{8}\ \mathfrak{M}_{\odot}$ of hydrogen to helium $\sim 6 \times 10^{60}$ ergs. Over a lifetime of $\sim 2 \times 10^{17}$ sec for the Galaxy, this gives a mean energy production $\sim 3 \times 10^{43}$ ergs/sec, corresponding to about -20 for the average absolute bolometric luminosity of the Galaxy.

If, on the other hand, we have to provide for a 75% He content, not in a mass of only $2 \times 10^{9}\ \mathfrak{M}_{\odot}$, but throughout a mass ten times greater than this, the mean absolute bolometric luminosity comes out at $-22{\cdot}5$, considerably in excess of the present luminosity, even if we allow a 1^{m} bolometric correction for the light produced by the red giants.

To sum up we can ask the question:

Is the composition of the disk population more similar to spiral arm population I or to halo population II? If to the latter, then the present rate of production by the *e*-process and by hydrogen burning are adequate to explain the production of the nuclei concerned. If the former, then we seem to have evidence, not unequivocal it is true, but not insignificant either, that the disk population II stars were produced in an early phase in which stellar activity exceeded the present activity by a factor of the order of 10, in which the activity was of the same order as we observe at the present day in the Large Magellanic Cloud.

DISCUSSION

CHAIRMAN: L. SPITZER

BAADE

Should you not consider supernovae of type II rather than those of type I which, according to our best knowledge, are old stars? Supernovae II are associated obviously with stars of large mass because they occur only in the spiral structure. Cas A is an example in our own Galaxy. You would have also right away greater frequency and you would eject larger masses.

HOYLE

Probably type I occurred over a mass range from 2.0 down to perhaps 1.5 times the Sun. I would be glad to use type II, but I thought you would say that they would not throw off sufficient material. If they can give an increase of 10 this would be fine. The difficulty about helium still remains, however.

SCHWARZSCHILD

Putting things in a conservative way HOYLE and FOWLER have shown what combination of temperature and density will produce the heavy elements. This is a great step forward. To locate where these conditions exist is the next step, and we can hope that they are right in believing that this is the interior of stars. The evidence for the increase in heavy elements with the age of the galaxy supports this. However, it does not necessarily mean that He production occurs mainly in stars. GAMOW's mechanism may work up to mass 4.

HOYLE

That is why a knowledge of the He concentration in extreme population II is so important.

FOWLER

It is amusing to note that the only process which we are really certain occurs in stars, namely 4 H → He, is assigned by SCHWARZSCHILD to a primeval event.

LEMAÎTRE

How sure can we be that hydrogen was the starting point? The construction of the elements by a building up process is itself an assumption, though it is interesting that even the heaviest elements like Californium can be explained in this way. I have never thought in this way, but believed that the primeval universe would begin with something simpler.

FOWLER

There seems to be accumulating evidence that the nuclear physics of build-up processes from hydrogen does fit the "universal" abundance distribution of the elements. The sample of the universe which is available to us has at least been seriously modified by neutron capture, for example. However, the Japanese group at Kyoto is looking very hard at the idea of primeval nucleogenesis in a way quite distinct from that of GAMOW. Their primeval conditions of temperature and density are very similar to those in stellar interiors.

HOYLE

In the sense of nuclear physics hydrogen and helium are the most unstable elements, since their fusion supplies more energy per unit mass than is the case for any other nuclei. It is strange that the least stable form of matter should be so abundant if it is not the starting point.

VI.

POPULATIONS STELLAIRES DE NOTRE GALAXIE

THE STARS WITHIN 15 PARSECS OF THE SUN

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I. *Introduction*

The Yale 1952 Catalogue of Trigonometric Parallaxes contains 167 entries for stars with $\pi \geqslant 0''.100$ and entries for 407 stars with $\pi \geqslant 0''.067$. In many cases a single entry represents two or more stars of a multiple system. The discovery and parallax determination of all the stars within 10 and 15 parsecs is of course not complete. The Salpeter luminosity function gives 0.12 stars/pc^3 as the star density in the solar neighborhood. We therefore expect that the total number of stars with $\pi \geqslant 0''.100$ and $\pi \geqslant 0''.067$ should be 503 and 1700 respectively. This shows that parallax data is available for less than 30 per cent of the nearby stars. The discovery situation is even more serious for the white dwarfs. Various authors estimate that about 10 per cent of the stars in the solar neighborhood are white dwarfs. This suggests that 170 white dwarfs exist with $\pi \geqslant 0''.067$. Parallaxes for only 15 are known within this limit. Many candidates exist, but the faintness of the white dwarfs has made observations difficult.

Incomplete as the parallax catalogue is, it provides the only sample for which the color-magnitude diagram of the nearby stars can be found.

II. *The Data*

Several important studies of the nearby stars have appeared in recent years. In 1950 Eggen [1] published photoelectric observations for 78 stars within 14 parsecs of the sun. Later Eggen [2] published a much extended list and discussion of photoelectric observations for 237 stars with $\pi \geqslant 0''.049$. This list was 84 per cent complete for the stars with $\pi \geqslant 0''.049$ which were earlier than K5, for which π had been determined by two or more observatories, and which were not white dwarfs or members of binary systems with $\Delta M < 2$ magnitudes between the components. In the time after Eggen's paper, additional data have appeared for part of the remaining stars with $\pi \geqslant 0''.067$. The present report is a review of Eggen's work but includes all additional photoelectric data which have become available (closing data was February 1957). First rate photometric material is now available for 195 of the 408 entries in the parallax catalogue with $\pi \geqslant 0''.067$. The 195 entries contain data for 204 individual stars. Over 90 per cent of the remaining 213 stars which have not been observed are dK5 or later. Therefore, the photoelectric data is nearly complete for stars in the Yale π Catalogue earlier than dK5 with $\pi \geqslant 0''.067$.

All data have been reduced to the M_v, $B\text{-}V$ photometric system of Johnson and Morgan. The transformation equations $B\text{-}V = 0.965\ (P\text{-}V)_E + .121$; $V = V_E$ (Eggen [2]) were used to convert Eggen's magnitudes and colors to V and $B\text{-}V$. The data for the white dwarfs are from D. L. Harris [3].

III. *The Color-Magnitude Diagrams*

Figure 1 shows the M_v, $B\text{-}V$ diagram for stars with $\pi \geqslant 0''.100$. Probable errors of the magnitudes are shown as vertical lines. They were computed as if the error in the parallax was the only contributor. The probable error due to

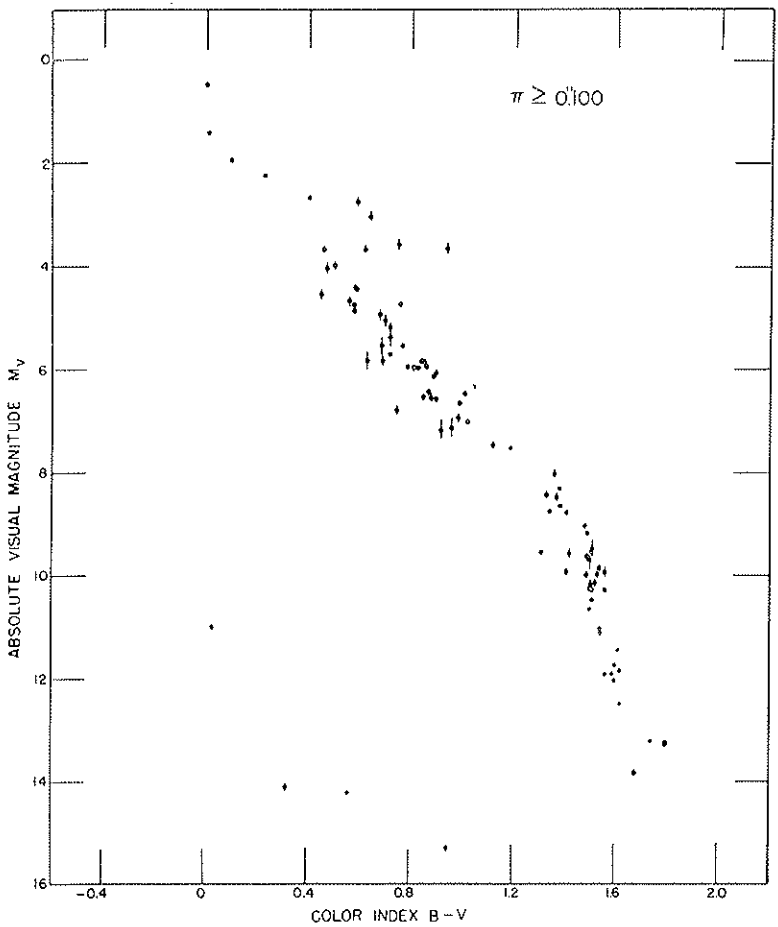

FIGURE 1 — The color-magnitude diagram for stars within 10 parsecs of the sun. The probable errors of the magnitudes are computed as if the entire error was due to $\delta\pi$.

photometric errors in the apparent magnitudes are 0.02 magnitudes or less and are negligible.

Three features of Figure 1 should be noted. (1) Four white dwarfs are present. The brightest is σ^2 Eri (40 Eri B) at $M_v = 11.00$, $B\text{-}V = 0.03$. The faintest is Wolf 489 at $M_v = 15.27$, $B\text{-}V = 0.96$. Nine white dwarfs are known with accurate parallaxes within 10 parsecs. Only the four with adequate photometric data have been plotted. (2) A few subgiants begin to appear between $M_v = +3.0$ and $M_v = +4.0$. The five conspicuous stars which lie above the main sequence are, in order of their brightness, η Boo, ζ Her, μ Her A, δ Eri, and β Hyi. (3) A few subdwarfs are present which lie one magnitude or less fainter than the main sequence. The three most conspicuous subdwarfs are γ Pav at $M_v = 4.53 \pm 0.16$, $B\text{-}V = 0.45$; ζ^1 Ret at $M_v = 5.84 \pm 0.24$, $B\text{-}V = 0.63$; and Groombridge 1830 at $M_v = 6.78 \pm 0.09$, $B\text{-}V = 0.75$. The first two can be observed only from the southern hemisphere. (EGGEN obtained the photometric data for southern objects during his visit to Mount Stromlo in 1951). It is interesting that ζ^2 Ret forms a common proper motion pair with ζ^1 Ret. These stars are 310 seconds of arc apart. The measured parallaxes are not identical (π for ζ^1 Ret$=0''.106 \pm 0''.012$, π for ζ^2 Ret$=0''.097 \pm 0''.012$) but are close enough so that the true value could be the same. Both stars are subdwarfs.

Figure 2 shows the M_v, $B\text{-}V$ diagram for stars with $\pi \geqslant 0''.067$. The white dwarf sequence, the subgiant region, and the subdwarf region are all significant features. It is of interest to list the data for the individual white dwarfs and subgiants. Table 1 gives the astrometric and photometric data for known white dwarfs listed in the 1952 Yale Parallax Catalogue with $\pi \geqslant 0''.067$. Accurate photometric data are available for nine of these (HARRIS [3]). Table 2 gives the data from which the 18 subgiants were plotted in Figure 2.

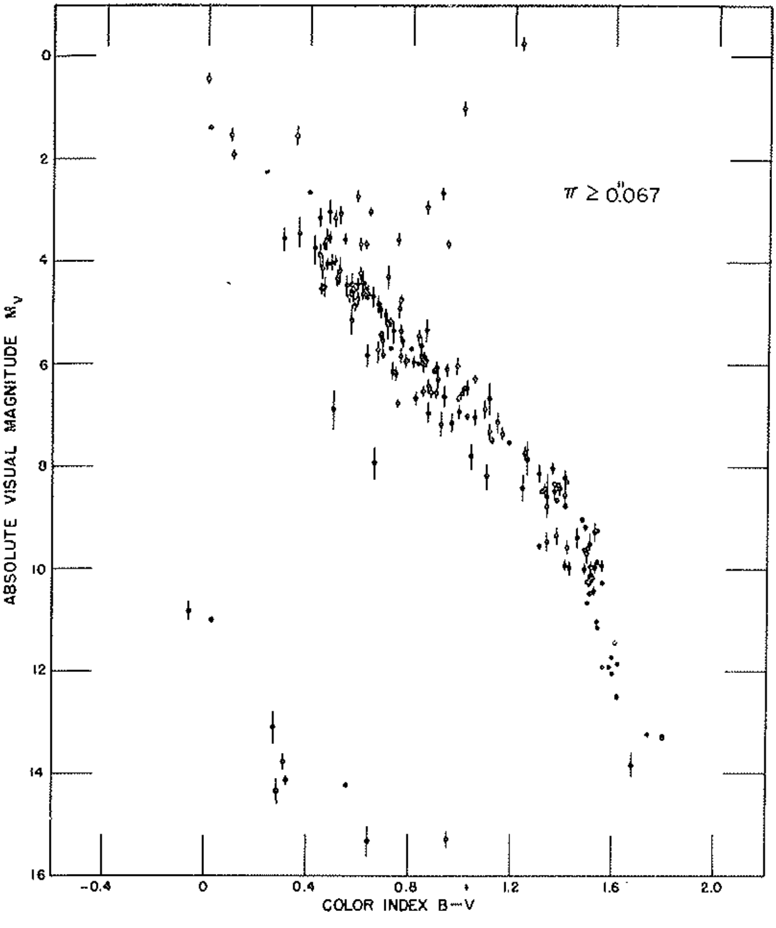

FIGURE 2 — The color-magnitude diagram for stars within 15 parsecs of the sun. The two anomalous stars intermediate between the main sequence and the white dwarfs are Yale no. 291 and Yale no. 4148. The parallaxes for these stars may be spurious.

TABLE 1

White Dwarfs with $\pi > 0''.067$

Yale No.	π	ε	V	M_v	$B-V$	*Name*
1577*	0″.375	4	—	—	—	α C Ma B
1805*	0.288	4	—	—	—	α C Mi B
160	0.236	4	12.36	14.23 ± .04	0.56	van Maanen 2
2716*	0.203	8	(12.0)	(13.54 ± .09)	(−0.1)	L 145-141
945	0.200	4	9.50)	11.00 ± .04	0.03	40 Eri B
1882*	0.170	30	(14.5)	(15.65 ± .38)	(0.5:)	L 97-12
1813	0.164	8	13.04	14.11 ± .11	0.32	LPM 269
3112	0.131	12	14.68	15.27 ± .20	0.96	Wolf 489
5808*	0.120	7	—	—		L 362-81
2642	0.080	13	14.24	13.76 ± .16	0.31	Ross 627
2976	0.078	11	15.90	15.36 ± .31	0.64	Wolf 457
4709	0.076	12	13.69	13.09 ± .34	0.27	L 997-21
4895	0.072	7	11.54	10.83 ± .21	−0.07	W 1346
3597*	0.069	8	(13.2)	(12.40 ± .25)	(0.0)	CPD-37° 6571B
791	0.068	11	15.20	14.36 ± .35	0.30)	Wolf 219

* not plotted in Figures 1, 2 or 3.

TABLE 2

Subgiants with $\pi \geqslant 0''.067$

Name	*Yale No (1952)*	π	ε	*Wt*	V	M_v	$B-V$	*Type*
α CMi	1805	0″.287	4	65	0.37	2.67 ± .03	0.40	F5 IV-V
α Aql	4665	0.198	4	63	0.77	2.25 ± .04	0.23	A7 IV-V
β Hyi	69	0.153	7	18	2.75	3.67 ± .10	0.62	G1 IV
ζ Her A	3799	0.110	4	68	2.79	3.01 ± .08	0.64	G0 IV
δ Eri	788	0.109	4	50	3.48	3.67 ± .08	0.94	K0 IV
μ Her A	4060	0.108	6	28	3.41	3.58 ± .12	0.75	G5 IV
η Boo	3175	0.102	5	35	2.69	2.73 ± .11	0.59	G0 IV
β Vir	2739	0.098	5	36	3.61	3.57 ± .11	0.54	F8 V
β Gem	1826	0.093	5	34	1.16	1.00 ± .12	1.00	K0 III
α Boo	3242	0.090	5	46	−0.07	−0.29 ± .12	1.23	K2 III p
ι Per	647	0.084	5	37	4.06	3.66 ± .13	0.60	G0 V
β Cas	16	0.072	7	23	2.27	1.55 ± .21	0.35	F2 IV
η Cep	4966	0.071	4	52	2.40	2.68 ± .12	0.92	K0 IV
μ Ara	4027	0.071	7	18	5.04	4.30 ± .21	0.71	d G0
β Aql	4705	0.070	4	57	3.71	2.93 ± .12	0.86	G8 IV
α For	664	0.070	6	29	3.86	3.09 ± .19	0.52	F6 V
γ Ser	3604	0.069	7	23	3.82	3.03 ± .22	0.48	F6 V
θ Boo	3274	0.067	6	24	4.03	3.17 ± .19	0.50	F7 V

Two stars in Figure 2 appear to be anomalous. They are numbers 291 and 4148 in the Yale 1952 Catalogue of Trigonometric Parallaxes. These stars fall two magnitudes below the normal main sequence. The astrometric data is inconclusive and must be checked before their intermediate position between the main sequence and the white dwarfs can be considered established. Both stars have parallaxes determined at only one observatory. The measured values may be spurious. For Yale 291 the Cape Observatory gives $\pi = 0''.068 \pm 0''.013$ with a listed spectral class of K0. The photometric data are $M_v = 6.90 \pm 0.41$, $B\text{-}V = 0.50$. For Yale 4148 the McCormick Observatory gives $\pi = 0''.070 \pm 0''.010$ with a listed spectral class of G0. The photometric data are $M_v = 7.92 \pm 0.31$, $B\text{-}V = 0.66$.

Figure 2 contains much information closely connected with the subject of this conference. I wish to make only two points from these data. The first concerns the position of the subgiants and the second the existence of subdwarfs.

Point 1: Figure 3 is a composite diagram. The individual stars from Figure 2 are plotted and the schematic outline of the positions of the open cluster color-magnitude diagrams are superposed. The M 67 line is the lowest with NGC 752, Hyades, Praesepe, and Coma clusters following in that order. No shift in $B\text{-}V$ or M_v was made to fit the galactic cluster data to the data of Figure 2. The fit depends on the adopted moduli of the galactic clusters.

To strengthen the data for the subgiants in the region of the M 67 sequence, ten additional stars were added to Figure 2. The stars were all subgiants or giants and are tabulated in Table 3. Seven are subgiants with $0''.067 > \pi \geqslant 0''.052$ and were taken from EGGEN's list of nearby subgiants [4]. The three giants γ Tau, ε Tau, and δ Tau were added from VAN BUEREN's cluster parallax data for the Hyades and from JOHNSON and MORGAN's photometric data.

TABLE 3

Additional Subgiants with $0''.067 > \pi \geqslant 0''.052$ *Plus Three Hyades Giants*

Name	*Yale No (1952)*	π	ε	*Wt*	*V*	M_v	*B-V*	*Type*
λ Aur	1199	0".066	6	29	4.68	3.78 ± .20	0.61	G0 V
γ Cep	5725	0.064	5	43	3.20	2.23 ± .17	1.03	K1 IV
υ And	331	0.062	5	35	4.08	3.04 ± .18	0.54	F8 V
31 Aql	4541	0.059	5	38	5.12	3.97 ± .18	0.76	G8 IV
τ Boo	3144	0.056	6	24	4.50	3.24 ± .25	0.48	F7 V
ν^2 CMa	1543	0.052	7	22	3.87	2.45 ± .29	1.10	K1 IV
σ^2 UMa	2266	0.052	8	24	4.78	3.36 ± .25	0.48	F7 IV-V
γ Tau*	—	0.0257	0.5	—	3.61	0.66 ± .05	0.99	K0 III
ε Tau*	987	0.0253	0.5	—	3.55	0.56 ± .05	1.03	K0 III
δ Tau*	965	0.0244	0.5	—	3.73	0.66 ± .05	0.98	K0 III

* Cluster parallax by VAN BUEREN, B.A.N. No. 432.

EGGEN [4] first pointed out that nine subgiants in the present data lie below the M 67 line. These are, in order of redness, β Vir, ι Per, λ Aur, β Hyi, μ Ara, μ Her, 31 Aql, δ Eri, and ν^2 CMa. The probable errors of the absolute magnitudes of these stars are given in Tables 2 and 3. The average δM_v due to the quoted $\delta\pi$ error is 0.16 magnitude. These nine stars lie, on the average, 0.7 magnitude fainter than the M 67 sequence. This difference is 4 times the probable error. The probability that nine stars could accidently be in error in the M_v, *B-V* plane by this amount is small. We must conclude that field stars do exist in the subgiant region fainter than the M 67 sequence. EGGEN has previously emphasized this point. Three stars within 10 parsecs of the sun strengthen this conclusion because of the small probable error of the quoted π. These probable errors are $\delta M_v = \pm 0.10$ for β Hyi, $\delta M = \pm 0.12$ for μ Her, and $\delta M_v = \pm 0.08$ for δ Eri. δ Eri is particularly striking. It lies 0.95 magnitudes below the M 67 sequence and has the smallest probable error of the group.

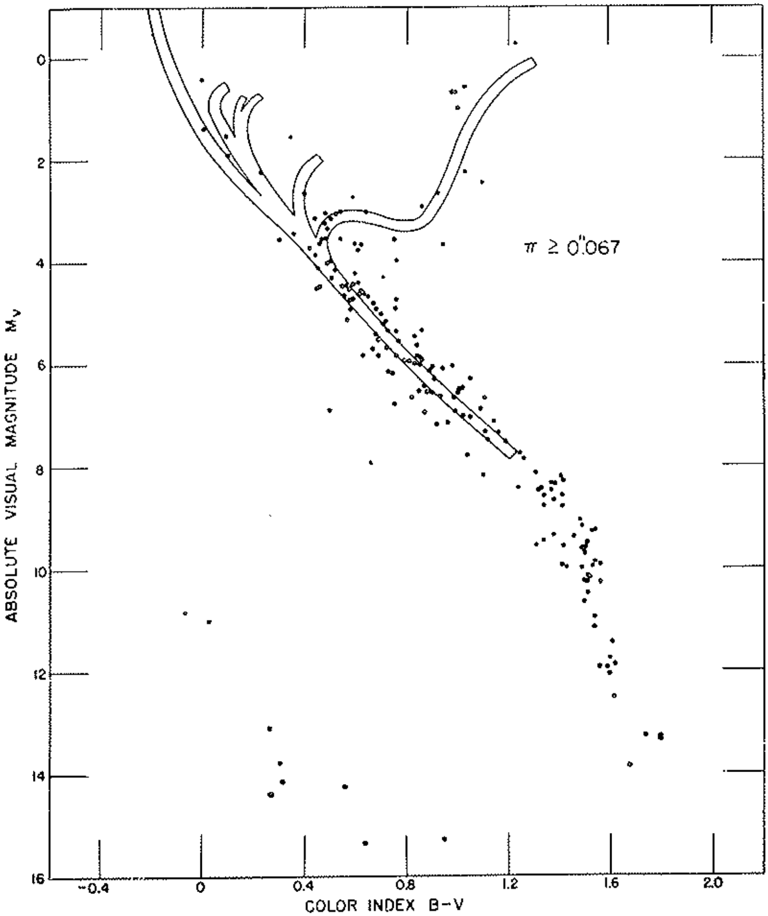

FIGURE 3 — A composite diagram showing the points of Figure 2 with the schematic color-magnitude diagrams for galactic clusters superposed. Seven stars with $0''067 > \pi \geqslant 0''052$ and three giants in the Hyades have been added to the points of Figure 2.

This group of faint subgiants is important for the problem of dating stars in the solar neighborhood. *If* these stars have followed evolution tracks parallel to those in M 67, then they are older than stars in M 67 and in globular clusters (which we believe are about 5×10^9 years old). If the main sequence termination point for these stars is 0.7 magnitude fainter than in M 67, then there is an age difference of $\Delta T/T = 0.7\ \delta M_v$ or $\Delta T = (0.7)\ (0.7)\ (5 \times 10^9) = 2 \times 10^9$ years. Either the stars actually average 7×10^9 years old or, (1) the tracks of evolution fainter than M 67 are not parallel but dip down from a brighter break point or (2) the ideas of evolution are incorrect.

It is interesting to note that these nine faint stars have a normal $B\text{-}V = f(U\text{-}B)$ relation and that GREENSTEIN's spectroscopic study of δ Eri shows no abnormal features such as weakness of metal lines. This evidence again suggests that stars exist which are older than the globular clusters but which have a high metal content. Again we are led to the conclusion that there may have been a separation of the chemical elements between the disk and the halo $\sim 5 \times 10^9$ years ago or longer — a conclusion also suggested by the evidence in the M 3 - M 67 case which was discussed earlier in this conference.

Point 2: Figure 2 shows a significant number of stars which lie below the normal main sequence. These are the so-called subdwarfs. The data support the view that there is no subdwarf "sequence" but rather a continuous band of subdwarfs ranging from 0 to 1 magnitude fainter than the normal main sequence. Subdwarfs have been discussed for many years, usually from the standpoint of the spectral class, absolute magnitude diagram (the classical H-R diagram). In the H-R plot, the subdwarfs appeared from 1 to 2.5 magnitudes fainter than the main sequence. But, as GREENSTEIN has pointed out [5], the spectral class assigned to the subdwarfs was usually too early because of the weakness of the lines. This had the effect of displacing the subdwarfs too far to the left in the H-R diagram which gave a large pseudo magnitude shift from the main sequence. This classification difficulty is partly overcome by using color indices rather than spectral types because, for a star with weak lines, a measured color is closer to a temperature scale than is an estimated spectral type.

Figure 2 shows that the subdwarfs do not lie from 1 to 2.5 magnitudes below the main sequence in the M_v, B-V plane but have a maximum difference of about 1 magnitude. However, we may still ask if even the observed B-V is a precise measure of the temperature. All subdwarfs are characterized by weaker Fraunhofer lines than normal main-sequence stars. The line-blanketing changes the measured B-V from what would have been observed in the continuum (see SCHWARZSCHILD, SEARLE, and HOWARD [6]). We can produce the observed subdwarf region if the stars are from 0 to 0.2 magnitude bluer than normal main-sequence stars, due to a difference in the blanketing. In support of this suggestion, due to SCHWARZSCHILD and his group, it is significant that JOHNSON and KNUCKLES [7] have measured both U-B and B-V for 77 stars with $\pi > 0''.050$ and find a correlation between the magnitude difference from the main sequence and the observed excess in U-B. Their $\Delta V = f[\delta(U\text{-}B)]$ relation agrees well with a correlation predicted with fractional blanketing coefficients taken from solar data (MICHARD [8]). This suggests that the subdwarfs in Figure 2 lie below the main sequence *only because* of the effect of lines on the B-V color. The consequence of this is that no subdwarfs will appear in the M_{bol}, log T_e plot when proper blanketing corrections are applied.

IV. *Summary*

(1) All available photoelectric data for stars with $\pi \geqslant 0''.067$ are presented in Figures 1 and 2. The data are mostly due to EGGEN.

(2) The data show white dwarfs in a region extending from $M_v = 11.0$, B-$V = 0.0$ to $M_v = 15.5$, B-$V = 1.0$. The entire photometric data are due to D. L. HARRIS.

(3) More than 20 subgiants exist with $\pi > 0''.050$. Nine of the subgiants average 0.7 magnitudes fainter than the M 67 sequence. If these stars have followed an evolutionary track parallel to the M 67 tracks, then they are 2×10^9 years older than those in M 67. Spectroscopic and photometric evidence for δ Eri show no deficiency in the abundance of the metals.

(4) Many subdwarfs are present in the solar neighborhood. These lie between 0 and 1 magnitudes fainter than the main sequence. JOHNSON and KNUCKLES' measurements show that the subdwarfs have an ultraviolet excess which increases with the magnitude difference from the normal main sequence. The excess, interpreted with a line blanketing model, suggests that the subdwarfs may fall on the normal main sequence in the M_{bol}, log T_e plane.

REFERENCES

[1] O. J. EGGEN, Ap. J., *112*, 141, 1950.

[2] — A. J., *60*, 401, 1955.

[3] D. L. HARRIS, Ap. J., *124*, 665, 1956.

[4] O. J. EGGEN, Pub. A. S. P., *67*, 315, 1955.

[5] J. L. GREENSTEIN, Proc. of the Third Berkeley Symposium on Statistics, Vol. III, 11, 1956.

[6] M. SCHWARZSCHILD, L. SEARLE, and R. HOWARD, Ap. J., *122*, 353 1955.

[7] H. L. JOHNSON and C. F. KNUCKLES, Ap. J., *126*, 113, 1957.

[8] R. MICHARD, B.A.N., *11*, 228, 1950.

DISCUSSION

CHAIRMAN: B. LINDBLAD

BAADE

Can the theorists say whether the stars falling below the M 67 branch can be explained by difference in chemical composition instead of by age?

HOYLE

I think it would be very difficult, but perhaps not impossible, to obtain by calculation an evolutionary track starting at +3.5 and bending downwards after leaving the main sequence so as to include δ Eridani.

SCHWARZSCHILD

SANDAGE has approached a central problem: a search for the oldest objects as a means of dating the age of the galaxies. But the age determination from clusters of one age family must always have a much higher weight than the lower envelope of a scatter of families. There are two K stars here, δ Eri and μ Her, which we should examine in every possible way to see if they have a normal evolutionary history.

BLAAUW

What are the velocities of these stars in the subgiant group?

SANDAGE

I think about 30 kilometers per second.

Blaauw

Then they share in the general galactic rotation and cannot well belong to the oldest population in the Galaxy.

Spitzer

What would the error in parallax have to be to move these two subgiants up to the M 67?

Sandage

The magnitude difference is about ten times too great to be accounted for by an error in parallax.

Schwarzschild

Does Morgan know if the spectrum is normal?

Morgan

Delta Eridani is the only well-established K subgiant midway between the giant and main sequence regions. It is leaned on heavily for calibration of spectroscopic parallaxes. Its general spectroscopic characteristics seem to be normal and are intermediate between the giants and the main sequence.

Schwarzschild

It appears that δ Eri and possibly μ Her are not abnormal in composition or velocity. If they are older than anything else in the Galaxy the simple relations I proposed yesterday would have to be abandoned.

Morgan

Would you abandon your simple relation on account of one star?

Schwarzschild

I should need at least three!

Sandage

There are at least three on the diagram!

SPITZER

I notice that all along the main sequence there is a scatter of stars appreciably above the main sequence. Although all three stars are used to define the envelope, only one of them is unmistakably very peculiar.

SANDAGE

I think it should be admitted that within 15 parsecs the deviation from M 67 is not well enough defined by the small sample of stars. When one goes to 20 parsecs, the number of subgiants fainter than M 67 increases but also the error in the absolute magnitude due to parallax errors increases. Perhaps the only convincing way to prove older age than M 67 is to find older clusters. NGC 188 is a candidate, but the colour-magnitude diagram is yet to be obtained.

LINDBLAD

One must be careful not to give too much weight to the trigonometrical parallaxes.

OORT

Can HOYLE and SCHWARZSCHILD say how certain it is that the evolutionary tracks follow exactly those of M 67? Is there no possibility of a valley?

HOYLE

Considering the approximations that were used in the calculation this is a possibility. The level of 4.0 is a little worrying because the new calculations already increase the age upwards. To explain a track breaking off at the 4th magnitude requires a great age.

HERBIG

STRUVE and his collaborators have developed a process for the evolution of close binaries involving mass exchange that results in a somewhat peculiar late-type star. Is it possible that this anomalous star δ Eri might be the result of such evolution? If so, the age difficulty would possibly vanish. Duplicity of this type might be difficult to detect observationally, so that this possibility may not be easy to dispose of.

SPITZER

There is another explanation closely related to that proposed by HERBIG for the apparent great age of these stars. If a giant loses gas by ejection shortly after it moves off the main sequence, its luminosity would be less than the computed value, and its age would appear too great. We believe that all Type I giants do eject matter. Possibly δ Eri or μ Her began this ejection at an earlier stage than other giants.

HOYLE

That might well be the case.

MORGAN

As one goes to somewhat smaller parallaxes a number of stars appear about 1½ magnitudes above δ Eridani in luminosity.

SPITZER

Does δ Eridani show rotational broadening?

HERBIG

Rotational broadening was not detected in δ Eri or μ Her in the Lick survey of line widths in later-type stars.

MORGAN

These stars would well repay detailed analysis with high dispersion.

SANDAGE

GREENSTEIN has performed a detailed analysis for both δ Eri and μ Her, as regards chemical composition, and finds that they are normal. This is not yet published.

THE POPULATION OF THE GALACTIC NUCLEUS AND THE EVIDENCE FOR THE PRESENCE OF AN OLD POPULATION PERVADING THE WHOLE DISK OF OUR GALAXY

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In my first paper (Galaxies and their Stellar Populations) I showed that the brightest stars of the disk of the Andromeda nebula, if we disregard the population of the spiral arms, are the red giants of the population II. But although they appear in huge numbers the strength of the population II is insufficient to explain the total light emitted by the disk as BAUM and SCHWARZSCHILD first pointed out two years ago [1]. More recently, MORGAN [2] concluded that in fact most of the light of the central region of the Andromeda nebula must come from "ordinary" giants because of the observed strength of the CN bands in the integrated spectrum. This is about as far as direct observations in the Andromeda nebula will lead us. For a more detailed picture of the disk population of an Sb galaxy we have to turn to our own Galaxy.

I. *The Evidence for an Old Population Pervading the Whole Disk of our Galaxy*

Even in our Galaxy the study of the disk population is beset with difficulties. Because our sun is practically in the plane of the Galaxy, large parts of the galactic disk are blotted out by obscuring clouds. Moreover, the position of the sun in a spiral arm leads to complications if we try to separate the stellar populations in our immediate neighborhood. For these reasons our present knowledge about the composition of the galactic disk is still extremely meagre, especially insofar as the large-scale picture is concerned. Nevertheless, we are in a position to answer at least a few basic questions.

The question which I would like to discuss first is whether the disk of our Galaxy contains a population II analogous to the one which we find in the disk of the Andromeda nebula. It is clear that only population II objects which are observable over large distances can provide the answer. Outstanding in this respect are the novae on account of their high luminosities and the planetary nebulae which can be detected on objective-prism plates by their Hα emissions even if they are heavily obscured. Plots of the spatial distribution of the novae in our Galaxy have been published by McLaughlin [3] and Kukarkin [4], of the planetary nebulae by Berman [5]. They show at a glance that both novae and planetary nebulae form the kind of flattened system that we should expect for the disk of our Galaxy. We must assume, therefore, that in our Galaxy the population II is not only present in the spherical halo but also in the galactic disk. But while the population II makes up the entire halo it is, as we shall see later, only one of the populations of the galactic disk.

II. *Globular Star Clusters Which are Members of the Galactic Disk*

The presence of a strong population II in the disk of our Galaxy leads at once to the question whether there are globular clusters which are members of the galactic disk. The first hint that such clusters actually exist is contained in a paper by W. Becker [6]. Becker examined the 50 globular clusters for which Mayall [7] had determined integrated spectral types and noted that in contrast to the globular clusters of early type (A and F) which occur in all longitudes the G-type globular clusters are restricted to the longitude range of the galactic center (315° to 5°) and to low latitudes. A few months ago MORGAN [2] independently called attention to this concentration of the G-type globular clusters in the region of the galactic center.

To get a clearer picture of the situation we examine briefly the concentration to the plane of the Galaxy for globular clusters of different spectral types. The 49 globular clusters for which MAYALL determined spectral types at the Crossley reflector provide the material.

In Table I they are ordered according to spectral type into 5 groups. The mean latitude of the clusters of each group is given in the third column.

TABLE I

Sp.	*n*	$\overline{\|b\|}$
A5 — A9	6	39°.0 ± 9°.8
F0 — F4	8	31°.5 ± 8°.1
F5 — F9	12	27°.3 ± 5°.6
G0 — G2	13	17°.0 ± 3°.1
G3 — G5	10	8°.5 ± 1°.5

Table I shows that, as far as concentration to the galactic plane is concerned, the first 3 sub-groups can be put together into one group A5 to F9. In fact, this group can be extended to G0. This has been done in Table II.

TABLE II

Sp.	*n*	$\overline{\lvert b \rvert}$	$\overline{\lvert z \rvert}$
A5 — G0	31	29°.3 ± 3°.7	8.1 kpc
G1 — G2	8	15°.6 ± 3°.8	4.4 »
G3 — G5	10	8°.5 ± 1°.5	1.5 »

In the last column of this Table are given the mean distances from the galactic plane for the three groups. To allow for absorption LOHMANN's [8] corrected distances of globular clusters were used. It is obvious that we are dealing with two groups of globular clusters — the well-known halo group with spectral types from A5 to about G0 which shows little, if any, concentration to the plane of the Galaxy, and a second group of spectral types G3 - G5, which is strongly concentrated to the galactic plane and which we shall call the disk group. The intermediate group, made up of spectral types G1 - G2, is probably not real but represents a mixture of the first two groups which cannot be separated because of the limited accuracy of the spectral types.

Table III, in which the sky has been divided into 3 zones of equal areas, gives a more detailed picture of the distributions of the two groups.

TABLE III

$\lvert b \rvert$	*A5 - G0*			*G1 - G2*			*G3 - G5*		
	n	$\overline{\lvert b \rvert}$	$\overline{\lvert z \rvert}$ *kpc*	*n*	$\overline{\lvert b \rvert}$	$\overline{\lvert z \rvert}$ *kpc*	*n*	$\overline{\lvert b \rvert}$	$\overline{\lvert z \rvert}$ *kpc*
0°-19°	11	11°.3	2.1 ± 0.5	5	0°.5	2.4 ± 0.5	10	8°.5	1.5 ± 0.4
20°-42°	13*	29°.3	8.9 ± 1.8	3	27°.7	7.2 ± 3.1	0	. . .	. . . . . .
43°-90°	6	62°.8	13.5 ± 2.5	0	. . .	. . . . . .	0	. . .	. . . . . .

(*) NGC 2419 omitted.

It shows that, in contrast to the halo group which is distributed all over the sky, the disk group is restricted to the equatorial zone of the Galaxy. It will therefore be strongly affected by the heavy absorption in low latitudes which can lead to the complete obscuration of clusters. The percentage of clusters lost in this way can be roughly estimated from the similar loss of the halo group in the equatorial zone. From the data given in Table III one would estimate that the number of the halo clusters in the equatorial belt should at least be tripled. This would raise the true number of the clusters of the disk group in MAYALL's material to $n \sim 30$. This number has to be doubled since the globular clusters investigated by MAYALL represent about one-half of those known. Altogether there should be about 60 globular clusters which are members of the disk group. Since their mean $\overline{|z|}$ must be considerably smaller than the $\overline{|z|} = 1.5$ kpc derived in Table III, the designation "disk group" is fully justified.

We know very little about this disk group of globular clusters since the observers have concentrated in the past on the more easily observable clusters of the galactic halo. For only one member of the disk group, NGC 6838, color-magnitude diagrams have been published by CUFFEY [9] and W. BECKER [10], but their accuracy is too low to permit definite conclusions. Our present knowledge of the physical nature of these clusters rests, therefore, entirely on their integrated spectra. That these alone set the disk clusters apart from the halo clusters has recently been shown by MORGAN [2]. Using as criteria for the spectral type the absolute intensity of Hγ on the one hand and the intensities of the strong Fe I lines on the other, MORGAN found that the globular clusters of the galactic halo have spectral types of F6 to F8 as judged by the strength of their hydrogen lines, but that the spectral type indicated by the strength of the metallic lines is about three-quarters of a spectral class earlier (the metal lines are too weak for the spectral type inferred from Hγ). In contrast to the halo clusters, those of the disk have G-type spectra (G2 to G8) and the spectral type inferred from the strength of either the hydrogen or the metallic lines is about the same. We have strong reasons to believe, as I pointed out in my first paper (Galaxies and their Stellar Populations), that the observed weakness of the metallic lines in the halo clusters indicates a real low abundance of the metals. Obviously the disk clusters have a nearly normal content of metals since for them no appreciable discordance between the spectral type from hydrogen and metallic lines exists. This would suggest that in their physical makeup they are much closer to M 67 than to the globular clusters of the halo. But we need color-magnitude diagrams of a number of disk clusters in order to get a clearer picture of their chemical composition. Such data are likely to throw a new light on the composition of the disk of our galaxy, since these clusters are undoubtedly the representatives of a population which pervades large parts of the galactic disk.

III. *The Population of the Galactic Center Region*

A typical feature of the Sa and Sb galaxies are the spheroidal systems which occupy the center regions of these galaxies. To get information about the composition of the center region of our own Galaxy, I have investigated a field at $l = 328^{\circ}.2$, $b = -4^{\circ}.3$ (VAN TULDER's pole) for variable stars. It is as close as one can get to the galactic center if one wants a field for which the absorption is uniform, and it has as its center the globular cluster NGC 6522. During the years 1945-1949, 137 plates of the field were taken at the 100-inch. On account of its low declination ($\delta = -30^{\circ}$) most of the plates were obtained in the months July to September. The series was brought to an end when the increasing sky brightness, caused by the lights of the Los Angeles valley, made further observations of the field difficult. For a thorough search of the variables I have intercompared 27 pairs of plates at the blink comparator. Altogether 285 variables were found in a field of 42′×32′. Six of them are members of the globular cluster NGC 6522. The subsequent work on the variables (estimates of the brightness and derivation of the light curves) has been carried out by Dr. S. GAPOSCHKIN.

For the following discussion I shall restrict myself to the variables within 15.8 minutes of arc of NGC 6522, since some absorption patches in the outer parts of the plate field have caused losses in the number of the observed variables. No such losses are to be feared for distances up to 15′.8 from NGC 6522 since in this inner area, as we go outwards, the number of the variables increases proportional to the plate area. In this central region, which comprises an area of 0.220 square degrees, 182 variables were found, leaving out the 6 members of NGC 6522. Their distribution according to types is shown in Table IV.

TABLE IV

*182 Variables within 15′.8 of NGC 6522**

Type	*All types incl.*		*Physical var. only*	
RR Lyrae's	40.7	percent	46.9	percent
RV Tauri's	2.7	»	3.1	»
Long per. var's	9.9	»	11.3	»
Mira's	6.0	»	7.0	»
Semireg. - Irr.	22.5	»	25.9	»
Eclips. systems	13.2	»	. . .	»
Misc. - Undet.	5.0	»	5.8	»

(*) The 6 members of NGC 6522 have been omitted.

Column two gives the frequencies of the different types if all variables are included; column three if the eclipsing systems are disregarded.

Table IV shows that the cluster-type variables are by far the most frequent class of variables. There are 336 cluster-type variables per square degrees in this field. Their strong concentration toward the center of the Galaxy is indicated by their magnitude distribution, which rises to a very sharp maximum between the photographic magnitudes 16.8 and 17.8 [11]. To get a quantitative picture, one has to determine the density distribution of the cluster type variables along the line of sight, with proper allowance for the absorption. Since it would lead too far if I presented these computations in detail, I shall give here only the main results. Adopting for the field a photographic absorption of 2.75 magnitudes as indicated by the color excess of NGC 6522, one determines first the density maximum of the cluster-type variables along the line of sight. Its distance from the sun, together with the known inclination of the line of sight against the plane of the Galaxy, permits one to compute the distance of the galactic center ($R_0 = 8.2$ kpc). With the position of the galactic center thus fixed relative to the line of sight — the smallest distance between the two is 0.61 kpc — one can now determine the density of the cluster-type variables along the line of sight as a function of R, their distance from the galactic center. I have obtained well-determined densities for 6 points along the line of sight with distances R from the galactic center which range from $R = 0.6$ kpc to $R = 2.7$ kpc. They fit very closely the relation

$$\log n = 1.20 - 0.690\, R,$$

where n is the number of cluster-type variables per 10^6 cubic-parsecs and R the distance from the galactic center, measured in kiloparsecs. With the density distribution as a function of R thus known, we can finally compute the number of cluster-type variables within a sphere of radius R around the galactic center by integration and obtain:

R	*Total number of Cluster-type var's. within R*
1 kpc	21,300
2 »	61,100
3 »	84,800
∞ »	99,300

The preceding table leaves no doubt about the presence of a strong population II in the center region of our Galaxy. Since the steep gradient of its density function appears well established, it is tempting to identify this population II as a population of the central spheroidal system which our Galaxy, like other Sb spirals, must possess.

Very curious is the frequency distribution of the periods of the cluster-type variables which we find in the center region of our Galaxy. In contrast to all other regions thus far investigated, the variables have a frequency maximum at $P=0.33$ days. Moreover, instead of having nearly symmetrical light curves of small amplitudes, as is the rule for cluster-type variables of this period, they have asymmetrical light curves and normal amplitudes. It is true that we know a small number of cluster-type variables in our Galaxy which show this same abnormal behavior. But it is puzzling that in VAN GENT'S [12] field at $l=327$, $b=-18°.5$, for which the line of sight passes the galactic center at a distance of 2.6 kpc, the numerous cluster-type variables both with respect to their periods and light curves are of the usual type. It will be interesting to see the results for the field at $l=331°.7$, $b=-6°.5$ which has been observed at the Radcliffe Observatory and which is now under investigation at the Leiden Observatory.

Returning to Table IV we note that the other types of physical variables found in our field confirm the impression that the population of the galactic center region is predominantly a population II. The RV Tauri variables need no further comment since their membership in the population II is now well established. They are probably stronger represented than indicated in Table IV since a number of doubtful cases may have been put into the group of the semiregular and irregular variables. The next group, called long-period variables in Table IV, comprises the red variables with periods ranging from about 70 days to 200 days and with amplitudes between 0.7 and 2 magnitudes. They are well known in globular clusters where they are lying along the giant branch of the color-magnitude diagram. The long-period variables of Table IV seem to be typical members of this group. They have a mean period of 150 days, a mean amplitude of 1.0 magnitudes, and a mean absolute photovisual magnitude of −2.0 if we use the cluster-type variables of the field as standards. The next group of long-period variables, the Mira variables, have a pronounced frequency maximum at $P = 225$ days and a mean absolute photovisual magnitude at maximum of −2.5. We have not yet a clear picture of the Mira-type variables which, judged by their different concentration to the plane of the galaxy and their kinematical properties, seem to be composed of at least 3 groups. But it is practically certain that the well-known high-velocity group with periods between 150 and 250 days belongs to the population II. The distribution of the periods of the Mira variables of our field indicates that we are dealing essentially with this group. Their high luminosity is an additional argument. The last group of the physical variables in Table IV, the semi-regular and irregular variables, hardly needs further comments. It is an ill-defined group to begin with, and spectroscopic observations are probably needed if one wants to establish order among them.

I have stated already that the types of physical variable stars which we find in the central region of our Galaxy point to a stellar population which is predominantly, if not entirely, a population II. In this connection the following additional information will be of interest. Many years ago Humason obtained the integrated spectrum of the Sagittarius Cloud with a slit spectrograph which was attached to the mounting of the Mount Wilson 10-inch refractor. This spectrograph, with a collimator of 24 inches and a camera of 3 inches focal length, integrated over a solid angle of 4.2 degrees. With the slit E-W the spectrograph was carefully set on the brightest part of the Sagittarius Cloud ($18^h3^m.5$, $-28°40'$, 1925.0). Humason [13] has described in a short note the spectrum which he had obtained and which he classified as F5. At my request he recently re-examined the spectrum and classified it by the strength of Hγ and the G-band only, the same criteria which Morgan uses. As expected, this led to a somewhat later spectral type, F8-G0. Unfortunately, Humason's spectrum provides no information about the strength of the weaker metallic lines, which got lost in the very long exposure because the spectrograph had no temperature control. All we can say therefore at present is that the integrated spectrum of the center region of our Galaxy in the range $\lambda\lambda$3900-4300 is of a considerably earlier type than that of the center of the Andromeda nebula, which Morgan and Mayall (14) have classified as gG8 to gK3. This is in agreement with the following observations. In 1946 Stebbins and Whitford [15] intercompared at my request the color of NGC 6522 with the colors of a number of areas in the surrounding field. These areas had been carefully selected to represent the rich surrounding field and were free from foreground stars. In each case the colors of cluster and field agreed within 0.01 magnitude. This meant, since NGC 6522 itself is located in the center region of our Galaxy (its distance from the sun is 10.1 kpc), that the intrinsic color of the galactic center is the same as that of NGC 6522. The integrated spectral type of NGC 6522 has recently been determined by MORGAN [16] at the Cassegrain spectrograph of the McDonald Observatory. It turned out that NGC 6522 belongs to the halo group of globular clusters with weak metallic lines but its spectral type determined from the strength of Hγ and the CH/Hγ ratio is F8-Go. We have, therefore, strong reasons to believe that in integrated color and spectral type the central region of our Galaxy resembles the globular clusters of the Galactic halo. This would imply that, in contrast to the Andromeda nebula where the light of the center region comes predominantly from stars of normal metal content, the light of the center of our own Galaxy comes overwhelmingly from stars of low metal content. It should not be difficult to settle this question by repeating HUMASON's observation with a modern spectrograph in a suitable location.

IV. *The Disk Population in the Neighborhood of the Sun*

I pointed out already in the introduction that the location of the sun in a spiral arm of our Galaxy introduces certain complications if we want to study the disk population in our immediate neighborhood. In the following discussion I shall restrict myself, therefore, to just one question: Of what kind are the oldest stars in the surroundings of sun? To answer it we need the color-magnitude diagram of the stars in our neighborhood, in particular that of the region below $+3^{M}$ where the oldest stars leave the main sequence for the subgiant and giant branches. Such a diagram has recently been published by EGGEN [17], based on stars nearer than 50 parsecs for which trigonometric parallaxes are available. Although a diagram of this sort cannot claim any high precision, it should be trustworthy in its main features. EGGEN's diagram leaves little doubt that the majority of the old stars in our neighborhood are of the M 67 or a very closely related type. The absolute magnitude of the giants ($M_v \sim 0$) in particular suggests that they are stars with a normal metals-to-hydrogen ratio.

REFERENCES

[1] W. A. Baum and M. Schwarzschild, A. J., *60*, 247, 1955.
[2] W. W. Morgan, P.A.S.P., *68*, 509, 1956 and *69*, 291, 1957.
[3] D. B. McLaughlin, A. J., *51*, 136, 1945.
[4] B. W. Kukarkin, *Erforschung der Struktur und Entwicklung der Sternsysteme*, Berlin, 1954, Fig. 25.
[5] L. A. Berman, L.O.B., *18*, 57, 1937.
[6] W. Becker, *Sterne und Sternsysteme*, 2nd edition, 166, 1950.
[7] N. U. Mayall, Ap. J., *104*, 290, 1946.
[8] W. Lohmann, Z. Ap., *30*, 234, 1952.
[9] J. Cuffey, Ap. J., *98*, 49, 1943.
[10] W. Becker, Z. Ap., *34*, 107, 1954.
[11] W. Baade, P. Obs. U. Michigan, *10*, 17, 1951.
[12] H. van Gent, B.A.N., 227 and 243, 1933.
[13] M. L. Humason and al., P.A.S.P., *39*, 368, 1927.
[14] W. W. Morgan and N. U. Mayall, P.A.S.P., *69*, 291, 1957.
[15] J. Stebbins and A. E. Whitford, Ap. J., *106*, 49, 1947.
[16] W. W. Morgan, P.A.S.P., *68*, 509, 1956.
[17] O. J. Eggen, A. J., *62*, 45, 1957.

DISCUSSION

CHAIRMAN: B. LINDBLAD

THACKERAY

Would it not be worth while to look for similar information from the velocities of planetary nebulae? JOY usually observed only one or two plates of cluster variables near the maximum. I wonder if the velocity amplitude had any effect on the correlation?

BAADE

The solar motion for the planetaries contained in Lick Volume XIII is about 35 kms/second. This agrees with BERMAN's result that they are members of the disk population. We need more work on cluster variables in low latitudes ($b < 20^\circ$) because our present data are far from being representative for cluster type variables within 500 parsecs of the galactic plane.

THACKERAY

STIBBS has material for the radial velocities of a few southern cluster variables. Care is required regarding the velocity variation.

OORT

JOY has observed complete velocity curves of RR Lyrae variable which give a check on the mean velocity.

MORGAN

It seems impossible that the periodic velocity amplitude of the RR Lyrae variables can interfere with these results. The separation for periods shorter and longer than 0.45 day is sharp and without overlap. BAADE seems to imply that the short-period group belongs to the disk population and the long-period group to the halo population. This is a most important result.

BAADE

This simple distinction is not quite sufficient for the nuclear region.

OORT

The disk population is much more numerous.

HECKMANN

It should be possible to make SCHMIDT surveys for cluster variables?

OORT

One must survey a large volume of space, since a sphere with one kpc radius contains only 20 or 30.

BLAAUW

Would you recommend a red survey?

BAADE

Not necessarily. It is better to look for a region of relatively uniform absorption, but sufficiently transparent over large distances. With the infra-red you have scale difficulties.

SCHWARZSCHILD

How many cluster variables are known in the solar neighbourhood with large amplitudes, and periods less than 0.4 days?

BAADE

I should have to ask OOSTERHOFF.

SCHWARZSCHILD

I am worried about the assumption of equal absolute magnitudes for these physically different cluster variables. Could one get statistical parallaxes from so small a number?

OORT

Not to better than half a magnitude.

NASSAU

M stars are as characteristic of the disk and nucleus as are cluster variables.

BAADE

We have not answered SCHWARZSCHILD's question about the luminosities of the two classes of cluster variables. There is one piece of evidence on this point. In addition to the field which I studied I reduced SHAPLEY's observations at lat. −19° where the extra-galactic nebulae come through in about normal numbers. The true distance moduli differ by only $0^{m}.13$. By itself this could be an accident, but the plot of the density of the cluster type variables against distance from the galactic centre for my region and SHAPLEY's, shows that the points for the two fields lie on the same line, which gives additional confidence that the luminosities are the same.

SCHWARZSCHILD

Not too much weight should perhaps be given to this continuity, since it connects two physically different samples.

SANDAGE

Some combination of errors in the absorption toward the centre and the absolute magnitude of the nuclear variables would give the same effect.

O'CONNELL

OORT has been long interested in the precise photometry of cluster variables. Can he tell us about the present state of this programme and the improvement of the zero-point of the period-luminosity curve?

OORT

At Leiden VAN HERK is measuring the proper motions of some 50 RR Lyrae variables from plates taken by VAN MAANEN at Mt. Wilson. This may yield important material for the redetermination of the zero-point of the period-luminosity curve. We need better magnitudes, colours and colour excesses; some work by KRON at Lick will shortly be finished which will improve the situation here.

The space velocities of RR Lyrae variables already computed indicate that a fair percentage of the stars measured by JOY have velocities greater than the velocity of escape. These may be members of the general field of the local cluster, unless our absolute magnitudes are all badly wrong, which it is somewhat difficult to believe. The existence of a fair percentage of interlopers from extra-galactic space is not so unlikely. If you suppose that the composition is like that of the halo in the proportion of RR Lyrae stars and subdwarfs, the total mass in the volume of the local cluster would be about ten times the mass of the visible nebulae.

O'CONNELL

By how much do their velocities exceed the velocity of escape?

OORT

By about 100 kms per second. At least four of these objects could not be reduced to the velocity of escape.

LINDBLAD

How did they acquire these velocities?

OORT

They are interlopers which do not belong to the system. To reduce the space motions to below the escape velocity for the four high-velocity stars requires the absolute magnitude of these stars to be at least +1 instead of 0.

SANDAGE

If one believes the photometry of M 3 and corrects the position of the standard main sequence for ultra-violet excess, the magnitude of the RR Lyrae stars in M 3 is about +1. This may not be significant, but is of interest because of OORT's comment.

HECKMANN

Would BAADE recommend a search for slow motion variables in the disc population?

BAADE

Yes, if a suitable Schmidt telescope is available. But it would require a very careful selection of the field so as to guarantee great transparency along the line of sight. For transparencies over great distances the Cygnus cloud is ideal. But most informative would be fields nearer to the galactic centre.

MORGAN

The Scutum cloud would be a good transparent region in very low galactic latitude.

SANDAGE

We have a long series of 48″ Schmidt plates taken at 20 minute intervals over 8 nights in the blue and visual on the Scutum cloud. We should like suggestions as to who would be able to help in reducing this material.

HECKMANN

The Groningen machine might help.

BLAAUW

We would be glad to participate.

O'CONNELL

What is the limiting magnitude on these plates?

SANDAGE

I think that a survey could be made complete to between 18^m and 19^m in the blue.

OORT

THACKERAY asked a question about radial velocities of planetaries. Most of the new ones lie in the direction of the centre and it is important to have more velocities.

THACKERAY

There is a good deal of unmeasured material at the Cape. I wondered what its order of priority was relative to work on RR Lyrae variables.

LINDBLAD

In the planetaries we have no physical distinction between the two velocity groups. That makes it more difficult, but, if there are two groups there, it should be possible to isolate them all the same.

OORT

There are not many planetaries in the halo.

BAADE

Only one is known. Near the Coma cluster of galaxies HARO found a few years ago a small and very faint planetary nebula which is beyond doubt a member of the galactic halo.

MORGAN

If we subtract the disk population and also the globular clusters of later spectral type from the nuclear region, there may be little left to show a strong nuclear concentration for the halo population.

SOME CHARACTERISTICS OF THE STRONG AND WEAK-LINE STARS

W. W. Morgan
Yerkes Observatory, University of Chicago

There are three general categories of stars in the neighborhood of the sun whose spectra contain the weak-line characteristics to an extreme degree. In the *Yerkes Spectral Atlas,* attention was called to the peculiarities in the spectra of the cluster-type variable RR Lyrae and the high-velocity F star HD 140283. These two stars can be considered as spectroscopic prototypes for the cluster type variables in general and for the extreme weak-lined F group investigated by Miss Roman, respectively. To these two groups can now be added a third: certain F—K semiregular variable stars of high luminosity. The weak-lined nature of the spectra of several members of this group was noted some years ago; in 1942, P. C. Keenan called attention to the combination of weak lines and spectroscopic evidence of high luminosity for the K-type semiregular variable SV UMa; in 1952, A. H. Joy described the weak-lined characteristics of the semiregular variables AB Leo and W LMi. These observations may now be generalized to apply to a group of F—K variables of high luminosity and high velocity. The third group bears striking similarities to certain semiregular variables studied by Joy in globular clusters; the extreme weak-lined characteristics of some globular cluster giants have also been described by A. J. Deutsch.

The three groups described possess the common characteristic of exceedingly high velocity; they apparently belong to a Galactic subystem having a very low velocity of rotation around the galactic center; it seems likely that these pronounced weak-lined stars should be considered representative of the "Halo" population in the neighborhood of the sun. If this is confirmed by further observations, a spectroscopic separation of Halo stars from those of the flattened disk may be feasible.

A most promising line of investigation for large objective prism cameras would be a survey and cataloguing of extreme weak-lined stars; this may be the most efficient manner available of separating some categories of stellar populations.

It is highly probable that the stellar population of the nuclear region of our galaxy resembles that of the great Sb spiral M 31. If this is so, we can conclude that the principal contributors to the light from the central region of the Galaxy are giant stars of spectral classes G8—M. These giant stars do not seem to be of the extreme weak-lined variety; it appears, therefore, that there are marked differences in the stellar population of the Galactic halo and the nuclear regions.

SOME FEATURES OF STELLAR POPULATIONS AS DETERMINDED FROM INTEGRATED SPECTRA

W. W. Morgan
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The general stellar population of galaxies, except for the nearest, is so faint that observation of the individual stars which contribute most to the luminosity is far beyond the limit of any existing telescope. Even in the case of the globular clusters of our Galaxy, only the brighter stellar members can be observed efficiently; in the case of the fainter stars in globular clusters — as well as the general stellar population of the vast majority of galaxies — direct individual observations of spectral types and luminosities are impossible.

If we wish to obtain information on spectral types and absolute magnitudes of stars in these remote systems, it is necessary to devise methods of interpreting spectra of a highly composite nature. When a wide spectrographic slit is placed across the central part of a Galactic globular cluster, some thousands of stars probably contribute to the resulting spectrum; when the same procedure is applied in the case of distant galaxies, the number of stellar contributors to an integrated spectrum probably runs into millions.

It might therefore be concluded that little precise information can be derived from highly composite spectrograms. However, recent work carried out jointly with N. U. Mayall at the Lick, Mount Wilson-Palomar and McDonald Observatories indicates that certain fairly unique conclusions can be reached. In the case of the Great Nebula in Andromeda, it can be shown that the principal contributors to the light of the main body are giant K stars, and that large numbers of M stars are also present. It can also be shown that the stellar population of irregular galaxies of the Magellanic Cloud type is quite different from that of M 31; in the case of such irregular systems, the principal contributors to the light in the blue and violet spectral regions are A and F stars. There seems to be a definite correlation between form and stellar population for the great majority of all galaxies; those of types Sc, SBc, and Irregular contain relatively large numbers of early-type stars; intermediate systems such as M 51 and M 101 show a mixed population; considerable numbers of early-type stars are present — together with appreciable relative numbers of stars of later type. In the case of Sb systems similar to M 31 and M 81, the dominant population by luminosity is made up of giant stars of class K. The relative number of early-type stars in these systems is minor. The giant elliptical systems have similar population (by luminosity) to that of the inner parts of M 31 and M 81.

Certain unique results have also been derived for a number of globular clusters in our own galaxy from spectrograms obtained at the McDonald Observatory. The Galactic globular clusters fall into two general groups: 1) those located at great distances from the galactic plane, and 2) a group of clusters situated within the highly flattened system. Integrated spectra of the first group show that the principal contribution to their light comes from "weak-lined" F stars; the second group appears to have a very different stellar constitution; here the spectra are roughly similar to those of the central parts of the Sb galaxies, and suggest a very different kind of stellar population from that observed in the case of the globular clusters distant from the galactic plane.

The globular cluster NGC 6356 can be taken as representative of the second group; we can make the following spectroscopic comparisons: the integrated spectrum of this globular cluster resembles that of the inner part of M 31 in the spectral range λλ 3850 — 4350, with the exception that the hydrogen lines are somewhat stronger in NGC 6356. The spectrum of the latter resembles closely that of the SB0 galaxy NGC 3384 over the same spectral range mentioned above; the integrated type is late G, and there is some evidence for the presence of CN giants.

A rich field now seems to be available for the discussion of stellar populations of clusters and galaxies from investigations of integrated spectra; when spectroscopic observations are available from the ultraviolet to the infrared, it seems feasible to construct rough HR diagrams for the principal contributors to the luminosity of galaxies of various type. This work is being continued by MORGAN at the Mount Wilson-Palomar and McDonald Observatories.

DISCUSSION

CHAIRMAN: B. LINDBLAD

LINDBLAD

It may be of some interest to mention that already from my early photographs of the spectrum of the Andromeda nebula it was possible to conclude that it is generated by giant K or G stars, from the strength of the cyanogen bands.

SCHWARZSCHILD

Could MORGAN clarify the spectral differences in the globular clusters?

MORGAN

In the case of M 15 and M 92 we have very extreme cases of spectral peculiarity — metallic lines absent, H and K weak — the weak-line star with its most pronounced characteristics. In the case of M 3 and other halo clusters (M 13, ω Cen) the peculiarities are not so extreme; the line Ca 4226 is too strong for the metallic background.

SCHWARZSCHILD

Is the degree of peculiarity correlated to the spectral type?

MORGAN

Yes, except for one under-exposed doubtful case. The peculiarity diminishes with advancing spectral type. The type is determined from the ratio of the G band to Hγ, from the intensity of the H lines, and from the metallic lines.

SCHWARZSCHILD

Can SANDAGE say if the sequence is related to positions on the colour-magnitude diagram?

SANDAGE

Yes, the peculiar ones have bluer giant branches, but the colour difference is only 1/10th of a magnitude for the whole range of spectral classes involved.

BAADE

If the Galaxy is an Sb spiral we should expect the bulge to have a K spectrum. NGC 6522 however is a halo type cluster of class F8. I asked STEBBINS to measure the colour index of NGC 6522 and the field in four or five spots carefully chosen to avoid foreground stars. The field and cluster colours agreed to within $0^m.01$, though the absorption was $2^m.15$.

MORGAN

You would not expect to observe the pure spectrum of the nucleus. CODE has pointed out that there would be an optical depth effect due to foreground objects. The agreement may be accidental.

BAADE

What is the spectral type of M 82?

MORGAN

Type A.

BAADE

Yet its integrated colour is about the same as that of an E-galaxy. There are other irregular systems which show early spectra not agreeing with integrated colours, though both classes of observation seem correct.

SPITZER

What is the range of spectral types found for globular clusters?

MORGAN

The earliest are classed as F by their H lines. The later types are composite G5 or later. I did not expect they would be so late, so the comparison stars chosen had not late enough spectral types. NGC 6522 is near the nucleus, but its spectrum is most similar to some of those of the halo, although it is near the galactic plane.

SANDAGE

There is not a single colour-magnitude diagram for any of MORGAN's low latitude clusters. Because we expect from MORGAN's spectroscopic results that the diagrams should be like M 67, since they have very strong metallic lines, the observation of these clusters is important, and is under way at Mt. Wilson.

SPITZER

Does the spectrum of the dwarf elliptical M 32 resemble that of a globular cluster?

MORGAN

No, it is later than that of weak-line globular clusters.

LINDBLAD

ÖHMAN found a similar result from an analysis of a spectrum of fairly large dispersion taken by him at Mount Wilson.

HECKMANN

What dispersion would be needed to detect weak-line stars?

MORGAN

An objective prism dispersion of around 100 Å/mm at Hγ would give the most precise results; however, a dispersion of around 250 Å/mm at Hγ could be used successfully if great care is exercised, and if there is good transmission in the ultraviolet.

BAADE

The facts as they stand are: 1) the brightest stars of the Andromeda nebula are of visual absolute magnitude —3; 2) the integrated spectrum clearly shows that M 31 is mainly composed of normal strong-line stars. How are these to be reconciled?

SPITZER

The light from M 31 is presumably much the same as that from our own Galaxy, where we know that the disk stars are predominant. Between the arms of Andromeda the first stars resolved are the halo giants, because these are the brightest, but most of the light comes from the disk giants.

In M 31 we have a mixture of types and the disk light outweighs the halo, if MORGAN's spectral classification is to be believed.

BAADE

The halo component must be quite weak compared with the disk component.

SANDAGE

There is no evidence against this, since BAADE with the 200-inch resolves only to $M_v = -2$ in M 31. He cannot reach M 67 type stars. BAUM and SCHWARZSCHILD's study of the count/brightness ratio in M 31 pointed to the conclusion that M 67 type stars contributed to the light in a major way.

STRÖMGREN

Returning to HECKMANN's suggestion, it is worth pointing out that 2-colour exposures, one in the ultraviolet and one at 4800 Å, say, can be used to select weak-line stars, subdwarfs in high galactic latitudes, as well as the objective prism method. This procedure can, of course, be used for fainter stars.

MORGAN

My remarks about galaxies require one qualification. They apply to about 80% of galaxies. The rest however, are usually recognisable on direct photographs as being abnormal.

BAADE

May I ask if the counts of BAUM and SCHWARZSCHILD could be used to estimate the strength of the halo population?

SANDAGE

MORGAN's spectroscopic evidence seems so conclusive that it would seem secure to accept the strong-line giant stars as the principal contribution to the light and then take BAUM and SCHWARZSCHILD's results as confirmation.

BAADE

How does MORGAN account for the colour of M 82?

MORGAN

It is very peculiar. There are no bright blue supergiants in M 82, although large numbers are observed in its companion, M 81. The abnormal colour may be due to the effect of exceedingly large dust clouds. The spectroscopic observation is quite definite: the principal contributors to the luminosity of M 82 are A stars of luminosity near the main sequence.

BAADE

About one-fifth of the irregulars in our neighborhood are like this.

SANDAGE

No. Isn't is true that only a few are known like M 82? There is 3077, 520, and possibly one in front of the Boötis cluster of galaxies.

KINEMATIC PROPERTIES OF THE STRONG AND WEAK-LINE STARS

ADRIAAN BLAAUW (*)
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ABSTRACT

The velocity distributions projected on the galactic plane are shown for the principal spectral groups discussed earlier by Miss ROMAN and for the A0 to A9 stars according to DELHAYE. A resemblance is shown to exist between the velocity distribution of the A-type main-sequence stars and that of the G8III strong-line stars, which is in agreement with the current theory of stellar evolution. The kinematic properties of the other spectral groups are briefly discussed with reference to the current picture of stellar evolution.

It has been shown by Miss ROMAN [1] that within the spectral classes F5 to K5 a spectroscopic subdivision can be made which separates stars of different velocity dispersion. She studied the stars brighter than visual magnitude 5.5 and north of −20° declination, and discussed the frequency distributions of the space velocities, corrected for the solar motion, for the various spectral subgroups.

The present remarks deal with the patterns of the velocity distributions projected on the galactic plane, and with their interpretation on the basis of the evolutionary tracks in the HR diagram. Previous discussions related to this subject have been

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given, a.o., by VYSSOTSKY [2], SANDAGE [3], and H. M. JOHNSON [4].

Figures 2a, 2b, 3a, 3b, 4a, 4b, 5, 6 and 7 show these projections for Miss ROMAN's most frequently occurring spectral groups; these groups are indicated in the upper right hand corner of the diagrams. The diagrams marked luminosity class III contain also a few stars of types II-III and III-IV. The subdivisions called "Strong-line stars" and "Weak-line stars" by Miss ROMAN are shown in separate diagrams, except for K1III, where both are shown in Figure 5. The component U is in the direction of $l=0°$, $b=0°$; the component V in the direction $l=90°$, $b=0°$. The space velocities with respect to the sun were computed with the spectroscopic parallaxes given by Miss ROMAN. The solar motion was eliminated assuming a standard velocity of 20 km/sec toward $\alpha=18^h04^m$ and $\delta=+28°$. This differs somewhat from the elements found for some of the spectral groups, but by eliminating the same solar motion for all of them we provide a uniform frame of reference for the velocity patterns.

The average values of the speeds in the three components with respect to the mean velocity are given in Table 1. The component W is in the direction of the galactic pole.

The criteria for the classification into the "weak-line" and "strong-line" groups have been described in Miss ROMAN's papers. Whereas these names result from the systematic weakening of the lines in part of the stars in the spectral range F5 to G5, they refer to a different kind of spectroscopic discrimination in the later types. For G8 to K1 the names refer to two groups which also have different velocity dispersions, but the "weak-line" group is characterized by the relatively stronger G band and Ca I 4226. Eighty-five percent of the bright G8 to K1 giants according to Miss ROMAN belong to one of these two groups, whereas the remaining 15% are assigned either to the group "weak CN" or to the one marked "4150". These latter two groups will not be discussed in the present paper. Both contain a large fraction of stars with high velocities.

TABLE I

Mean Velocities and Mean Speeds in the three components U ($l = 0°$, $b = 0°$), V ($l = 90°$, $b = 0°$) and W ($b = 90°$) in km/sec after elimination of the Standard Solar Motion (see text). n is the number of stars used.

		n	$\bar{U}$	$\bar{V}$	$\bar{W}$	$\overline{\lvert U-\bar{U}\rvert}$	$\overline{\lvert V-\bar{V}\rvert}$	$\overline{\lvert W-\bar{W}\rvert}$
F5 to F8	Str.-line	42	+ 7	0	− 1	19	11	10
	Wk-line	33	+ 9	− 7	− 8	21	18	16
G8III	Str.-line	41	+ 10	+ 3	− 1	18	8	6
	Wk-line	36	+ 11	+ 10	− 6	25	22	17
K0III	Str.-line	31	0	+ 5	+ 1	14	16	7
	Wk.-line	55	− 6	+ 6	− 1	24	21	16
K1III		28	+ 2	− 7	0	26	18	16
K2III		59	− 2	+ 1	− 1	21	14	14
K3III		66	+ 1	+ 1	0	18	18	14

No subdivision into such groups with different kinematical properties is made by Miss ROMAN for K2 to K5. Therefore, a single diagram represents the projected velocity distribution of all stars for each of the classes K2 and K3. The classes K4 and K5 are not represented here.

Inspection of these projected velocity patterns shows the following characteristics.

1. In types G8III Strong and Weak (Figures 3a and 3b) the distribution is quite irregular and deviates considerably from an ellipsoidal distribution. It seems as if in type G8III Strong we are dealing with two concentrations in the projected

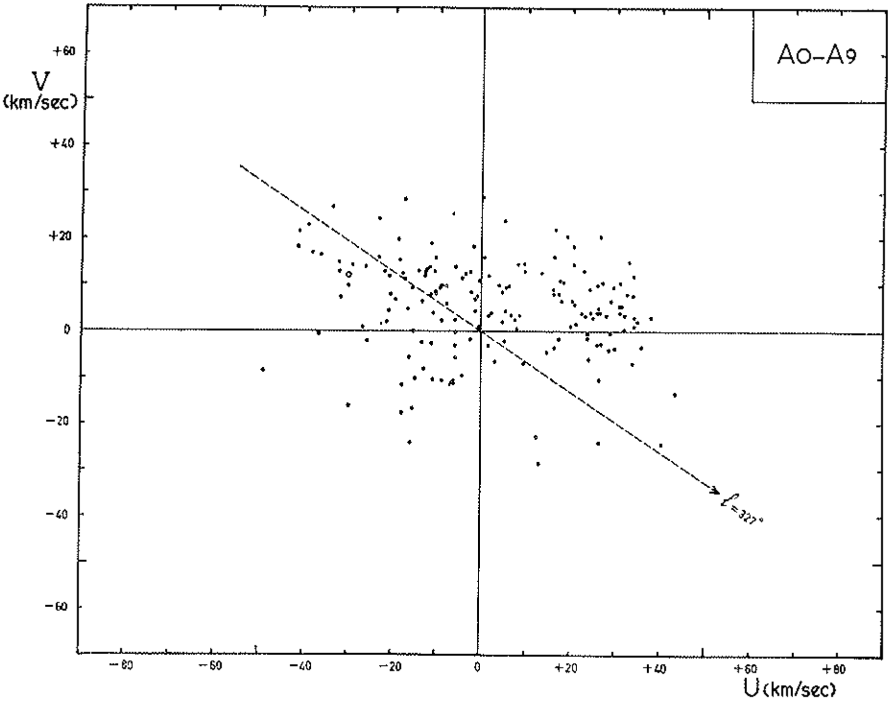


FIG. 1 — Velocity distribution projected on the galactic plane. Main-sequence stars A0-A9.

velocity distribution, centered approximately around U = −10, V = +5 and U = +25, V = +5. For types G8III Weak the dispersion of velocities is much larger, but not symmetric with respect to the zero point of velocities. There is a tendency for the dots to occur in the region of the last mentioned concentration of G8III Strong stars.

2. For the K0III stars (Figures 4a and 4b) we notice again a considerable difference between the dispersions of the strong- and weak-line stars. The dispersion for the strong-line stars is not larger than for G8III Strong, but the velocity pattern is

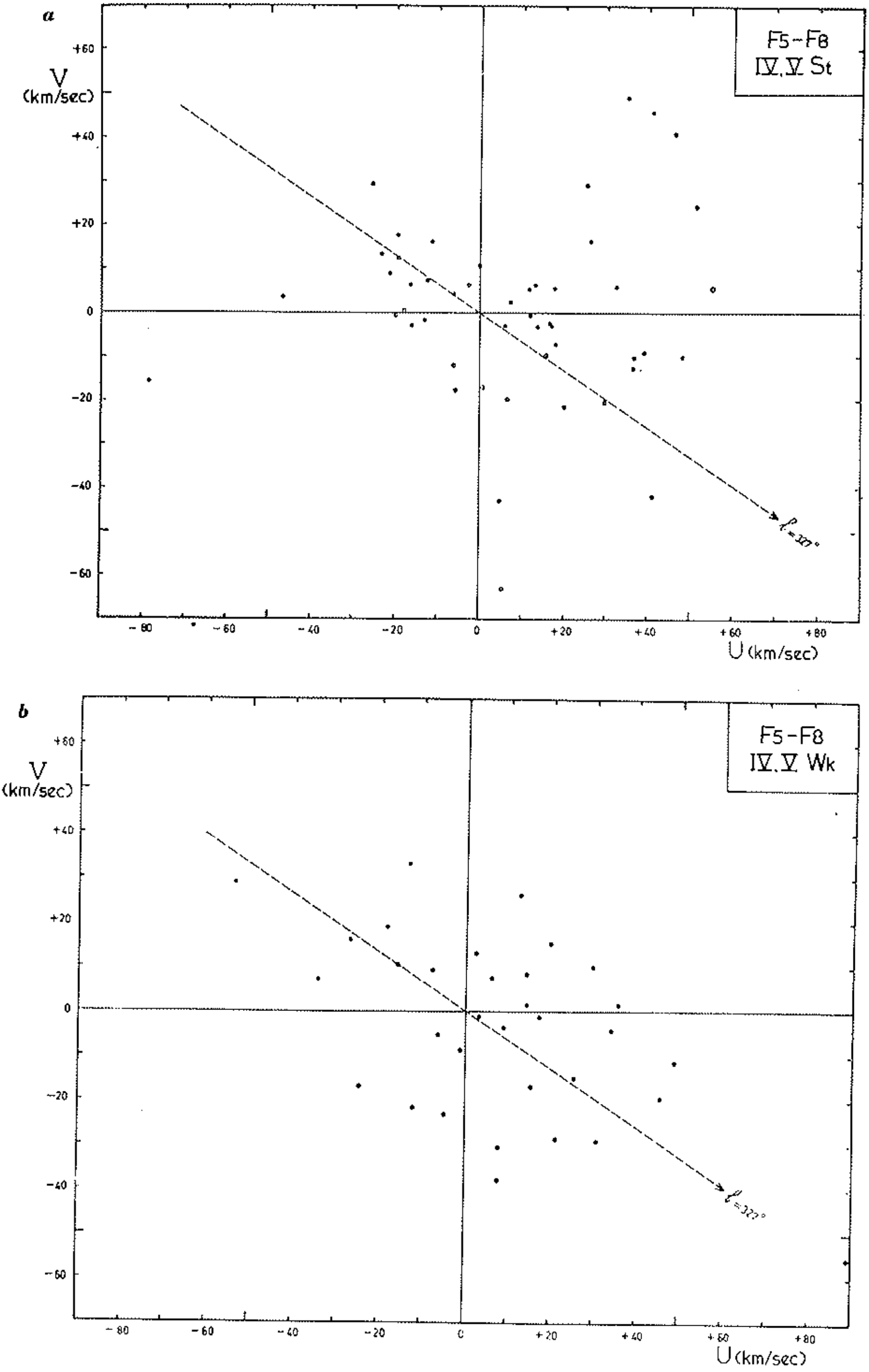


FIG. 2 — Velocity distribution projected on the galactic plane. (*a*) Strong-line stars, main sequence F5-F8. (*b*) Weak-line stars, main sequence F5-F8.

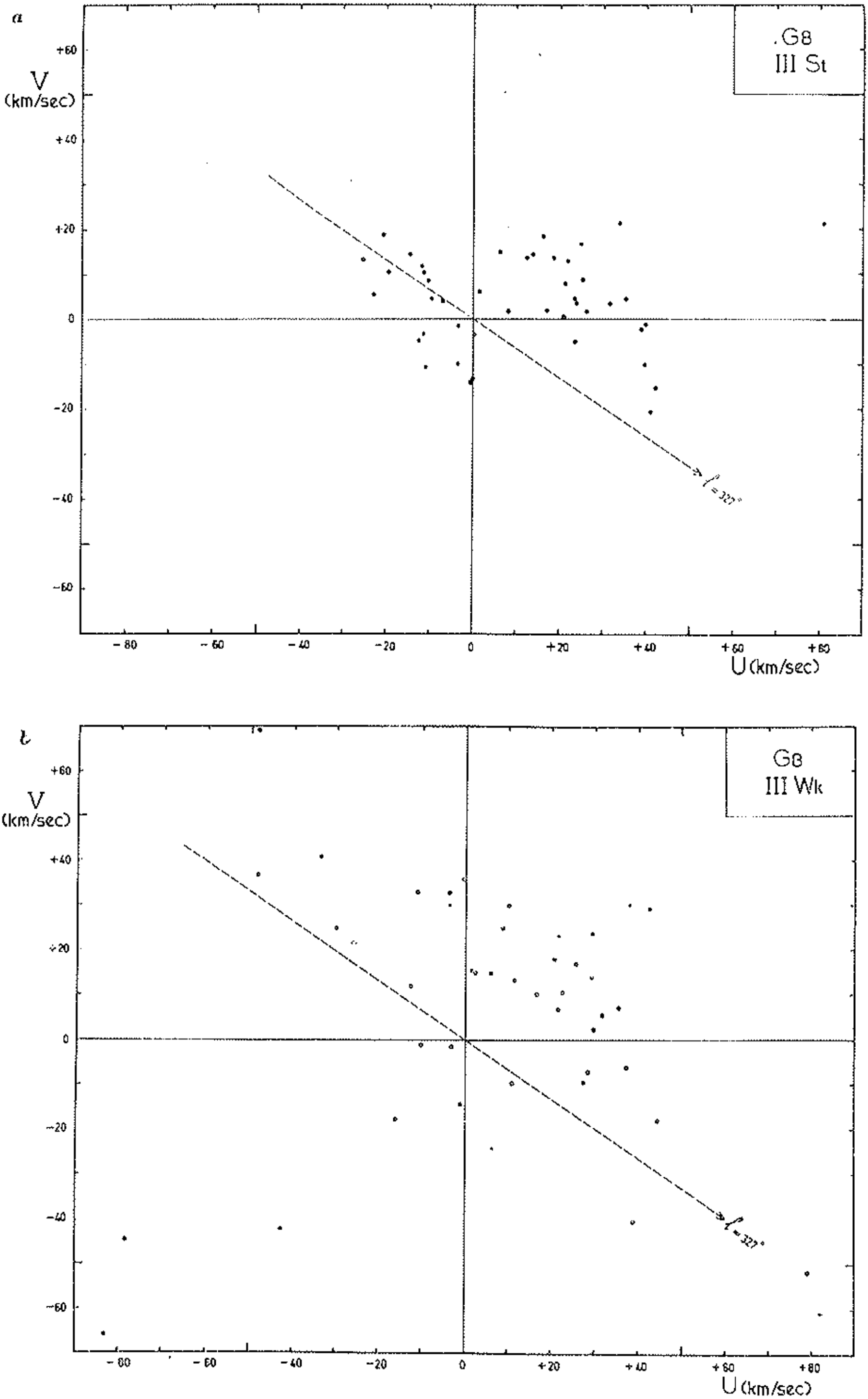
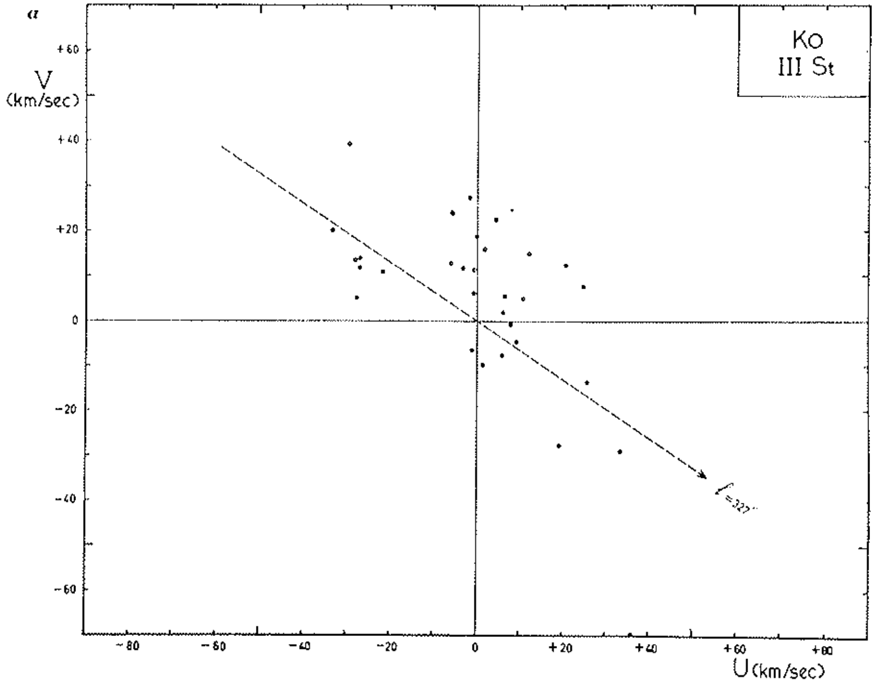


FIG. 3 — Velocity distribution projected on the galactic plane. (*a*) Strong-line stars G8III. (*b*) Weak-line stars G8III.



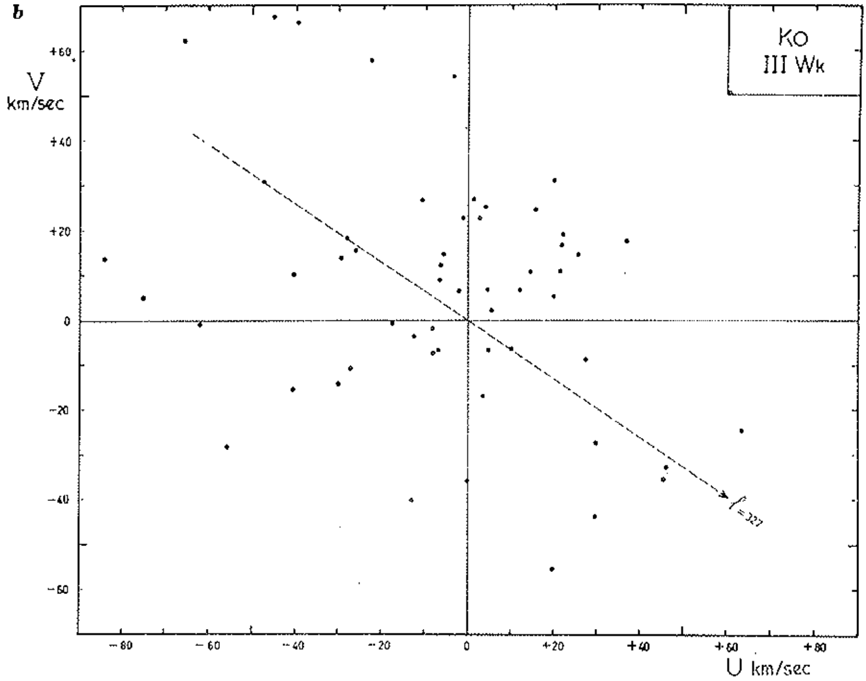


FIG. 4 — Velocity distribution projected on the galactic plane. (*a*) Strong-line stars KoIII. (*b*) Weak-line stars KoIII.

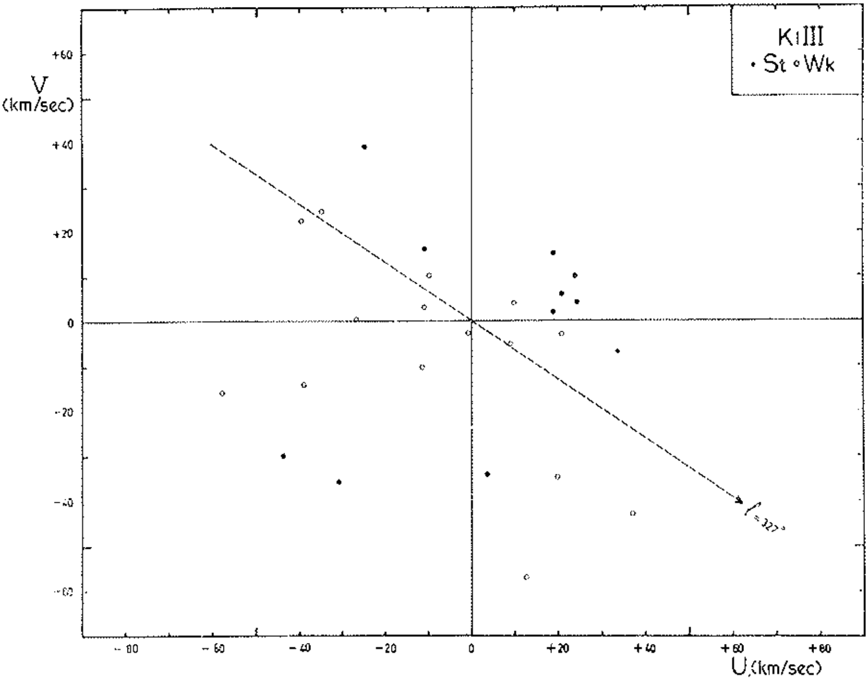


FIG. 5 — Velocity distribution projected on the galactic plane. Strong- and weak-line stars K1III.

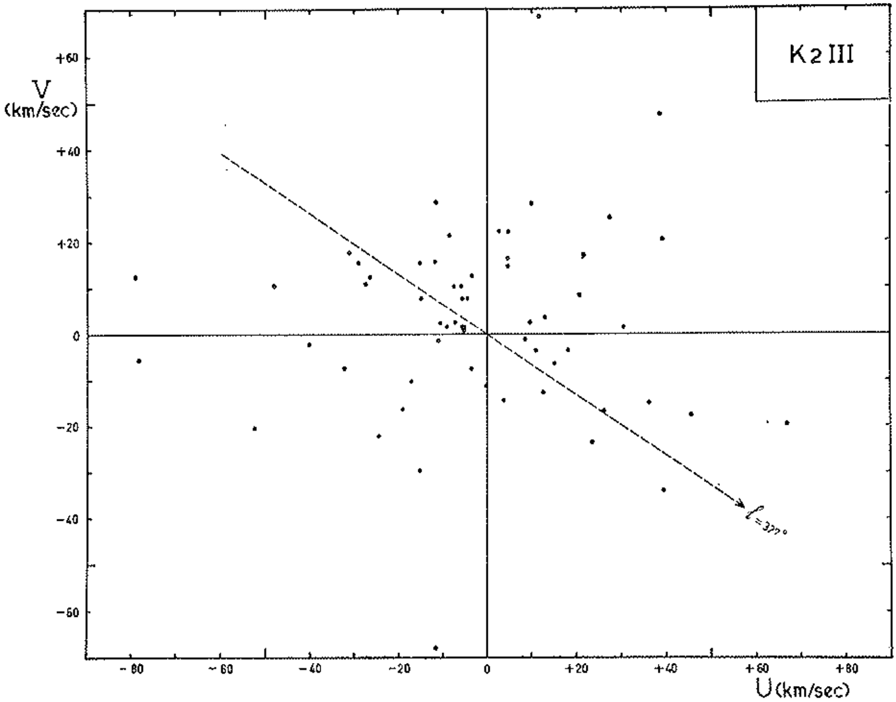


FIG. 6 — Velocity distribution projected on the galactic plane. K2III stars.

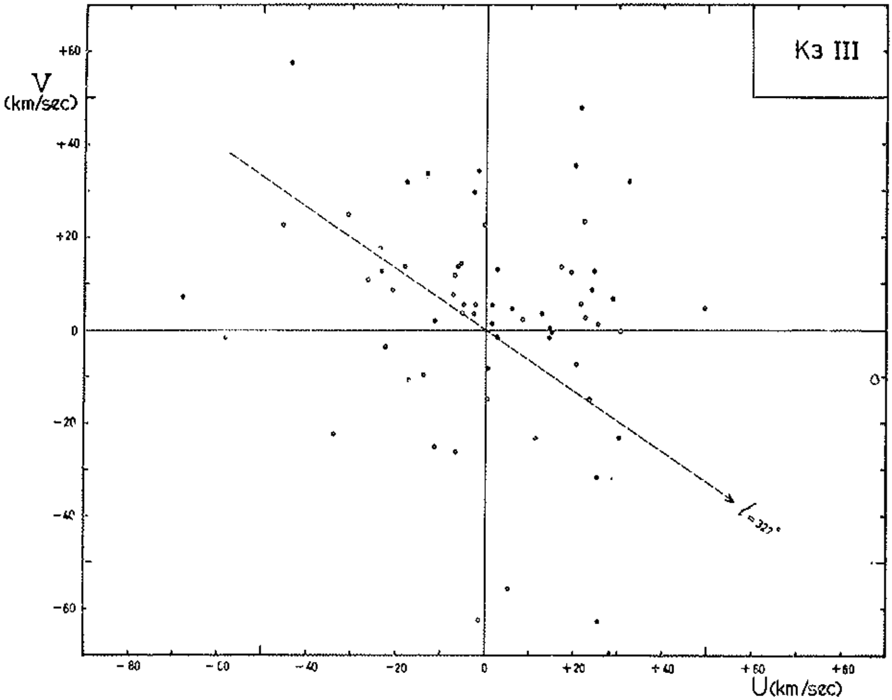


FIG. 7 — Velocity distribution projected on the galactic plane. K3III stars.

definitely different. The two concentrations noted among G8III Strong seem to be absent here, and we find most of the velocities to occur in the region between the two.

3. In class K1III (Figure 5) too few stars are available for a reliable statistics, but among both the strong- and the weak-line stars the dispersion is large.

4. For K2III and K3III (Figures 6 and 7), where we have no further discrimination according to spectral criteria, we find large velocity dispersions and no pronounced concentrations.

5. The main-sequence stars of types F5 to F8 (Figures 2a and 2b) show a more irregular distribution for the strong-line

stars than for the weak-line stars, but it is impossible to state whether velocity concentrations in the diagram are present.

The most interesting of these features is the pattern for the G8III strong-line stars. The presence of the two concentrations appears significant when we compare this pattern with that of the main-sequence stars of types A0 to A9. Diagrams showing this pattern have been published by various investigators and we reproduce here the one published by Delhaye [5]. This refers to the stars brighter than visual magnitude 6.5 and is based on the Mount Wilson catalogue of spectroscopic parallaxes [6]. See Figure 1. In this figure we recognize the occurrence of two regions of concentration of the projected velocity vectors, quite similar to the pattern for the G8III Strong stars. This resemblance suggests a narrow physical relation between the two spectral types. Such a relation is in fair agreement with the current concept of stellar evolution. This can be illustrated by means of the diagram given by Sandage in his contribution to the present conference and also shown in a previous article by this author [7]. According to this figure the stars of spectral type G8III, whose visual absolute magnitude according to Miss Roman is about zero, represent an evolutionary stage immediately following that of stars around type A0 with absolute magnitudes about +1. That the time elapsed between these two stages must be relatively short, follows from the fact that in open clusters, like M 11, the Hyades and Praesepe, the region between the main sequence and the giant branch is void of stars (the Hertzsprung Gap). According to the same evolution picture the stars of type K0III, whose absolute magnitude is about +0.7 according to Miss Roman, represent a stage following that of late A type stars with absolute magnitudes around +2. The fact that the velocity distributions of the G8 and K0 giants are so different (Figures 3 and 4) seems to be due to the fact that their preceding stages on the main sequence have rather different mean ages. According to Sandage's diagram these ages are about 4.5×10^8 yrs and 12×10^7 yrs, respectively.

The velocity distributions of the main sequence stars and the giants do not fit entirely in the evolutionary picture, for the late A-type stars, which are included in DELHAYE's diagram, seem to correspond with the G8 giants better than with the Ko giants. The data available at present on the space velocities do not justify a more refined analysis; the purpose of the present remarks is mainly to show that a careful investigation of a more extensive material of space velocities (for instance one including all the stars brighter than visual magnitude 7.0) might well give important additional information on the evolutionary relation between main-sequence and giant stars.

The larger velocity dispersion shown by the main-sequence F5 to F8 stars of the weak-line group, compared to the strong-line group, must probably be interpreted as a consequence of their greater mean age. The dispersion shown by the weak-line stars is of the same order as that of the giants of types K2III and later. The difference between the G8III strong- and weak-line stars is perhaps also an age effect. The fact, that among the weak-line stars mainly one of the velocity concentrations of the strong-line group is represented, then indicates that the strong-line stars are closer in age to the preceding A-type stars than the weak-line stars.

I am much indebted to Miss N. G. ROMAN, who kindly put her computations at my disposal for the first stages of this investigation.

REFERENCES

[1] N. G. ROMAN, Ap. J., *112*, 554, 1950; *116*, 122, 1952.
[2] A. N. VYSSOTSKY, Publ. Astr. Soc. Pac., *69*, 109, 1957.
[3] A. SANDAGE, Ap. J., *125*, 435, 1957.
[4] H. M. JOHNSON, Publ. Astr. Soc. Pac., *69*, 54, 1957.
[5] J. DELHAYE, B.A.N., No. 395, 1948.
[6] W. S. ADAMS, A. H. JOY, M. L. HUMASON, A. M. BRAYTON, Ap. J., *81*, 187, 1935.
[7] See Page 42.

DISCUSSION

CHAIRMAN: B. LINDBLAD

HECKMANN

Why is the centre of the velocity ellipsoid not at the origin of coordinates for each group?

BLAAUW

The solar motion was not independently determined for each group.

LINDBLAD

For A stars we get a small solar motion due to the presence of the Ursa Major stream.

SCHWARZSCHILD

Can you estimate how long a peculiar velocity distribution of this kind could persist?

BLAAUW

The age of the A and G8III stars involved is around 5×10^8 years or 2 revolutions of the galaxy. A group of stars with small internal motions might well survive the dispersing tendency in velocity space for several revolutions of a galaxy. For K1III stars with 3×10^9 years the situation would be different; here indeed a much larger velocity dispersion is observed.

CLASSIFICATION SPECTROPHOTOMETRIQUE DES POPULATIONS STELLAIRES

DANIEL CHALONGE

Résumé des recherches effectuées à l'Institut d'Astrophysique de Paris
par
J. BERGER, D. CHALONGE, L. DIVAN, A-M. FRINGANT, C. MENNERET,
F. VAN'T VEER, B. WESTERLUND

CLASSIFICATION SPECTROPHOTOMÉTRIQUE À TROIS DIMENSIONS

I. *Définition des paramètres employés.* — Chaque étoile est définie par les valeurs numériques de trois paramètres λ_1, D et φ_b dont voici la définition. La fig. I reproduisant l'enregistrement d'un spectre stellaire, les lignes en trait discontinu ABC et DE représentent respectivement les fonds continu visible et ultraviolet. La discontinuité de Balmer D se produit à une longueur d'onde variable mais voisine de 3700 Å (longueur d'onde des points C et D) et

$$D = \log \frac{\text{intensité en C}}{\text{intensité en D}}$$

La longueur d'onde λ_1 est celle du point K situé sur la ligne BD qui joint les points de plus forte densité entre les raies de Balmer d'ordre élevé, à égale distance entre les deux fonds continus. Cette longueur d'onde, facile à mesurer, varie dans le même sens que la longueur d'onde λ_0 de la dernière raie de

Balmer visible (qui est difficile à mesurer surtout sur des spectres à faible dispersion).

Le grandeur φ_b est le gradient spectrophotométrique absolu du fond continu pour l'intervalle spectral 3800-4800 Å

$$\varphi_b = \frac{C_2}{T_b}\left(1 - e^{-\frac{C_2}{\lambda T_b}}\right)^{-1}$$

(où C_2 est l'une des constantes de la fonction de Planck)

Ce mode de classification ne s'applique qu'aux étoiles comprises entre les types O et les premiers types G.

Pour plus de détails, voir [1, 2, 3, 4].

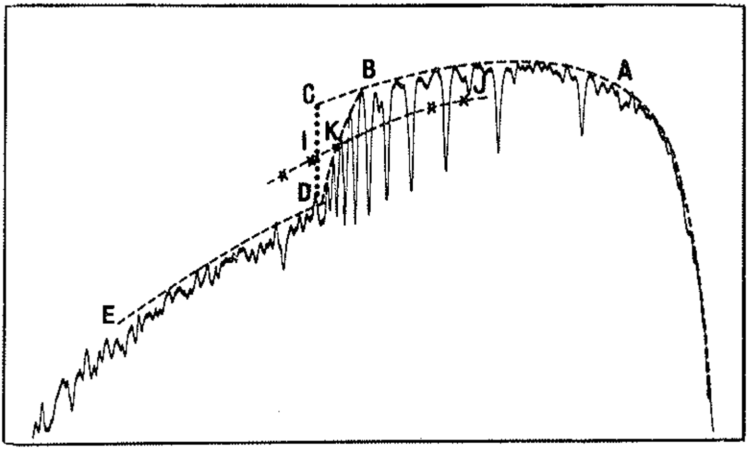


FIG. 1 — *Enregistrement microphotométrique du spectre d'une étoile B* pour la définition des trois grandeurs λ_1, D, φ_b.

2. *Précision des déterminations des paramètres.* — Avec le spectrographe utilisé [5] les erreurs moyennes sur les valeurs des paramètres (chaque valeur étant déduite d'une douzaine d'observations) sont 0,003 sur D; 1 Å sur λ_1; 0,03 sur φ_b.

Mais pour les types O et B0 et pour les types plus avancés que F6 pour lesquels la discontinuité D est faible, les erreurs moyennes sur D et λ, atteignent les valeurs de 0,01 pour D et 3 Å pour λ_1.

Voir [6].

CLASSIFICATION DES ÉTOILES DE LA POPULATION I

3. *Classification des "étoiles normales". La surface* Σ. — Lorsque les trois paramètres d'une étoile sont déterminés, il est possible de la représenter par un point de coordonnées λ_1, D, φ_b dans l'espace.

Les points figuratifs des étoiles qui peuvent être classées dans la classification MK (et que, pour abréger, nous appellerons "étoiles normales") viennent alors se placer au voisinage immédiat d'une surface Σ dont la fig. 2 représente une maquette.

Sur cette maquette sont tracées deux familles de courbes: les courbes de niveau, $\varphi_b = c^{te}$ séparent les diverses sous-classes spectrales; celles de la seconde famille (grossièrement orthogonales aux premières) séparent les diverses classes de luminosité.

La surface Σ est ainsi divisée en quadrilatères curvilignes dont chacun correspond à un symbole de la classification MK. On voit immédiatement que la nouvelle classification est plus précise que la classification MK puisque dans l'étendue d'un quadrilatère (c'est-à-dire dans l'intérieur d'un symbole MK) on peut distinguer une série d'étoiles ayant des caractéristiques différentes.

Pour placer les étoiles dans la nouvelle classification et trouver leur classification MK, on utilise non la maquette de la fig. 1 mais les projections sur le plan $\lambda_1 D$ de la partie inférieure (fig. 3) et de la partie supérieure (fig. 4) de la surface Σ. On a marqué à côté de chacune des projections des courbes séparant les sous-classes spectrales, la valeur de φ_b correspondante. Lorsque l'on connait les valeurs des paramètres d'une étoile, il est facile de marquer le point correspondant sur l'une des fig. 3 ou 4 et de voir, en comparant son φ_b à ceux des courbes voisines, s'il se place sur la surface Σ ou dans son voisinage.

On voit sur la fig. 4 que, dans la région rélative aux étoiles naines (V) ou sous-géantes (IV) des dernières sous-classes A et

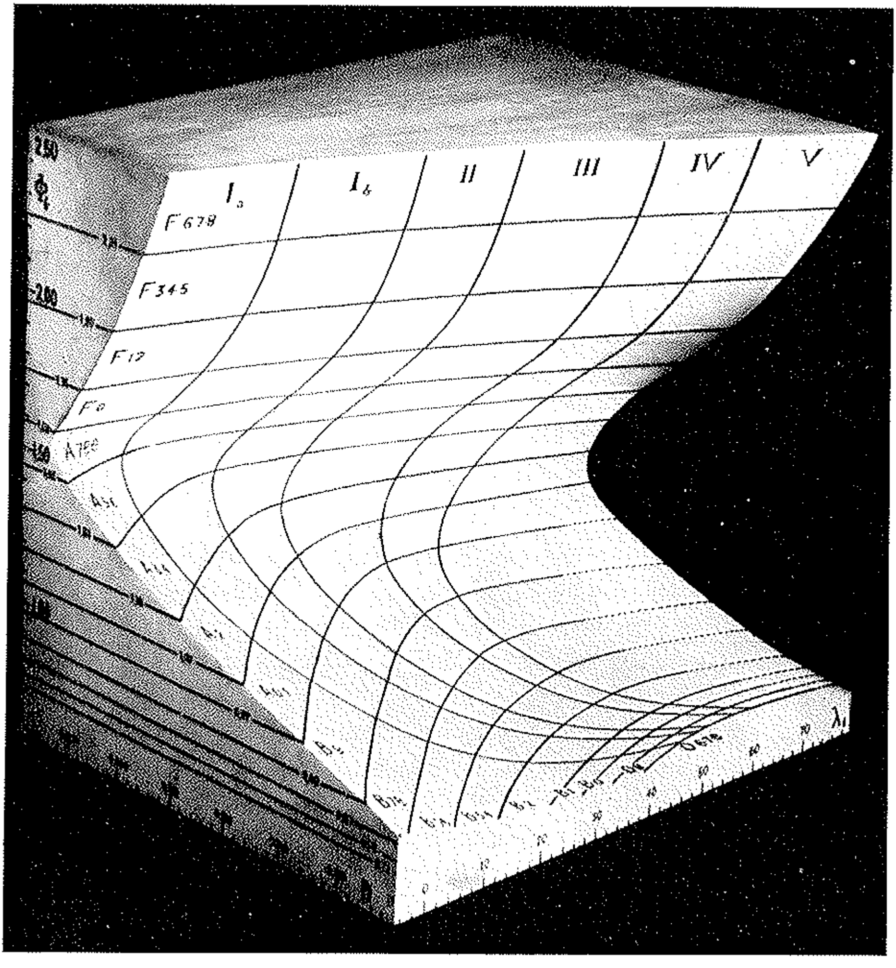


Fig. 2 — *Maquette de la surface* Σ. En abscisses, lire λ_1— 3700 au lieu de λ_1.

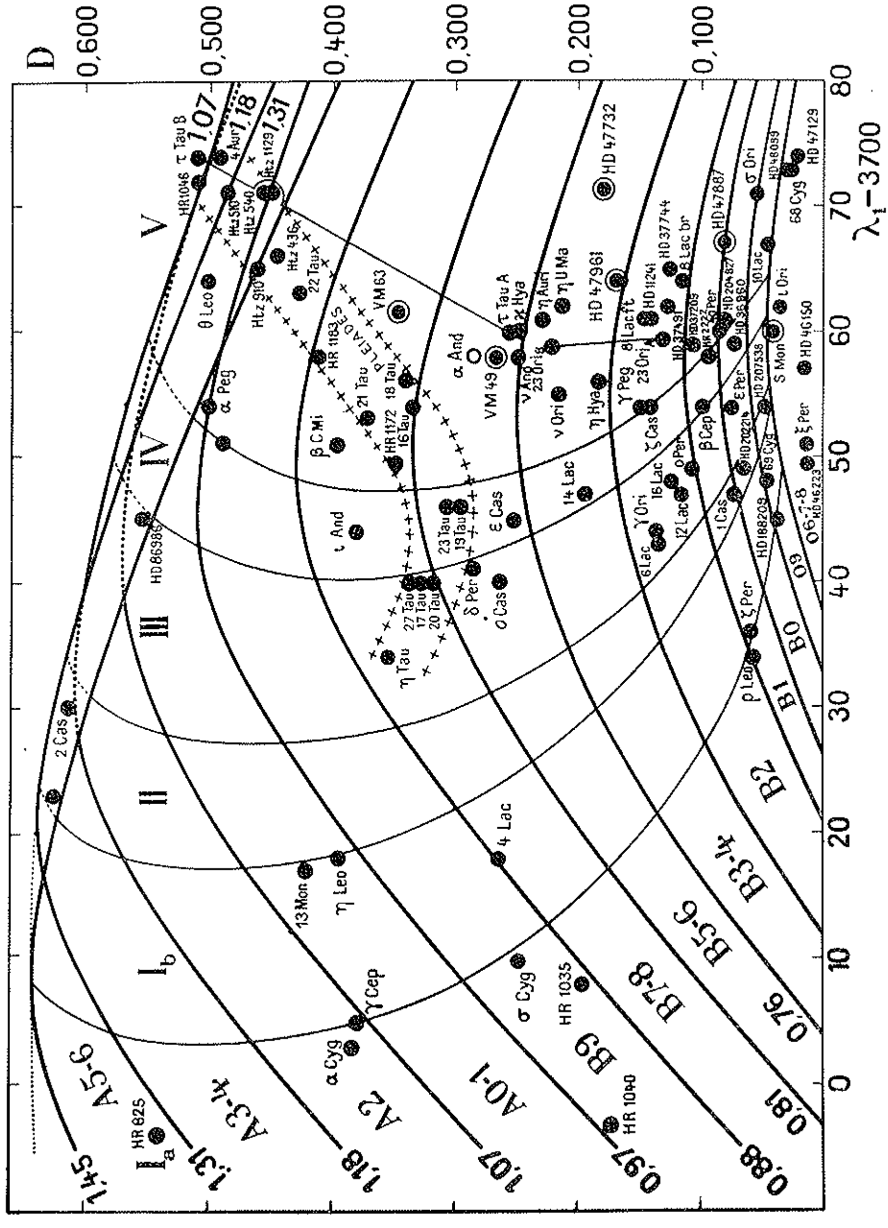


FIG. 3 — *Projection de la partie inférieure de la surface Σ sur le plan* $\lambda_1 D$. Les symboles employés sont les mêmes que pour la fig. 4.

de la classe F, les courbes $\varphi_b = c^{te}$ sont sensiblement des droites parallèles: cette partie de la surface Σ est donc assimilable à un cylindre et il sera commode dans l'exposé qui va suivre de considérer les projections des points figuratifs des étoiles correspondantes sur la section droite de ce cylindre qui est représentée par la droite xy de la fig. 4.

La section droite elle-même est représentée sur la fig. 5 (les abscisses se lisent sur la droite xy de la fig. 4). La courbe σ représente la section de Σ et on voit que les points figuratifs des étoiles normales ne se placent pas exactement sur Σ mais seulement dans son voisinage: ce fait important sera discuté et confirmé plus loin.

4. *Classification des étoiles à raies métalliques* (J. BERGER, A-M. FRINGANT, C. MENNERET [7]). — Un certain nombre d'étoiles à raies métalliques ont été classées et leurs points figuratifs sont représentés sur les fig. 4 et 5 (✻). *Ces points se placent nettement en dehors et au-dessus de la surface.*

Le point représentatif de l'étoile 63 Tau se place plus loin de Σ que celui de HR 1403: la première présente avec plus d'intensité que la seconde les caractères d'une étoile à raies métalliques; dans la classification de WEAVER [8], on pourrait représenter 63 Tau par le symbole ML 3 et HR 1403 par ML 1.

La région de l'espace (λ_1, D, φ_b) située au-dessus de la partie de Σ relative aux types A7V - F2V, correspondrait donc aux étoiles à raies métalliques, les caractères "métalliques" étant d'autant plus marqués que l'on s'éloigne davantage de Σ.

La composante brillante de l'étoile double HR 4021 étudiée par J. BERGER [9], tombant dans cette région de l'espace, a été classée comme étoile à raies métalliques.

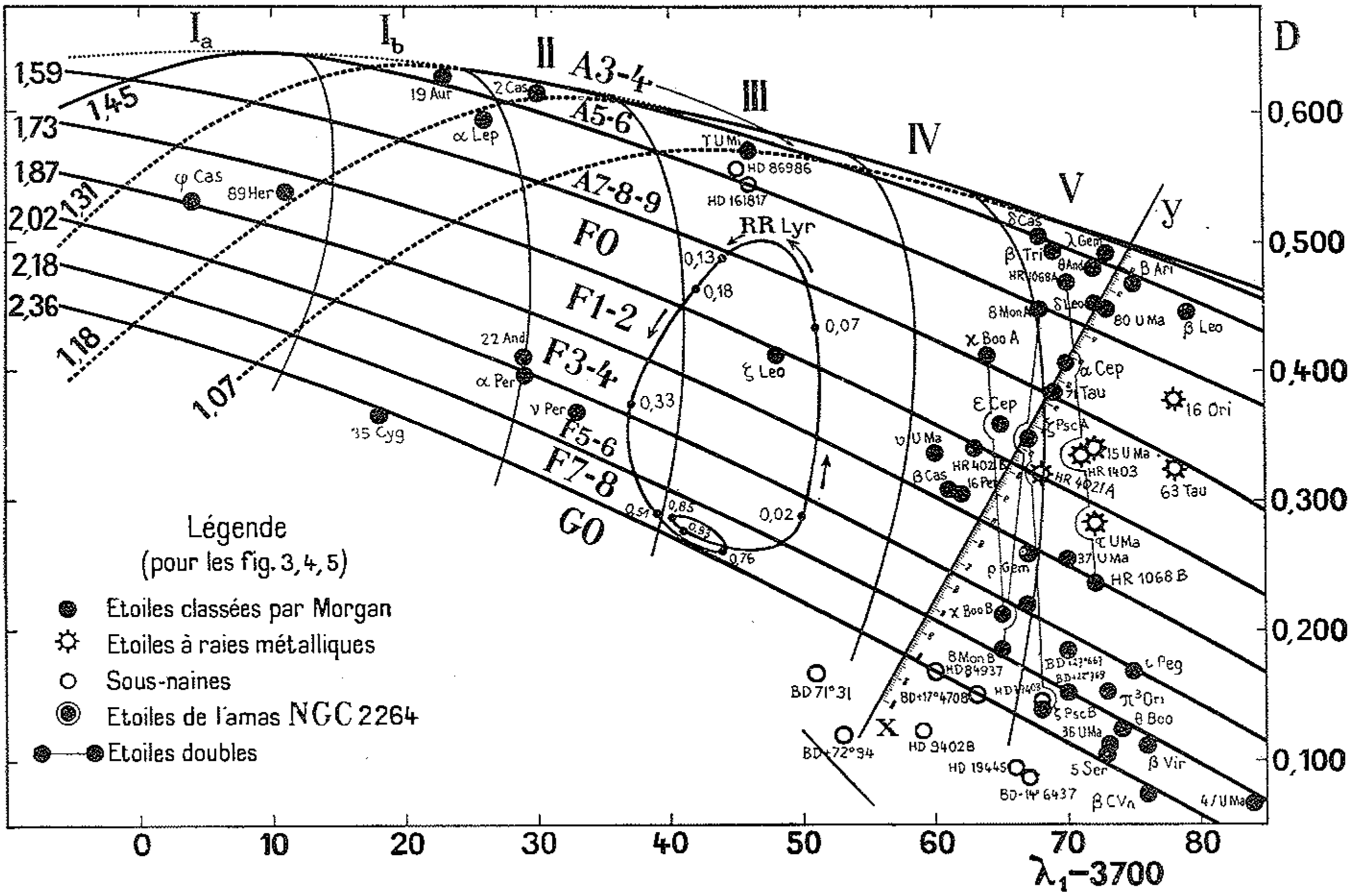


Fig. 4 — *Projection de la partie supérieure de la surface Σ sur le plan $\lambda_1 D$. xy est la trace du plan vertical suivant lequel on coupe Σ* (voir fig. 5).

CLASSIFICATION DES ÉTOILES DE LA POPULATION II

5. *Classification des sous-naines* (L. DIVAN [10]). — Plusieurs sous-naines de la liste donnée par Miss ROMAN [11] ont été classées et leurs points figuratifs sont portés sur les fig. 4 et 5 (o). *Ils se placent, eux aussi, en dehors de Σ mais au dessous de la région relative aux sous-classes F6-8 IV.*

La faible valeur de *D* pour ces sous-naines (fig. 4) explique l'"excès d'ultraviolet" que leur reconnaissent les photométristes.

L'étoile à grande vitesse HD 77408 à laquelle Miss ROMAN ne reconnait pas le caractère de sous-naine, se place sur la fig. 5, dans la région des sous-naines, mais plus près de Σ que les sous-naines de la liste de Miss ROMAN: on peut donc la considérer comme présentant des caractères de sous-naine atténués et intermédiaires entre ceux des sous-naines typiques et ceux des étoiles normales.

Il semble donc y avoir un passage continu entre les sous-naines et les étoiles normales.

La sous-naines de "type A" HD 86986 se place elle aussi en dehors et au-dessous de Σ: elle a en effet les coordonnées $\lambda_1 = 3745$, $D = 0{,}555$, $\varphi_b = 1{,}20$.

L'étoile à grande vitesse "de type A" HD 161817 se place aussi en dehors et au-dessous de Σ mais très près: ses coordonnées sont $\lambda_1 = 3746$, $D = 0{,}543$, $\varphi_b = 1{,}34$.

La fig. 4 montre que toutes les sous-naines et étoiles à grande vitesse considérées ont des λ_1 de sous-géantes ou de géantes. Cela pourrait s'expliquer par une pression électronique plus faible due à une composition différente (moins de métaux).

6. *Classification de RR Lyrae* (A-M. FRINGANT [12]). — Les paramètres de RR Lyrae ont été déterminés pour un cycle moyen (négligeant la période de 41 jours) et le point figuratif décrit, en projection sur le plan $\lambda_1 D$, la courbe de la fig. 4 (les phases sont inscrites pour 9 points de la courbe). Dans

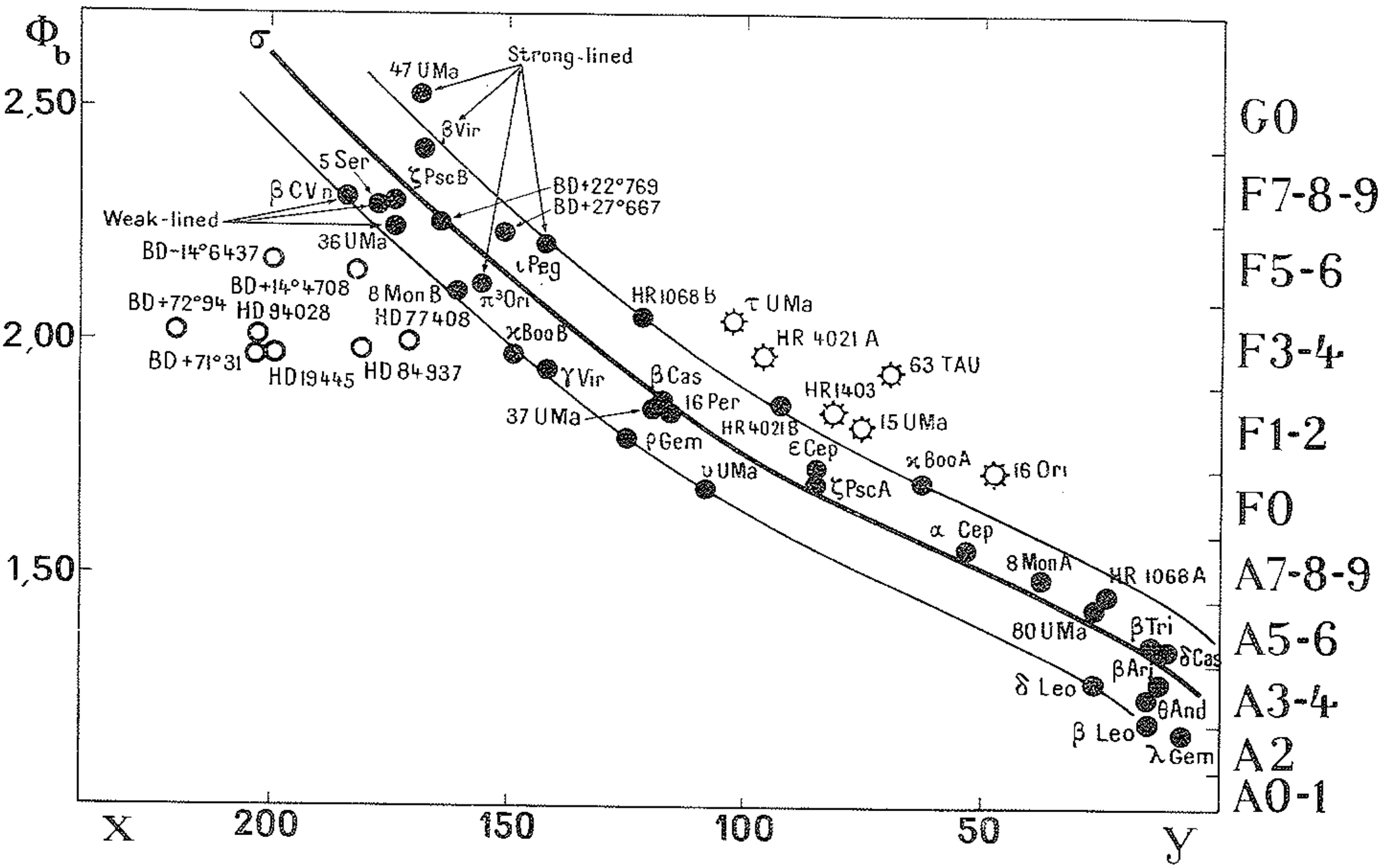


Fig. 5 — *Coupe de la partie supérieure de Σ par le plan vertical xy* (dont la trace est marquée sur la fig. 4). Les abscisses (en unités arbitraires) sont les divisions portées sur *xy* (fig. 4). Les symboles sont les mêmes que pour la fig. 4.

l'espace, le point figuratif reste constamment au-dessous de Σ comme le montre le tableau I dans lequel on a porté, pour diverses valeurs de la phase, la valeur de φ_b mesurée et celle $\varphi_b(\Sigma)$ du point de surface Σ qui a mêmes coordonnées $\lambda_1 D$. Le point figuratif reste plus près de Σ que pour les sous-naines: il en est le plus près au voisinage du maximum.

TABLEAU I

Phase	φ_b	$\varphi_b(\Sigma)$	*Phase*	φ_b	$\varphi_b(\Sigma)$
0,02	1,88	2,08	0,51	2,00	2,29
0,07	1,53	1,66	0,76	2,05	2,32
0,13	1,46	1,61	0,85	2,00	2,29
0,18	1,61	1,68	0,93	2,08	2,30
0,33	1,82	1,99			

Cette étude montre que les étoiles de la population II étudiées jusqu'ici se placent toutes dans la région de l'espace (λ_1, D, φ_b) *située au-dessous de la partie de* Σ *relative aux types A6 II-V à F8 II-V.*

STRUCTURE DU SPECTRE CONTINU VISIBLE

7. *Etoiles normales naines* (J. BERGER, D. CHALONGE, L. DIVAN, A-M. FRINGANT [13]). — L'étude du spectre continu visible va fournir un nouveau critère pour différencier les divers types d'étoiles.

Le spectre continu du Soleil peut être décrit avec une assez bonne approximation, du rouge au début de l'ultraviolet, par une température de couleur unique: ce qui signifie que dans tout ce grand domaine spectral le rayonnement continu du Soleil est à peu près proportionnel à celui d'un corps noir (*).

(*) *Note à la correction* — En réalité des travaux tous récents montrent que ce résultat n'est qu'approximatif. Mais le raisonnement qui suit garde sa valeur: les diverses étoiles sont comparées à une étoile Go dont le rayonnement reste assez voisin de celui d'un corps noir.

Nous admettrons qu'il en est de même pour les étoiles de type Go. Pour toutes les étoiles que nous considérons ici on peut, de même, décrire le fond continu bleu-violet ($\lambda < 4900$ Å ou $1/\lambda > 2{,}15$) par une température de couleur T_b ou un gradient absolu φ_b. Mais nous allons voir que pour les longueurs d'onde plus grandes le phénomène se complique.

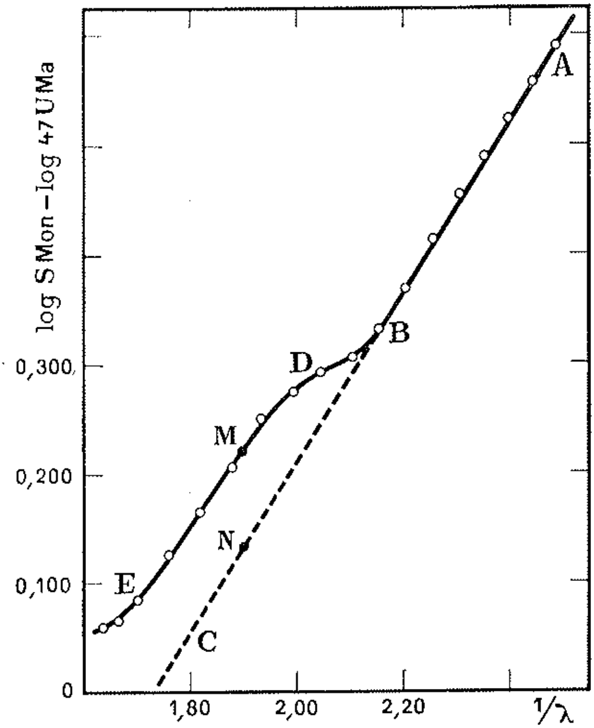


Fig. 6 — *Comparaison du spectre continu visible de S Mon (O6) à celui d'une étoile Go (47 UMa)* supposée rayonner proportionnellement à un corps noir (température T_b).

Comparons S Mon (O6) à 47 UMa (GoV). La courbe qui représente la variation en fonction de $1/\lambda$ du rapport des intensités des fonds continus de S Mon et 47 UMa (fig. 6) est parfaitement rectiligne pour $1/\lambda > 2{,}15$ (région AB) puisque les deux étoiles rayonnent proportionnellement à des corps noirs de températures différentes.

Mais si, pour les longueurs d'onde supérieures à 4900 Å ($1/\lambda < 2{,}15$), S Mon continuait à rayonner comme dans le bleu violet proportionnellement au corps noir de température T_b, la courbe de la fig. 6 serait la courbe BC en trait discontinu (sensiblement en ligne droite avec la partie AB). Mais on observe en réalité la courbe en trait plein DE qui présente avec la première partie une sorte de discontinuité vers 4900 Å: le rayonnement de grande longueur d'onde de S Mon est donc supérieur à celui que représente la courbe en trait discontinu; pour $1/\lambda = 1{,}9$ l'écart $MN = \delta_\lambda$ entre les deux courbes est égal à 0,09 ce qui correspond à un rayonnement de S Mon 1,25 fois plus grand que celui du corps noir considéré.

On peut représenter ce phénomène autrement (fig. 7) en portant, en fonction de $1/\lambda$, l'écart δ_λ entre le rayonnement réel et le rayonnement d'une étoile qui, du rouge à l'ultraviolet, rayonnerait avec la température de couleur T_b observée pour S Mon pour $1/\lambda > 2{,}15$.

$$\delta_\lambda = \log \text{S Mon} - \log \mathfrak{B}_\lambda(T_b)$$

où $\mathfrak{B}_\lambda$ représente la fonction de Planck.

Pour $1/\lambda > 2{,}15$ la courbe se confond avec l'axe des abscisses. Si l'on compare, de la même façon, à 47 UMa des naines E de type de plus en plus avancé, on observe les résultats suivants:

a) pour les classes O, B0, B1 la courbe $\delta_\lambda = \log E - \log \mathfrak{B}\ (T_b)$ fonction de $1/\lambda$ est à peu près superposable à la fig. 7, c'est-à-dire que les écarts δ_λ sont très voisins de ceux de S Mon, mais T_b décroît (c'est-à-dire φ_b croît) lorsque l'on se déplace vers les types plus avancés;

b) pour les classes B2 à B8, δ_λ commence à être sensiblement plus petit;

c) à partir de la classe Ao, δ_λ est nettement plus faible que pour les types antérieurs et on observe des courbes successives telles que celles de la fig. 8 (T_b continuant à décroître et φ_b à croître).

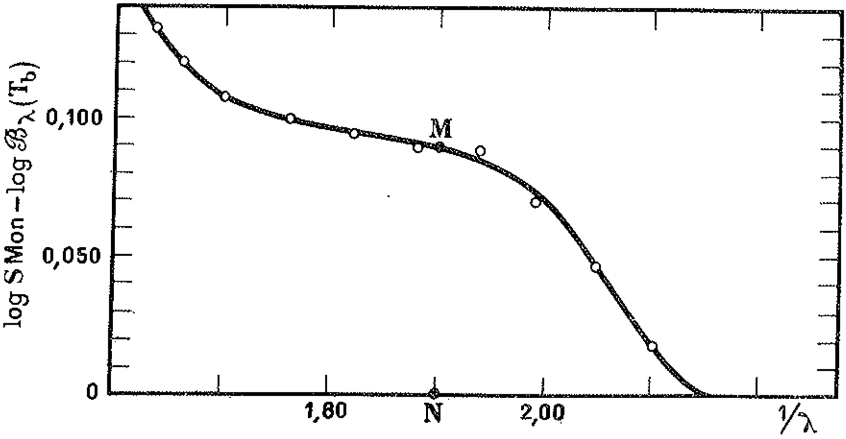


FIG. 7 — *Comparaison du spectre continu de S Mon à celui du corps noir de température* T_b. Cette courbe se déduit de celle de la fig. 6: les abscisses sont les mêmes; les ordonnées de la fig. 7 sont les différences entre les ordonnées des courbes BDE et BC de la fig. 6 (toutefois l'échelle des ordonnées à été augmentée sur la fig. 7).

Si l'on avait comparé à 47 UMa une série de supergéantes de type variant de O à F, on aurait observé les courbes de la fig. 9: pour les types O et B l'excès δ_λ du visible sur le rayonnement du corps noir est sensiblement le même que pour S Mon. Mais à partir de B9I, δ_λ augmente et les courbes successives s'élèvent: après un maximum, au delà du type A5I, δ_λ décroît rapidement et il s'annulerait vraisemblablement pour une sous-classe G (les observations n'ont pas encore été poussées jusque là).

Ce phénomène semble difficile à expliquer en faisant intervenir simplement les propriétés absorbantes connues de l'hydrogène et de l'hélium: tout ce que l'on peut dire pour l'instant

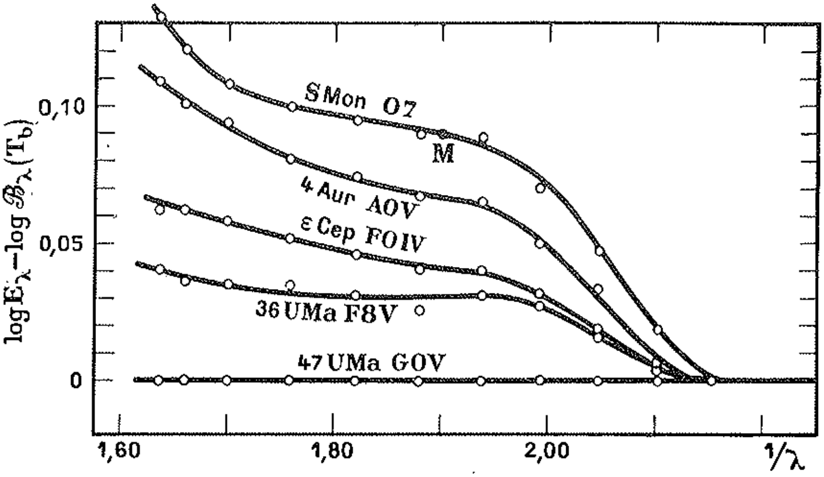


FIG. 8 — *Variation du spectre continu visible entre les types O7 et G0 (naines et sous-géantes)*. Série de courbes analogues à celle de la fig. 7.

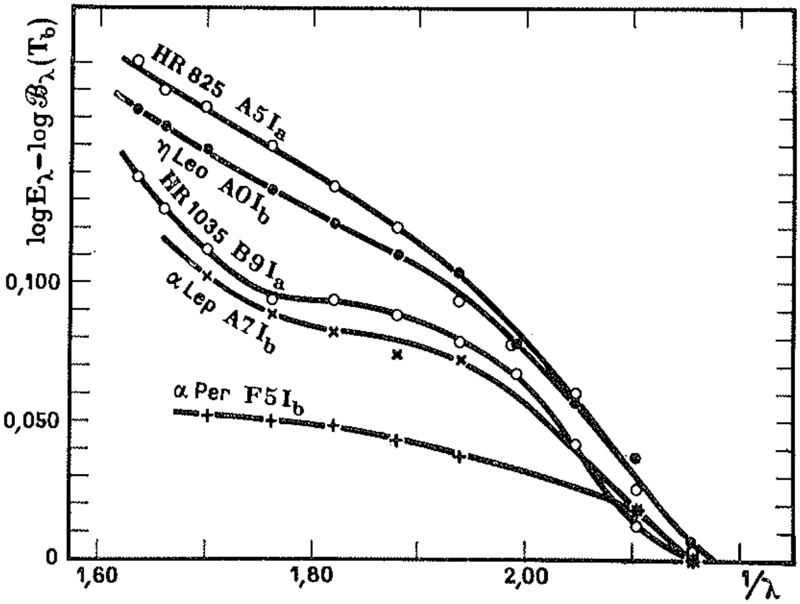


FIG. 9 — *Variation du spectre continu visible entre les types B9 et F5 (supergéantes)*. Série de courbes analogues à celle de la fig. 7.

est qu'il s'observe dans la matière stellaire à haute température, fortement ionisée. Le phénomène s'atténue (le rayonnement visible tendant peu à peu à devenir proportionnel à un rayonnement de corps noir) à partir du type Ao chez les naines et d'un type un peu plus avancé que A5 chez les supergéantes: cette atténuation pourrait donc être attribuée à l'apparition de la couche d'ions négatifs hydrogène qui empêche d'observer le rayonnement des couches plus chaudes, siège du phénomène.

8. *Etoiles à raies métalliques et sous-naines* (J. BERGER, A-M. FRINGANT, C. MENNERET [7] et L. DIVAN [10]). — L'étude spectrophotométrique des étoiles à raies métalliques et des sous-naines montre que la courbe d'énergie de ces étoiles dans le visible n'est pas déterminée seulement par la valeur de φ_b.

La fig. 10 représente la comparaison à 47 UMa de deux étoiles à raies métalliques (63 Tau et HR 1403), d'une étoile normale (ε Cep) et de deux sous-naines (HD 77408 et HD 19445) ayant toutes sensiblement le même φ_b, c'est-à-dire représentées par des points situés à peu près sur une même horizontale (fig. 5). L'étoile située le plus à droite sur la fig. 5, 63 Tau, rayonne comme un corps noir dans tout le spectre visible et la sous-naine HD 19445 située le plus à gauche a un excès de grandes longueurs d'onde comparable à une AoV. La fig. 11 qui représente la variation de δ_λ pour les mêmes étoiles traduit le même phénomène.

De ces observations on peut déduire les deux conséquences suivantes:

a) *le simple examen du spectre visible* (valeurs de φ_b et de δ_λ) *permettrait de différencier les naines de type normal, les étoiles à raies métalliques et les sous-naines;*

b) on vérifie que l'*on peut passer de façon continue des étoiles à raies métalliques aux étoiles normales et aux sous-naines, c'est-à-dire de la population I à la population II.*

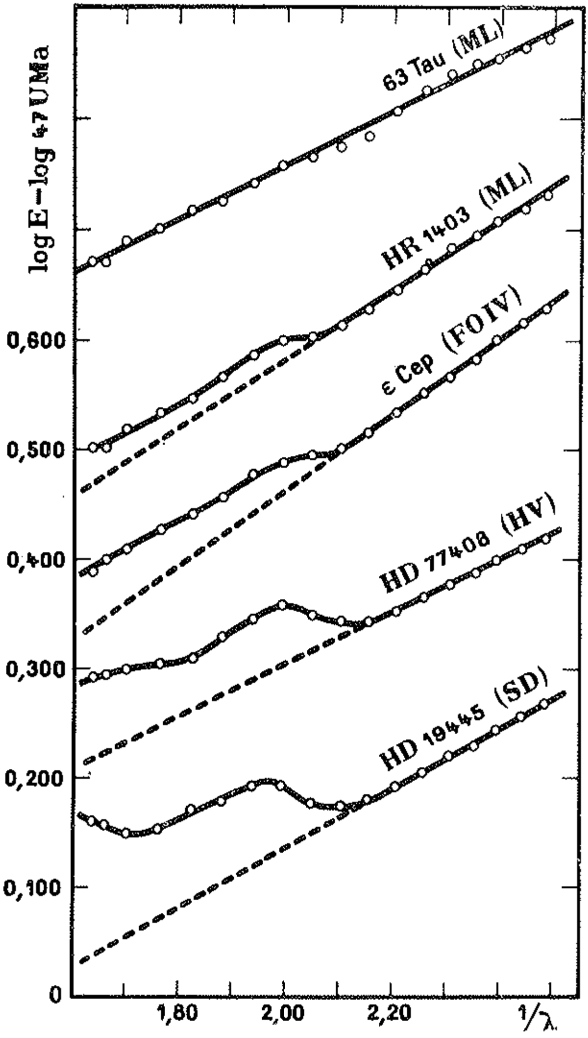


Fig. 10 — *Comparaison des spectres continus visibles d'une série d'étoiles.* Il s'agit de 5 étoiles (à raies métalliques, normale, à grande vitesse, sous-naine) ayant sensiblement le même φ_b (voir fig. 5).

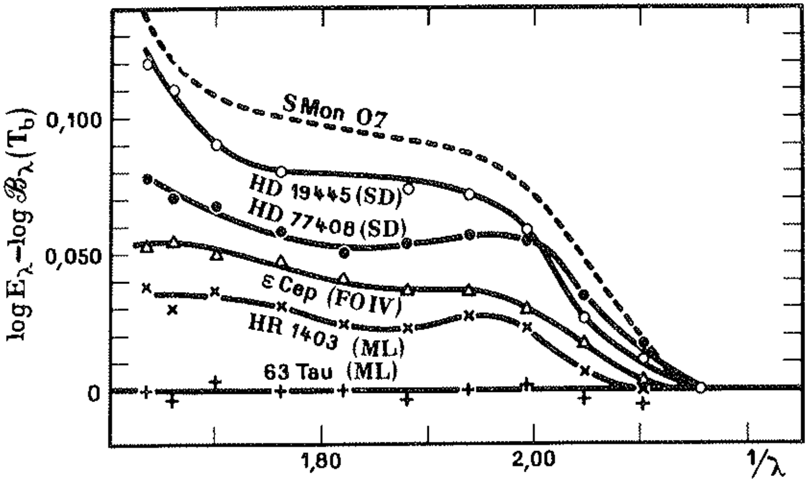


FIG. 11 — *Comparaison des spectres continus visibles d'une série d'étoiles.* Cette figure concerne les mêmes étoiles que la fig. 10. Les courbes sont déduites de celles de la fig. 10 comme la courbe de la fig. 7 l'a été de celle de la fig. 6.

RETOUR SUR LA CLASSIFICATION DES ÉTOILES NORMALES DES TYPES A ET F

9. *La classification précise de ces étoiles dépend de trois paramètres.* — On a déjà noté au § 3 que les points figuratifs des étoiles A et F des classes de luminosité IV et V ne se placent pas exactement sur la surface Σ mais dans son voisinage immédiat (fig. 5). Cette dispersion n'est pas due aux erreurs expérimentales, les écarts des points figuratifs les plus éloignés de la section σ de Σ étant supérieurs aux erreurs moyennes: l'épaisseur du volume dans lequel se groupent les points est de l'ordre de 0,25 à 0,30, comptée parallèlement à l'axe φ_b. Si les points se plaçaient tous sur Σ, la classification des étoiles correspondantes dépendrait de deux paramètres seulement, ces paramètres pouvant se ramener à la température et à la gravité et on pourrait admettre que toutes ces étoiles ont exactement

la même composition. *Le fait que les points ne se placent pas exactement sur Σ mais dans son voisinage montre qu'une classification rigoureuse exige l'intervention d'un troisième paramètre*: la composition des étoiles normales pourrait donc varier dans certaines limites assez étroites et nous allons voir en effet dans le paragraphe suivant que des étoiles ayant une même origine semblent présenter une dispersion moins grande.

10. *Classification des composantes des Hyades et de l'amas galactique de Coma Berenices* (F. VAN'T VEER [14] et B. WESTERLUND [15]. — Un certain nombre de composantes des Hyades ont été classées et, en projection sur le plan $\lambda_1 D$, les points figuratifs occupent toute la largeur de la bande des naines (fig. 17): mais sur la section par le plan xy (fig. 12) ils occupent une bande mince située à l'intérieur de la bande plus large qui contient les étoiles de toutes origines (cette bande est celle de la fig. 5; elle est reportée, en trait discontinu, sur la fig. 12). L'étoile isolée qui se place au-dessus de la bande des Hyades a été peu observée (toutes les autres l'ont été en général 4 ou 6 fois) et sa place est mal définie.

Un petit nombre d'étoiles de l'amas de Coma Berenices ont été observées (en n'y comprenant pas les étoiles à raies métalliques): elles sont représentées sur les fig. 18 (en projection sur le plan $\lambda_1 D$) et 13 (en projection sur la section xy). Sur cette dernière figure, elles semblent également se concentrer dans une bande voisine de celle des Hyades (figurée en trait continu) mais il sera nécessaire d'en observer davantage pour confirmer ce fait.

L'étendue de la dispersion des points sur la fig. 5 tiendrait donc à l'origine variée des étoiles considérées.

11. *Les étoiles "strong-lined" et "weak-lined" de Miss* ROMAN (L. DIVAN [16]). — Miss ROMAN [17] a divisé les étoiles plus avancées que F5 en étoiles à raies fortes (strong-lined) et à raies faibles (weak-lined) et a montré que les caractéristiques cinématiques de ces dernières les plaçaient parmi les étoiles à grande vitesse.

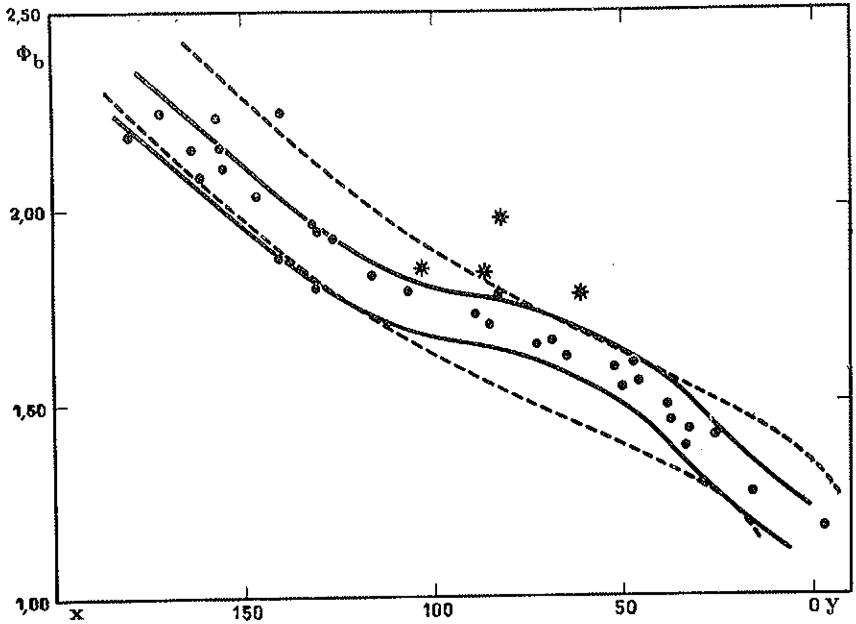


FIG. 12 — *Projection sur le plan xy des points figuratifs de quelques Hyades.* Cette figure est analogue à la fig. 5 mais seuls y sont portés les points figuratifs des Hyades. La bande limitée par les courbes discontinue est la même que sur la fig. 5 : les étoiles normales (●) semblent localisées dans une bande beaucoup plus étroite (limitée par les courbes continues). Les étoiles à raies métalliques sont représentées par ★.

On pouvait donc se demander si l'hétérogénéité que la classification tridimensionelle permet de constater parmi les étoiles des types A et F ne s'apparentait pas avec cette classification de Miss ROMAN.

Les recherches entreprises sur ce sujet par L. DIVAN ne portent encore que sur un trop petit nombre d'étoiles pour permettre de conclure avec précision, mais sur 7 des étoiles classées par Miss ROMAN les weak-lined se placent (fig. 5) à la limite inférieure du volume contenant les étoiles F, c'est-à-dire, comme on pouvait s'y attendre, au voisinage des sous-naines, et trois strong-lined se placent à la limite supérieure de ce même

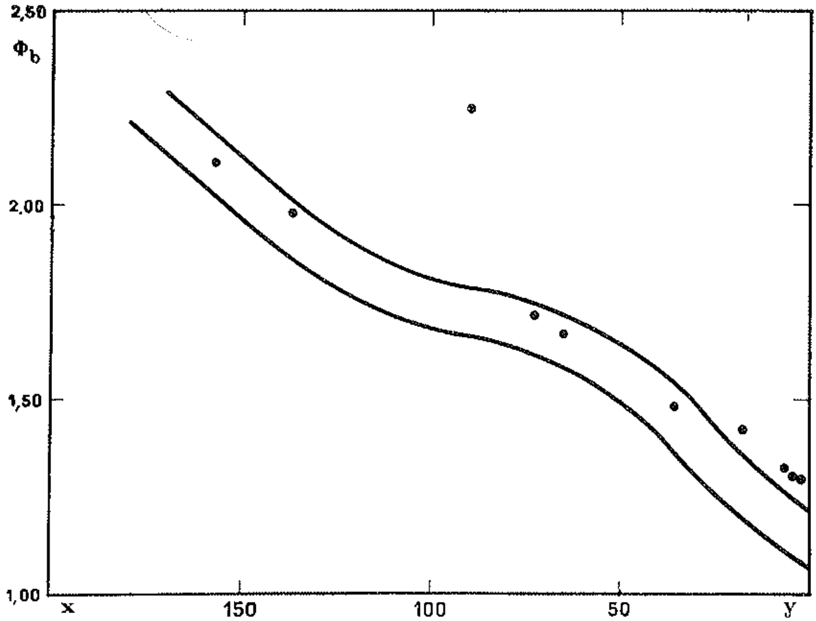


FIG. 13 — *Projection sur le plan xy de quelques membres de l'amas de Coma.* Figure analogue à la précédente. Les deux courbes sont celles qui, dans la figure 12, limitent les Hyades.

volume. Il y a une exception: π^3 Ori qui, bien que classée strong-lined, se place au voisinage de la limite inférieure.

Il y a donc une indication qu'il pourra être rendu compte de la classification de Miss ROMAN.

CLASSIFICATION DE QUELQUES ÉTOILES PARTICULIÈRES

12. *Les "sous-naines" des Hyades.* (L. DIVAN [18]). — On a signalé que les Hyades et quelques autres amas ouverts, c'est-à-dire appartenant à la population I, contenaient des sous-naines, type d'étoiles rencontré jusqu'ici seulement dans la population II. L. DIVAN a commencé l'étude des deux "sous-

naines" les plus brillantes des Hyades [19], BD + 22°769 et BD + 27°667.

Bien que cette étude ne soit pas achevée, ces deux étoiles semblent se placer (fig. 5) parmi les étoiles F5-6 et pas du tout dans la région des sous-naines. De plus, leur discontinuité visible paraît nettement plus petite que celle des sous-naines (fig. 14) et comparable à celle des étoiles F parmi lesquelles elles se classent (fig. 15).

Il faut d'ailleurs remarquer que les caractéristiques photométriques (*U-B, B-V*) données par JOHNSON et KNUCKLES pour ces deux étoiles [19] confirment le résultat annoncé ici.

Les étoiles en question ne présenteraient donc aucune des caractéristiques de la population II.

13. *Les "spectrum-variables"* (L. DIVAN [20]). — L'une de ces étoiles, α And, a été étudiée et si les valeurs de λ_1 et D déterminées la placent parmi les B6 (fig. 3), la valeur de $\varphi_b = 0{,}98$ et sa discontinuité visible (fig. 16) sont sensiblement celles d'une A0. Dans l'espace (λ_1, D, φ_b) elle se place donc en dehors de Σ et au-dessus de sa partie inférieure.

Le fait que α And soit une étoile double spectroscopique ne permet pas de rendre compte de ces anomalies.

BARBIER et CHALONGE ont signalé [21] des résultats analogues pour une autre spectrum variable α^2 CVn (mais ils n'ont pas étudié sa discontinuité visible) qui se placerait par conséquent elle aussi hors de Σ, dans la même région que α And.

DIFFÉRENCES DES PROPRIÉTÉS DES ÉTOILES APPARTENANT À DES AMAS OUVERTS DIFFÉRENTS

14. *Hyades et amas galactique de Coma Berenices.* (F. VAN'T VEER [14]). — JOHNSON et KNUCKLES ont signalé [19] des différences entre des étoiles de même type appartenant aux amas des Hyades et de Coma Berenices : les membres de ce dernier amas présenteraient un excès d'ultraviolet par rapport à ceux des Hyades.

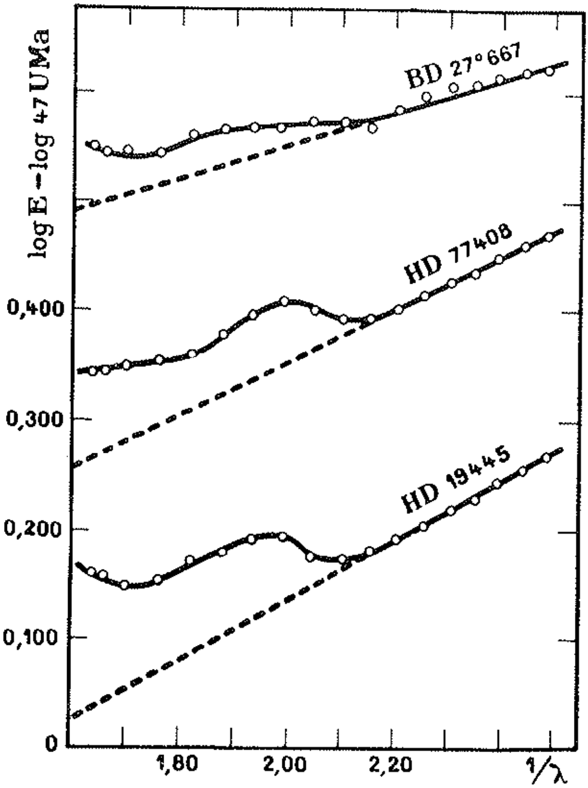


Fig. 14 — *Les "sous-naines" des Hyades.* Comparaison du spectre continu visible d'une de ces prétendues sous-naines (BD 27°667) aux spectres continus d'une étoile à grande vitesse (HD 77408) et d'une sous-naine (HD 19445). Les trois spectres sont rapportés à ceux de l'étoile 47 UMa.

Ce fait s'explique parfaitement dans la classification tridimensionnelle: les fig. 17 et 18 montrent qu'en moyenne les étoiles de Coma sont plus naines que celles des Hyades. Elles ont, en effet, en général un λ_1 plus grand: cela apparaît bien

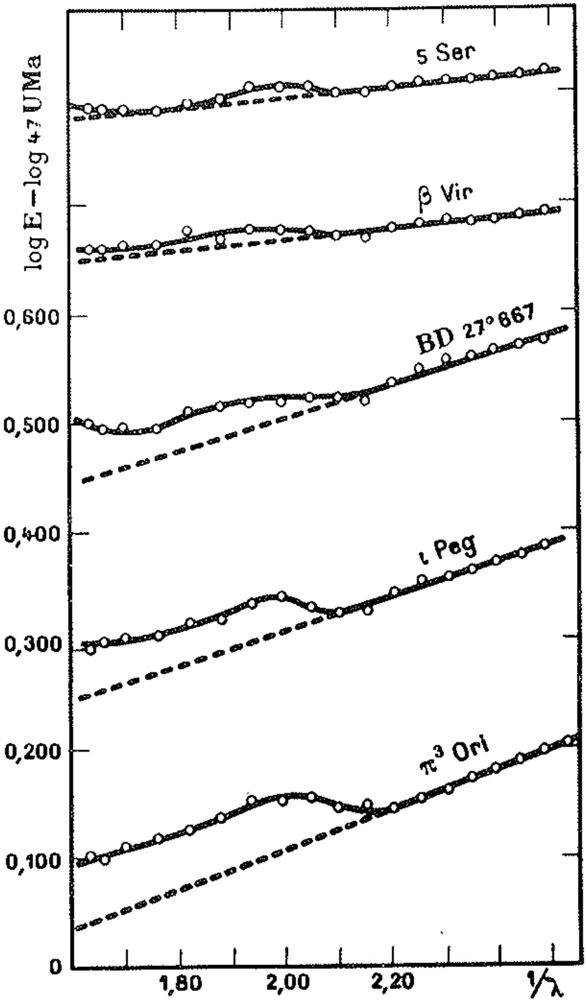


Fig. 15 — *Les "sous-naines" des Hyades.* Comparaison du spectre continu visible de BD 27°667 à ceux d'étoiles normales ayant une classification voisine (fig. 4 et 5).

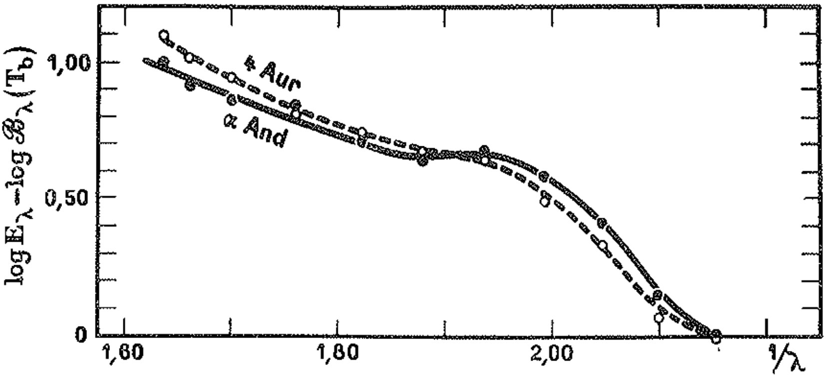


Fig. 16 — *Comparaison du spectre continu visible de α And à celui d'une étoile A0 normale (4 Aur).* Les spectres sont présentés comme sur la fig. 7.

sur la fig. 18 où l'on a figuré en trait discontinu les limites entre lesquelles se placent les Hyades. Etant plus naines, les étoiles de Coma ont une discontinuité de Balmer plus petite que celles des Hyades de même type spectral: cette plus petite discontinuité explique l'excès d'ultraviolet observé.

15. *Pléiades et NGC 2264.* — La fig. 3 donne les limites de l'amas des Pléiades et il apparaît bien que celles de l'amas, beaucoup plus jeune, NGC 2264 (dont les composantes sont représentées par ⊙) coupent les limites des Pléiades. Il sera intéressant de rechercher dans la région commune si les étoiles des deux amas présentent des différences et s'il est possible de mettre en évidence dans la région des étoiles B des différences de structure analogues à celles qui sont apparues pour les types A et F. La présence de matière interstellaire rend cette comparaison plus délicate. Le travail est en cours.

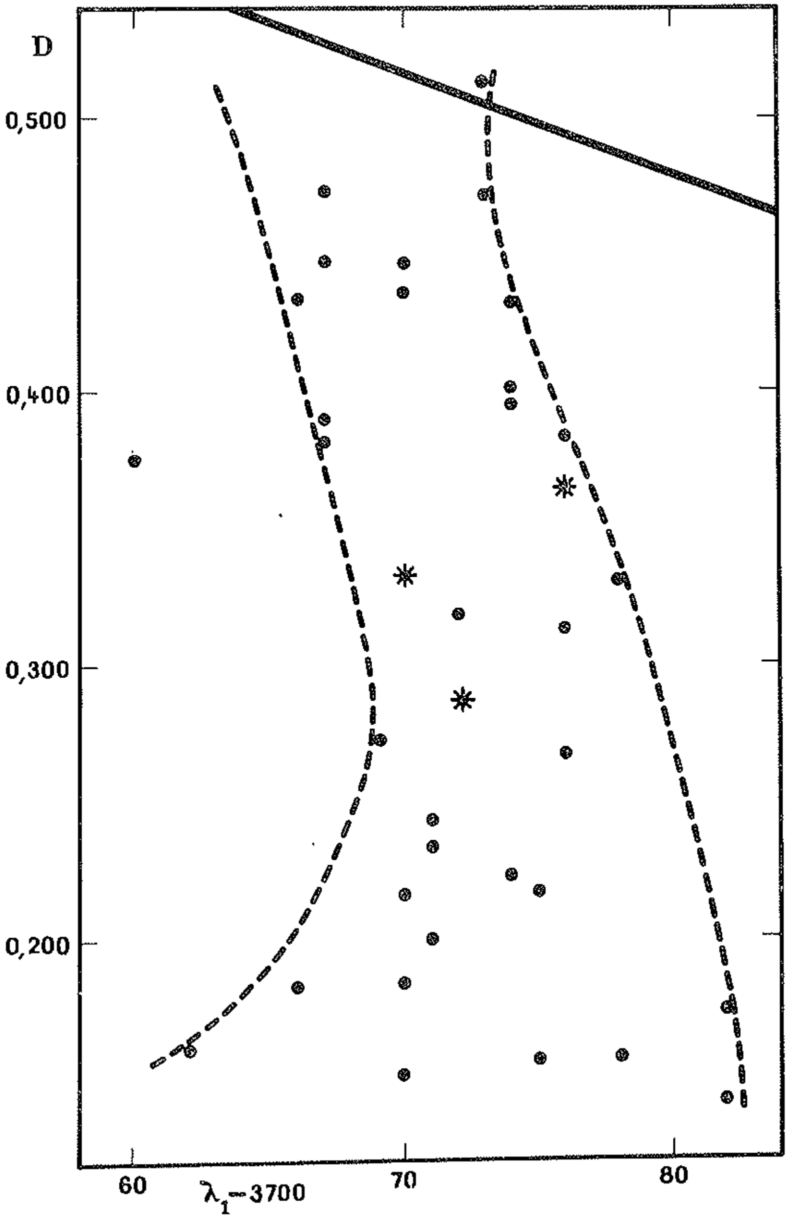


FIG. 17 — *Classification de quelques Hyades.* Projection de leurs points figuratifs sur le plan $\lambda_1 D$. Tous ces points, sauf un, sont contenus dans la bande limitée par les deux courbes en trait discontinu. Le trait plein est la projection du contour apparent de Σ (fig. 4). ● étoiles normales; ★ étoiles à raies métalliques.

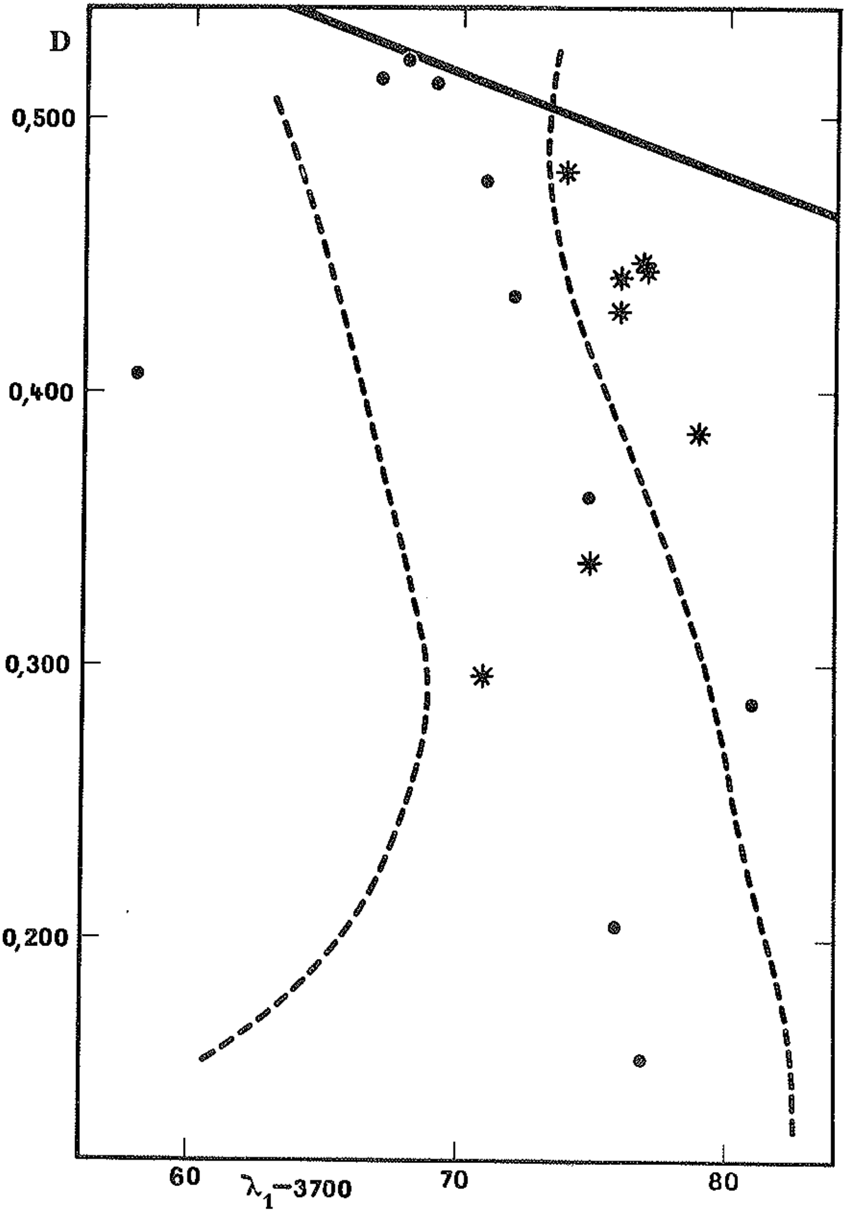


Fig. 18 — *Classification de quelques membres de l'amas de Coma.* Les courbes en trait discontinu sont celles qui limitent les Hyades sur la fig. 17. Voir la légende de la fig. 17.

ETALONNAGE EN MAGNITUDES ABSOLUES DE LA CLASSIFICATION TRIDIMENSIONNELLE

16. *Remarques générales.* — La classification tridimensionnelle nous a permis de classer et de différencier de nombreuses espèces d'étoiles. Chaque groupe de valeurs des paramètres λ_1, D et φ_b caractèrise un type d'étoile et ses propriétés particulières: à chaque groupe doit donc correspondre en particulier une magnitude absolue M et il serait important de déterminer la fonction M (λ_1, D, φ_b).

Pour résoudre ce problème les méthodes suivantes sont employées:

a) la classification d'étoiles proches, à parallaxe connue, permet d'amorcer la graduation en magnitudes de la région des naines de type F;

b) la classification de membres d'amas ouverts, bien connus et exempts de matière interstellaire, comme les Hyades, doit permettre de préciser la graduation de la région des étoiles F et de l'étendre jusqu'aux étoiles A;

c) mais la méthode la plus efficace pour achever la graduation de la région des naines des types F et A semble être celle qu'utilise J. Berger: elle repose sur la classification d'étoiles multiples dont les composantes, largement séparées, ont des différences de magnitude connues et appartiennent à ces types spectraux.

Lorsque la région des naines F et A sera graduée, il sera possible d'étendre la méthode des étoiles doubles à la graduation d'autres régions de l'espace (λ_1, D, φ_b): si une étoile brillante de type O ou B, par exemple, possède un compagnon faible représenté par un point de la région déjà graduée, la magnitude absolue de la composante brillante sera immédiatement connue.

L'éxécution de ce programme est encore loin d'être achevée. Aussi ne sera-t-il possible de faire état dans les paragraphes suivants que de résultats très partiels et très incomplets.

17. *Graduation de la région des naines et des sous-géantes des types F et A.* (J. Berger [22]). — Les *différences de magnitude absolue* entre les composantes d'une étoile multiple étant déterminées par photométrie, sont connues avec une pré-

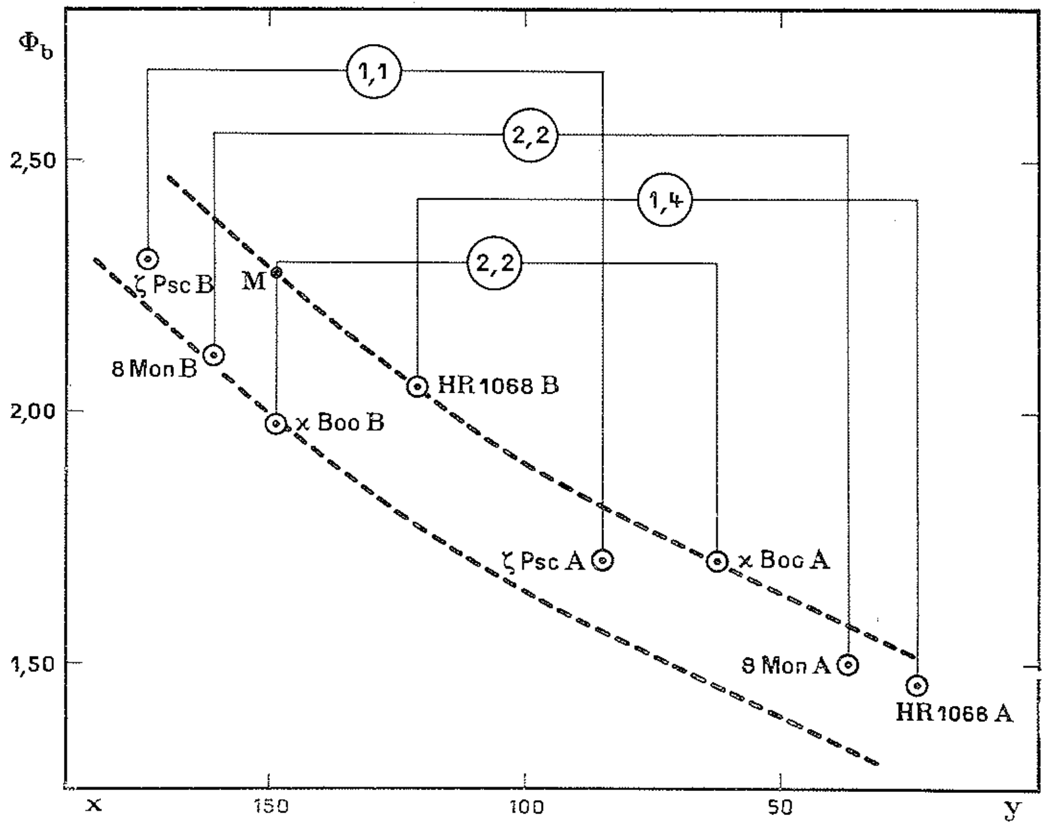


FIG. 19 — *Projection sur le plan xy des points représentatifs de quelques étoiles doubles.* Les nombres dans les cercles sont les différences de magnitude. Les courbes en trait discontinu représentent les limites du volume dans lequel se placent les étoiles normales (fig. 5).

cision bien plus grande que les *magnitudes absolues* d'étoiles simples, déduites des mesures de parallaxes; de plus, elles ont peu de chances d'être affectées par l'absorption interstellaire.

Aussi allons nous commencer par déterminer, à partir de la classification de quelques étoiles doubles, la loi de *variation de la magnitude absolue* dans la portion considérée de l'espace. La connaissance de quelques magnitudes absolues précises (déterminées à partir des parallaxes) permettra d'obtenir ensuite la magnitude absolue en chaque point de l'espace.

Soit donc ΔM la différence de magnitude absolue entre des étoiles représentées par deux points voisins de l'espace $(\lambda_1, D, \varphi_b)$. Nous pouvons écrire

$$\Delta M = \frac{\partial M}{\partial \lambda_1} \Delta \lambda_1 + \frac{\partial M}{\partial D} \Delta D + \frac{\partial M}{\partial \varphi_b} \Delta \varphi_b \tag{1}$$

ou $\Delta\lambda_1$, ΔD, $\Delta\varphi_b$ représentent les différences de coordonnées de ces deux points.

Les cinq étoiles doubles du tableau II, dont les composantes sont contenues dans la région de l'espace à graduer (voir fig. 4 et 19) ont été classées avec une précision assez bonne et l'on peut écrire cinq équations analogues à (1).

Dans ce système d'équations, les quantités ΔM, $\Delta\lambda_1$, ΔD, $\Delta\varphi_b$ sont connues et l'on peut en déduire les valeurs moyennes des dérivées partielles $\frac{\partial M}{\partial \lambda_1}, \frac{\partial M}{\partial D}, \frac{\partial M}{\partial \varphi_b}$ (en supposant que ces quantités ne varient pas dans de trop larges limites).

La résolution par la méthode des moindres carrés, de ce système de cinq équations à trois inconnues, conduit aux valeurs suivantes

$$\frac{\partial M}{\partial \lambda_1} = -0{,}049^{*}, \quad \frac{\partial M}{\partial D} = -15{,}97, \quad \frac{\partial M}{\partial \varphi_b} = -3{,}62 .$$

(*) *Note à la correction* — L'examen de la fig. 4 et du tableau II montrent que les valeurs de $\Delta\lambda_1$ sont petites pour les étoiles doubles considérées. La quantité $\frac{\partial M}{\partial \lambda_1}$ ne peut donc être déterminée avec précision. Un calcul plus précis fait récemment à partir de couples mieux choisis donne une valeur petite mais positive pour $\frac{\partial M}{\partial \lambda_1}$ (comme on pouvait le prévoir). Ce résultat ne change rien aux conclusions de ce paragraphe.

Ces valeurs permettent de retrouver, avec une bonne approximation, les valeurs observées de ΔM, ainsi que le montre le tableau III.

TABLEAU II

*	$\lambda_1 - 3700$	D	φ_b	ΔM
HR 1068 A	70	0,469	1,47	1,4
HR 1068 B	72	0,236	2,05	
8 Mon A	68	0,448	1,50	2,2
8 Mon B	65	0,186	2,11	
ϰ Boo A	64	0,412	1,70	2,2
ϰ Boo B	65	0,213	1,97	
ζ Psc A	67	0,349	1,70	1,1
ζ Psc B	68	0,140	2,30	
HR 4021 A	68	0,320	1,95	0,6
HR 4021 B	63	0,340	1,74	

TABLEAU III

*	ΔM *observé*	ΔM *calculé*
HR 1088	+ 1,4	+ 1,52
8 Mon	+ 2,2	+ 2,12
ϰ Boo	+ 2,2	+ 2,15
ζ Psc	+ 1,1	+ 1,12
HR 4021	+ 0,6	+ 0,69

On peut faire au calcul précédent les deux critiques suivantes: d'une part, les cinq étoiles doubles utilisées ne sont pas encore classées avec toute la précision désirable (chaque étoile n'ayant encore été observée que 6 fois, en général); d'autre part, elles sont dispersées dans un grand volume et l'on peut craindre que les trois dérivées partielles n'y varient notablement. Aussi les valeurs trouvées pour ces trois dérivées peuvent elles être considérées seulement comme de premières approximations.

Néanmoins il est facile de vérifier qu'elles permettent de calculer avec une assez bonne précision la différence de magnitude absolue entre les étoiles simples du tableau IV, dont la classification est faite dans le système (λ_1, D, φ_b), et qui sont situées dans la région de l'espace considérée (fig. 4 et 5). L'avant dernière et la dernière colonne du tableau donnent respectivement les valeurs de M calculées par la méthode qui vient d'être décrite (en comparant les cinq premières étoiles à la sixième, π^3 Ori) et celles observées (déduites des parallaxes trigonométriques).

TABLEAU IV

*	$\lambda_1 - 3700$	D	φ_b	M (*calculé*)	M (*mesuré*)
α Cep	70	0,407	1,56	1,83	2,0
ε Cep	65	0,359	1,73	2,23	2,3
γ Vir	67	0,219	1,95	3,57	3,6
ι Peg	75	0,175	2,13	3,23	3,4
β Vir	76	0,110	2,41	3,21	3,8
π^3 Ori	73	0,154	2,12	—	3,7

De même, pour 22 membres de l'amas des Hyades qui ont été classées, on a déterminé les magnitudes absolues par différence avec π^3 Ori. Les valeurs ainsi calculées sont en accord satisfaisant avec les valeurs admises.

On peut aussi essayer de calculer, toujours par comparaison avec π^3 Ori, la magnitude absolue de sous-naines, bien que les points représentatifs de ces étoiles se trouvent franchement en dehors du domaine (déjà trop vaste) dans lequel le calcul des trois dérivées partielles a été fait. Le tableau V donne les résultats, pour trois des sous-naines les mieux classées et il est intéressant de constater, que, malgré l'extrapolation faite, leur ordre de grandeur est satisfaisant.

TABLEAU V

*	$\lambda_1 - 3700$	D	φ_b	M (*calculé*)
HD 19445	66	0,094	1,97	5,54
HD 94028	59	0,121	2,01	5,31
HD 84937	60	0,168	1,98	4,50

Malgré les réserves faites précédemment, ce premier essai de détermination des magnitudes absolues en divers points de l'espace (λ_1, D, φ_b) semble donc encourageant.

Il importera maintenant de préciser ces premiers résultats en classant avec précision un plus grand nombre d'étoiles doubles: il sera alors possible de calculer plus exactement les quantités $\frac{\partial M}{\partial \lambda_1}, \frac{\partial M}{\partial D}, \frac{\partial M}{\partial \varphi_b}$ dans plusieurs régions voisines de l'espace et d'étudier leurs variations.

Le problème de l'étalonnage en magnitudes absolues de l'espace (λ_1, D, φ_b) semble donc pouvoir être ainsi résolu dans la région des naines et sous-géantes des types F et A, où la détermination directe de quelques parallaxes précises permettra de fixer l'origine de l'échelle des magnitudes.

Remarque — La classification des quelques étoiles doubles qui vient d'être faite confirme en outre que les étoiles F se distribuent dans un volume autour de la surface Σ ainsi que le montre la fig. 19. Le calcul des dérivées partielles permet, de plus, d'évaluer la différence de magnitude absolue entre deux étoiles dont les points représentatifs sont situés sur les deux faces du volume (comme M et $\varkappa$ Boo sur la fig. 19) et se projettent au même point du plan $\lambda_1 D$: leurs φ_b différant de 0,30 environ, leurs magnitudes absolues diffèrent de $0{,}30 \times \frac{\partial M}{\partial \varphi_b} = 1{,}1$, l'étoile la plus brillante ayant le plus grand φ_b.

18. *Extension de la graduation en magnitudes absolues aux autres régions de l'espace* (λ_1, D, φ_b). (J. Berger [22]). — La méthode des étoiles doubles qui vient d'être décrite, est évidemment applicable à toutes les régions de l'espace, pour déterminer la loi de variation des magnitudes absolues.

Son extension au domaine des naines de type B est commencée. Elle laisse pressentir qu'ici aussi les étoiles doivent être représentées par les points d'un volume mince voisin de la surface Σ.

Lorsque la loi de variation des magnitudes sera connue dans une nouvelle région, il sera nécessaire, pour passer des différences de magnitude aux magnitudes elles-mêmes, de connaître quelques magnitudes en valeur absolue dans cette région: cette détermination peut se faire, elle aussi, à partir de la classification d'étoiles doubles. Voici, a titre d'exemple, comment pourra être obtenue la magnitude absolue d'une naine de type B5.

L'étude de l'étoile double τ Tau a été faite complètement et a conduit aux résultats suivants (tableau VI et fig. 3).

TABLEAU VI

*	$\lambda_1 - 3700$	D	φ_b
τ Tau A	60	0,255	0,86
τ Tau B	74	0,510	1,14

τ Tau A se classe dans la région des B5V. Les valeurs des trois paramètres de τ Tau B ainsi que celle de φ_{uv} permettent de reconnaître une étoile normale ayant un rougissement interstellaire négligeable et correspondant au type A2V. Lorsque le domaine des étoiles A sera gradué, la magnitude absolue de τ Tau B sera connue. On peut estimer qu'elle sera de l'ordre de +1,2 et, la différence de magnitude entre les deux composantes étant égale à 3,0, la magnitude absolue de τ Tau A sera connue et voisine de 1,2 - 3,0 = - 1,8.

D'autre part, le point représentatif de τ Tau A se plaçant au voisinage immédiat de ceux de ν And et de ϰ Hya (Tableau VII et fig. 3), on peut en conclure que les magnitudes absolues des trois étoiles sont très voisines.

Tableau VII

*	$\lambda_1 - 3700$	D	φ_b
ν And	58	0,249	0,91
ϰ Hya	60	0,248	0,87

On peut encore donner l'exemple de la détermination de la magnitude absolue d'une supergéante, ζ Per. Le compagnon de ζ Per a été observé: il se classe dans la région des A3V et lorsque cette région de l'espace sera graduée en magnitudes nous pourrons calculer la magnitude absolue de ce compagnon. Elle sera vraisemblablement de l'ordre de +1,8. Et la différence de magnitudes des deux composantes étant d'environ 7,0 (valeur à améliorer) la magnitude absolue de ζ Per doit être voisine de 1,8 - 7,0 = - 5,2.

Ces quelques indications donnent une idée de la méthode par laquelle on peut espérer résoudre le problème de la graduation en magnitudes absolues de l'espace (λ_1, D, φ_b).

CONCLUSION

La classification tridimensionnelle nous a donc conduits aux résultats suivants:

1) Elle permet de classer avec beaucoup plus de précision que les autres systèmes les étoiles "normales" de la population I et montre que cette classification exige en réalité trois paramètres;
2) Elle permet de classer les étoiles à raies métalliques, les "spectrum variables" (population I), les sous-naines, RR Lyrae (population II) et permettra peut être de rendre compte de la division par Miss ROMAN des étoiles plus avancées que F5 en "strong-lined" et "weak-lined";
3) A chaque groupe de trois paramètres semble correspondre une étoile et une seule et par suite une magnitude absolue bien définie et une méthode est indiquée pour déterminer cette magnitude;
4) Deux exemples (sous-naines et comparaison de l'amas de Coma à celui des Hyades) montrent que l'"excès d'ultraviolet", que l'on considère géneralement comme dû à des variations dans l'intensité et le nombre des raies métalliques, peut s'expliquer en réalité par une variation dans la grandeur de l'absorption continue de Balmer;
5) Il semble que l'amas des Hyades ne contient pas de véritable sous-naine.

Cet ensemble de résultats et notamment la position relative dans la classification des divers types d'étoiles considérés peut contribuer à jeter quelque lumière sur la parenté de constitution existant entre elles et sur leur évolution.

BIBLIOGRAPHIE

[1] D. Chalonge et L. Divan, Contr. I.A.P. N⁰ 150.

[2] D. Chalonge, Colloque sur les classifications stellaires. Paris, 1953.

[3] D. Chalonge, *Vistas in Astronomy*. Vol. 2, 1328-36, 1956.

[4] D. Chalonge, Ann. d'Astroph., *19*, 258, 1956.

[5] A. Baillet, D. Chalonge, J. Cojan, Ann. d'Astroph., *15*, 144, 1952.

[6] D. Chalonge, Journ. Astron. U.R.S.S., *33*, 474, 1956.

[7] J. Berger, A-M. Fringant, C. Menneret, Ann. d'Astroph., *19*, 294, 1956.

[8] H. F. Weaver, Ap. J., *116*, 612, 1952.

[9] J. Berger, Colloque sur la structure de la Galaxie. Paris, 1957.

[10] L. Divan, Ann. d'Astroph., *19*, 287, 1956.

[11] N. Roman, A. J., *59*, 307, 1954.

[12] A-M. Fringant, J. O., *39*, 178, 1956.

[13] J. Berger, D. Chalonge, L. Divan, A-M. Fringant, Ann. d'Astroph., *19*, 269, 1956.

[14] F. Van't Veer, Colloque sur la structure de la Galaxie. Paris, 1957.

[15] B. Westerlund, J. O., *39*, 166, 1956.

[16] L. Divan, Colloque sur la structure de la Galaxie. Paris, 1957.

[17] N. Roman, Ap. J., *112*, 554, 1950 et *116*, 123, 1952.

[18] L. Divan, Contr. IAP (sous presse).

[19] H. L. Johnson and C. F. Knuckles, Ap. J., *122*, 209. 1955.

[20] L. Divan, Colloque sur la structure de la Galaxie. Paris, 1957.

[21] D. Barbier et D. Chalonge, Ann. d'Astroph., *4*, 30, 1941.

[22] J. Berger, Colloque sur la structure de la Galaxie. Paris, 1957

[23] A. Van Maanen, Contr. Mt Wilson, *18*, N⁰ 45.

DISCUSSION

CHAIRMAN: B. LINDBLAD

BLAAUW

You referred to subdwarfs in open clusters. I believe that GREENSTEIN finds the radial velocities of suspected subdwarfs in the Hyades region do not confirm cluster membership.

SANDAGE

GREENSTEIN and MÜNCH have observed the radial velocities of JOHNSON's subdwarfs in the Hyades, and I understand that they believe none of them to be members.

CHALONGE

If they were different from normal stars, we would need a fourth dimension in the classification, in order to distinguish all the different kinds of stars.

BLAAUW

The velocities differ by 10 to 15 km/sec.

NASSAU

What is the limit in apparent magnitude for your spectrophotometric observations?

CHALONGE

We reached 10 m with difficulty, using the 80 cm reflector.

LINDBLAD

The main labour must be the gradient determination.

SCHWARZSCHILD

Would STRÖMGREN think that the peculiar behaviour of the continuum revealed in CHALONGE's analysis represents a negative effect of line blanketing?

STRÖMGREN

Possibly, but, as mentioned by CHALONGE, the effects remained when higher dispersion was used. Could this dispersion have still been too low?

CHALONGE

High dispersion spectra of the sun obtained recently at Pic du Midi by LABS and NECKEL have confirmed that it has a single colour temperature and we have compared the spectrum of S Mon to that of a black body and found an excess in the visible. Our dispersion is 250 Å/mm at $H\gamma$, but we have checked with 40 Å/mm from type O to F2. The measures by KIENLE and his collaborators (1938-1940) give the same discontinuity.

STRÖMGREN

I believe they were not sure that in the ultraviolet and far violet the effects of the lines had been avoided. Do the measures at 250 Å/mm include the effect of the lines?

CHALONGE

Yes, we have the same result as far as F2, but this might produce discrepancies for types later than F2.

SCHWARZSCHILD

A most important feature in CHALONGE's figure 5 is seen near the top where the observational material is fairly plentiful. There is a continuous series of objects running through strong-line stars, weak-line stars, high-velocity stars to extreme subdwarfs. It looks as though we have a continuous sequence, measured by an astrophysical criterion, with no major gaps.

CHALONGE

I might point out the way that NGC 2264 runs on figure 3. It cuts the path of the Pleiades and may present some interesting differences as compared with the Pleiades.

BAADE

The fine results presented by CHALONGE show how much can be derived in this field from data of limited extent but very high precision.

SPECTROPHOTOMETRIC CLASSIFICATION OF THE POPULATION GROUPS

BENGT STRÖMGREN
Yerkes and McDonald Observatories (*)

1. Spectrophotometric methods for two-dimensional classification of stars from low-dispersion objective prism spectra were developed by LINDBLAD [1] in 1920 and the following years. Methods of stellar classification through photographic spectrophotometry were investigated further in 1935 by BARBIER, CHALONGE, and VASSY [2] and by ÖHMAN [3] who showed that the Balmer discontinuity is a very useful classification index. A few years later BARBIER and CHALONGE [4] devised a method of two-dimensional classification through photographic spectrophotometry around the wave length of the Balmer discontinuity.

In recent years the methods of spectral classification through photographic spectrophotometry have been further improved and applied by CHALONGE and his collaborators [5]. This work is discussed by CHALONGE in the present volume, p. 345. We also refer to extensive photographic-spectrophotometric investigations for classification purposes made by PETRIE [6], WESTERLUND [7], HOSSACK [8], and HALLIDAY [9].

Since 1950 the author has investigated methods of spectral classification through photoelectric narrow-band photometry [10], [11]. Most of this work was carried out at McDonald

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Observatory. A summary of results obtained for B, A and F stars is given below. These investigations have dealt largely with classification problems of population I stars, but they have a bearing also on the question of classification of the population groups. This problem will be considered in the present paper, reference is made however to the paper by the author in this volume, p. 245, where results concerning the discrimination of the population groups through photoelectric narrow-band photometry are further discussed.

The fact that Lindblad's method of two-dimensional classification with the help of low-dispersion spectra was successful indicated that it should be possible to achieve the purpose through photoelectric narrow-band photometry using band widths of the order of 50 Å. The author's investigations confirmed the expectation. This work was carried out with interference filters isolating spectral regions of half-widths between 15 Å and 150 Å.

For the B, A and F stars two indices were determined photoelectrically, an index l measuring the strength of $H\beta$, and an index c indicating the magnitude of the Balmer discontinuity. Five interference filters and one glass filter were used for the purpose. The wave lengths of maximum transmission and the half-widths of the filters are given below. Additional glass filters were used together with the interference filters to eliminate transmission regions several hundred Ångström removed from the transmission peaks of the interference filters.

Filter			λ *max*	*Half-width*
a	Interference	filter	5000 Å	90 Å
b	»	»	4861	35
c	»	»	4700	100
d	»	»	4500	80
e	»	»	4030	90
f	Glass filter		3600	350

The intensities through the six filters were measured in succession. Consequently only nights with a photometric sky were usable. Below (p. 408) we shall briefly describe a photoelectric photometer in which an $H\beta$-index is determined through simultaneous interference filter measures in such a way that high accuracy is obtained even with a non-photometric sky.

The $H\beta$-index l is defined as

$$l = \text{constant} + 2.5\ [1/2 \log I\ (a) + 1/2 \log I\ (c) - \log I\ (b)]$$

while the Balmer discontinuity index c is

$$c = \text{constant} + 2.5\ [2 \log I\ (e) - \log I\ (d) - \log I\ (f)].$$

The wave lengths are chosen in such a way that the indices are unaffected by interstellar absorption, very nearly. It may be noticed that the transmission regions of the filters a, c, d and e do not contain Balmer lines, in particular that filter e transmits between $H\delta$ and $H\varepsilon$.

As a result of the photoelectric 6-filter measures the location of a star in a c-l diagram is obtained (cf. Fig. 1 and Fig. 2).

2. We shall discuss problems of the calibration of the classification based on the indices c and l, limiting ourselves first to population I stars. Comparison of location in the c-l diagram with spectral classes and luminosity classes on the MK system shows a very satisfactory correspondence, cf. [10] and [11]. In this comparison the A and F stars, and the B stars, respectively, are treated separately because of the well known ambiguity in the determination of spectral class from the Balmer discontinuity. For the B stars the previous work has recently been extended by CRAWFORD [12]. For about 100 B stars for which MK classification was available he found excellent correspondence between the location in a diagram equivalent to the c-l diagram and the MK spectral type and luminosity class.

The next step in the calibration process is the derivation of the relation between c and l on the one hand and a color index such as B-V on the UBV system as well as absolute visual magnitude M_v on the other.

We shall first consider the calibration for the F stars (A9 - F7). In previous investigations the F stars were divided into two groups, A9 - F1, and F2 - F7, and linear relations were assumed to relate B-V or M_v with c and l within each group. It has been found desirable to carry out a non-linear calibration for the group of F stars as a whole. The results are based on observations obtained for nearby F stars, mostly brighter than apparent magnitude $5^m\!.5$ and within 50 pc. For these stars it could be assumed that there is no appreciable interstellar reddening so that the measured B-V gives the intrinsic color. Furthermore, fairly accurate values of M_v were available from trigonometric parallaxes. These were supplemented by cluster parallaxes for a number of Hyades stars (VAN BUEREN [13]).

Figure 1 shows the distribution of the stars in question in the c-l diagram. The F stars are to the right of the vertical line corresponding to $c = 0^m\!.800$. The calibration was limited to stars of luminosity classes III, IV and V, and metallic-line stars were excluded. From Fig. 1 it is clear that supergiants and metallic-line stars can be segregated from their location in the c-l diagram. However, the available material was insufficient for a quantitative calibration of these stars.

The B-V calibration of c and l was obtained through a process of iteration. From Fig. 1 it is seen that the distribution of the F stars in the c-l diagram indicates a well defined lower boundary which can be represented with sufficient accuracy by a straight line. This line was taken as a standard reference line. From a number of stars close to the reference line the relation between c and B-V was derived. Next, the B-V value predicted from this relation, was compared with the measured B-V value for the stars located at points more than $0^m\!.015$ above the standard line, and the deviation was compared to the vertical distance Δl from the standard line. The ratio $\Delta(B\text{-}V)/\Delta l$ was

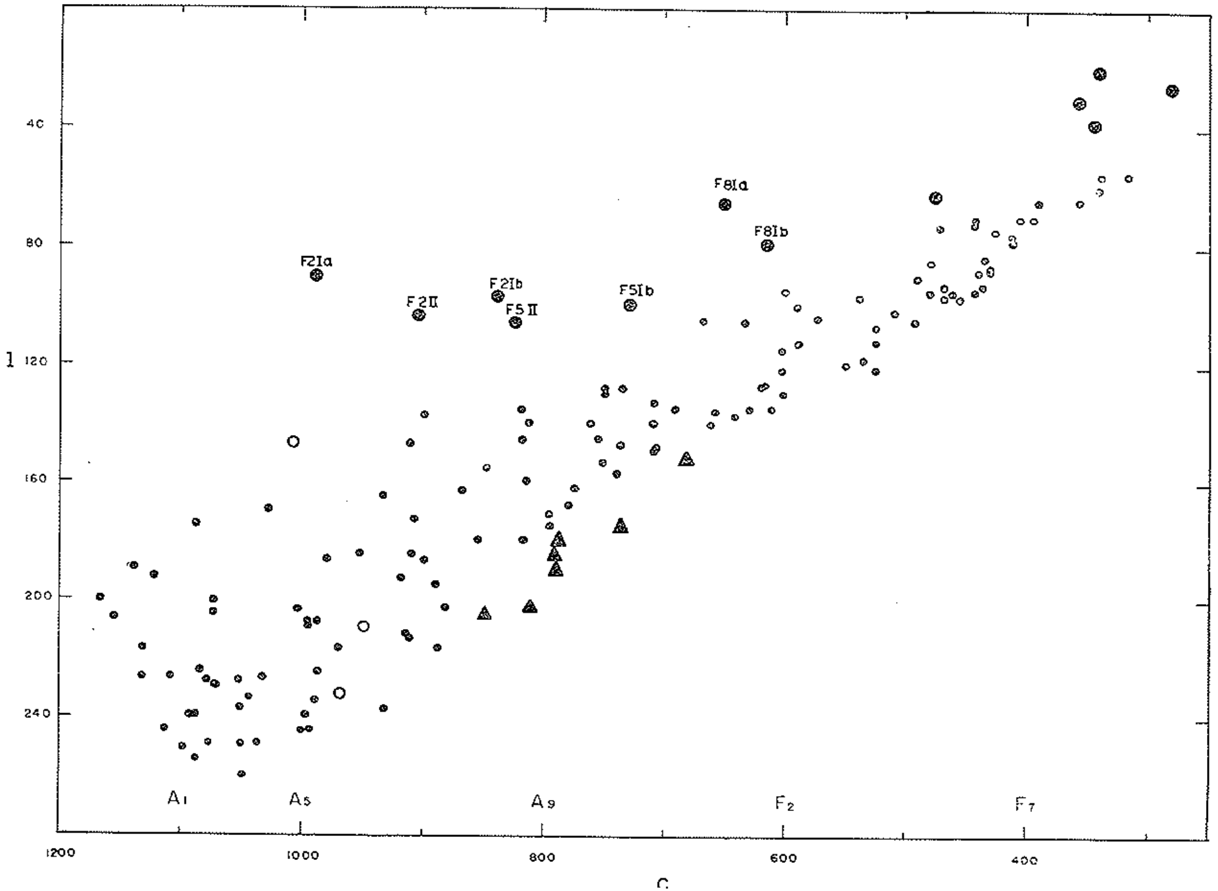

FIG. 1 — The c-l diagram for A and F stars (mostly brighter than apparent visual magnitude 5.5). The small filled circles correspond to stars of luminosity classes III-V, the large filled circles to luminosity classes I and II, the triangles to metallic-line stars, and the large open circles to spectrum variables. The spectral classes indicated above the c-axis are for main-sequence stars. The abscissa and ordinate shown are c and l, respectively, in units of $0^m.001$. The photometric p.e. (1 observation) corresponds approximately to the diameter of the large circles, both in c and l.

derived as a function of c. In the second approximation the B-V values for the stars close to the standard line ($\Delta l < 0^{m}.015$) were reduced to the standard line using the $\Delta(B\text{-}V)/\Delta l$ values just found. An improved relation between c and B-V for the standard line was thus obtained, and the whole process was repeated until there was no further change.

Calibrations for the color index U-B and the absolute visual magnitude M_v were obtained in a similar way.

From the filter photometry described above a useful color index can be derived, namely

$$e - a = \text{constant} + 2.5\ [\log I\ (a) - \log I\ (e)].$$

The color index is very closely, although not perfectly, correlated with B-V. It was calibrated in terms of c and l in the same way as B-V.

The results obtained are shown in the following Table 1. The table gives the standard-line relation between c and l (lower boundary of the $c - l$ distribution), and the values of B-V, M_v, U-B, and $e - a$ for stars on the standard line as functions of c. It gives, further, the variations of these quantitaties with vertical distance Δl above the standard line. Also shown is the spectral class.

TABLE 1

c	l standard line	*Sp. class*	$B-V$ standard line	$\frac{\Delta(B-V)}{\Delta l}$	M_v standard line	$\frac{\Delta M_v}{\Delta l}$	$U-B$ standard line	$\frac{\Delta(U-B)}{\Delta l}$	$e-a$ standard line	$\frac{\Delta(e-a)}{\Delta l}$
$0^{m}.400$	$0^{m}.086$	F7	$0^{m}.487$	1.8	$4^{m}.2$	89	$-0^{m}.03$	2.1	$0^{m}.540$	2.0
0.450	097	F5	443	1.9	4.0	82	− 03	2.3	495	2.2
0.500	108	F3	404	2.0	3.8	76	− 03	2.5	454	2.4
0.550	119	F2	371	2.1	3.6	69	− 02	2.6	418	2.5
0.600	130	F2	342	2.2	3.4	62	− 01	2.5	387	2.6
0.650	142	F1	319	2.0	3.2	55	+ 01	2.2	362	2.3
0.700	153	F0	302	1.7	3.1	49	+ 02	1.8	341	1.8
0.750	164	F0	285	1.3	2.9	42	+ 04	1.5	321	1.4
0.800	175	A9	268	0.8	2.7	35	+ 06	1.2	300	1.0

For a given value of c the standard-line column gives $l(st.\ l)$. With $\Delta l = l(st.\ l.) - l$ the corrections to $B\text{-}V$, M_v, $U\text{-}B$ and $e\text{-}a$ as found from c for the standard line are evaluated. With increasing height Δl above the standard line, $B\text{-}V$ and $e\text{-}a$ increase, while M_v decreases, in other words the corresponding star becomes increasingly redder and more luminous.

We can now estimate the accuracy obtainable through $c\text{-}l$ classification in the range considered in two ways. The known probable errors in the photometric determination of c and l can be converted into probable errors for $B\text{-}V$ and M_v, using the relations obtained through the calibration. Also, the residuals in $B\text{-}V$ and M_v found for the calibration stars through comparison of observed values and values computed from c and l lead to an estimate of the accuracy. The latter takes into account the effects of any cosmical scatter in the relation between $B\text{-}V$ or M_v, and c and l. The probable error of one observation of l was determined from a comparison of results obtained during different nights in the same observing period with the 82-inch reflector of the McDonald Observatory (approximately one month). The p.e. varied somewhat from one observing period to another, depending on photometric observing conditions, the range being $\pm 0\overset{m}{.}003$ to $\pm 0\overset{m}{.}005$. For c the corresponding values are $\pm 0\overset{m}{.}006$ and $\pm 0\overset{m}{.}008$.

Comparison of observations obtained in different years, and comparison with observations taken with new and improved instrumentation (cf. [24]) indicate that the probable errors of one observation may be 1.1 - 1.2 times higher than those derived from intercomparisons for different nights witbin the same observing period. We shall adopt the values $\pm 0\overset{m}{.}004$ p.e. for l and ± 0.008 p.e. for c in the following discussion.

From the relation between $B\text{-}V$, and c and l as given in Table 1 it is then found that the photometric p.e. (1 observation) of $B\text{-}V$ derived from c and l is $\pm 0\overset{m}{.}007$ in the average for the group of F stars considered (A9 - F7), the p.e. in l contributing the major part of the p.e. in $B\text{-}V$. This corresponds to a p.e. in the spectral class determination equal to $\pm 0^{\mathrm{m}}.025$ of a spectral class.

An analysis of the residuals, observed minus computed *B-V*, leads to a probable error (1 observation) of $\pm 0^{\mathrm{m}}.008$ for *B-V* predicted from *c* and *l*, again for the group of A9 - F7 stars. This includes the effect of cosmical scatter in the relation between *B-V*, *c* and *l*. It may be noted that the largest residual, observed minus computed *B-V*, is $0^{\mathrm{m}}.03$, and that for 45 of the 47 unreddened nearby F stars used in the calibration the residual is $0^{\mathrm{m}}.02$ or smaller.

A corresponding investigation of the accuracy with which the absolute visual magnitude M_v can be predicted from *c* and *l* leads to the following results. The average photometric p.e. (1 observation) for the F stars is $\pm 0^{\mathrm{m}}.2$ in M_v. From the residuals a p.e. (1 observation) of $\pm 0^{\mathrm{m}}.2$ is derived.

The accuracy of the calibration for M_v can undoubtedly be improved by future investigations including a larger number of stars. Proper motions and radial velocities could be utilized in addition to trigonometric parallaxes and cluster parallaxes. However the present calibration is probably correct within a few tenths of a magnitude.

From the results of the calibration, in particular the column $\Delta M_v/\Delta l$ in Table 1, it is seen that the accuracy in the determination of M_v decreases as one approaches spectral class G0. This is connected with the fact that $H\beta$ becomes weaker and no longer well measurable with the chosen band width.

The results obtained for the group of F stars show that the effect of cosmical scatter on the relations between *B-V* or M_v, and *c* and *l* is small, or negligible. We turn now to the analysis of *U-B*, and we shall see that the situation is different in this respect.

3. The photometric p.e. (1 observation) of *U-B* predicted from *c* and *l* is about the same as for *B-V*. However, the residuals, observed minus predicted *U-B*, are much larger than

for *B-V*, indicating the effect of cosmical scatter. The residuals correspond to a p.e. of $\pm 0\overset{\mathrm{m}}{.}024$, with residuals in *U-B* ranging from $-0\overset{\mathrm{m}}{.}06$ to $+0\overset{\mathrm{m}}{.}09$ for the group of population I F stars considered.

The data indicate that three-dimensional classification is necessary for satisfactory representation. For the stars in question it is natural to think of a chemical-composition parameter as the third parameter. Variations in the ratio of the abundances of heavy elements to that of hydrogen would explain the cosmical scatter. Such variations would affect the relation between *U-B* and (*c*, *l*) in a variety of ways, but probably strongest through the variations in the depression of the ultraviolet intensity by absorption lines.

In this connection reference is made to the investigation of JOHNSON and MORGAN [14] on the relation between *U-B* and *B-V*. For the F stars there is considerable scatter in this relation. With the addition of the observed *l* indices we can now exclude the possibility that the scatter is solely, or largely, due to variations in absolute magnitude. JOHNSON [15] from a comparison of the (*U-B*), (*B-V*) relation for different galactic clusters has concluded that there is a significant difference in chemical composition between the Hyades and Coma Berenices clusters.

CHALONGE has emphasized that the results of photographic spectrophotometry demonstrate the existence of third-parameter variations. A full discussion is presented by CHALONGE in this volume, p. 345.

We wish to stress the fact that the magnitude of the cosmical scatter due to variations of the chemical-composition parameter depends on the particular index studied, as is shown by the difference between the case of *B-V* and that of *U-B*. From the practical point of view this is of course important. When the purpose is a study of color excesses through comparison of measured color indices and intrinsic color indices predicted from *c* and *l* we choose *B-V* because the effect of cosmical scatter is quite small. On the other hand we may choose *U-B* if the purpose is a study of the variations of the third parameter. In another chapter of this volume (p. 245) the author discusses results obtained through investigation of variations of an index *m*, defined by

$$m = \text{constant} - 2.5\ [\log I\ (a) + \log I\ (e) - 2 \log I\ (d)]$$

which measures in a more direct way than *U-B* the variations of chemical composition.

The discussion has so far been limited to population I F stars. We shall now consider the case of extreme population II stars of class F in the present context. Miss ROMAN [16] has shown that there exists in the galactic neighborhood a well defined group of F stars characterized by very high spatial velocity and relatively very weak metal lines. *UBV* photometry by Miss ROMAN indicated a relative strengthening of the ultraviolet, with *U-B* values that are about $0^{m}_{.}2$ more negative than expected according to the value of *B-V* if the normal (*B-V*), (*U-B*) relation is used. Miss ROMAN has found that these extreme population II F stars are located about one magnitude below the main sequence in the H-R diagram.

A few of the population II F stars in question have been measured with the interference filters. It was found that they are easily segregated from the population I F stars, both through the relative strength of the ultraviolet, and through the value of the index *m* (cf. this volume, p. 253). The negative residual in *U-B* is $0^{m}_{.}15 - 0^{m}_{.}20$ for extreme population II F stars, thus considerably outside the range for population I F stars. We refer to the further discussion of this question on p. 256.

We can make use of the calibration of *c* and *l* for population I F stars as given in Table 1 for the purpose of an investigation of the (*B-V*), (*U-B*) relation and its dependence on absolute magnitude. Table 2 below, derived from Table 1, gives the (*B-V*), (*U-B*) relation for the standard line, i.e. for the lower boundary of the distribution in the *c-l* diagram, as well as for stars of absolute magnitude 1^{m} brighter than those on the standard line.

TABLE 2

$B-V$	$U-B$ *for standard line*	$U-B$ *for stars* 1^{m} *brighter*
$+0^{\mathrm{m}}.50$		$0^{\mathrm{m}}.00$
0.45	$-0^{\mathrm{m}}.03$	00
0.40	− 03	+ 02
0.35	− 01	+ 05
0.30	+ 02	

The dependence of the (*B-V*), (*U-B*) relation on absolute magnitude (cf. JOHNSON [15]) is clearly shown. It should be emphasized that the composition parameter of course influences the relation. The values given in Table 2 are average values for the sample of nearby population I stars considered. For higher precision larger samples must be used, or samples better defined, e.g. through specification of the index *m*.

We note that the average star of luminosity class V is somewhat brighter than what corresponds to the standard line, and that the (*B-V*), (*U-B*) relation for class V stars would be expected to fall between the two relations given in Table 2.

Since the (*B-V*), (*U-B*) relation depends both on the absolute magnitude and the chemical-composition parameter, one cannot from *B-V* and *U-B* draw accurate conclusions regarding chemical composition without additional knowledge concerning the absolute magnitude, nor is it possible to compare absolute magnitudes accurately without further information regarding the chemical compositions of the stars in question. However, if the *UBV* photometry is supplemented with measures of the index *l* (or better *c* and *l*, which may in fact be necessary if interstellar absorption is important) then an independent determination of

M_v becomes possible, and it is safe to draw conclusions regarding chemical composition. Also, measures of the index *m* will supply independent information regarding chemical composition.

In the case of the F stars of extreme population II the chemical-composition effect is considerably larger than the effect of a change in absolute magnitude alone, and it dominates the picture.

Disregarding now for a moment the complication due to variations of the chemical-composition parameter, we interpret the lower boundary of the distribution in the *c-l* diagram as the locus of stars of age zero. With increasing age of a star the representative point will move upward in the *c-l* diagram. From the calibration data as given in Table 1 we then derive the zero-age relation between *B-V* and M_v shown in Table 3. For comparison the zero-age relation given by JOHNSON and HILTNER [17] is also tabulated.

TABLE 3

Sp. class	*B - V*	M_v	M_v *according to* JOHNSON *and* HILTNER
F0	$+0^{\mathrm{m}}.30$	$3^{\mathrm{m}}.0$	$3^{\mathrm{m}}.2$
F2	0.37	3.6	3.6
F5	0.44	4.0	4.0

The table gives M_v for zero age.

The observational material now available is insufficient for a discussion in which the stars are divided in groups according to chemical composition, but it would seem quite possible to extend the investigation in this direction and to determine the zero-age relation as a function of, say, the chemical-composition index *m*.

We note that for F0 stars of luminosity classes III, IV and V ($0^m.140 < l < 0^m.170$) B-V changes very little with c, and can be predicted from l with very good accuracy. Thus in this range the combination of UBV photometry and measures of the index l will give very satisfactory color excesses. If the measured U-B is corrected for interstellar absorption according to the color excess found in B-V, then l and this corrected U-B, i.e. $(U\text{-}B)_0$, will give M_v with fair accuracy, although not with the precision obtainable from c and l. For late F-type stars this procedure would not give satisfactory accuracy, as can easily be deduced from the calibration data given in Table 1.

4. With regard to c-l classification for the A stars we refer to a previous investigation [11], cf. also Fig. 1. For A3 - A8 stars of luminosity classes III, IV and V it was found that the following linear relations yield a calibration of satisfactory accuracy

$$B\text{-}V = 0^m.626 - 0.564\ l - 0.347\ c$$
$$M_v = 2^m.84 + 26.4\ l - 7.2\ c$$

The probable errors (1 observation) corresponding to the probable errors in c and l are here $\pm 0^m.003$ for B-V and $\pm 0^m.12$ for M_v. From the residuals probable errors (1 observation) including the effect of cosmical scatter equal to $\pm 0^m.005$ in B-V (corresponding to ± 0.02 of a spectral class) and $\pm 0^m.12$ in M_v were determined. There is thus little or no effect of cosmical scatter here.

We have already referred to the ambiguity in the c-l classification which is a consequence of the fact that the Balmer discontinuity has a maximum, for main sequence stars located near A0. For example, the position of a B5V star in the c-l diagram is about the same as that of an F2V star. When rough spectral classification is available this ambiguity presents no difficulty at all. The B stars are then treated separately. Measures of an additional index indicating the strength of the K line might serve the same purpose. A complication arises only for the spectral range A0-A2, corresponding to the range from $-0^{m}.02$ to $+0^{m}.08$ in $(B\text{-}V)_0$, i.e. $B\text{-}V$ corrected for interstellar absorption. Here fairly accurate classification from spectra is required to resolve the ambiguity. If it is known that interstellar absorption is small or negligible, then measured $B\text{-}V$ indices will serve the purpose. Additional measures of a K-line index would probably be the most satisfactory general solution.

5. We turn now to questions of the classification of B stars with the aid of the indices c and l. Fig. 2 shows the distribution of B stars in the $c\text{-}l$ diagram. Again we see that it is easy to segregate the supergiants. In discussing the calibration we shall limit ourselves to stars of the luminosity classes III, IV and V, as before. Furthermore we shall exclude emission line stars.

There is again a well defined lower boundary to the distribution in the $c\text{-}l$ diagram. The line in Fig. 2 corresponding to the I Ori and II Sco associations coincides with the lower boundary, very nearly. The stars of luminosity class III are all well above the lower boundary. Among the stars in the spectral range B7 - B9 it is striking that the nearby field stars of luminosity class V generally lie considerably above the lower boundary. This is undoubtedly an age effect. The nearby field stars are on the average considerably older than the association stars that lie close to the lower boundary. The spectroscopic age effect is here so relatively small that the stars are generally classed in luminosity class V, however the $c\text{-}l$ classification shows the age effect very clearly. We shall return to the question. For a discussion based on a more extensive material obtained with the 36-inch reflector of the McDonald Observatory (and the photometer described on p. 408) we refer to CRAWFORD [12].

We consider next the calibration of the $c\text{-}l$ diagram for intrinsic color $(B\text{-}V)_0$, or $(U\text{-}B)_0$. It is well known from the

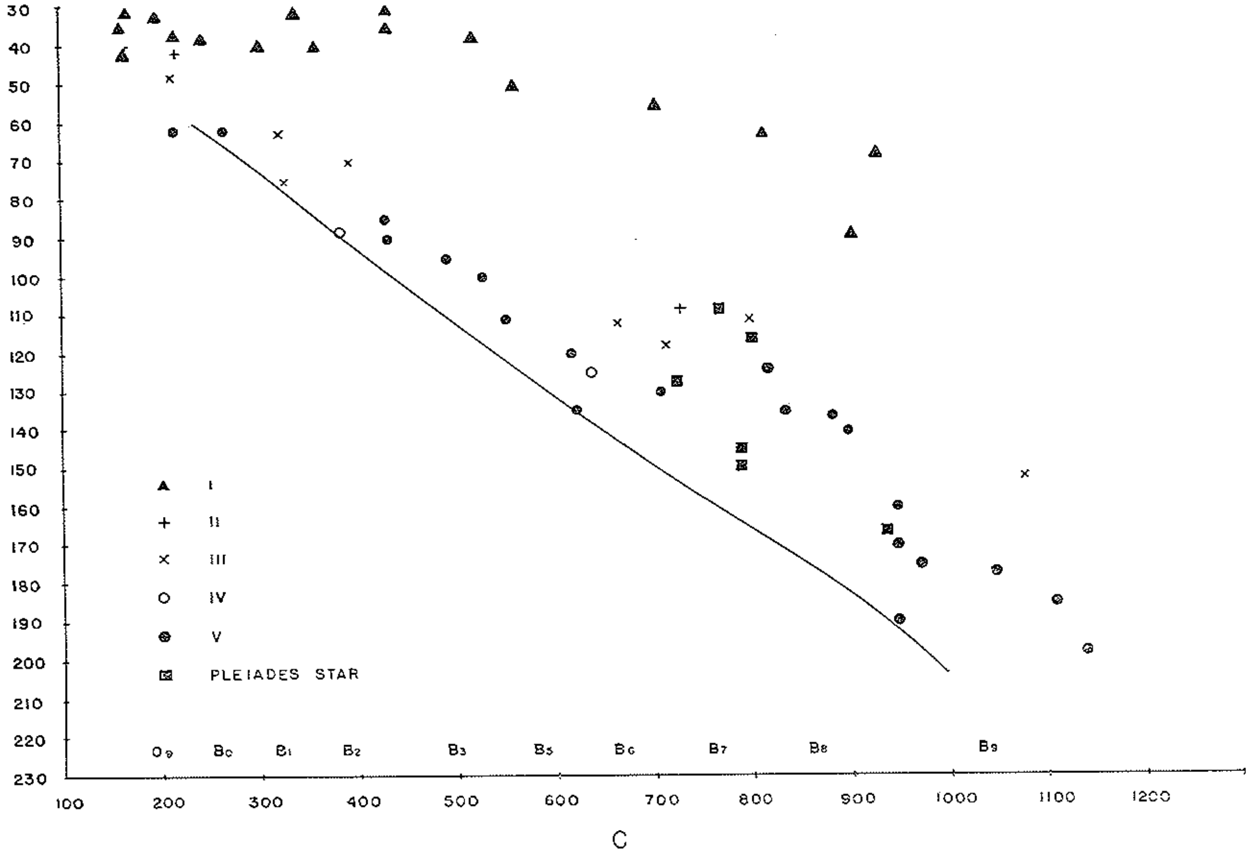

FIG. 2 — The *c-l* diagram for B stars (mostly brighter than apparent visual magnitude 5.5). The abscissa and ordinate shown are *c* and *l*, respectively, in units of $0^m.001$. The curve indicates the average location of stars in the associations I Ori and II Sco, excepting the relatively few stars in the supergiant area. The scatter of the association stars around the curve is characterized by a root mean square deviation in *l* from the curve equal to $\pm 0^m.007$. The spectral classes indicated above the *c*-axis are for stars of luminosity classes III-V.

work of W. Becker [18], Johnson and Morgan [14], Morgan and Harris [19], and Hiltner and Johnson [20] that for B stars *UBV* photometry (or an equivalent three-band photometry) will yield intrinsic colors $(B\text{-}V)_0$ and $(U\text{-}B)_0$ corrected for interstellar absorption. There is for the B stars of luminosity classes III, IV, and V a practically perfect correlation between $(B\text{-}V)_0$ and $(U\text{-}B)_0$, as well as between $(U\text{-}B)_0$ and the spectral class, cf. [19]. The calibration problem in question is therefore solved when we establish the relation between location in the c-l diagram and $(U\text{-}B)_0$. We choose $(U\text{-}B)_0$ because its variation with spectral type is much larger (3.7 times) than that of $(B\text{-}V)_0$. When $(U\text{-}B)_0$ is known, $(B\text{-}V)_0$ and the spectral type follow according to Morgan and Harris [19].

For the calibration 31 B stars of luminosity classes III, IV and V with small or moderate interstellar reddening ($A_v < 0\overset{m}{.}4$) were available. For these $(U\text{-}B)_0$ values of high accuracy are known. It was found that there is a practically unique relation between c and $(U\text{-}B)_0$, independent of l. Table 4 shows the derived relation, and also gives $(B\text{-}V)_0$ and the spectral class corresponding to $(U\text{-}B)_0$ according to Morgan and Harris [19]. The relation between c and $(U\text{-}B)_0$ is nearly linear.

Table 4

c	$(U-B)_0$	$(B-V)_0$	*Sp class*
$1\overset{m}{.}00$	$-0\overset{m}{.}19$	$-0\overset{m}{.}05$	B9
0.90	−0.29	−0.07	B8
0.80	−0.39	−0.10	B7
0.70	−0.50	−0.13	B6
0.60	−0.61	−0.16	B5
0.50	−0.73	−0.20	B3
0.40	−0.85	−0.23	B2
0.30	−0.99	−0.27	B1
0.20	−1.14	−0.31	O9

B stars of luminosity classes III, IV and V, Be stars excluded.

The scatter in the relation between c and $(U-B)_0$ for the calibration stars in question corresponds to a p.e. of a difference equal to $\pm 0^{\mathrm{m}}.012$ on the $(U-B)_0$ scale. The photometric p.e. in c is $\pm 0^{\mathrm{m}}.008$ for 1 observation. The mean number of observations of c is 1.4. Allowing for the average ratio between the c scale and the $(U-B)_0$ scale we find a p.e. of $\pm 0^{\mathrm{m}}.008$ on the $(U-B)_0$ scale due to the c-photometry. Thus, if we assume a p.e. of $\pm 0^{\mathrm{m}}.008$ for the $(U-B)_0$ values, the scatter in the relation is fully accounted for. The latter value is quite plausible, and there is therefore no evidence for cosmical scatter in the relation between c and $(U-B)_0$. The p.e. for 1 observation of c corresponds to $\pm 0^{\mathrm{m}}.009$ on the $(U-B)_0$ scale, $\pm 0^{\mathrm{m}}.003$ on the $(B-V)_0$ scale, and ± 0.010 of a spectral class.

It should be noted that for B stars *UBV* photometry can take the place of c-photometry, at least for small or moderate interstellar reddening. It may in fact here often be advantageous to combine *UBV* photometry and l-photometry. For the F0 stars we found (p. 397) that *UBV* photometry could be substituted for c-photometry without great loss of accuracy whereas c-photometry appears necessary for late F stars.

We turn finally to the calibration of the B star c-l diagram for absolute visual magnitude. As is well known from the discussions of the corresponding calibration problem of spectroscopic absolute magnitudes this is a difficult problem. We can present accurate results only for a part of the c-l diagram, and shall supplement these with brief references to further work now in progress.

The best source of information for fundamental (geometrical) distances of B stars is the Scorpio-Centaurus stream, cf. Blaauw [21] and [22]. We have used the visual absolute magnitudes determined by Bertiau [23] for members of this association to derive a calibration of the c-l diagram for the region close to the lower boundary, i.e. the age-zero line, and up to $l = 0^{\mathrm{m}}.100$ which is populated by the stars in question. For 20 stars visual absolute magnitudes of good accuracy as well as precision photometry were available (*). The result of the calibration is given in the following Table 5.

TABLE 5

M_v as a Function of l for Stars Near Age-Zero Line

l	M_v	*Sp. class*
$0\overset{\mathrm{m}}{.}100$	$-1\overset{\mathrm{m}}{.}7$	B 2.5
0.120	−1.0	B 4
0.140	−0.5	B 6
0.160	−0.1	B 7
0.180	+0.3	B 8
0.200	+0.6	B 9

The residuals *O-C* in M_v correspond to a probable error of a difference equal to $\pm 0\overset{\mathrm{m}}{.}25$. The available l-values for the Sco - Cen stars have a precision given by a p.e. of $\pm 0\overset{\mathrm{m}}{.}002$. On the M_v-scale this according to Table 5 corresponds to a p.e. of $\pm 0\overset{\mathrm{m}}{.}04$. Since the p.e. of the absolute magnitudes derived from the stream motions can hardly be more than $\pm 0\overset{\mathrm{m}}{.}15$ there is evidence of a cosmical scatter contributing about $\pm 0\overset{\mathrm{m}}{.}2$ to the p.e. Even with this amount of cosmical scatter the accuracy obtained in the determination of M_v is quite satisfactory in many applications.

The following causes may contribute to the cosmical scatter. 1. Differences in chemical composition, particularly in the helium-hydrogen ratio. 2. Effects of stellar rotation. 3. $H\beta$ emission. Since stars with visible $H\alpha$ emission were eliminated any $H\beta$ emission present must be very weak. 4. Binary character of the star.

(*) Since the paper was presented the author in collaboration with D. CRAWFORD has obtained further $H\beta$ photometry at McDonald Observatory. The new results which confirm and supplement the data presented have been included in the discussion at this point. Cf. also [12] and [24].

The last mentioned cause is probably of some importance although known double-line spectroscopic binaries were not included among the calibration stars. For a binary star the measured l is a mean of the l-values for the two components taken with weights proportional to the intensities of the components, while M_v of course corresponds to the sum of the component intensities. The following Table 6 gives the amount ΔM_v by which the binary will appear too bright for its measured l, computed on the assumption that the relation between l and M_v is linear. For the larger magnitude differences there may be considerable deviations from this assumption (l is always below about 0ᵐ260). The tabulated ΔM_v is then an overestimate.

TABLE 6

Magnitude difference between components	ΔM_v
0ᵐ0	0ᵐ7
0.5	0.7
1.0	0.7
1.5	0.6
2.0	0.4
2.5	0.3

It is seen that the effect is appreciable, and that it must be taken into account, statistically at least, in applications of the c-l method to the determination of absolute magnitudes. It may be noted that for all double-line spectroscopic binaries ΔM_v is fairly close 0ᵐ6. On the other hand, the estimated average mass ratio for single-line spectroscopic binaries of spectral class B is about 7 (cf. e.g. HYNEK [25]), and the corresponding ΔM_v is less than 0ᵐ1.

In this connection we wish to emphasize that the effect of binary star character on the distribution of the stars of a cluster or association in the *c-l* diagram is generally quite small. For stars close to the zero-age line binary star character will only cause a shift nearly parallel to the line, so that the distribution of Δl above the age-zero line is not appreciably altered. Quite generally, if the true distribution of the cluster or association stars is one of small scatter around a given curve of moderate curvature in the *c-l* diagram, then binary star character will not appreciably widen the distribution. This is, of course, a situation different from that which is encountered in studies of color-magnitude diagram of clusters and associations. The feature in question may well prove to be important in future discussions pertaining to age and chemical composition based on the distribution of stars in the *c-l* diagram.

Returning to the question of M_v calibration of the *c-l* diagram, we shall discuss results obtained from measures of B stars in the Pleiades cluster. The distance modulus of the Pleiades has been evaluated through comparison of the color-magnitude distribution of the Pleiades cluster with that of the Hyades cluster (directly or via the Praesepe cluster). For the Hyades stars accurate geometrical distances are available (VAN BUEREN [13]). EGGEN [26] found a distance modulus of $5^{\mathrm{m}}.58$ for the Pleiades cluster using stars in the color range B-V $+0^{\mathrm{m}}.4$ to $+0^{\mathrm{m}}.6$. HARRIS [27] derived $5^{\mathrm{m}}.57$ from stars in the same range, while MITCHELL and JOHNSON [28] obtained $5^{\mathrm{m}}.52$ from stars in the B-V range $+0^{\mathrm{m}}.55$ to $+0^{\mathrm{m}}.85$. In comparing the Pleiades and the Hyades color-magnitude distributions it is assumed that the difference caused by the different ages is negligible. This assumption is justified for the color range in question, the corresponding error in the distance modulus being probably less than $0^{\mathrm{m}}.1$. We may also note in this connection that the chemical composition of the Pleiades and Hyades clusters appear to be very nearly the same (cf. p. 257 of this volume), a fact which gives further justification for the assumption of identical color-absolute-magnitude distributions. We take the distance modulus of the Pleiades to be $5^{m}.55$, the value adopted by HARRIS [27].

The absolute visual magnitudes for 6 Pleiades B stars with measured c and l have been compared with those following from the Sco - Cen calibration valid near the age-zero boundary line in the c-l diagram. The Pleiades stars form a sequence about $0^{m}.2$ in c to the right of the boundary line (cf. CRAWFORD [12]). At $l \sim 0^{m}.160$, with $M_v \sim 0^{m}$, there is agreement with the Sco - Cen calibration within $0^{m}.1 - 0^{m}.2$, while at $l \sim 0^{m}.110$ the Pleiades stars are about $0^{m}.5$ brighter for their l than if they fitted exactly on the Sco - Cen calibration.

We conclude from the comparison of the Sco - Cen and Pleiades results, first, that the general assumption of a unique $l - M_v$ relation may lead to appreciable error, and secondly that there is a certain area in the l-c diagram where the Sco - Cen $l - M_v$ calibration (cf. Table 5) yields quite satisfactory results, namely for the range $0^{m}.15 - 0^{m}.20$ in l, not only near the age-zero boundary line, but up to distances $\Delta c \sim 0^{m}.2$ to the right of the line. The area corresponds to B7 - B8 stars of luminosity class V with absolute magnitudes M_v $-0^{m}.2$ to $+0^{m}.5$.

Although the calibration result thus obtained is quite limited it should have a nnmber of important applications, e.g. the determination of distance moduli both for clusters and associations and for field stars.

Further work on stars in clusters and associations, as well as on B8 and B9 stars within 100-200 pc, will undoubtedly further strengthen and extend the calibration results obtained. An extension of the calibration near the age-zero boundary line to B0 has already been achieved through observations of stars in the I Orion, I Lacerta and II Perseus associations, cf. [12], and further work is now in progress. A preliminary calibration for stars near the zero-age boundary line, which extends the calibration given in Table 5, is given below.

TABLE 7

M_v as a Function of l for Stars Near the Age-Zero Line

l	M_v	*Sp. class*
$0^{m}.060$	$-3^{m}.9$	O9
070	-3.4	B0
080	-2.9	B1
090	-2.3	B2
100	-1.7	B2.5

The rate of change of M_v with l is greater here than for the less luminous B stars (cf. Table 5). A photometric p.e. (1 observation) of $\pm 0^{m}.004$ now corresponds to a p.e. of about $\pm 0^{m}.2$ in M_v.

6. Let us finally consider the problem of calibration of the *c-l* diagram with a view to determination of stellar ages. Referring to the previous remarks concerning the age effect in the *c-l* diagram we note that a calibration is possible if a sufficient number of curves, each representing the distribution of the stars of a cluster or association, can be drawn in the *c-l* diagram, provided that independent evaluation of the age of each cluster or association is available. Furthermore, there is hope that it may prove possible in the future to compute theoretical curves representing different ages in the *c-l* diagram, or a corresponding diagram.

If we compare the separation of the curves in the *c-l* diagram representing the Sco - Cen association and the Pleiades cluster, respectively, with the scatter of the stars in the *c-l* diagram for each group separately, we gain an impression of the accuracy that may be achieved in age determination with the *c-l* diagram. For B8 stars with $M_v \sim 0^{m}$ we estimate that the p.e. of an age determination from the *c-l* diagram is $\sim \pm 30$ million years, once satisfactory calibration becomes available. For more luminous stars the accuracy is naturally higher corresponding to the fact that evolution is more rapid. It should be emphasized that age determination from the location in the *c-l* diagram is possible for field stars once the calibration with the help of clusters and associations has been carried out.

In concluding the discussion of the B stars in the *c-l* diagram we remark that comparison of curves representing different associations, when carried out for the less luminous stars that have not yet moved appreciably during the life-time of the association, may lead to important conclusions regarding differences in chemical composition, particularly with regard to the helium-hydrogen ratio. Comparison of associations in different spiral arms, or in different galaxies, might prove interesting.

7. The filter set described on p. 386 included an $H\beta$ interference filter with a half-width of 35 Å. The author has recently carried out measures with an $H\beta$ interference filter of half-width 15 Å made by Baird-Atomic, Inc. The scale of the new $H\beta$-index L is more than twice as wide as that of l (cf. STRÖMGREN and CRAWFORD [24]). Comparing measures of L and l it was found that the relation is linear. The B stars, and the A and F stars must be treated separately. This need arises because the narrow band does not take in the entire $H\beta$ line when the line is strong, and hydrogen lines of equal equivalent width on either side of the Balmer maximum do not of course have identical profiles. For faint $H\beta$ lines completely within even the 15 Å filter band the $L - l$ relation is however identical for B and F stars.

The wider scale in the $H\beta$-index is quite advantageous. As we have seen, most of the photometric p.e. in B-V and M_v for B stars, is contributed by the photometric p.e. in the $H\beta$-index. When the scale of the latter is doubled it means that the photometric p.e. for these quantities is practically halved. For measures where the photometric p.e. is largely determined by the statistical scatter of the photoelectric signal this means that, because a p.e. two times bigger can be tolerated, the limiting intensity will be more favorable by a factor of four. This more than compensates for the light loss due to the use of a narrower band.

In the photometric procedure for the determination of *c* and *l*, described on p. 387, intensities through six filters were measured in succession. We shall briefly describe a photometer for determination of an *H*β-index through simultaneous measures with two suitable filters. Two versions of this type of photometer have been constructed and used for *H*β photometry.

In the first version a slightly tilted narrow *H*β filter is used to transmit a narrow *H*β band to one photomultiplier while it reflects the light on either side of the transmission band toward a mirror that channels the light through a wide *H*β filter to a second photomultiplier (comparison band). The ratio of the two photomultiplier signals is an *H*β-index. As expected, this type of photometer yields results that are practically independent of the transparency of the terrestrial atmosphere.

The second version uses a 30 per cent - 70 per cent beam splitter to divide the star light into a stronger beam that goes to one photomultiplier (P1) and a weaker beam that is channelled into a second photomultiplier (P2). Successive measures are made with a 15 Å and a 150 Å *H*β interference filter in the light path to P1. Simultaneous measures are made with P2, however here a 150 Å *H*β filter remains in the light path for both measures. It is easy to see that the ratio of the successive P1 signals divided by the ratio of the successive P2 signals is an *H*β-index which is independent of the atmospheric transparency, and also independent of the relative sensitivity of the two photomultipliers. Integrators of a type developed by WEITBRECHT [29] are used to produce the photomultiplier signals.

In actual practice the second *H*β photometer proved to be the most accurate (*). As expected it can be used without loss of accuracy with a non-photometric sky, even through thin clouds with extinction of more than a magnitude. The accuracy is about the same as that achieved with the 6-filter photometer (p. 387) and a perfect photometric sky. The scale is almost as wide as the *L*-scale, and twice as wide as the *l*-scale.

The limiting magnitude of this *H*β photometer is characterized as follows. With an integrating time of 1 minute *H*β photometry with a p.e. $\pm 0^{\mathrm{m}}.010$ (corresponding to a p.e. of $\pm 0^{\mathrm{m}}.005$ on the *l*-scale) is obtained for a star of $11^{\mathrm{m}}.0$ with the McDonald Observatory 82-inch reflector. A total integrating time of 1 hour is perfectly possible and would yield a limiting magnitude of about $15^{\mathrm{m}}.5$. If the accuracy requirement were relaxed to $\pm 0^{\mathrm{m}}.010$ on the *l*-scale, which would still permit a classification accuracy quite satisfactory for many purposes, the limiting magnitude (82-inch, 1 hour integrating time) would be about $17^{\mathrm{m}}.0$. This limiting magnitude is about 5^{m} fainter than that obtained with a conventional slit spectrograph for MK classification (dispersion $\sim$ 100 Å per mm) for the same telescope and exposure time.

(*) When the paper was presented only the first version of the new *H*β photometer had been tested. A brief summary of the performance of the second version is included here.

REFERENCES

[1] B. Lindblad, *Spectrophotometric methods for determining stellar luminosity*. Ap. J., *55*, 85, 1922. Also Nova Acta Reg. Soc. Scient. Upsala, Ser. IV, Vol. *6*, No. 5, 1925.

[2] D. Barbier, D. Chalonge and E. Vassy, Jour. Phy. et Rad., *6*, 137, 1935.

[3] Y. Öhman, Stockholm Observ. Ann. Vol. *13*, No. 1, 1935.

[4] D. Barbier and D. Chalonge, Ann. d'Ap., *2*, 254, 1939.

[5] D. Chalonge and L. Divan, Ann. d'Ap. *15*, 201, 1952. Also M. Hack, Ann. d'Ap., *16*, 417, 1953.

[6] R. M. Petrie, Publ. Dom. Astrophysical Obs., *9*, 251, 1953.

[7] B. Westerlund, Upsala Obs. Ann. Vol. *3*, No. 6, 1951, No. 8, 1953; No. 10, 1953.

[8] W. R. Hossack, Ap. J., *119*, 613, 1954.

[9] I. Halliday, Ap. J., *122*, 222, 1955.

[10] B. Strömgren, Vistas in Astronomy (Ed. A. Beer), Vol. *2*, 1336, 1956. Cf. also B. Strömgren and K. Gyldenkerne, Ap. J., *121*, 43, 1955. K. Gyldenkerne, Ap. J., *121*, 38, 1955.

[11] B. Strömgren, Third Berkeley Symposium (Ed. J. Neyman), Vol. *3*, 49, 1956.

[12] D. Crawford, Ap. J., unpublished.

[13] H. G. Van Bueren, B. A. N., *11*, 385, 1952.

[14] H. L. Johnson and W. W. Morgan, Ap. J., *117*, 313, 1953.

[15] H. L. Johnson and C. F. Knuckles, Ap. J., *122*, 209, 1955.

[16] N. G. Roman, A. J., *59*, 307, 1954.

[17] H. L. Johnson and W. A. Hiltner, Ap. J., *123*, 267, 1956.

[18] W. Becker, Ap. J., *107*, 278, 1948.

[19] W. W. Morgan and D. L. Harris, Vistas in Astronomy (Ed. A. Beer), Vol. *2*, 1124, 1956.

[20] W. A. Hiltner and H. L. Johnson, Ap. J., *124*, 367, 1956.

[21] A. Blaauw, Pub. Kapteyn Astr. Lab. Groningen, No. 52, 1946.

[22] — Ap. J., *123*, 408, 1956.

[23] F. Bertiau, Thesis Louvain, 1956, Ap. J. (in press).

[24] B. Strömgren and D. Crawford, Ap. J., unpublished.

[25] J. A. Hynek, Astrophysics (Ed. J. A. Hynek), Chapter 10, 1951.

[26] O. Eggen, A. J., *60*, 407, 1955. Also Third Berkeley Symposium (Ed. J. Neyman), Vol. *3*, 1, 1956.

[27] D. L. Harris, Charlottesville Cosmic Distance Scale Conference, 1957.

[28] R. J. Mitchell and H. L. Johnson, Ap. J., *125*, 414, 1957.

[29] R. H. Weitbrecht, Rev. Sc. Instr., *28*, 883, 1957.

DISCUSSION

CHAIRMAN: B. LINDBLAD

SPITZER

What is the signal to noise ratio at 11th magnitude?

STRÖMGREN

One could work to about 1% accuracy, with one minute accumulation time at the Cassegrain focus of the 82″.

SCHWARZSCHILD

Your program and that of CHALONGE was originally intended for early type stars and it is only just at the limit that the F stars get in, though this is where the main problems of population types begin. Is anyone concentrating on F to K stars?

STRÖMGREN

I may mention the work of GYLDENKERNE on G and K stars with interference filters using LINDBLAD's broad spectral features. This work was published two or three years ago in the *Astrophysical Journal*. In our 8-colour instrument we have templates prepared for this type of work.

SCHWARZSCHILD

Is the arrangement suitable for discriminating population differences?

STRÖMGREN

Yes, if combined with MK luminosity classification based on Sr II. If to the CN and CH-band discontinuity MORGAN's Sr II line criteria are added you would get a workable 3-dimensional classification, though perhaps not the best one.

SCHWARZSCHILD

Are the strontium lines strong?

STRÖMGREN

They are rather hard to use because the strongest is fairly faint and close to Fe lines, but the strength could be measured with a spectrograph-photometer, and it would not be necessary at first to go to faint magnitudes.

OORT

Were you intending to start a program of this kind?

STRÖMGREN

Yes. When the 8-colour instrumentation comes into operation it would be easy to proceed along these lines.

LINDBLAD

Were many of the 2000 stars you mention for your program near the galactic pole?

STRÖMGREN

No, I referred to B, A and F stars in clusters, and B and A stars in associations. The program for the galactic pole is so far limited to about 100 stars.

VII.

GROUPÈS DES POPULATIONS ET FONCTIONNEMENT CINEMATIQUE DANS NOTRE GALAXIE

EVOLUTION DE NOTRE GALAXIE

DYNAMICS AND EVOLUTION OF THE GALAXY, IN SO FAR AS RELEVANT TO THE PROBLEM OF THE POPULATIONS

J. H. Oort
Leiden Observatory

The differences in kinematic properties of various types of stars can best be illustrated by considering their distribution in a direction perpendicular to the galactic plane. The behaviour of the principal types is indicated in Table 1. The objects have been arranged approximately in order of galactic concentration. The column marked "density" shows the contribution to the average density near the sun, in solar masses per 1000 cubic parsecs; $\overline{|z|}$ gives the mean distance from the galactic plane in parsecs, while the average random velocity in this co-ordinate is shown under $\overline{|Z|}$.

The data were compiled from various sources. Some of them are very uncertain. In a few cases, like the subdwarfs, they were estimated by the author. The velocity distribution of the white dwarfs was computed by E. Raimond, mainly from transverse velocities of 23 stars with parallaxes larger than $0\overset{''}{.}050$. Because of the interest attaching to white dwarfs in connection with the problem of the stellar populations, the following results of this computation may be added: The mean random velocity in the direction of the centre was found to be 39 km/sec, and in the transverse direction in the galactic plane

TABLE 1

Object	*Density* ⊙/(*1000 pc*^{3})	$\overline{\lvert z\rvert}$ *pc*	$\overline{\lvert Z\rvert}$ *km/sec*	$\overline{\lvert v_r\rvert}$ *km/sec*
O–B5	.09	50	(3.5)	
B8–B9	.8			
δ Cep variables	.001			
galactic clusters	.04	80	(5.5)	
interstellar matter	25.	125	8	
A0–A9	1.	110	7.6	
F0–F9	3.	(200)	12.2	
dG0–dG9	4.	(270)	15	
dK0–dK9	9.			
dM	29.			
gG0–gG9	.8	(290)	15.7	
gK0–gK9	.1			
gM	.01			
dark companions	5.:			
N		(240)	14	
white dwarſs	8.:	(270)	15	
planetary nebulae	.000 005	340	(18)	
novae		440	(21)	
R (normal sp.			23	29
long-per. var. M6e–M8e	.000 7	(540)	24	27
long-per. var. M4e–M5e	.000 3	(1100)	37	46
long-per. var. M0e–M3e	.000 1	(1100)	36	94
Humason–Zwicky stars			40?	
subdwarſs	1.5	(3900)?	73?	120
RR Lyr var. per. $\leqslant 0^{d}.42$	.000 003	(900)	31	44
RR Lyr var. per. $> 0^{d}.42$	.000 006	(3500)?	67?	85
R (peculiar)				87
globular clusters	.001	3000	(61)	101
total	87.			

28 km/sec. Of the 23 stars 4 have random motions exceeding 80 km/sec. Although selection effects will certainly have made this number too high, it would seem that the velocities are sufficiently high to indicate that most white dwarfs belong to a disk population II.

Recent measures of the 21-cm line in absorption have indicated that, contrary to the working hypothesis on which the estimate of the mean density of interstellar matter in the table was based, an important fraction of individual interstellar clouds may have a considerable optical thickness in the 21-cm line. As a consequence the true mean gas density may be larger, perhaps hy as much as 50%.

In many cases the value of $\overline{|z|}$ was not observed directly but computed from $\overline{|Z|}$, using recent data for K_z, the acceleration in the z direction. In other cases $\overline{|Z|}$ was computed from $\overline{|z|}$. Values so computed are shown in parentheses. In a number of cases better information on dynamical differences is given by the radial velocities, irrespective of their direction; in such cases the mean random radial velocities have been added in the last column.

From a recent study by E.R. HILL and the author, the total density of matter at $z=0$ was found to be 10.0×10^{-24} g/cm^3, or 150 solar masses per 1000 pc^3, with an estimated uncertainty of about 10%. Comparing this with the total density estimated in Table 1, we see that there is probably a sizable contribution by stars of still unknown type; these must be fainter than +18 absolute magnitude. We may remark that the ratio of mass- to light-density, $\mathfrak{M}/L$, in solar units, was found to be 2.4 in the vicinity of the sun, and 4.2 for a cylinder perpendicular to the galactic plane. Both values are much smaller than those found in the Andromeda nebula.

A somewhat schematic summary of the various dynamical and distributional characteristics encountered in the Galactic System, is shown in Table 2. The names given to the various population groups are those which were provisionally adopted in the last session of the *semaine*. On evolutionary grounds two kinds of disk populations are distinguished in Table 2, the one being an old population, with very strong concentration towards the centre, the other a mixture of old and relatively young stars. The numbers given in the line "axial ratio" are meant to give a rough indication of the amount of flatness of the various distributions. The data refer to equidensity surfaces extending somewhat beyond the sun, and for which, at the sun's distance from the centre, z equals $\overline{|z|}$ for the objects concerned. The differences in concentration to the centre are very great. In the first three columns the central density is probably several thousand times the density near the sun, while for the interstellar gas the density in the nuclear region may even be less than in our neighbourhood.

The line $Z_{\text{h.e.}}$, which has been copied from data given by SCHWARZSCHILD (cf. p. 210), gives the total mass density of elements heavier than helium expressed in the hydrogen density as unit. The indicated ages are, of course, only schematic.

The last line shows an attempt to estimate the total masses contained in the various population groups. Considering our fragmentary knowledge, such estimates are evidently extremely uncertain. They may nevertheless give an indication of how much mass has gone into stars during the various evolutionary phases. The mass of the gas has been taken from the 21-cm measures. The intermediate population I was estimated with the aid of SCHMIDT's model of the mass distribution in the Galactic System [1]. The number given is very rough, and may well be an overestimate. The total mass, of 70×10^9 solar masses, was likewise taken from this source. The mass of the halo population II has been computed from the density of the subdwarfs as given in Table 1, on the supposition that their distribution through the System is the same as that of the globular clusters. The distribution of these latter was taken from SCHMIDT's publication [1]. It may well be, of course, that in addition there are other and fainter types of stars belong-

TABLE 2.

Population	*Halo population II*	*Intermediate population II*	*Disk population*		*Intermediate population I*	*Extreme population I*
Some typical members	*subwarfs* *glob. clusters* *RR Lyr var.* *with per.* $> 0^{d}.3$	*high.-vel F-M* *long-per. var.*	*planet. neb.* *bright red giants* *novae*	*weak-line stars*	*strong-line stars* *A stars* *Me dwarfs*	*gas* *supergiants* *T Tauri stars*
$\overline{\lvert z \rvert}$ (parsecs)	2000	700	450	300	160	120
$\overline{\lvert Z \rvert}$ (km/sec)	75	25	18	15	10	8
Axial ratio	2	5	$\simeq$ 25	?	?	100
Concentration toward centre	strong	strong	strong	?	little	little
Distribution	smooth	smooth	smooth	?	patchy, spiral arms	extremely patchy, spiral arms
$Z_{h.e.}$ (Schwarzschild)	0.003	0.01	—	0.02	0.03	0.04
Age (10^9 years)	6	6.0 to 5.0	5	1.5 to 5	0.1 to 1.5	< 0.1
Total mass ($10^9 \odot$)	16	47			5	2

N.B. — The above headings in Table 2 are those that were finally adopted by the meeting after prolonged discussion (except that it was decided to call the second last column "Older population I" instead of "Intermediate population I", cf. p. 524). In the original paper columns 3 and 4 were headed "Disk population II" and "Transition I-II" respectively, and these are the columns 3 and 4 which are referred to in the discussion on pp. 517-24. The meeting finally decided to amalgamate the original columns 3 and 4 under the heading of "Disk population", and this column forms column 3 of the Table at the end of the Summaries (p. 533).

ing to the extreme population II. The number given must be considered as a lower limit. All the remaining mass has tentatively been attributed to the intermediate population II and the disk populations. The number given, 47×10^9, should accordingly be considered as an upper limit. There is, however, *some* indication that the mass of the disk population II must be considerable: in order to explain the observed rotation curve a very strong mass-density gradient just inside the sun's distance from the centre is required. This can only be due to a disk population of high-velocity stars of unknown type.

We shall now discuss the problem of how these differences in distribution may be understood. For this we must consider the evolution of the Galactic System. The evolution has been investigated by several astronomers, in particular by SPITZER and by HOYLE. The following remarks have, at least partly, been inspired by these studies.

From the amount of central concentration of the entire mass of the Galactic System we should be able to derive at least a rough indication of *how ordered* the large-scale motions were in the primeval gas out of which the System was formed. If these motions had been very well-ordered, no great concentration towards the centre could have resulted: we should have obtained a roughly homogeneous disk. This is certainly far from what we observe in the Galactic System, but it may resemble the state of affairs in late Sc spirals. These have relatively small masses and small densities (*), which is in line with what we would expect on this picture.

On the opposite side of the sequence of galaxies we have the elliptical systems. These must have originated from parts of the primeval gas which had relatively little resultant rota-

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(*) If for density we take the total mass in a *column*. The masses would be small because usually only small parts of the primeval medium would satisfy this very special condition.

tion, so that the concentration to the centre could become great, and simultaneously the average density could become high.

It is also understandable that the more resultant angular momentum there would be relative to irregular streamings, the longer it would take for the system to reach a well-ordered state. Whether or not this can explain the fact that systems like the Magellanic Clouds have advanced so little in the ordering process, I do not know. If not, we would be led to the conclusion that they have been formed much later than the Galactic System. This does not appear so very plausible. Certainly, their globular clusters and RR Lyrae variables must be old.

The stars and clusters belonging to the halo population II must evidently have been born in the earliest stages after the mass of primeval gas from which the Galactic System was to form had detached itself from the rest of the gas in the expanding universe. Possibly, they existed already before this detachment took place. During the subsequent stages the gas gradually contracted to a rotating disk having an angular momentum of the same order as the resultant angular momentum contained in the original body of gas. In tbe contracting process the gas clouds lose large-scale kinetic energy through collisions, the heat produced being radiated away (cf. HOYLE, p. 281). The *stars* formed in the early stages cannot lose kinetic energy in this way. Their present distribution must therefore reflect to some extent the size and shape of the original mass of gas, except that they may have acquired a considerable concentration toward the centre. Inasmuch as it is unlikely that the original mass would have had a very flat shape, it is natural that the distribution of the oldest population shows relatively little flattening.

We may assume that also during the contracting stage — which must have been relatively brief compared with the total age of the system — stars have been formed in relatively large abundance. These are the stars which we have classed as intermediate population II. Relatively small differences in age will have resulted in stars showing considerable differences in distribution.

The disk populations have evidently been formed after the gas had completed its contraction to a thin disk. The star-forming process in this disk is still continuing to-day. The intermediate and extreme populations I consist of those objects that have been formed most recently.

These suggestions do not yet suffice to explain the great difference between the distribution of the gas and that of the disk population II. If the motions in the primeval mass were largely un-ordered it must have contracted to a disk with a strong central concentration. In order to understand the difference just mentioned, we must assume that the star-forming process was much more rapid in these dense central parts. As a consequence, the excess density was soon used up in the formation of stars and a relatively homogeneous gas remained. We must suppose, then, that the rate at which interstellar gas condenses into stars varies with a rather high power of the average interstellar density. If this is so, the period directly after the contracting phase of the primeval gas had been completed should have been the period of most intense star building. From what we know about the nearly "normal" chemical composition of the disk population II it might be concluded that it was also at this stage that the greatest change in the composition of the interstellar medium took place.

We may infer that in the subsequent stages, as the interstellar gas was gradually used up, also the rate of star formation became slower. This appears plausible also from another angle. At present, only about 1/6th of the total mass density near the sun is interstellar. If the rate of star formation had remained the same all during the last 5×10^9 years and would continue in the same way, the Galactic System would be deprived of its interstellar gas in another 10^9 years. This would imply that it would lose its spiral characteristics in a time equal to 1/6th of its present age. The fact that the great majority of the flat stellar systems, in so far as they do not lie in dense clusters, display spiral structure, makes it seem unlikely that the Galactic System and the Andromeda nebula (in which the fraction of gas is similar) could be so near the end of their lives as spirals. It seems more probable that the star-building process is now much slower than in the past and that therefore the gas will not be used up in anything like as short a time as estimated above. I do not think that such an assumption would necessarily conflict with the views that SALPETER has put forward.

I shall not at present consider in detail the possible ways in which stars might be formed from the interstellar clouds. It seems plausible to assume that, at least in the case of massive stars, collisions between gas clouds play an important role. This may well explain the existence of the bridges of luminous material that ZWICKY and others have found to exist between galaxies that have apparently been in collision. After such an encounter colliding clouds from the two systems will be spread over a region connecting them, and stars of high luminosity may be expected to have been formed in that region. The region in question may be straight or curved, depending upon the parameters of the collision of the two galaxies and upon their rotations.

A final point that I should like to discuss is whether, and in how far, the random motions of stars may have systematically increased after their formation. This problem has been studied by SPITZER and SCHWARZSCHILD [2].

As is well-known the velocities of most O and B stars in our vicinity are quite small (cf. Table 1). For A-type stars and for so-called strong-line stars they are considerably higher, the mean Z velocity lying between 8 and 10 km/sec, as against 3.5 km/sec for the earlier types.

We remark, firstly, that the average value of z of the O and B stars (about 50 pc) is much smaller than that of the gas clouds. This may again be due to the circumstance that star building is favoured by higher gas density in such a way that it varies with a power of the density which is higher than one.

The higher velocities of the A stars might be ascribed to a greater thickness of the gas layer at the time of their formation. Alternatively, the layer of gas might have had the same thickness, but the A stars formed farther away from the plane than the B stars. Neither explanation appears very likely. It seems more plausible to assume that the velocities of the stars gradually increase after their formation, as a consequence of encounters with large complexes of interstellar clouds, as suggested by SPITZER and SCHWARZSCHILD. Since the publication of their paper considerable evidence for the existence of very massive cloud agglomerations has become available.

It seems of interest to study the behaviour of galactic clusters in this connection. In Table 3, compiled from TRUMPLER's catalogue of galactic clusters [3], the clusters within 1 kpc from the sun have been arranged according to TRUMPLER's classes 1, 2 and 3 and according to the spectral type of the earliest stars, respectively. The table gives the numbers of clusters in each group, the mean distance from the galactic plane in pc, the median spectrum of the brightest stars, and the age in millions of years, estimated from the preceding column.

TABLE 3

Class	*n*	$\overline{\lvert z \rvert}$	*Sp.*	*T*	*earliest type*	*n*	$\overline{\lvert z \rvert}$	*Sp.*	*T*
1	21	56	B4	250	O -B4	20	44	B1.5	120
1-2	21	56	B6	350	B5-B8	22	53	B7.5	380
2 or 2-3	25	95	B9 5	500	B9-F0	25	106	A0	540

It will be observed that there is a regular progression in $\overline{|z|}$ with age. In this case, as the clusters in the lower lines are assumed to have developed from clusters in the earlier divisions, it seems unlikely that they would have *originated* at different average distances from the plane. Assuming that the differences are caused by encounters with interstellar cloud complexes, we can now derive a direct numerical estimate of the amount of increase in velocity per unit of time. We find that in about 0.3×10^9 years the average z increases from 49 to 106 pc, corresponding to an increase in velocity from $|\bar{Z}| = 3.5$ to $|\bar{Z}| = 7.3$ km/sec. As SPITZER and SCHWARZSCHILD have pointed out, the increase of the energy per unit of time diminishes with increasing random motion, so that it seems unlikely that during the evolution of the galactic disk the process could have led to average Z velocities much exceeding 10 or 12 km/sec, even though the interstellar density may have been rather larger in the past than it is at present. The greater spread of the disk population II may have to be ascribed to other causes.

REFERENCES

[1] M. SCHMIDT, B.A.N., *13*, 15, No. 468, 1956.

[2] LYMAN SPITZER, Jr., and MARTIN SCHWARZSCHILD, Ap. J., *118*, 106, 1953.

[3] ROBERT J. TRUMPLER, Lick Bull. *14*, 154, 1930.

DISCUSSION (*)

CHAIRMAN: A. D. THACKERAY

BLAAUW

Would the spherical distribution of the earliest halo stars have been distorted by the changing gravitational field, in later phases of the contraction of the gas, so as to assume a spheroidal form?

OORT

The gravitational effect is difficult to separate from the effects of the turbulent motions. The globular clusters must have preserved these motions. I doubt whether the spheroidal distributions of intermediate types could be accounted for in this way.

HECKMANN

If the primeval velocities were high, it would not make much difference.

OORT

These velocities of course are related to the total mass and size of the protogalaxy.

(*) It is important to note that the table referred to in the following discussion is the original six-column Table 2 of Professor OORT's paper (cf. note to the Table p. 419). The same table forms the basis of the discussions after the Summaries (pp. 517-24). The change to a five-column table, by amalgamating columns 3 and 4 of the original table, was made towards the end of the discussions (see p. 524).

BAADE

EGGEN's recent colour-magnitude diagram for the solar neighbourhood indicates that, although we are in a spiral arm, a strong disk component of the M 67 type is present. My suggestion is that the strong-line stars and those in the class you call "transitional I-II" should be denoted "disk population". From the physical side your disk population II is a very sparse one.

OORT

I presume that the processes of star formation in the disk at an early stage included supernovae of type I which changed the chemical composition of the gas, and that nearly simultaneously with the formation of population II there was a change in the constitution of the interstellar medium.

BAADE

Most of the solar neighbourhood stars have metal lines of normal strength. However, MORGAN's integrated spectra show that the metal-poor disk population in M 31 contributes only little to the light, even at the centre.

OORT

Their contribution to the mass must be considerable. They must have a strong central concentration and form the bulk of the mass of the galaxy.

BAADE

The division between the strong and weak-line stars in Miss ROMAN's sense is not very sharp, as we learned a few days ago.

OORT

The transition may have occurred soon after the formation of a smooth disk.

BAADE

The stress should be on physical properties because age differences are at present still uncertain.

LINDBLAD

We have realized for some time that the evolution of the system involves two phases, one of initial condensation of gas into stars and the other where stars are separated from the central layer by velocity dispersion. Central concentration is a critical factor in the discrimination between the two phases when considering the creation of sub-systems of considerable dispersion. The process of star formation is probably favoured by a certain temperature limitation. It is most likely to occur first near the surface of the system, where the velocity dispersion must decrease. Therefore the initial formation of stars should occur first near the surface regions, as I have proposed in a recent paper in "*Vistas in Astronomy*".

SPITZER

It seems that BAADE and OORT disagree on the Z content of disk population II. Planetary nebulae are observed to have about the same composition as the sun, which is difficult to reconcile with a low metal content for the stars in the third column of OORT's table.

BAADE

But we know of a planetary nebula in the halo (HARO's) and of another in a globular cluster of the halo type (M 15). On the other hand there is strong evidence for the existence of a disk population containing RR Lyrae variables, i.e. presumably of low metal content.

BLAAUW

To clarify the position of weak-line stars in OORT's table we will have to subdivide them into different groups. They are a mixture of stars of different spectral and kinematic properties.

OORT

My allocation of these stars was somewhat symbolic. We have not really sufficient knowledge of them yet.

O'CONNELL

It is very much to be hoped that by the end of our meetings we shall be able to reach some clear decisions about nomenclature.

A recommendation from this meeting to the IAU would carry great weight.

Morgan

In comment on some details of Oort's classification, I notice, first, that he has used an old label — Population I — in a new fashion. Secondly, classification by age is exciting and fundamental, but it involves a parameter whose value may undergo violent changes in the next few years. Perhaps we need a simpler or less extended classification for the present time at least.

Schwarzschild

If it is true that we have a continuum in which age is decisive, the subdivisions are somewhat artificial and cannot have too sharp a meaning. Some of them have, however, a physical significance. The dynamical history of the galaxy falls presumably into two parts, a period of decaying turbulent velocities, followed by one in which the velocity dispersion remains approximately constant. Hence the division between the 2nd and 3rd column of Oort's Table is real. Secondly, if we assume that stars in the last four columns arose from spiral structure and that velocity dispersion is increased by encounters with gas clouds, only more recent stars will be apparently connected with the spiral structure, and this justifies the division after column 4. With these three phases therefore, we can divide Oort's table into three groups of two columns, the middle two corresponding to stars formed when turbulence decay had finished, but which have lost their apparent connection with the spiral structure. They must form the disk. May I ask Oort if, when we look at the Andromeda nebula, it would be true to say that light at the solar distance comes from column 4 objects and that of the nucleus from column 3? It appears that Baade's "disk population" is not only your column 3 but includes column 4.

Oort

The point in favour of separating disk population II is its central concentration. Baade's disk population has a strong contribution from column 4.

BAADE

There is good evidence that column 2 contains objects in the same physical group as planetary nebulae and novae. I have observed large numbers of long-period variables in NGC 185, and this suggests that columns 2 and 3 are physically the same. I entirely agree with SCHWARZSCHILD's calling column 1 halo, and columns 2, 3 and 4 disk.

SCHWARZSCHILD

I should like to question BAADE's assumption that if two types of object occur in an elliptical galaxy we are justified in putting them in the same column; e.g. BAADE's grouping of long-period variables, novae and planetary nebulae justifies their being placed in adjacent columns only.

BAADE

The argument is stronger than this. In the Andromeda nebula 96′ from the nucleus, outside the spiral arms where the brightest population II stars are resolved, the long-period variables appear, so the connection is not confined to E galaxies. Long-period variables of the disk are all population II, not spiral arm objects, since they show no concentration toward the latter. We should not bring velocity into the classification. This has already led to confusion when it was formerly supposed that cluster variables must have a spheroidal distribution.

OORT

Long-period variables may have formed partly in the contracting stage and partly in the disk.

MORGAN

Could we retain OORT's subdivisions with the headings over column 1 "halo"; over 2, 3 and 4 "disk"; and over 5 and 6 "arm"?

STRÖMGREN

OORT's suggestion that the enrichment of heavy elements occurred largely at the time when the concentration to a disk had occurred and there was still an enormous concentration of gas toward the centre, makes this phase so important, chemically and kinematically, that the dividing line between what we call population I and population II might be put there, right after the end of this phase.

FOWLER

It is important in considering the formation of the elements in the solar system to have a fairly precise location of the position of the sun in OORT's table. Was the sun formed after 50% or more of the gas had been condensed into stars?

OORT

Perhaps the sun belongs to column 4 when most of the heavy elements had been formed, but I have not much confidence in this estimate.

SALPETER

We must carefully distinguish between the nucleus and regions farther out. The nucleus may have contributed more to column 3, the farther regions to column 4.

SCHWARZSCHILD

We can see that planetary nebulae and novae have strong central concentrations. Perhaps this is typical also of column 4 objects.

BAADE

This may be indicated by the integrated spectrum of the Andromeda nebula.

MORGAN

It is important to distinguish between light distribution and mass distribution.

SANDAGE

In which column of OORT's table would clusters like M 67 fall?

OORT

Column 3 or 4.

SANDAGE

In fitting M 67 into the table, the colour-magnitude diagram of high-velocity stars with trigonometrical parallaxes appears to give a clue. The stars with trigonometrical parallaxes in Miss ROMAN's catalogue of high velocity stars define an M 67-like diagram. The mean velocity of this group of stars is about 100 km/sec. The relatively high metal content of M 67 would place it somewhere to the right of column 4 whereas the age and high velocity of M 67-like stars would place it nearer column 3.

OORT

There are no extreme subdwarfs in M 67.

SANDAGE

No. Stars in M 67 appear to have a normal main sequence and no *UV* excess in the *UBV* photometry.

MORGAN

There are considerable differences between M 67 and the nucleus of M 31; the latter has large numbers of giants of later type than in M 67.

SALPETER

Regarding the variation between the nucleus and the disk, if the nuclear stars were formed suddenly 5×10^9 years ago, but the disk stars more slowly, stars of columns 3 and 4 could have tbe same composition in spite of their different ages.

OORT

I think that column 3 stars were formed during the enrichment of heavy element content and column 4 objects afterwards.

SANDAGE

MORGAN's spectra in M 31 would seem to indicate that column 3 does not contribute much light to the disk population. If SALPETER is right that column 3 represents the nuclear population, while column 4 is the major contributor to the disk, then we should expect a spectroscopic difference between these two regions. Can MORGAN say if there is any difference in the spectrum between the nuclear and the outlying disk?

MORGAN

HORACE BABCOCK's early spectra of M 31 with the Mayall spectrograph show no difference between the bright, amorphous central disk and the nuclear region, but this observation is not of the highest weight and repetition is important.

OORT

The stars in outer parts of Andromeda are not pure disk stars. There must be an important contribution from the halo.

MORGAN

I was speaking of much nearer the centre.

ON THE FORMATION OF GALAXIES AND TYPE II STARS

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Star clusters and associations are concerned with star formation in groups, the number of stars per group being of the order of a few hundreds, or of a few thousands. We do, however, have evidence of star formation in groups of millions, or even of thousands of millions. The globular clusters are groups of the order of a million, while the elliptical nebulae are groups containing thousands of millions of stars that seem as if they must have had a common origin that coincided very closely with the origin of the nebulae themselves. Thus, if we suppose that the elliptical nebulae condensed from gas clouds, the condensation of the gas into stars seems as if it must have proceeded contemporaneously with the formation of the nebulae, otherwise it is difficult to understand the large dynamical motions possessed by the stars in these systems. A similar argument applies to the stars scattered throughout the halo of the Galaxy.

The aim of the present paper is to see why this contemporaneous formation of stars may have taken place.

It will be assumed that gravitation is the force producing condensation. Write G for the gravitational potential of a gas cloud — i.e. G is the energy required to expand the cloud (against the gravitational forces) to infinity. Also write E for the thermal energy contained within the material of the cloud. Under conditions of hydrostatic equilibrium, with radiation pressure neglected, and no body forces other than the pressure gradient, the relation $G = 2E$ must be satisfied. If $G < 2E$ the cloud expands, if $G > 2E$ the cloud contracts. It is useful to derive one or two simple formulae. As general orders of magnitude we can write

$$G \sim \frac{\gamma \mathfrak{M}^2}{V^{1/3}} \;, \quad E \sim \frac{3}{2} \frac{\mathfrak{M} \mathfrak{R} T}{\mu} \;, \quad \mathfrak{M} = \rho V ,$$

where $\mathfrak{M}$ is the mass of the condensation,
V is the volume of the condensation,
ρ is the density of material within the condensation,
μ is the mean molecular weight of the material,
T is the temperature of the material,

and γ, $\mathfrak{R}$ are the Newtonian gravitational constant and the gas constant respectively.

By a simple elimination it follows immediately that the condition for contraction ($G > 2E$) yields

$$\mathfrak{M} > \sim \left(\frac{3 \mathfrak{R} T}{\mu \gamma} \right)^{3/2} \rho^{-1/2} \;, \tag{1}$$

The numerical application of this formula will be considered at a later stage.

In thermodynamics, two special forms of compression are frequently considered, an adiabatic compression and an isothermal one. Let us follow this procedure — physical reasons will be given later for doing so.

Under adiabatic conditions all energy released by gravitation is ultimately dissipated into thermal energy. Thus

$$dE = dG \;,$$

for each step in the contraction. Integrating we have

$$E - E_0 = G - G_0 \;,$$

where E_0, G_0 are the initial values of E, G. It follows immediately that E eventually increases to $\frac{1}{2}G$ ($E_0 < \frac{1}{2}G_0$) as G increases during the compression. An adiabatic compression therefore leads to a rise in the thermal energy that ultimately becomes sufficient to provide hydrostatic equilibrium. This case is realized to a high degree of approximation in a contracting stellar condensation.

A very different situation appears to arise in the case of an isothermal contraction. Suppose the condensation contracts from volume V to volume $x^{-3}V$. The gravitational energy released in such a condensation is of order $G\mathfrak{M}^2(x-1)V^{-1/3}$, while the thermal energy generated by direct compression is of order $3\mathfrak{M}\,\mathfrak{R}\,T\,\mu^{-1}\log x$. To maintain the isothermal condition the latter energy must be removed from the gas. In later considerations we shall find that radiation serves to remove the energy. Assuming for the moment that this is the case, we see that the energy of concentration is dissipated by simple compression and radiation only if

$$G M^2 (x-1)\, V^{-1/3} \doteqdot 3\,\mathfrak{M}\,\mathfrak{R}\,T\,\mu^{-1}\log x \;.$$

An examination of the properties of the formulae appearing in this equation shows that two requirements must be met if the equation is to be satisfied

(a) $G\mathfrak{M}^2V^{-1/3}$ must be comparable with $3\mathfrak{M}\,\mathfrak{R}\,T\mu^{-1}$
(b) x cannot be too large, only 2 or 3.

These requirements have a simple interpretation: the condensation must be only just unstable against contraction, and it must not contract too far.

It is now instructive to consider what happens if (a) is not satisfied, if indeed $G\mathfrak{M}^2V^{-1/3}$ greatly exceeds $3\mathfrak{M}\,\mathfrak{R}\,T\,\mu^{-1}$. Then very little of the gravitational energy passes directly into thermal energy. Thus the gravitational energy released in a contraction of the whole cloud passes mainly into dynamical energy, *and the dynamical energy is sufficient to re-expand the cloud almost back to the initial volume.* There is therefore no permanent contraction *of the cloud as a whole.* But there can be a permanent contraction of parts of the cloud, for there will be subregions of the cloud that do satisfy (a). These regions can contract by a factor of 2 or 3, the energy of contraction being dissipated by radiation. And after the subregions have contracted in this way, conditions (a), (b) can again be satisfied by "sub-sub-regions" within the "subregions". And so on.

In this way, by a process of fragmentation, an initial cloud of very large mass can achieve an extremely rapid dissipation of energy, more rapid than can apparently be achieved by turbulence or by shock-waves. The accelerating nature of the fragmentation process is easily seen from the following considerations. The time required for an appreciable contraction of an unstable cloud is of order $(\rho\,\gamma)^{-1/2}$. Now ρ increases by a factor of order 10 at each stage of fragmentation. This means that the time scale decreases by $10^{-1/2}$. Indeed the time required for an infinity of fragmentation stages exceeds the time for the first stage only by the factor

$$1 + 10^{-1/2} + 10^{-1} + 10^{-3/2} + \ldots = 1/(1 - 10^{-1/2})$$

It appears therefore that fragmentation can proceed to an advanced stage in only a little greater time than the time required for the first condensation to take place. It is to this feature of the process that the appearance of stars during the earliest stages in the formation of a galaxy is attributed. But before turning to such considerations, it is interesting to see why the isothermal condition is likely to be applicable during the formation of galaxies.

If dust is initially absent from the material — a plausible supposition — hydrogen is the main source of radiation. Now hydrogen has the curious property that it is a very poor radiator for $T < 10^4$ °K, but is a very powerful radiator for $T \sim 1.5 \times 10^4$ °K. This is precisely the property required to maintain the isothermal condition, for the release of thermal energy during contraction is amply adequate to guarantee that T does not fall below 10^4 °K, but it is not adequate to raise T above $1{\cdot}5 \times 10^4$ °K. The temperature is accordingly confined within a narrow range. Hence the isothermal condition is satisfied to a good approximation, and accordingly the fragmentation process may be expected to operate.

Now what will be the order of the mass of the first regions to condense? If T, ρ are specified, an estimate can be obtained from formula (1). With $T = 1{\cdot}5 \times 10^4$ °K, $\rho = 10^{-27}$ gm per cm^3, $\mu = 2/3$, we obtain

$$\mathfrak{M} > \sim 1.4 \times 10^{10}\ \mathfrak{M}_\odot\,.$$

The coincidence of this value with the masses of the galaxies is an encouraging feature of these considerations, simple as they are. Indeed if we put $\rho = 10^{-28}$ gm per cm^3, which represents the mean density within the Local Group, we obtain a mass in quite close agreement with that of the Galaxy.

One point remains. The fragmentation cannot go through an infinity of steps, since sooner or later the isothermal condition must fail. This follows because the density, and hence the opacity, increases at each stage of condensation. Ultimately the opacity becomes high enough to prevent the free escape of radiation, and ultimately an approximation to an adiabatic condition is set up. When this stage is reached, hydrostatic equilibrium becomes operative (in a good approximation) and fragmentation ceases.

An obvious problem is to calculate the masses of the fragments at this final stage. A year or two ago I made such a calculation and found the final masses to be exactly of stellar order [1], the mean final fragment mass turning out to be $\sim 1{\cdot}5\ \mathfrak{M}_\odot$, although a considerable spread about this value seems possible.

I would like now to return to the starting point of this paper, where the difference between star formation in comparatively small numbers, such as occurs in the spiral arms of the Galaxy, and star formation on the large scale exemplified by the elliptical nebulae, was mentioned. It appears that our classification into stars of Types I and II ought to take account of this difference. So far we have discussed classification according to age and chemical composition. There also seems to be the possibility of classifying the stars according to the scale of the process in which they originated. It is obviously too early to seek any firm classification along these lines, but I feel that such considerations should be taken account of in the long run, as more becomes known of the precise conditions under which stars are formed.

REFERENCE

[1] F. Hoyle, Ap. J., *118*, 513, 1953.

DISCUSSION

CHAIRMAN: A. D. THACKERAY

SALPETER

In the process of subdivision how much of the energy appears as dynamic energy in the motion of the fragments relative to each other?

HOYLE

Perhaps 1/3, and this supplies the dynamic energy of the stars.

SPITZER

My first remark is that HOYLE has shown that nature can follow the sequence he describes. It is not obvious that it will do so in fact. Whether or not smaller fragments will develop depends on the time-scale of their contraction. Secondly, I am not clear why he prefers the initial state of the galaxy to have the present-day dimensions.

HOYLE

If the fragments are optically thin their time-scale diminishes by geometrical progression.

SPITZER

Then the condensation of fragments proceeds more rapidly than the condensation of the large mass?

HOYLE

Another way of describing this is to say that stars will condense more quickly than the main mass in regions of higher density. On SPITZER's second point the assumption of an initial size of the Galaxy not much greater than the present size gives a better explanation of OORT's table.

SPITZER

Otherwise the sub-fragments would be at too great a distance from the centre.

HOYLE

Yes. One would then have already condensed, compact bodies fitting into a larger region of space then the Galaxy occupies at the moment, and it is not at all clear that one could get this down to the present volume of space.

OORT

The contraction depends on the initial rotation. If this is great it cannot contract much.

LEMAÎTRE

How far does HOYLE's theory apply to the collision of gaseous clouds?

HOYLE

The general mechanism here is that the collision produces a compression leading to radiation of thermal energy and leaves a higher gas density, where star formation may be possible.

SCHWARZSCHILD

Where would you put the change-over in the star formation mechanism in OORT's 6-column table?

HOYLE

After the second column.

SCHWARZSCHILD

How long have you for star formation from pure hydrogen?

HOYLE

I should estimate 2×10^9 years.

SCHWARZSCHILD

Then you have only a factor of 4 in the rate of star formation between the "rush" and the "trickle".

HOYLE

I am a little doubtful whether we can give anything like an accurate time-table for the formation of different parts of the Galaxy, at any rate at the present stage.

SCHWARZSCHILD

But the first column should be a much quicker stage.

HOYLE

Unless we have to wait for the very high temperature gas to cool.

SCHWARZSCHILD

During this time there is no formation of stars and heavy elements.

HOYLE

The temperature drop may not be simultaneous in different places.

SPITZER

I understand that 2×10^9 years includes the waiting time.

MASS EXCHANGE WITH THE INTERSTELLAR MEDIUM AND THE FORMATION OF TYPE I STARS

LYMAN SPITZER, Jr.
Princeton University Observatory

According to present concepts, much of the interstellar matter in a spiral arm is involved in a continuing cycle. Material condenses to form young stars of Population Type I. The more massive of these stars eject much of this material, possibly enriched in helium and other elements, back into space during their giant phase. Supernovae also eject mass, presumably supplying the iron and the heavier elements which were less abundant when the Galaxy was formed. The observational evidence for this point of view has been presented in the other papers in this series, and also in a forthcoming book by SCHWARZSCHILD [1] (*). While the evidence is perhaps not entirely conclusive, it is certainly very persuasive, and this point of view will here be assumed correct.

These processes of mass ejection and star formation are briefly discussed in the present paper from the standpoint of astrophysical theory. At the present time no adequate theory of these processes exists. Nevertheless an examination of theoretical possibilities may be useful in the analysis of stellar populations, in that it suggests certain effects that may be important and points out additional observations that would be of interest.

(*) I am much indebted to Professor SCHWARZSCHILD for a manuscript copy of this material.

The following sections are devoted to three distinct problems. The first section analyzes mass ejection from giant stars. The next section is devoted to the mixing of the ejected material with the rest of the interstellar gas. The final section treats the recondensation of the gas to form new stars. In each section, the conclusions derivable from the observations are given first, and then certain theoretical consequences and interpretations of these conclusions are presented.

I. *Mass Ejection*

Ejection of mass by stars of different types has been discussed by a number of workers. A survey of this field, and references to earlier work, has been given by BIERMANN [2]. Here we restrict ourselves to ejection by red giants, for which the statistical evidence for mass ejection seems rather strong. According to SCHWARZSCHILD [1], a typical Type I giant star ejects about one solar mass in 10^8 years. The mass, luminosity and radius of such a star may be taken as about $2\mathfrak{M}_\odot$, $100L_\odot$ and $10R_\odot$, respectively. If the rate of ejection is assumed to be constant, then $4\pi\rho v r^2$ must be constant in both space and time, where ρ and v are the density and outwards velocity, respectively, of the ejected gas at the distance r from the star. With the assumed rate of mass loss we find, just above the stellar surface (at $r=10R_\odot$),

$$\rho v \approx 10^{-7}\ \frac{\text{gm}}{\text{cm}^2\ \text{sec}} \tag{1}$$

If v is set equal to 10^7 cm/sec, we find that ρ is 10^{-14} gm/cm^3, corresponding to a particle density of 6×10^9 H atoms/cm^3, if the material is assumed to be mostly hydrogen. The absorption produced by these atoms is proportional to the total number, N, of ejected atoms per square centimeter column in the line of sight, which is given by

$$N=\int_R^\infty n\,dr = nR \approx 4\times10^{21}/\text{cm}^2\ , \tag{2}$$

where R is the stellar radius, equal again to $10R_\odot$.

This value of N is relatively small. In the reversing layer of the sun, for example, the number of H atoms above the level $\tau = 1$ is about 2×10^{24}. Moreover, the density we have found for the ejected material is less than that in the reversing layer by a factor smaller than 10^{-6}, with a corresponding increase in the level of ionization. Neutral and singly ionized atoms of elements such as Fe and Ca, with lines of low excitation potential in the visible spectrum, should be too scarce to be detectable. More highly ionized atoms produce detectable absorption lines only if excited to a high energy level, a process for which few photons are available outside a yellow or red giant. Thus one would not expect to observe the ejected atoms spectroscopically. A very much lower value of the assumed ejection velocity, v, would greatly increase the difficulty of finding an adequate mechanism; in such a case one would essentially have to explain the quasi-static support of an enormously extended atmosphere. We may conclude that in all probability uniform ejection of material at the assumed rate would not be detectable spectroscopically.

In view of this result it is surprising that ejection of material by the red supergiant α Her has been found by DEUTSCH [3], with a rate of mass ejection about equal to the value assumed earlier in this paper. This result is particularly surprising in that the observed absorption lines are produced, in part, by material extending beyond the companion of α Her, at a distance of some 700 astronomical units from the supergiant. Since n varies as $1/r^2$, for v constant, N is much reduced below the value found in equation [2], and is about 3×10^{17} H atoms/cm^2 for the assumed rate of mass loss, and with the measured expansion velocity of about 10 km/sec. The observed strength of the observed lines of neutral and ionized calcium requires a very much lower level of ionization than would be found with uniform density. To explain the observations DEUTSCH therefore assumes that the ejected gas is concentrated in clouds, with a density about 10^7 times as great as the mean value at that distance. While gases above stellar surfaces and between the stars seem to be generally non-uniform in their distribution, so enormous a concentration factor is rather remarkable, and must be accepted with some reserve. Certainly one cannot be sure that all ejected shells will be so obliging as to allow spectroscopic detection by virtue of such very great concentration factors.

We turn next to a discussion of the mechanisms that may be responsible for the ejection of mass. One obvious condition to be satisfied is that the mechanism must provide the necessary power, which is an appreciable fraction of the stellar luminosity. The escape velocity from a giant of mass $2\mathfrak{M}_\odot$ and radius $10R_\odot$ is about 300 km/sec. To provide the potential energy necessary for mass ejection, at a rate of $1\mathfrak{M}_\odot$ in 10^8 years, requires a power, P, of $0.08L_\odot$. Hence the ratio of P to the stellar luminosity, L, equal to 100 $L_\odot$, is given by

$$\frac{P}{L} \approx 0.001 \tag{3}$$

This relatively high ratio of P to L at once excludes radiation pressure as a possible mechanism for mass ejection at the assumed rate. When a photon travelling outwards from a star is scattered back to the star by an atom, the fraction of the photon energy which is transferred to the atom is $2v/c$, or about 0.002, if v equals the escape velocity. Since only the radiation in absorption lines is presumably available for exerting pressure on an expanding shell, the total power available from this source is several orders of magnitude less than required.

Another possibility is that the material escapes by evaporation from a stellar corona. While this mechanism can certainly not be excluded at the present time, the energy input required to the corona seems rather high. In the sun, the energy input to the corona is presumably about equal to the sum of the energy conducted inwards and the energy radiated outwards; together these have a rate of $4 \times 10^{-7}L_\odot$, according to VAN DE HULST [4]. If the energy input results from the acoustic waves generated by turbulence, as assumed by BIERMANN [5] and by SCHWARZSCHILD [6], some increase of input would be expected in a red giant, where the turbulent velocities are perhaps five times greater than in the sun. Whether so large an increase in energy input is possible, however, is somewhat conjectural at present.

Yet another possibility is that hydromagnetic effects are somehow responsible. Such effects are presumably responsible for ejection of energetic particles by the sun — see the survey by BIERMANN [2] — as well as for prominences, surges and other types of activity observed above the solar surface. Understanding of these hydromagnetic processes is still in a very rudimentary stage. However, if the level of magnetic activity were increased many times over the level observed in the sun, and if the velocity of escape were less, appreciable mass ejection would certainly not be surprising. Possibly internal magnetic fields within the ejected material might confine the gas and account for so large a difference in density between the observed clouds and the inter-cloud medium.

Evidently this entire subject of mass ejection is in a somewhat uncertain state. The process is not understood theoretically and the direct spectroscopic observations are so limited and so puzzling that firm conclusions are difficult to draw. The chief result that may be obtained from this discussion is that mass loss can conceivably be a very general phenomenon. For almost any star the assumption of extensive mass loss is difficult to refute on the basis either of spectroscopic observation or of astrophysical analysis of the ejection process.

II. *Mixing of Interstellar Material*

We next consider the extent to which mixing of the interstellar gas may be expected to produce uniform composition. Some observational evidence on this point is provided by galactic clusters. From the remarkably small scatter in the best observed colour-magnitude sequences for clusters, SCHWARZSCHILD (private comunication) has inferred that $\Delta Z/Z$ in a single cluster probably does not exceed ten percent, where Z is the mean fraction of heavy elements inside the stars of the cluster, and ΔZ is the dispersion of the Z values for single cluster stars from this mean. Evidently within the gases which condensed to form a single cluster mixing has been relatively effective.

On the composition of the field stars the observational evidence is much less complete. Since Z in the interstellar medium is believed to increase with time, and since the age of a single field star can usually not be determined directly, it is not possible to determine how much of the scatter in the Hertzsprung-Russell diagram for field stars is due to inhomogeneities of composition in the gas and how much is due simply to differences of age. Apparently $\Delta Z/Z$ for field stars of the same age could be appreciably larger than 0.1 without our knowing it.

Let us examine how good mixing should be to ensure uniformity of composition to within ten percent, despite random fluctuation in the number of supernovae, in which the heavy elements are presumably made. Red giant stars are so much more numerous than supernovae that purely random fluctuations of the spatial distribution of these objects need not be considered in this connection. According to the statistics of supernovae and of heavy element formation, within 5×10^9 years one supernova has appeared, on the average, within each sphere of radius 30 pc. To ensure the specified uniformity requires mixing over a sphere of at least 150 pc radius, or 300 pc diameter, in which 100 supernovae occur within 5×10^9 years.

In the absence of other effects, the motions of interstellar clouds are entirely adequate to produce such mixing. With BLAAUW's [7] estimate of 10 clouds in the line of sight per kiloparsec and with a root mean square velocity (two-dimensional) in the galactic plane of 10 km/sec, it is clear that each element of a cloud will collide with another cloud in about 10^7 years, travelling 100 pc between collisions. If the motions are assumed to be random between collisions, we find that only 10^8 years are needed to travel the required 300 pc. This time is somewhat reduced when account is taken of the motion perpendicular to the galactic plane; a cloud which has risen to some distance above the plane can travel further parallel to the plane without collision. Evidently in 5×10^9 years such motions would reduce to somewhat less than ten percent the fluctuations of $\Delta Z/Z$ in the gas resulting from random fluctuations in the number of supernovae. However, other effects may modify this simple picture. The concentration of grains by radiation pressure, proposed by SPITZER [8], may be expected to increase Z systematically within cloud complexes. As the grains are pushed together, diffusing through the gas, the heavy elements constituting these grains will be concentrated relative to hydrogen and the noble gases. While the evidence from galactic clusters indicates that Z is not increased very drastically by this mechanism, some inhomogeneities may result.

In addition, the presence of a galactic magnetic field may seriously impair the mixing of the interstellar medium. If the field is weak, and without much effect on the gas motions, turbulence may still manage to mix the gases rather effectively. A quasi-random field of about 10^{-6} gauss, of the type proposed by SPITZER and TUKEY [9], would probably have little effect on large-scale mixing. However, a nearly uniform field of about 10^{-5} gauss, of the type proposed by CHANDRASEKHAR and FERMI [10], would certainly modify the mixing. It is not clear physically what happens when a supernova goes off in a strong uniform magnetic field, since the hydromagnetic phenomena involved are complicated. Certainly the tendency of the lines of force to remain nearly straight and the tendency of the gas to follow the lines of force will weaken turbulent mixing. Perhaps sheets of the outwards moving supernova material might penetrate between the lines of force of the initial medium, but how much mixing might result in this way is uncertain.

All the foregoing discussion is concerned with mixing over less than a thousand parsecs. If systematic differences are present in the rate of heavy element formation in different regions of the Galaxy, corresponding differences of chemical composition between different regions seem very likely (*). Complete mixing of all the gas in the Galaxy seems very unlikely in the present state of our system.

One may conclude that some mixing of the interstellar gas must certainly occur, but one cannot say how much. Caution should be used in assuming that either the heavy-element content, Z, or the helium content, Y, is constant throughout any region of the interstellar gas at any one time.

III. *Formation of Stars*

The observational evidence for the formation of young stars in spiral arms is very clear. At the present rate of star formation, according to SCHWARZSCHILD [1], in 5×10^9 years a total mass of $0.05\ \mathfrak{M}_\odot/\mathrm{pc}^3$ condenses into stars brighter than $+3$ in absolute magnitude; a star brighter than this limit has a time of evolution less than the present age of the Galaxy. A large fraction of these stars, perhaps all of them, are formed in groups — associations or galactic clusters — with about 100 such stars to a group. Thus in a cube 500 pc on a side, corresponding roughly to a 500-pc length of spiral arm, 500 such stars, or about 5 clusters, form in 10^6 years.

It is of interest to enquire where, in the irregular distribution of matter between the stars, this star formation takes place. A cloud of mass $\mathfrak{M}$ will contract gravitationally only if the gravitational energy exceeds twice the thermal energy; i. e., if

$$\frac{\mathfrak{M}}{l} > \frac{kT}{Gm} \approx 200\ \frac{\mathfrak{M}_\odot}{pc} \tag{4}$$

(*) I am indebted to a remark of Dr. STRÖMGREN for directing my attention to this problem.

where l is the approximate diameter, or length of the cloud; T is the absolute temperature, which we have set equal to 100° K. The other symbols in equation (4) have their usual meanings.

TABLE 1

Characteristics of Interstellar Clouds

Object	*Small Globule*	*Large Globule*	*Intermediate Cloud*	*Large Cloud*
$\mathfrak{M}/\mathfrak{M}_\odot$	> 0.2	5 :	1.3×10^3	3×10^4
$l(pc)$	0.06	0.5	8	40
$\dfrac{\mathfrak{M}/\mathfrak{M}_\odot}{l}$	> 3.3	10 :	160	750
$n\left(\dfrac{H}{\mathrm{cm}^3}\right)$	$> 7 \times 10^4$	3×10^3:	200	40

To investigate whether different types of interstellar clouds are contracting gravitationally, some physical characteristics of four different types of observed clouds are given in Table 1, adapted from a previous table by BOK [11], but with different names for the different columns. The two types of globules cover the range of sizes observed for Barnard's dark objects. A typical intermediate cloud is the Coalsack. The so-called "large cloud" is similar to, although somewhat smaller than, the structures listed by GREENSTEIN [12]. The masses in Table 1 have been obtained on multiplying BOK's values for the total mass of dust by 100, to allow for the presence of gaseous hydrogen. This is consistent with the results obtained by LILLEY [13], who found a good correlation between the 21-cm radiation and the photographic obscuration from large cloud complexes. Since the true ratio of hydrogen to dust is not definitely known, the resulting values in Table 1 are only estimates. This is particularly true of the globules, for which the mass even of the dust is based on very limited information. In the case of small globules, no stars are seen shining through, and we can only set a lower limit on the total extinction and thus on the total mass. For the large globules no detailed star counts are available, and it is not possible to determine the uncertainty in the total extinction estimated by BOK. The values of the true diameters are also uncertain, but probably less so than the masses.

Examination of the values of $\mathfrak{M}/l$ in the third row indicate that the large cloud could be contracting gravitationally. Such a contraction can take place, however, only if the internal motions are not much greater than the random thermal motions of about 1 km/sec. The velocity dispersion in a small high-velocity interstellar cloud is apparently more nearly 5 km/sec, according to SPITZER and SKUMANICH [14], but it is entirely possible that in a large cloud, moving more slowly, the internal velocity dispersion may be less than 1 km/sec. If the velocity dispersion is actually this low, then $\mathfrak{M}/l$ is sufficiently greater than the critical value so that subregions of a large cloud, with low internal velocity dispersion, might start to contract. Moreover, as the turbulence decays, gravitational contraction will presumably begin. Altogether it is entirely reasonable to assume that a typical large cloud ultimately becomes the birthplace of many galactic clusters and associations.

How such a cloud forms in the first place is in itself an interesting problem. The concentration of dust grains, under the action of radiation pressure, may play an important role (SPITZER [15]). Also, temperature differences between H I and H II regions may have a large effect.

For an intermediate cloud, $\mathfrak{M}/l$ is about equal to its critical value, and it is uncertain whether or not this cloud is contracting gravitationally. On the other hand the density is so great that one would expect the cloud to expand if its kinetic temperature were as great as 100° K; it has been shown elsewhere (SPITZER [16]) that pressure equilibrium is likely to be maintained in the interstellar medium, when gravitational forces are unimportant. Both these difficulties may be resolved if we assume that the temperature is substantially less than the 100° observed in H I regions generally (VAN DE HULST, MULLER, and OORT [17]) and closer to the theoretical values computed by SPITZER and SAVEDOFF [18]. At a temperature between 20° and 40° an intermediate cloud would clearly be capable of gravitational contraction, if internal motions were not excessive. One may surmise that structures of about the size of the Coalsack condense from a typical large cloud. The internal temperature falls as the density and the rate of radiation both increase, and intermediate clouds condense to form a number of galactic clusters.

The role played by the globules in this evolutionary picture is most obscure and puzzling. If the mass estimate for a large globule is assumed correct, such an object cannot be contracting gravitationally unless its temperature is less than 5° K. There is no reason to expect so low a temperature in a dense cloud if, as is assumed in the mass estimate, the optical thickness of the cloud is only about 1.5 mag. The gas should not cool appreciably below the equilibrium temperature of the grains, which VAN DE HULST [19] estimates at about 20°. A more reasonable interpretation of a large globule is that the total mass of this object is at least 100 $\mathfrak{M}_\odot$, and that the system is contracting to form a small cluster. Measures of colours and spectral types for stars seen in these small dark regions would indicate whether the mass of dust can be as small as assumed. A statistical analysis of the number of such globules observed might also give helpful information.

Yet another interpretation of the large globules is that the ratio of gas to dust is much less than assumed, and that in such objects the concentration of grains has occurred to an extreme degree. If the total extinction through such a globule is no greater than 1.5 mag, and if the globule is in approximate pressure equilibrium with the surrounding gas, we may be forced to this explanation.

The interpretation of a small globule offers essentially the same problems as a large globule, and need not be discussed in detail.

Thus we see that only the large cloud and the intermediate cloud can be identified with a reasonable probability as birthplaces of star groups. If all stars originate in clusters or associations, we need look no further for structures to form single stars. If an appreciable fraction of field stars are formed singly, or in small groups, then some other mechanism may be needed. Possibly compression of the interstellar gas by some transient effect — the explosion of a supernova, as suggested by ÖPIK [20], or the expansion of the H II region around a young early-type star, as suggested by OORT [21] — may lead to gravitational instability of the compressed layer, and to formation of single or multiple stars. However, a discussion by SAVEDOFF [22] of the expanding Orion region suggests that at the compression likely to be reached the condensing masses would still be very much greater than the solar mass, and it is not clear that separate stars can be formed in this way. Such a mechanism may provide an alternate means for the formation of clusters and associations.

Once a cloud has started to contract, the physical processes governing the subsequent evolution become rather complicated. While a detailed analysis is beyond the scope of the present paper, it may be of interest to survey some of the outstanding problems. The fragmentation of a large mass into smaller masses and ultimately into stars may well take place by a process similar to that analyzed by HOYLE in the previous paper in this series. The higher abundance of heavy elements and the presence of grains will certainly modify the process from that which occurred when type II stars were formed. Two important categories of problems are those associated with the magnetic field and the angular momentum, either of which separately would certainly hinder the formation of separate stars. It has been shown (MESTEL and SPITZER [23]) that the magnetic field can actually escape at least partially from a contracting cloud when the ratio of ions to neutral atoms is very small (less than 10^{-6}); but it is still not clear whether the turbulent processes discussed by VON WEIZSÄCKER [24] and others are adequate to diminish the angular momentum sufficiently. Possibly the residual magnetic field may be helpful in this respect.

In conclusion, one may infer that the physical properties of the known interstellar clouds seem to be appropriate to make them birthplaces for large groups of stars. While the detailed physical processes followed in the evolution from cloud to star are still quite uncertain, theory indicates no insuperable difficulty to the course of such evolution.

REFERENCES

[1] M. SCHWARZSCHILD, *Evolution and Structure of the Stars* (Princeton U. Press), in press, 1958.

[2] L. BIERMANN, *Gas Dynamics of Cosmic Clouds*, I. A. U. Symposium Series, Symposium No. 2, North Holland Publ. Co., Amsterdam, Chapt. 39, 1955.

[3] A. DEUTSCH, Ap. J., *123*, 210, 1956.

[4] H. C. VAN DE HULST, *The Sun*, edited by G. P. KUIPER (Univ. of Chicago Press), Chapt. 5, Sect. 20.2. 1953.

[5] L. BIERMANN, Zs. f. Ap., *25*, 161, 1948.

[6] M. SCHWARZSCHILD, Ap. J., *107*, 1, 1948.

[7] A. BLAAUW, B. A. N., *11*, 459, No. 436, 1952.

[8] L. SPITZER, Ap. J., *94*, 232, 1941.

[9] L. SPITZER and J. TUKEY, Ap. J., *114*, 187, 1951.

[10] S. CHANDRASEKHAR and E. FERMI, Ap. J., *118*, 113, 1958.

[11] B. J. BOK, *Centennial Symposia*. Harvard Obs. Monograph No. 7, p. 58, 1946.

[12] J. L. GREENSTEIN, Harvard Ann., *105*, 359, 1937.

[13] A. E. LILLEY, Ap. J., *121*, 559, 1955.

[14] L. SPITZER and A. SKUMANICH, Ap. J., *116*, 452, 1952.

[15] L. SPITZER, *Centennial Symposia*, Harvard Obs. Monograph, No. 7, p. 87, 1946.

[16] — Ap. J., *120*, 1, 1954.

[17] H. C. VAN DE HULST, C. A. MULLER and J. H. OORT, B. A. N., *12*, 117, No. 452, 1954.

[18] L. SPITZER and M. SAVEDOFF, Ap. J., *111*, 593, 1950.

[19] H. C. VAN DE HULST, Rech. Astr. de l'Obs. d'Utrecht, *11*, Part. 2, Section 4, 1949.

[20] E. J. ÖPIK, Irish Astr. J., *2*, 219, 1953.

[21] J. H. OORT, B. A. N., *12*, 177, No. 455, 1954.

[22] M. SAVEDOFF, Ap. J., *124*, 533, 1956.

[23] L. MESTEL and L. SPITZER, M. N., *116*, 503, 1956.

[24] C. F. VON WEIZSÄCKER, Zs. f. Ap., *24*, 181, 1947.

DISCUSSION

CHAIRMAN: O. HECKMANN

O'CONNELL

Have you discounted the spectroscopic observations of eclipsing binaries in considering mass ejection?

SPITZER

I was discussing giants rather than early types. The most persuasive examples of mass ejection are stars with visible shells.

It is uncertain whether the mass ejected from the binaries really leaves the system for good, but I would not discount the possibilty that they do contribute to mass ejection.

OORT

There is little observational evidence on the concentration of grains. It is strange that the centre of Orion, which was originally a large cloud concentration, has a normal spectrum with no indication of concentration of heavy elements.

SPITZER

The explanation I gave does not require an abnormal abundance of heavy elements in the clouds, but rather fewer grains between the clouds. The rate of grain production and concentration cannot exceed the rate of creation of heavy elements.

OORT

L. WOLTJER in Leiden has recently made an investigation that may be relevant to the problem of the transformation of elements in supernovae. From spectra of the Crab nebula taken by MAYALL he has estimated relative abundances of H, He, N, O, Ne and S in the filamentary shell. The accuracy of such abundance estimates from emission lines is low, mainly because of lack of sufficient information on radiative ionization cross-sections. The available evidence indicates that helium is overabundant relative to hydrogen by a factor of between two and three. The abundance of the other elements seems to be about normal compared to hydrogen and helium.

SPITZER

This is a very important result.

OORT

The visible shell contains only one-tenth of a solar mass, so there may be heavy elements in the unobserved inner parts. Yet the observation of the almost normal abundances in the shell seems to be slightly disquieting.

BAADE

Perhaps supernovae of type II are the source of the heavy elements.

SPITZER

Does the spectrum of the Cassiopeia cloud support this?

BAADE

Its spectrum is very peculiar because of the high excitation.

OORT

Supernovae of type I are more violent than supernovae of type II, so that, if the former are insufficient, supernovae of type II are not likely to be better.

BAADE

The advantage of considering supernovae II in this connection is that they are young objects in the spiral structure. Supernovae I are old stars and with them we should have to wait too long for the formation of the heavy elements.

HOYLE

The evidence for the presence of californium is limited to type I.

OORT

I am not very convinced by the californium decay theory.

THACKERAY

If we accept Eta Carinae as a supernova, different from supernovae I and II, as I think we must, then here is a case where the iron group is prominent, nitrogen is present, but O I, II or III are undetected.

SCHWARZSCHILD

With regard to mixing, can SANDAGE say anything about the relative composition of the neighbouring spiral arms in the Galaxy? Have we good colour-magnitude diagrams for clusters not in our own arm?

NASSAU

h and χ Persei, in the next arm beyond the sun away from the galactic centre.

BAADE

There is also M 11, which is in the first arm closer to the galactic centre.

SANDAGE

But these clusters are so obscured that it is difficult to distinguish reddening from ultraviolet excess. There is a differential reddening across *h* and χ Persei. Correction for the reddening is made star by star on the assumption that tbe unobscured colour of the star is normal.

SCHWARZSCHILD

Your discussion gives mass ejection a potentially larger role than has previously been considered. If every star in the central bulge ejects half its mass during its life and 20% of them die in 5×10^9 years, would that be enough to explain the clouds near the nucleus with velocities of 50 km/second?

OORT

The available mass density would be high enough, but the ejected matter would not confine itself to the disk.

STRÖMGREN

Can SPITZER say what the time scale would be for mixing from the centre of our Galaxy to the solar region through the mechanism he considered, i.e. collision between clouds.

SPITZER

It is a random walk problem; mixing by interstellar clouds moving 100 pc every 10^7 years would not be effective much beyond 2000 pc in 5×10^9 years.

MORGAN

On SCHWARZSCHILD's question it should be noticed that O associations in spiral arms would be good subjects for investigation. For NGC 6231, HOUCK is publishing results of three colour photometry. There are two associations in the Perseus arm in longitudes 103° to 105°, and a new association at around 115°, at an estimated distance of 4000 pc. The earliest type stars are of types agreeing to one-tenth of a class. In no case is the absorption too great for accurate observation.

STRÖMGREN

Are the main-sequence B stars in the association MORGAN mentioned bright enough to allow use of high dispersion for quantitative chemical analysis?

MORGAN

You would need the 200-inch telescope.

HOYLE

How much would the star cloud condense before breaking up into stars?

SPITZER

Considerable contraction of the star cloud, before fragmentation, would be consistent with your own picture of an increase in density occurring before the next stage.

HERBIG

Is there any real evidence for the association of globules with newly born stars? They show no association with T Tauri stars. Moreover, in many regions where star formation appears to be most active, e.g. the Orion nebula, there are few globules. What evidence is there that they have anything to do with star formation?

SPITZER

The globules must be fairly dense objects, and if they are held together by gravity they may form stars. It is not clear how else they could be held together.

HERBIG

OORT suggested that tendrils of dark matter, such as those in NGC 2244, might mark places in which stars were likely to be formed, but a search for T Tauri stars there has produced negative results.

SPITZER

This result seems very important.

FOWLER

Would your amount of mixing rule out the idea that the solar system obtained all its heavy elements from one supernova?

SPITZER

No.

OORT

HERBIG's results might be explained if in associations stars were formed only of larger mass and brightness, while T Tauri stars were formed in quieter regions.

HERBIG

There are plenty of T Tauri stars in Orion, and some in NGC 2244.

BAADE

In IC 5146 blue plates show only a bright O-type star, but infrared plates show that it is the centre of a faint cluster of T Tauri stars.

OORT

I should like to withdraw my last remark.

O'CONNELL

Are the results on IC 5146 published?

BAADE

No. They will appear in a paper by WALKER.

SCHWARZSCHILD

If the sun obtained its metal content from a single event we should expect much bigger fluctuations in metal content from star to star.

FOWLER

We must clearly distinguish between the formation processes for light elements (C-Ca), the iron group (V-Ni), and the heavy elements ($A > 70$). In a single supernova of type I the light elements and the iron group may or may not be changed radically; on the other hand, current ideas of element formation suggest that the heavy element abundance will be greatly increased (by 10^3). On the other hand, the more numerous type II supernovae may produce the iron group. The observed uniformity is not inexplicable on the basis of a single type I supernova plus numerous type II supernovae.

SALPETER

The evidence of uniform chemical composition is not very good for the heavier elements.

SCHWARZSCHILD

The presence of the iron has to be explained.

FOWLER

This is the result of an equilibrium process.

SANDAGE

For the past several days we have been assuming that a *UV* excess in the *UBV* photometry indicates a low metal abundance. This seems to be such an important point in the development of our arguments that I should like to ask if it is absolutely certain that an ultra-violet excess requires low metal abundance. Could an excess be explained for example, by lower electron pressure in an extended evolving star compared with a main sequence star of the same *B-V*? Could the excess in subdwarfs be an absolute magnitude effect? CHALONGE's measurements of the Balmer jump differences between normal main sequence stars and subdwarfs suggest an absolute magnitude effect.

SCHWARZSCHILD

It seems most likely that an ultra-violet excess does indicate low metal abundance.

THE VERTEX DEVIATION OF THE VELOCITY ELLIPSOID AND THE EVOLUTION OF TYPE I STARS IN OUR GALAXY

BERTIL LINDBLAD
Stockholm Observatory

We shall begin by considering the observed velocity ellipsoid in our surroundings. There is a vertex deviation from the direction towards the centre, which seems to be most clearly defined for stars near the galactic plane. It has often been looked upon as a purely accidental disturbance of a regular velocity ellipsoid, which under dynamical equilibrium in an arbitrary field of central force should have its line of vertices in the galactic plane directed towards the centre. It is possible to show, however, that under the actual conditions prevailing the vertex deviation may be a stationary phenomenon, which may show us something concerning the past history of the stars of population I in our surroundings.

In the discussion we shall introduce what I have called the dispersion orbits, i.e. the orbits along which an association of stars tends to disperse in the regular central field. The properties of these orbits are as follows. Let $\varkappa$ be the frequency of oscillation in the radial direction for objects moving in orbits which differ little from a circular orbit. We have

$$\varkappa = 2\sqrt{\omega(\omega - A)} \ .$$

Let us plot $\varkappa$ as a function of ω in the system. In a certain region, about a certain circle of radius R_o we let the mean of the derivative $\frac{d\varkappa}{d\omega}$ be equal to n, thus

$$\frac{\overline{d\varkappa}}{d\omega} = n \ .$$

Introduce a coordinate system with angular speed

$$\omega' = \omega - \frac{1}{n} \varkappa \ .$$

In this coordinate system the expression for $\xi = R\text{-}R_o$ becomes to the first order

$$\xi = c_1 + c \cos n (\theta' - \theta'_0) \ .$$

where θ' is the angular coordinate, which is given by

$$\theta' - \theta'_0 = \frac{\varkappa}{n}(t - t_o) - \frac{c}{R_o}\sqrt{\frac{\omega}{\omega - A}} \sin \varkappa(t - t_o) \ .$$

Here we may set

$$\varkappa = \varkappa_o - n \frac{2A}{R_o} c_1 \ .$$

Orbits which differ slightly as to the parameters c, c_1, and θ'_0 will stay close together, but there will be differential motion in θ' depending on c_1.

In the general frequency function in the plane motion,

$$F(c, c_1, \theta'_0, t_0) \ ,$$

the parameter t_o will tend to become mixed out, especially if n is an integral number. In this case, moreover, the orbit will be closed, and θ'_0 may therefore be defined in a univocal way.

We may get an idea about the function $\varkappa(\omega)$ from the determination of ω as function of R made by the astronomers in Leiden from the observation of the 21-cm line. We have in our neighbourhood nearly $n = 2$.

The peculiar velocities u, v in radial and tangential direction relative to the local circular motion may be written

$$\left\{\begin{aligned} u &= -c\varkappa \sin n\,(\theta' - \theta'_0) \\ v &= 2cB\cos n\,(\theta' - \theta'_0) \end{aligned}\right.$$

from which for $n = 2$

$$\left\{\begin{aligned} c\sin 2\theta'_0 &= \frac{u}{\varkappa}\cos 2\theta' + \frac{v}{2B}\sin 2\theta' \\ c\cos 2\theta'_0 &= -\frac{u}{\varkappa}\sin 2\theta' + \frac{v}{2B}\cos 2\theta' \end{aligned}\right.$$

The parameters c and c_1 are given by

$$c^2 = \frac{u^2}{\varkappa^2} + \frac{v^2}{4B^2}\ , \quad c_1 = \xi - \frac{v}{2B}\ .$$

Let us assume that the frequency function

$$F(c_1\, c_1,\, \theta_0) = f(Q)$$

where Q is a function of second order in the velocities. The most general expression for Q may be written

$$\begin{aligned} Q = h^2c^2 + k_1c_1 + k_2c_1{}^2 + l_1\left[\frac{u}{\varkappa}\cos 2(\theta' + \psi_1) + \frac{v}{2B}\sin 2(\theta' + \psi_1)\right] + \\ + l_2\left[\left(\frac{u^2}{\varkappa^2} - \frac{v^2}{4B^2}\right)\cos 4(\theta' + \psi_2) + \frac{uv}{B\varkappa}\sin 4(\theta' + \psi_2)\right] + \\ + l_3\left(\xi - \frac{v}{2B}\right)\left[\frac{u}{\varkappa}\cos 2(\theta' + \psi_3) + \frac{v}{2B}\sin 2(\theta' + \psi_3)\Big)\right]\ . \end{aligned}$$

In order that we shall have under all circumstances symmetry of rotation in the density ρ, which is obtained by integrating over the velocities u, v, we should have

$$l_1 = l_3 = 0\ ,$$

and we assume also for simplicity

$$k_1 = k_2 = 0\ .$$

We have then

$$Q = L u^2 + 2 M u v + N v^2 \ ,$$

where

$$\left\{\begin{aligned} L &= \frac{1}{\chi^2}\left[h^2 + l_2 \cos 4(\theta' + \psi_2)\right] \\ 2M &= \frac{1}{B\chi}\, l_2 \sin 4(\theta' + \psi_2) \\ N &= \frac{1}{4B}\left[h^2 - l_2 \cos 4(\theta' + \psi_2)\right] . \end{aligned}\right.$$

It may now be shown that the three parameters h^2, l_2, ψ_2 are defined by the half-axes of the velocity ellipsoid and the vertex deviation, thus by

$$\alpha, \ \beta, \ \chi .$$

We have, among others, the relation

$$\frac{1}{4\alpha^2\beta^2} = LN - M^2 = \frac{1}{4\chi^2 B^2}(h^4 - l_2^2) \ ,$$

which shows that the density ρ is independent of θ' so that the rotational symmetry of ρ is preserved.

For the average velocity ellipsoid we may set

$$\alpha = 20.5 \ , \ \ \beta = 14.9 \ \text{km/sec} \ , \quad \text{and} \quad \chi = -12^\circ \ .$$

This gives, if we choose $\theta' = 0$ at the present position of the Sun,

$$\frac{l_2}{h^2} = 0.37 \ , \quad \psi_2 = -4^\circ.8 \ .$$

It can be shown that

$$Q = h^2 c^2 - l_2 c^2 \cos 4(\theta'_0 + \psi_2)$$

which shows that the apsidal lines have frequency maxima $(\theta'_0)_{\max}$ at

$$(\theta'_0)_{\max} = -\psi_2 + n \cdot 90^\circ = 4^\circ.8 + n \cdot 90^\circ \ .$$

This gives the following picture of the situation of the frequency maxima P in the apsidal lines and of the variation of the sign of χ. In the four points P we have $\chi = 0$. The same occurs at points situated 45° from P, but in P the ratio α/β is smaller than for the intermediate points. The condition that the velocity distribution in P shall have circular symmetry, i.e. that $\alpha = \beta$, is easily seen to lead to the relation

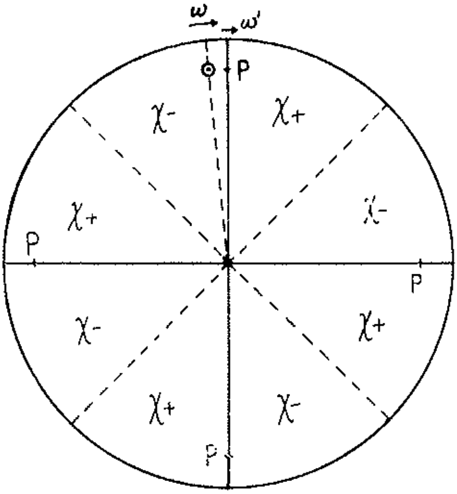

FIG. 1

$$\frac{l_2}{h^2} = \frac{\varkappa^2 - 4B^2}{\varkappa^2 + 4B^2} .$$

For the values of $\varkappa$ and B found in our surroundings this would demand $\frac{l_2}{h^2} = 0.58$, whereas we have found from the velocity ellipsoid near the Sun $\frac{l_2}{h^2} = 0.37$. The points P move with the angular velocity ω', which is about half the velocity ω of circular velocities close to the Sun. The present angular distance between one of the points P and the Sun is equal to ψ_2. We can imagine that around one of the points P there has once existed a vast condensation, perhaps an enormous turbulence element, which may have held together under a certain individual motion of rotation. The stars born out of this cloud can be supposed to have had a relative velocity distribution of circular symmetry in the galactic plane. In the process of dissolution the cloud has obtained differential galactic rotation, but in the first instance the circular symmetry of the relative velocity distribution may have been retained. The mean motion of the cloud follows the angular speed ω, whereas the points P follow the smaller angular velocity ω'. The cloud has been successively drawn out into a zone about a certain R_o, and the distribution will approach to a stationary distribution of the type considered here. The stars of population type I which are responsible for the vertex deviation of the velocity ellipsoid about the Sun may thus have originated in one and the same vast cloud, which by spreading its stars has caused the velocity distribution in our surroundings.

DISCUSSION

CHAIRMAN: O. HECKMANN

OORT

You suppose that stars of the original association were dispersed over the whole orbit.

LINDBLAD

They would be fairly well dispersed after a few revolutions.

OORT

Your original cloud must then have been very large; it could be part of the spiral arm.

BAADE

We observe a similar cloud, namely NGC 206 in the Andromeda nebula.

BLAAUW

Did you imply that G8 giants and A stars were much separated in evolutionary age? Actually the difference can only be a small part of the age of A stars, which is 5×10^8 years. We observe both these types in open clusters.

Lindblad

That is still more convenient for me.

Blaauw

What would the age difference be between the G giant phase and the preceding main sequence phase?

Schwarzschild

10% of their previous life; about 5×10^7 years.

INSTABILITY IN THE EXPANDING UNIVERSE AND ITS ASTRONOMICAL IMPLICATIONS

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University of Louvain

1. *Introduction*

The Universe is formed of nebulae which fill an elliptical space of radius R.

This radius is a solution of Friedmann's equation

$$\left(\frac{dR}{dt}\right)^2 = -1 + \frac{2\mathfrak{M}}{R} + \frac{R^2}{T^2}$$

and depends on the values of the two constants of this equation: $\mathfrak{M} = \frac{4\pi}{3} G\rho R^3$, approximately constant, is the mass of the universe, and T is related to the cosmological constant λ by $1/T^2 = \lambda/3$.

We consider a solution which starts from $R = 0$ with a diminishing velocity until the radius reaches, with a minimum velocity, a value R_E, called the equilibrium radius. Then the velocity increases up to the present value. The constant T is not very different from the inverse of Hubble's Constant, 4×10^9 years; from a geometrical view point, it is the sub-tangent to the curve (t, R).

The equilibrium $R = R_E$ is unstable. It is some aspect of this instability and its cosmological consequences which we propose to examine in this paper.

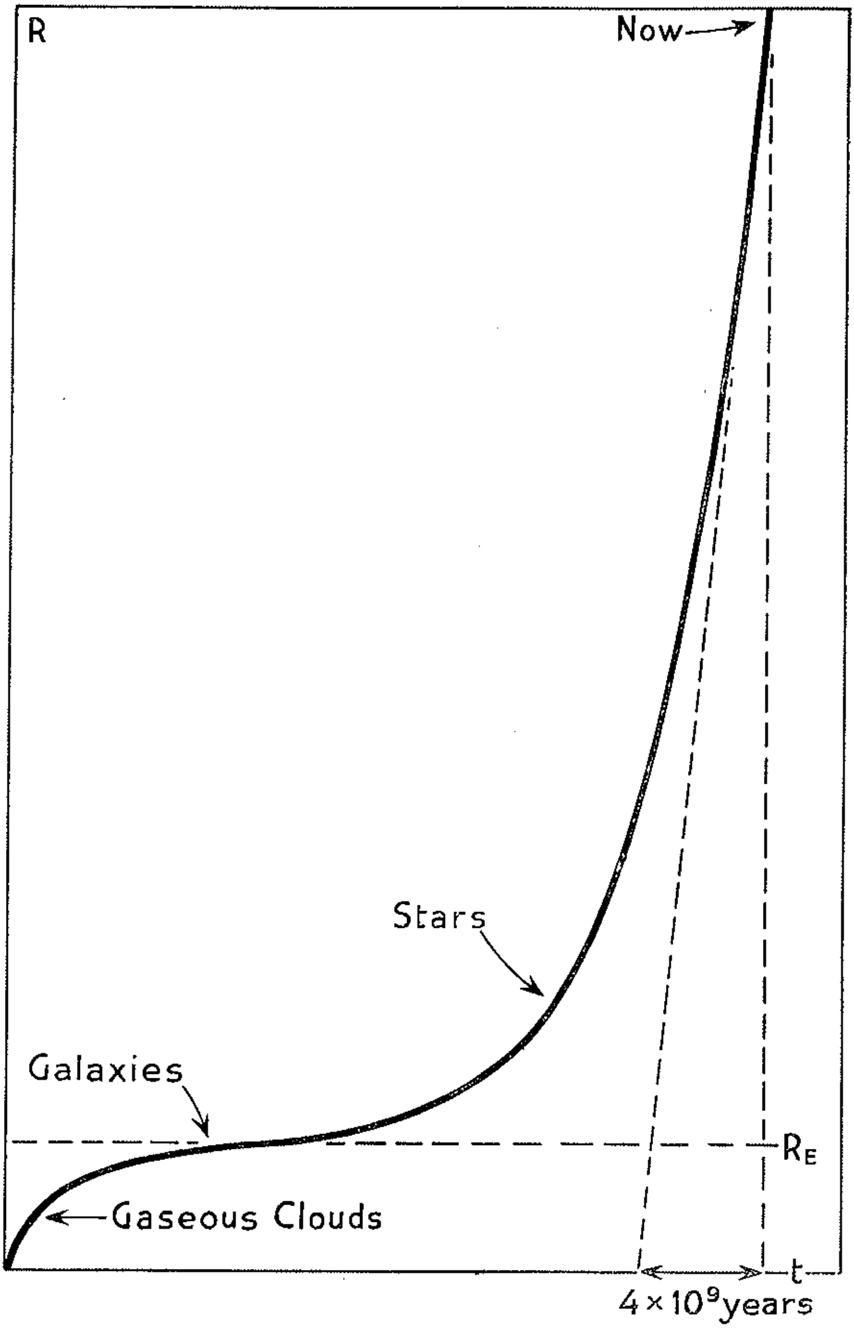

FIG. 1 — Change in Radius of Universe with Time. The actual radius is assumed to be ten times the equilibrium radius R_E. The time scale is given by HUBBLE's constant (subtangent of the curve). The main evolutionary processes are indicated.

2. *Physical Aspects.*

We have first to make clear the physical aspect of the theory, in order to understand the state of the matter when the radius of space reaches the equilibrium value R_E.

It is an obvious feature of the cosmological problem, that it must be considered under all its aspects and that it becomes meaningless when mutilated.

The physical beginning which fits the solution of FRIEDMANN's equation starting from $R = 0$ is provided by the Primaeval Atom Hypothesis.

Here the word "Atom" should be understood in the primitive Greek sense of the word. It is intended to mean absolute simplicity, excluding any multiplicity. The Atom is so simple that nothing can be said about it and no question raised. It provides a beginning which is entirely inaccessible.

It is only when it has split up into a large number of fragments by filling up a space of small, but not strictly zero, radius, that physical notions begin to acquire some meaning.

The first physical question which has to be considered is whether the resulting assembly of particles has to be described as a gas.

If one gives an affirmative answer to this question, one has to face the difficulty of understanding how such a gas, which presumably filled up an expanding space, has to be able, later on, to divide itself into separate nebulae.

To be more precise, we must make clear what has to be considered as characterizing a gas. It is not enough to have an assembly of a large number of particles. In order to be called a gas, such an assembly must have velocities with a distribution that is strongly concentrated around a mean velocity, the velocity of the gas, and distributed around this velocity according to a law not too different from the Maxwellian distribution which is realised in ordinary gases.

On the other hand, a mere assembly of particles with velocities spreading in every direction with speeds of the same order of magnitude could not be considered as a gas. It should be described as an assembly of corpuscular rays, as corpuscular radiation.

It is true that, by collisions, such radiation would finally reach a state of statistical equilibrium and become a gas. But in the extreme condition of expansion, starting (theoretically) with infinite velocity, it is not likely that such a statistical equilibrium would have had time to establish itself.

From that point of view, the problem which cosmology has to face is to understand how gas would finally arise from the primaeval radiation and then organise itself into nebulae and secondly to understand what would arise from the part of this primaeval radiation which would have escaped condensation into gases.

The second point gives an interpretation of the observed cosmic radiation, which may, of course, be only a partial one. In discussing this aspect of the theory, one must take into account for the rays the reduction of intensity due to the expansion. This phenomenon, quite analogous to the red shift of light, reduces the intensity of the rays in proportion to $1/R$. The total intensity of the cosmic rays is about 1/10,000 of the total energy of matter condensed in the stars. This means that cosmic rays and matter would have been of the same order of magnitude when the radius was only one ten-thousandth of its present value.

In the second place, one might have to take into account some absorption of the rays by the intergalactic gases, if any, and surely by the gas when they go through the galaxy. If one take as an estimate of the density of the intergalactic gases the density 10^{-30} of matter observed as stars, one finds an absorption which is quite negligible.

Nevertheless, it might provide qualitative changes in the composition of the rays. It may be that a part of the hydrogen and helium which is observed in the cosmic radiation is due to secondary phenomena owing to interaction with intergalactic gas.

In any case, it is significant that, even if such correction is not made, the observed cosmic radiation contains less hydrogen and helium in comparison with heavy elements than is the case for stellar matter.

One may think that hydrogen was not present, at least in such abundance, in the primaeval radiation of which cosmic radiation provides a sample, and to inquire what is the origin of this hydrogen [1] [2].

Coming to the question of the formation of gas from the primaeval radiation, one might expect that the radiation was formed of charged particles (as in the cosmic rays). Then these rays would act as electric currents and accordingly produce magnetic fields.

It might occur that, occasioually, such magnetic fields might have some stability and form magnetic regions moving with some definite velocity without too large change of the field.

Incoming particles which reach such regions with moderate relative velocities would not be able to escape. They would be kept together long enough for elastic collisions to be able to realize some approach to a Maxwellian distribution of velocities.

In this way, it seems possible to understand the formation of local gaseous clouds from the primaeval radiation.

When such a region of some extent has been formed it would easily increase by capture of the incoming radiation, even if this radiation reaches it, as the cosmic rays at the top of the atmosphere, with large velocities.

It is conceivable that, in this process of capture, the large kinetic energy of the incoming rays would be materalised, not only into electrons and mesons, but even into hydrogen and helium nuclei [1] [2].

One could understand, in this way, that the matter of the gaseous clouds, that will eventually form the stars, should be richer in hydrogen than the primaeval radiation, and therefore than the observed cosmic rays.

When comparing the intensity of the rays to the density of matter, one would have to take into account the metallic part of the stars, which is of the order of only one percent of the whole.

The relative velocity of the gaseous clouds must therefore be very great even if one takes into account that it is reduced as a consequence of the expansion. It is a well-known fact, so cleverly utilised by MILNE, that objects moving with abnormal velocities in the expanding space have a tendency to sort themselves and reach regions where their velocities are not so abnormal. This kinematic effect reduces the peculiar velocities in the proportion of $1/R$.

But, even so, one must expect that, when the radius of space reaches the equilibrium value R, the gaseous clouds will have large relative velocities.

3. *The Formation of Nebulae*

We must now consider the effect of the instability of the equilibrium on the assembly of rapid gaseous clouds.

In order to do that, we may restrict ourselves to the Newtonian approximation which is known to be valid for regions not too large in which Euclidean geometry and Newtonian mechanics are good approximations.

The only essential modification which has to be introduced in classical mechanics is that POISSON's equation must be modified by the introduction of a constant ρ_0 related to the cosmical constant λ or T.

One must write

$$\Delta V = 4 \pi G (\rho - \rho_0)$$

and the equilibrium consists in the fact that the real density ρ is nearly equal to the supplementary constant ρ_0, the so called cosmical density.

Detailed computations are not necessary to understand what will be the effect of such dynamical circumstances on our assembly of gaseous clouds.

There will occur ocasionally permanent attractive regions moving with some velocity. Every gaseous cloud reaching one of theses regions with small relative velocity will not be able to escape and would contribute to increase the incipient condensation.

The condensation will sort the clouds according to their velocities and the instability of the general field will result in the formation of an assembly of clouds which can be considered as the origin of the present nebulae.

4. *Initial Distribution*

It is easy to compute a model [3] for such an assembly of gaseous clouds and this may provide a natural starting point for a discussion of the further evolution of the system.

One assumes spherical symmetry and a static distribution which fills up uniformly the phase-space, that is the product of ordinary space by the velocity space. This uniform distribution is abruptly limited by the representative points of particles which are just able to escape from the condensation.

Some simple condition may be set up which is sufficient (but not necessary) to prevent such an escape.

Using this condition, one can compute a first approximation of the model. This approximation can be refined by perturbation if we wish to take account of the clouds which do not satisfy the condition introduced above and are otherwise prevented from escaping.

One finds a model in which particles with great angular momentum are in great number. It is well known that this is the condition which would lead to the occurrence of a disc in the nebula. These particles with great angular momentum are not able to take part in some primary process of collapse towards the center of the system and it is left to them to coalesce by some kind of z collisions.

5. *Radial Models*

It is also possible to work out simplified models [4] which may illustrate the main process of central collapse.

The simplest conceivable model is formed of gaseous clouds which move along the radii, and such that each cloud oscillates with the same amplitude to and fro along a radius. Phases have to be adjusted in order to make the system stationary.

There is a singularity at the center which provides a kind of dynamical nucleus. There is also a rather unsatisfactory singularity at the edge where the clouds have instantaneous rest and infinite congestion. This last singularity does not occur in another model where the velocity distribution at each point extends uniformly between two limits. In that case the velocity distribution is a line extending from one to the other of two opposite radial velocities, the one towards, the other away from the center.

In these radial models, the cosmological density has been neglected.

Both models provide distributions very similar to the distribution found by HUBBLE for the elliptical nebulae.

This result has been independently confirmed by the investigation of BELZER, GAMOW and KELLER [5]. Their treatment of the question is in some way more realistic than ours. They start from the observed distribution. Our model is over-simplified, but it is perfectly clear from the mathematical standpoint.

6. *Clusters of Nebulae*

Besides the effect of selection due to the instability that we have described already and which sorts the clouds with the required velocity in order to form an assembly of gaseous clouds from which the nebulae might have evolved, there are also other effects occuring on a larger scale which help us to understand the clustering tendency and generally the departures from homogenity in the distribution of the nebulae.

In order to study these effects, it is convenient to consider, in place of the slowly expanding universe passing through equilibrium, a universe staying in equilibrium like EINSTEIN's original universe [6].

Nevertheless, we have to take into account the fact that matter is endowed with large internal velocities.

We may suppose that the distribution of the velocities is such that the phase-space distribution would be uniform. According to LIOUVILLE's theorem, this situation will remain permanently without any interaction between the moving material (identified with the gaseous clouds, and later on with the nebulae which have evolved from them).

The problem will be to compute the motion of maximum velocity in every direction under the action of the gravitational field. This gravitational field is due to a density measured by the volume obtained by plotting in each direction the corresponding maximum velocity. The Newtonian approximation can still be applied with due allowance to the cosmical density ρ_0.

When spherical symmetry is accepted as a simplification, the angular momentum k will remain constant for each moving particle and the distribution shall be defined by the radial component of the velocity in both directions as a function of the distance r from the center, the time t, and the angular momentum k.

Partial differential equations, involving an integral evaluating the velocity-volume, can then be written up.

In the statical case, precise solutions can be obtained. They depend on two functions, the first of r the other of k; both are connected by a rather simple integral equation.

The most interesting case is when the function of k vanishes. In that case the distribution of velocities at each point is isotropic.

It is found that statical concentrations do occur, with central velocity up to about 2.3 times the velocity for uniformity.

They are kinds of stationary waves where the congestion remains permanent while the individual components pass through.

The size of the condensation is related to the velocity considered. In fact it is convenient to measure the radius r using as unit the length travelled during the cosmic time $T/\sqrt{3}$ with the maximum velocity postulated for the case of uniform distribution.

When one takes velocities of the order of the standard deviation in large clusters, say 600 km/sec, one finds radii of 4 to 5 million light years, corresponding to the theoretical values of the radius from 1.8 to 1.5.

These are comparable (though rather too large) to the size of the clusters of nebulae.

This raises the question whether the clusters of nebulae are not evolved from such standing waves formed during equilibrium.

It would be very important to be able to compute the evolution of such condensations during the general expansion. Unfortunately the equations to be solved are somewhat complicated. It would be necessary to introduce convenient boundary conditions [8]. Some progress has been obtained for distributions infinitely near Einstein equilibrium by finding solutions separating the time in an exponential factor $e^{\theta t}$ which can be described by Taylor developments in r and k [7].

It has been found that the distribution compatible with the boundary conditions strongly departs from isotropy and that some simplified assumptions which had been introduced under the name of quasi-isotropy are not admissible.

7. *General Clustering*

Nevertheless some results found under this condition seem to have at least a qualitative value in the general case.

It has been shown that the ϑ factor in $e^{\vartheta t}$ increases with the size of the condensation. It is of course equal to 0 for the static case and goes up by definition to 1 for the uniform expansion of the universe.

This gives some understanding of the fact that instability in a universe in equilibrium (approximate or exact), which could break down just as well towards contraction as towards expansion, does not contract in some part of space and expand in another.

Some clue to this arises in the present investigation, which is of course restricted to spherical symmetry. The distribution can be analysed in elementary solutions with time exponential factors. The greater this factor, the greater is the size of the fluctuation; thus, it is the larger one which must finally prevail even if locally the conditions had been in the reverse direction.

Thus a universe which will begin to collapse in the central region, while at a larger scale it expands, will eventually expand as a whole.

Nevertheless it must be expected that some trace of the initial collapsing region will remain in the final distribution and that would be observed as a cluster of nebulae.

Of course these conclusions depend essentially on the postulated large velocities of the constituent of the universe.

It implies that the clusters of nebulae would be of the nature of more or less stationary waves and that constituent nebulae would escape from the clusters and be replaced by field nebulae. The density would have to be proportional to the cube of the peculiar velocity.

Another consequence is that one would have to expect large scale fluctuations in the distribution of the densities and of the velocities of the nebulae.

In fact the larger a fluctuation due to the instability of the equilibrium through which the universe is supposed to have passed, the more permanent it is.

This may be important in the interpretation of astronomical observations which are generally discussed under the hypothesis of a strict uniformity in the distribution of densities and velocities. Such a perfect homogeneity does not seem very probable.

It may be emphasized that the present discussion depends entirely on the sign and value assumed for the cosmical constant; this itself depends on the essential correctness of the estimates of the mass of the nebulae.

This may be questioned, on the theoretical side as well as on the astronomical side.

Conversely, the great possibilities afforded by these considerations which are based on the instability and essentially depend on the cosmological term of Einstein's equations, may induce cosmologists not to reject it too lightly, even if its theoretical significance remains somewhat of an enigma.

REFERENCES

[1] G. Lemaître, *L'Enigme de l'Hydrogène*. Bulletin de la Classe des Sciences de l'Académie Royale de Belgique, *35*, 1158-1163, 1949.

[2] — *Cosmological Applications of Relativity*. Reviews of Modern Physics, *21*, 351-366, 1949.

[3] — *Un modèle de Nébuleuses*. Annales de la Société Scientifique de Bruxelles, *60*, 103-114, 1946.

[4] G. Lemaître et R. van der Borght, *Modèles de Nébuleuses à vitesses radiales*. Bulletin de la Classe des Sciences de l'Académie Royale de Belgique, *31*, 955-965, 1948.

[5] J. Belzer, G. Gamow and G. Keller, *On the stellar dynamics of spherical galaxies*. Astrophysical Journal, *113*, 166-180, 1951.

[6] G. Lemaître, *Modèles mécaniques d'Amas de Nébuleuses*. Bulletin de la Classe des Sciences de l'Académie Royale de Belgique, *34*, 551-565, 1948.

[7] — *Id.*, *37*, 291-306, 1951.

[8] — *The Clusters of Nebulae in the Expanding Universe*. South African Journal of Science, *449*, 80-86, 1952.

DISCUSSION

CHAIRMAN: O. HECKMANN

HOYLE

Is it at all possible that the clusters of galaxies should be gravitationally bound units?

LEMAÎTRE

It depends on the fact that their density is of the order of the equilibrium density 10^{-27}. The cosmological term balances the gravitational term.

SPITZER

What is the mean density of the Coma cluster?

OORT

If the mass to light ratio is about 100 the density must be nearly equal to that corresponding to the virial theorem.

SPITZER

Can LEMAÎTRE account then for the observed presence of neutral hydrogen in the Coma cluster with a mass about equal to the mass of the galaxies?

LEMAÎTRE

There is no theoretical objection to this.

SALPETER

Have you considered in your early stages the creation of anti-matter?

LEMAÎTRE

If there is any sense in a beginning of multiplicity, the sign must be decided in the first event. The theory is not reconcilable with a large region of anti-mass.

HOYLE

Is there any significance in the fact that LEMAÎTRE indicates on his diagram stars older than the Hubble constant?

LEMAÎTRE

The extent of the graph is quite indeterminate. The answer to questions of this kind must come from observations.

HECKMANN

Those of us who believe in the usefulness of the idea of an expanding universe must be interested in every attempt of this kind to draw a model in which expansion on the one side and the formation of stars and galaxies on the other side are essentially connected.

VIII.

RESUME DES DISCUSSIONS ET CONCLUSIONS

SUMMARY - FROM A PHYSICAL POINT OF VIEW

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Of the fivefold classification arrived at by the conference (cf. p. 533) I would like to make the following grouping:

(*a*) Extreme Type I and Older Population I,

(*b*) Disk Population,

(*c*) Halo Population II and Intermediate Population II.

This grouping is made for convenience in dividing up the various problems discussed by the conference. I will start with (*a*).

The central characteristic of the Extreme Type I is the close association of these stars with gas and dust lying near the plane of the Galaxy. A striking confirmation of this association was reported by Baade and Oort. Baade reported that star formation in M 31 occurs with maximum frequency at an angular distance of 50′ from the center of the nebula, while Oort gave the maximum density of interstellar atomic hydrogen at a distance of about 1° from the center.

To this may be added the close coincidence of the spiral arms within, say, 3 kpc of the Sun, as traced by neutral hydrogen, on the one hand, and by early type stars on the other. It is an obvious problem to try to extend this comparison to the whole Galaxy. Current views suggest that a spatial coincidence between gas and early type stars should exist throughout the Galaxy.

Next, a few words about star formation. It seemed generally agreed that all stars in group (*a*) may well have been formed in expanding associations. Evidence in favor of this view was presented by BLAAUW. Considerations such as those recently given by ROBERTS [1] indicate that the frequency of B-stars is entirely consistent with the present idea. The situation is less certain for the older Population I. Estimates by BLAAUW, and also by HERBIG on the frequency of T Tauri stars, show that the number of stars produced over a period of two or three billion years (assuming that associations have occurred at the present-day rate) is not of a seriously different order of magnitude from the number of stars of the older Population I. The data would not be inconsistent, however, with a somewhat greater rate of occurrence of associations, say by a factor 3.

The kinetic energy of expansion of an association is presumably derived from nuclear energy, from the conversion of hydrogen to helium within the bright stars that are formed within the association. Radiation from these stars presumably produces H II regions that serve as "explosion points", driving outwards the surrounding cooler gases. The stars themselves could scarcely derive appreciable kinetic energy from this process, however, but the removal of the gas from their vicinity reduces the restraining gravitational field acting on the stars; and it may well be that their original kinetic energy is then sufficient to produce an expansion and eventual dispersal of the association. We might also say that, if the original kinetic energy of the stars is not sufficient to produce dispersal, a permanent star cluster is formed. The problem remains to explain why the latter situation apparently occurs only in a minority of cases.

A further important problem concerns the origin of the very rapidly expanding star groups. As remarked by BLAAUW these cases seem to fall into a class different from the ordinary associations. Whether or not the release of nuclear energy is basically responsible for the high speeds, of order 100 km/sec, found in these groups is uncertain. BLAAUW pointed out that such velocities are sufficient to project the stars far out of the plane of the Galaxy. Subsequent ejection of material by these stars might well add gas to the halo. BLAAUW estimated that a mass of $10^8 - 10^9 \odot$ might have been added in this way to the halo during the whole lifetime of the Galaxy. A further remarkable feature of the rapidly expanding groups was the dominance of stars of spectral class earlier than B0.

While on the topic of clusters and association, SANDAGE raised a remarkable problem arising from the work of WALKER on the clusters M 8 and NGC 2264. Judged from the luminosities of the brightest stars near the main sequence, these are both very young clusters, with ages of about 3×10^6 years. Working down from the brightest stars it was expected by WALKER that the main sequence would be populated only down to the luminosity at which the Kelvin-Helmholtz contraction times equalled the ages of the clusters, i.e. about 3×10^6 years. At still lower luminosities, the stars should lie to the right of the main sequence in the H-R diagram, indeed very far to the right for stars with appreciably lower luminosities. Such stars would still be in the phase of gravitational contraction.

These expectations were confirmed, with the notable exception that the faint stars do not lie very much to the right of the main sequence. Apparently dwarf stars are able to dissipate their gravitational energy far more quickly than the simple Kelvin-Helmholtz theory would lead us to suppose.

Two explanations were mentioned during the conference. An obvious possibility is that condensing stars, dwarf stars in particular, lose energy into space by some process (or processes) in addition to ordinary thermal radiation from their surfaces. Indeed we know that this is the case for the T Tauri stars, described by HERBIG. And if we regard the Herbig-Haro objects as representing a stage of stellar condensation, the same is true for these objects. Moreover the rate at which energy is emitted in bright lines is of an order that would be significant in the present problem.

The second possibility, mentioned by SPITZER, is that mass loss plays an important role. Mass loss could speed up the process of stellar condensation in two ways. First, by providing an additional process whereby energy is lost into space, and second by shortening the effective Kelvin-Helmholtz contraction time.

Time is too short for me to discuss these suggestions in greater detail. All I would add is that any satisfactory explanation must fit the remarkable fact that in M 8 and NGC 2264 stars do lie on the main sequence down to exactly the luminosity that is predicted from the ordinary Kelvin-Helmholtz theory taken together with the estimated ages of these clusters.

Still referring to my group (*a*), contributions by SALPETER and SANDAGE gave strong support to the view that there is no very important difference between the stars of galactic clusters and the stars that are formed in expanding associations. It will be recalled that SALPETER adjusted the Van Rhijn luminosity function in such a way as to take account of the frequency of "star deaths" among the bright stars. SANDAGE has found that stars of the clusters M 67, Hyades, Praesepe, Pleiades, and h + χ Persei are in very satisfactory agreement with the resulting Salpeter function. Remembering that the van Rhijn function is derived from the general field of stars in the solar neighborhood, and that these stars have presumably been derived from long expanded associations, we arrive not only at a similarity of stellar content between clusters and associations, but also at a similarity between the long expanded associations that gave rise to the stars of the solar neighborhood and the associations formed in very recent times.

Possibilities for improving the Salpeter function were discussed. In particular, BLAAUW pointed out that the stars of the solar neighborhood contain a high velocity component that may very likely have had a different mode of origin to the others —

as is indicated by the fact that stars at high galactic latitudes do not possess the same luminosity function as the stars of the solar neighborhood. Possibly a better procedure would be to omit the high-velocity component altogether, or alternatively one might use a luminosity function based on all the stars lying in a cylinder normal to the galactic plane.

SALPETER also pointed out that an allowance for the rate of star deaths depends on the evolutionary tracks of the stars as they move away from the main sequence. The precise nature of these tracks is not really well known at the present time, so that an increase of precision is to be expected as more quantitative knowledge comes to hand in the field of stellar evolution. All in all, it was felt that present day procedures may lead to inaccuracies of order 3 in the estimated number of stars. Even so, it is remarkable that so much can be achieved by such straightforward considerations. The implication seems to be that the processes of star formation in the spiral arms of the Galaxy have not changed very much during the last two or three billion years.

Mention of stellar evolution brings me to SCHWARZSCHILD's very clear account of evolutionary tracks in the H-R diagram. Brevity forces me to confine myself to the following points:

1) The main sequence represents the position of stars in the H-R diagram at the time nuclear reactions first come into operation. Difference of initial chemical composition lead to the main sequence being a narrow band, rather than a line. Recent calculations suggest that the band has a width in luminosity of only about 0.25 mag.

2) Stars spend most of their lives near the main sequence.

3) Evolution carries stars to the right of the main sequence. Bright stars (brighter than $M_{pv} = 0.0$) move approximately horizontally to the right. Dwarfs move quite steeply upwards and to the right. This differing behavior leads to a concentration of giants in the region of the diagram defined very

roughly by $0.0 > M_{pv} > -3.0$, $1.2 < C.I. < 1.6$. That is to say, giants in this region are not derived from a more or less unique small segment of the main sequence. Consequently there is no simple mass-luminosity relation for giants. Age criteria can of course be used to separate the giants. For instance, we can be sure that giants found in an old star group must have been derived from the dwarf section of the main sequence, whereas giants found in a young star group must come from a much more luminous segment of the main sequence. These considerations were emphasized by both SCHWARZSCHILD and SANDAGE.

4) The precise form of the evolutionary tracks are influenced by the chemical composition of a star. In particular, it seems that stars move more to the right in the H-R diagram the higher their metal content. Quantitative calculations have demonstrated this property for stars with masses $\approx 1.25\ \odot$. Similar calculations are urgently required for stars of appreciably larger masses.

5) If a star becomes sufficiently distended during the giant phase it is probable that mass loss takes place. The large increase of radius weakens surface gravity, reducing the gravitational potential energy of the surface material, and thereby rendering the material particularly susceptible to ejection from the star.

6) It is probable that the ultimate evolution of a star carries it into the white-dwarf zone of the H-R diagram.

7) Little is known of those portions of the evolutionary tracks of the stars that connect the giants with the white-dwarf zone. Evidence for tracks moving left from the giant region is well known in the case of the stars of the globular clusters, while recent work by JOHNSON and SANDAGE shows that there is similar evidence for the cluster M 67. These stars have masses of order $1.25\ \odot$. No evidence is available that

similar leftward tracks exist in the evolutionary paths of appreciably more massive stars. It is possible that mass loss in the giant phase plays the dominant role in the later phases of the evolution of more massive stars. SCHWARZSCHILD suggested that such stars may move almost discontinuously from the giant region to a region lying below the main sequence, whence they evolve slowly to the white dwarf zone. Subdwarfs lying appreciably below the main sequence may represent this stage of evolution. This view is supported by the presence of subdwarfs in galactic clusters.

8) Little, if anything, is known of the whereabouts in the H-R diagram of the catastrophic stellar states. General opinion, for what it is worth, is that novae and the nuclei of planetaries may lie on a continuation of the leftward tracks of stars with masses $\sim 1.25 \odot$. The location of supernovae is quite unknown, although opinion is that such extreme catastrophic stars lie far to the left in the diagram — such stars are of very small size, that is to say.

9) The position of the different classes of variable stars is well-known in most cases. The considerations of 7) would require the Cepheids to occur at a fairly early evolutionary stage, as fairly massive stars move to the right from the main-sequence towards the giant zone.

After this brief review of the properties of the evolutionary tracks of stars in the H-R diagram I would like to refer once again to several differences between the stars of groups (*a*), (*b*), and (*c*).

In the following table Z represents the fraction by mass in the stars that is not hydrogen or helium (i.e. carbon, nitrogen, oxygen, ...). These Z values and the age values are based on the table given by SCHWARZSCHILD, while the estimates of total mass given in the third column are taken from the contribution by OORT.

Group	*Z*	*Total mass*	*Age*
(*a*)	0.02 to 0.04	$<10^{10}$ ⊙	$<5 \times 10^9$ years
(*b*)	0.01 to 0.02	$\sim 5 \times 10^{10}$ ⊙	$5 - 6 \times 10^9$ years
(*c*)	0.003 to 0.01	$\sim 10^{10}$ ⊙	$6 - 7 \times 10^9$ years

The differing Z values in the different groups provide strong evidence that the higher elements are synthesized in the stars, for it is reasonable to suppose that stars of group (*c*) are older than stars of group (*b*), which in turn are older than stars of group (*a*). The theory of element synthesis in stars was discussed by FOWLER and HOYLE. It is worth a very brief recapitulation of one or two of the main points of these contributions.

The theory is very promising because the changing structures of stars during their evolution provide a sequence of conditions under which many different types of nuclear process can take place. Thus the internal temperature can range from a few million degrees, at which hydrogen becomes converted into helium, to temperatures between 10^9 and 10^{10} degrees when supernova explosions very likely take place. The central density of a star can also change by a factor $\sim 10^6$ during evolution. Moreover timescales range between billions of years, which are the normal lifetimes for stars with masses of order ⊙, down to times of the order of days, minutes, and seconds, which are characteristic of the rise to catastrophic explosion.

From the standpoint of nuclear physics two major points may be mentioned. Through an interplay between experiment and theory it has become clear that helium acts as an energy source in evolving stars. The starting reaction $3He^4 \rightarrow C^{12}$ is followed by further processes in which oxygen, neon, magnesium, silicon, argon, and calcium (to mention the main elements) are produced. Moreover theoretical work on stellar evolution has shown that in the interiors of giants the conditions are right for such reactions to take place.

The second point concerns elements with atomic weight $> \sim 65$. These elements appear to have been produced by the addition of neutrons to lighter elements, probably to elements of the "iron peak", around atomic weight 56. The crucial point of the work described by FOWLER is that two distinct neutron processes have been at work, a slow process of neutron addition probably taking place in giants, and a very rapid process probably taking place in supernovae. It was shown that, as a consequence of the operation of these two processes, the abundances of almost all the isotopes of the heavy elements can be successfully explained in quite remarkable detail.

The question remains as to whether element production in stars is quantitatively adequate to explain the values of Z given in the above table. This question was considered by HOYLE, using present-day rates of occurrence of supernovae and of star deaths in general. The conclusion was that present-day rates seem adequate to explain the Z values of groups (*a*) and (*c*), but seem inadequate to explain the Z value of group (*b*) (on account of the larger total mass of the latter group). The discrepancy for group (*b*) may be as much as a factor 10. Combining this result with the estimated ages of the different star groups leads to the interesting additional conclusion that stellar activity during the early phases in the history of the Galaxy may have been on a very considerably greater scale than it is at the present time. A degree of stellar activity comparable with that now found in the large Magellanic Cloud is indicated.

Mention of the ages of the different groups brings me to the problem of age determinations. The best procedure currently available rests on a comparison of observed color-magnitude diagrams with theoretical evolutionary tracks. At present the theoretical tracks are scarcely accurate enough to give really reliable absolute age determinations. Uncertainties of the order of twenty or even thirty percent will not be removed until more precise theoretical work is available. The ages of the globular clusters come out at 7 ± 2 billion years. It is of interest in this connection that the ratio U^{235}/U^{238} found in the Earth, taken together with the nuclear theory described by FOWLER, indicates an age close to 6.6×10^9 years, for the very heavy terrestrial elements that were built by rapid neutron addition.

Although substantial uncertainties are undoubtedly contained in present-day determinations of absolute age, it has been suggested that a greater confidence can be felt in relative ages. Thus, if we determine the color-magnitude diagrams of a set of clusters, relative ages (it is argued) can be determined from the points at which the evolving sequences break away to the right from the main sequence. Stated as a question, if we order the clusters in terms of the luminosities at their respective break-off points do we thereby obtain the order of the ages of the clusters?

This question was discussed at some length by the conference. It was pointed out by SANDAGE that if we answer the question in the affirmative, then M 67 is older than M 3. Moreover there would seem to exist stars in the solar neighborhood that are older than M 67.

To express a personal view, I am most doubtful whether the question should be answered affirmatively. Of course, if there is a gross difference between the break-off points of two clusters, then the one with the higher break-off point will be the younger. But for small differences, particularly for stars with masses $\sim 1.25\ \odot$, it seems to me that differences of composition may cause inversions of order; i.e. the cluster with the lower break-off point might still be the younger. There is a physical reason for this that is perhaps worth mentioning.

With the rather low value for the carbon-nitrogen cycle rate that is indicated by recent experiments it turns out that the carbon-nitrogen concentration is important in determining how the break away from the main sequence takes place — this remark being for stars with masses $1.25\ \odot$. Before breaking from the main sequence the stars first move some way up the main sequence. The extent of this initial rise, which is of crucial importance in determining age, seems to depend rather importantly on the balance between the carbon-nitrogen cycle and the proton chain. The break away point is not therefore the sole criterion of age, and indeed it seems that an inversion of the break-off points may arise through the initial rise along the main sequence being different in two different clusters. Hence it seems that much more theoretical work remains to be done before we can really be confident of the relative age of "old" clusters such as M 3 and M 67 (where the stellar masses of the evolving stars lie just in region of 1.25 ⊙).

Problems of star formation for group (*a*), and of the ejection of material from stars back into the interstellar medium, were considered by SPITZER. He estimated that the total conversion of gas into stars of initial absolute magnitude brighter than +3.0 during the last 5 billion years amounts to 0.05 $\mathfrak{M}_\odot$ per cubic parsec. Stated somewhat differently, the production of such stars in a cube of side 500 parsecs (which is comparable with the diameter of a spiral arm) amounts to about 10^4 stars in 10^7 years.

To provide for the formation of these stars, clouds must be condensing from the interstellar gas. A comparison of gravitational and thermal energies showed that gravitational forces are strong enough to promote condensation in large clouds, but not in clouds much smaller than the well-known Coal Sack. Indeed it is difficult to see how small globules are able to hold themselves together at all. These considerations related to a gas temperature of order 100° K.

The question of whether chemical compositions are fairly uniform among stars condensing at a given epoch is evidently an important one. It is usually assumed that this is so, implying that the emission from stars of the products of element synthesis has been smoothly mixed through the interstellar medium. Two opposing effects require consideration. On the one hand the motions of the interstellar clouds will promote mixing, while on the other hand the presence of a strong magnetic field would greatly impede mixing. It remains an interesting problem to decide where the balance lies between these two effects.

The condensation problems arising for stars of group (*c*) and possibly also for group (*b*), were considered by HOYLE. It seems as if star formation in these groups was on a far vaster scale, and probably was compressed into a shorter time scale than has been the case for the formation of stars of group (*a*). These differences were thought to arise from the thermal conditions of the problem. Temperatures upwards of 10^4 deg. K. were considered. It was shown that under approximately isothermal conditions, clouds of very large mass, 10^{10} ⊙ or more, can fragment almost completely into stars. The formation of E galaxies, and of the nuclei and haloes of spirals was attributed to this high temperature fragmentation.

I come now to the last of the problems that I wish to discuss, namely the remarkable difference, reported by BAADE, between the periods of the RR Lyrae stars of the galactic nucleus and those of the globular clusters. The former was given as about 0.3 days and the latter as about 0.5 days. SANDAGE pointed out that on any reasonable basis this would imply a lower luminosity for the RR Lyrae stars of the nucleus. A rough method of estimation suggests that the luminosity difference between the two classes would be about one magnitude, giving $M_{pv} \simeq +1.0$ for the RR Lyrae stars of the nucleus.

This raises the difficulty that the solar distance from the galactic center, as determined from the RR Lyrae stars, would be in disagreement with the distance given by dynamical considerations. The situation might be saved by a revision of the correction for obscuration, and indeed WHITFORD has indicated that his original correction values may have been too large.

Although the situation is not very palatable in this respect, it does possess one attractive feature. It would allow us to say that the evolving stars of the nucleus are similar to those of M 67 (which possess a "horizontal branch" about one magnitude fainter than the horizontal branch of a globular cluster with large z-motion. Such an identification seems to fit the remarkable observations reported by MORGAN, who finds that the light from (1) Elliptical galaxies, (2) Nucleus of M 31, (3) Globular clusters in the nucleus with small z-motions, comes predominantly from CN normal giants probably of M 67 type. A similar situation may be expected in the nucleus of the Galaxy.

According to SCHWARZSCHILD and HOYLE the difference between M 67 and the giants of a globular cluster such as M 3 is due to a difference of metal content. In M 3 the metal content is low enough for the position of the giant branch to be dictated by the photospheric condition imposed by hydrogen. In M 67, on the other hand, the photospheric condition is imposed by metals, notably by magnesium. If we combine these remarks with the observations of MORGAN we can see why the colors of globular clusters such as M 3 on the one hand, and the colors of the elliptical galaxies and of the nuclei of the spirals on the other hand, are so characteristically different. We can also see why these colors are so constant from one object to another within the respective classes. The similarity (or difference) of color is not so much a product of the precise similarity (or difference) of the stars, as of whether metals play a dominant role in determining the photospheric boundary condition. If they do, then the giants will be of M 67 type; if they do not, the giants will be of M 3 type. And this applies even if the stars of two objects of similar color have somewhat different properties in other respects, e.g. a moderate difference of mass.

Suggestions for Further Work

It is one of the aims of this conference to make suggestions for further work. I shall confine myself to those problems that have a fairly strong theoretical connection.

1. *Time Scale Problems.* Much theoretical work remains to be done in studying the early evolutionary stages of stars with masses between $\mathfrak{M}_\odot$ and 2 $\mathfrak{M}_\odot$. The determination of the ages of old clusters and of the Galaxy itself depends on a comparison of this theoretical work with observation. At the moment it seems as if the oldest stars of the solar neighborhood have greater ages than the stars of globular clusters. It is obviously of great importance to determine whether or not this is really so.

2. It is known that the evolutionary behavior of giants is dependent on their metal content. But only a few cases have so far been studied in detail. It is desirable to determine the evolutionary giant tracks for a wide variety of chemical compositions and also for a considerable number of stellar masses.

3. The whole problem of stellar variability needs reassessment. It is known that characteristic types of variability are associated with particular localities in the color-magnitude diagrams. So far, we cannot be sure of the cause of variability; whether it is a consequence of the internal structure that a star takes up when it happens to lie in one of these localities, or whether variability is essentially an atmospheric phenomenon, associated only with the immediate sub-photospheric regions of a star. Progress on this point requires a knowledge of the interior structures of variable stars e.g. of the Cepheids, RR Lyrae stars, RV Tauri stars, etc. This in turn demands a far better understanding of evolutionary tracks than we possess at the moment.

4. The whole problem of what eventually happens to stars that lose mass to the interstellar medium is entirely without quantitative investigation.

5. Little if anything quantitative is known of the structure of stars at advanced evolutionary stages. Such knowledge is vital to a full understanding of the synthesis of the elements inside stars.

6. More investigation of the evolution of really massive stars, such as were reported by THACKERAY in his study of the large Magellanic Cloud, would be desirable.

7. As Father O'CONNELL pointed out, the study of binaries should yield information of great value to the theory of stellar evolution. Again at the moment our theoretical knowledge of the evolution of undisturbed stars (i.e. uninfluenced by their neighbors) is too undeveloped for us to attempt the more difficult problems posed by the binaries (where one component may interchange mass with the other).

8. The great bulk of our knowledge of stars and of stellar evolution is derived from the Galaxy and from a few nearby systems. Evidently a full understanding of the properties of stars must take all types of galaxies into account, as was pointed out by LINDBLAD and by LEMAÎTRE. An excellent start in this direction has been made by MORGAN's analysis of the integrated spectra of galaxies. On the theoretical side, we again need a knowledge of the evolutionary tracks of stars, not just for one or two values of the mass and chemical composition, but for a whole range of masses and of compositions — since the stellar content of different galaxies may well differ quite appreciably from one to another.

Computing Facilities

It may be as well to end by drawing attention to the rather unsatisfactory situation that exists as present in the provision of computing facilities for carrying out the theoretical work described above.

After a fairly extensive reconnaissance of the problem I have come to the conclusion that a complete evolutionary track for one star (i.e. a particular mass and a particular composition) can scarcely be worked out, using even the fastest of present day electronic computers, in less than 100 hours. The investigator can choose to follow the evolution in either a large number of steps each taking only 3 or 4 minutes or in a smaller number of longer steps, each taking perhaps 15 or 20 minutes. In both cases the total computation time is not much different from 100 hours.

This refers to just one star. The problems I have outlined above would require evolutionary tracks to be worked out for 10 to 20 different values of the mass and for 5 to 10 different initial compositions. All in all, the total computation time required for all cases adds up to some 10,000 hours. This estimate may conceivably be in error by a factor ~ 2, but I think by not much more. In any case the conclusion emerges that such a program of work, whether it involve 5000 hours or 10,000 hours, can scarcely be carried out on the initiative of one individual, or even on the initiative of the handful of people that have so far been working on the problem. If full information is to be provided, and I think we can agree on the desirability of obtaining full information, some concerted effort by astronomers as a whole is surely required. This is no more a project for the solitary worker than the building of a large telescope would be.

REFERENCE

[1] M.S. Roberts, P.A.S.P., *69*, 59, 1957.

SUMMARY - FROM THE ASTRONOMICAL POINT OF VIEW

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Hoyle has summarized the importance of the things we have discussed in this conference for the investigators interested in what one might call the inner life of a star. I shall try to summarize some of the facts and theories brought forward to describe the *appearance* of the stars and their behaviour. We have found it quite impossible to make a good separation; there will, accordingly, be a certain amount of overlap in the two summaries.

Before starting I should like to stress the far-reaching influence which the development of the idea of the stellar populations, the growing insight into the nature of the populations and the fantastically rapid evolution of our knowledge of the evolution of stars has had on the study of the complex structure of the Galactic System and on the understanding of this structure.

The appearance of a star depends mainly on two parameters: total mass and chemical composition of the medium from which it was formed. It has been suggested that, in the Galactic System, the latter quantity depends mainly, if not wholly, on the *period* in which the star was formed. In that case, mass and chemical composition determine also the age of the star.

Here we encounter two debatable points: Has the change in the chemical composition of the medium with time been the same in various parts of the System? We don't know. SCHWARZSCHILD and others take the point of view that they want to try how far they can get with this hypothesis. BAADE thinks that there may be evidence of differences, and that these may explain, for instance, why we see so little of the pure disk population II in our neighbourhood.

The second point is whether the chemical composition can be determined by one parameter. SCHWARZSCHILD thinks that, for the present, one parameter is indeed sufficient.

We might see more clearly in these questions if we knew more about the way in which the medium becomes enriched in heavy elements. This problem, as HOYLE has explained, is still in a very hypothetical state, although the suggestions which have been made are intriguing. But we cannot yet use them to get an insight into how the enrichment must have depended on the stage of development of the Galactic System, or on the region considered. The available evidence might be taken to indicate that at least some of the enrichment has been concentrated in a relatively brief phase of the history of the System. A priori it seems quite likely that the composition would show differences for different large regions, but not so much for small adjacent regions. If star formation, and nova formation, depends on a relatively high power of the gas density, then the denser parts should have more metals.

A large domain for further inquiry evidently remains here. What is the part played by supernovae of types I and II in the process of metal enrichment? Partly, this is a problem of physics, and partly one of statistical astronomy. On the one hand we should get better information on the distribution and frequency of various kinds of supernovae and ordinary novae. On the other hand the masses of the ejected shells should be better known. We must also investigate how much yellow giants could contribute.

An important question, which has been discussed on various occasions, is whether, beside mass and a one-parameter chemical composition, there is still a third parameter influencing the spectrum of a star in an observable degree. Some evidence favouring the existence of such an additional parameter has been given. Its physical nature has not been discussed. One might think of angular momentum, in so far as this influences ejection processes, or possibly of magnetic field strength.

Returning now to the two principal parameters, we consider the way in which they can be correlated with observable quantities and the methods by which we can study the relation between age and chemical composition. The first point has been treated in the greatest detail by STRÖMGREN and by CHALONGE. For the second problem by far the most direct and most illuminating information is furnished by the star clusters. As there is no reason for summarizing once more the excellent summary that was provided by SANDAGE (cf. p. 51), I shall restrict myself to mentioning a few special points.

The clusters yield invaluable information concerning objects dating from the earliest period of the Galactic System. The globular clusters in the halo may serve as prototypes of population II. In these clusters we find an exhibition of what types of stars are characteristic of a pure population II, as BAADE has repeatedly pointed out. They show us what stars look like which have the highest attainable age and in which metal content is lowest.

The globular clusters form an extremely important and well-defined pillar for our knowledge in this domain, indicating the type of colour-magnitude diagram, the peculiarities of spectrum and variability of the brighter stars, etc. Combined with theory these data have given valuable information about the evolutionary paths of stars of this age and composition.

A number of questions have remained unanswered: How do the various globular-cluster characteristics that were enumerated by SANDAGE and MORGAN (such as: position of the vertical branch, position and width of the variable-star gap, number and character of variables, spectra of brightest stars, integrated spectrum, etc.) correlate with each other? Also: Why are there differences between clusters which all seem to belong to the halo? With regard to the latter question, we might ask whether these differences are due to age differences only, or whether even in the earliest stage of the Galactic System there has already occurred an appreciable change in the chemical composition of the gas.

One important thing has clearly emerged from the data communicated by MORGAN, namely, that there *is* a category of globular clusters which differs strongly in chemical composition from the rest and probably resembles the case of M 67. The clusters of this category have smaller z components, and may be considered as belonging to an intermediate population II, or perhaps even to a disk population. It would seem extremely desirable to obtain colour-magnitude diagrams for some of them. BAADE has given some evidence indicating that among the RR Lyrae variables those with very short periods may likewise have a flat distribution, similar to that of novae and planetary nebulae.

Information concerning objects of intermediate age is still very meagre. So far, most of it comes from M 67. The colour-magnitude diagram differs strongly from that of a globular cluster like M 3. The difference is ascribed to a difference in heavy-element content. However, the break-off point on the main sequence is approximately the same as in M 3, or comes even at a little lower intrinsic brightness. It appears, therefore, that the two clusters cannot differ much in age. This indicates that the change in the composition of the interstellar gas may have been fairly rapid during the transition stage, when the gas had just completed its contraction to the disk.

A difficulty in following up the evolution to later stages of the Galactic System is formed by the scarcity of known clusters of ages between 0.5 and 5 times 10^9 years. In general, galactic clusters do not appear to grow much older than 0.5×10^9 years. The scarcity of older galactic clusters appeared at first to be puzzling, but various suggestions have been made during this meeting to indicate that former estimates of "evaporation" times have been too high, and that, probably, most galactic clusters can not live more than about 0.5×10^9 years.

The combination of observational studies of galactic clusters with theories of stellar evolution has proved a most fertile field for research. Among many other things one important point which is beginning to emerge from this is the evolutionary history of ordinary yellow giants.

For the stars which are *not* members of clusters the problem of fixing the age is much more difficult.

Great progress has been made, firstly in the school of W. W. MORGAN in the way of visual classification and, secondly, by STRÖMGREN and CHALONGE with their collaborators in photometric measurement of spectral characteristics. Considerable accuracy has been attained in the determination of two parameters, equivalent to temperature and luminosity. Although, theoretically, it might be possible to learn something about the age from these quantities, in practice the information on age of individual stars remains vague, except in the case of stars of very high velocity and old age, which can be readily distinguished spectroscopically. Miss ROMAN's distinction of weak-line and strong-line stars among ordinary main-sequence stars and yellow giants seems a first step in the direction of distinguishing younger and older stars among the common types. The use of ultraviolet excess as a further indicator of age appears promising.

SANDAGE has discussed the colour-magnitude diagram for near-by stars. He found some indications of stars which *seem* older than M 67. As it is improbable that they would actually be older, another explanation of the abnormal luminosities of these stars should be sought. It would be of importance to try to find more stars of this type and to study their kinematical properties.

An important advance in the understanding of the luminosity function has been attained by SALPETER's suggestion concerning the shape of the "original" luminosity function. This is a development of considerable significance, in connection with the history of the Galactic System as well as with estimates on the frequency of white dwarfs. SANDAGE has given evidence indicating that the same original luminosity function would hold in galactic clusters. This appears rather surprising, because conditions in dense clusters must have been rather different from those in the large dark clouds where, according to HERBIG's suggestion, ordinary main-sequence dwarfs may be born as T Tauri stars. SANDAGE has indicated that a similar function may apply also to globular clusters. The latter evidence is weak, however, and this should still be considered as an open question.

A number of results have been reported on the composition of other galaxies. From early studies by BAADE it was known that the brightest stars in the amorphous part and the disk of the Andromeda nebula and in its elliptical companions are bright yellow giants of the same absolute magnitude as the brightest stars in globular clusters. BAADE and Miss SWOPE have now obtained data on the colour-magnitude array in the near-by Draco system (a system of the Sculptor type). This also contains the bright yellow giants that are typical of a globular-cluster population. According to a recent private communication from BAADE the colour-magnitude array is also in its further aspects a replica of that of a globular cluster. RR Lyrae variables have been found in abundance in this system as well as in all other dwarf galaxies that are sufficiently near by.

Interesting information on the integrated spectra of galaxies has been reported by MORGAN. In the region λλ 3850 - 4100 the major contributors to the light of the amorphous parts of spirals, as well as of ellipticals and So nebulae, appear to be "normal" K giants, i.e., giants such as found in galactic clusters. But the presence of some *brighter* yellow giants is also indicated. In the irregular galaxies of the Magellanic Cloud type the light in this spectral region comes mainly from A-type stars, while in most Sb and Sc systems the spectrum is due largely to main-sequence F and G stars. The few available data on 21-cm emission indicate that the relative mass of interstellar gas varies from very small fractions in an elliptical system, to 1 or 2% in large Sb spirals, and perhaps up to about 50% in the Magellanic Clouds.

Elliptical galaxies are probably almost pure population II systems. We do not know, however, the proportion between halo and disk population II in these galaxies.

An important problem is to investigate possible differences in composition between various population II systems. There are two striking differences between elliptical galaxies and amorphous parts of spirals on one side and globular clusters on the other, viz. in the integrated colours and in the ratio of mass to luminosity.

THACKERAY has reported on spectra of supergiants in the Magellanic Clouds. Data on colour-magnitude diagrams of these galaxies are still very limited. They are one of the most urgent desiderata in present-day astronomy. Curiously enough, the emission nebulae in the Clouds appear to have the same chemical composition as those in the Galactic System.

The definitions and names of the various population groups have in the past given rise to some confusion. They have been clear in the case of globular clusters (pure population II) and the majority of galactic clusters (pure population I). It is more difficult for individual stars. It seems indicated to relate the definitions to an evolutionary picture of the Galactic System, in such a way as has been done in Table 2 on p. 419. In this table the age — and therefore the population group — has been related to the dispersion perpendicular to the galactic plane, the stars having presumably been formed in the successive stages of a mass of gas gradually contracting to a very flat disk. The discussion of this problem has indicated that the star-building process must have been greatly favoured by high values of the average interstellar density. The differences in z dispersion found among the stars formed after the contraction had been "completed" may have been caused by a gradual increase in random velocity caused by encounters with very massive agglomerations of interstellar clouds.

The main difficulty is that we need observable quantities for our definitions, and that in many cases the ages of individual stars cannot yet be derived from astrophysical measurements.

After considerable discussion a provisional agreement was reached about divisions and names; this has been indicated in the table just mentioned.

CONCLUSIONS

a) The colour-magnitude arrays in clusters give empirical information on the evolution paths followed by stars of different initial masses and various chemical compositions.

b) The differences in chemical composition of different types of stars are principally due to differences in the composition of the interstellar medium from which they were born.

c) During the life of the Galactic System this interstellar composition appears to have changed considerably, having gradually been enriched in heavy elements.

d) The large compositional differences between various globular clusters indicate that much of the enrichment must have taken place in the early stages of the Galactic System, before the gas had contracted to a disk.

e) In the galactic cluster M 67, whose age has been estimated as 5×10^9 years, the enrichment may already have practically reached its present value.

f) Most galactic clusters do not grow older than about 0.5×10^9 years.

g) The ages of stars which have left the main sequence may be estimated from colours and luminosities. A number of spectral criteria have been discussed which may serve to indicate ages for stars near the main sequence.

h) It is possible to estimate the distribution function of the masses (and luminosities) with which stars have formed in general interstellar space. A similar function may be derived for stars formed in galactic clusters. There is a remarkable and somewhat unexpected agreement between the two.

i) A tentative picture has been given of the evolution of the Galactic System. The following groups of stellar populations have been defined and attributed to certain epochs in this evolution:

halo population II
intermediate population II
disk population
intermediate population I
extreme population I

See Table 2 on p. 419 for the definition of these groups and for the various characteristics attached to them.

A few of the problems needing further research

1. Has the change in chemical composition been the same in all parts of the Galactic System?
2. Can chemical composition be adequately determined by one parameter?

3. Further investigations on ultraviolet excess as a correlate of age and average random velocity appear very desirable.
4. Can supernovae of types I and II have sufficed to cause the changes that have taken place in the composition of the interstellar gas? Which other stellar types can have contributed?
5. What has caused the striking differences in spectra, colour-magnitude arrays and variables, between various globular clusters all belonging to the halo?
6. What is the colour-magnitude diagram of the globular clusters with large heavy-element content, to which MAYALL and MORGAN have drawn attention?
7. Is the original luminosity function in clusters the same as that in the general vicinity of the sun?
8. There is a general lack of knowledge concerning stars belonging to the disk population II.
9. What causes the differences in stellar composition between globular clusters and elliptical galaxies, such as show up in their colours and mass-luminosity ratios?
10. Studies of colours and magnitudes of both bright and faint stars in the Magellanic Clouds are of the greatest urgency.

DISCUSSION

CHAIRMAN: B. STRÖMGREN

STRÖMGREN

The first point in our discussion concerns the divisions between the different population types. We have the suggestion of OORT on the blackboard in the form of a six column table (*).

MORGAN

There are three lines of approach, converging on a rough physical picture; the kinematic approach, the location in space, and the physical properties of the stars concerned. All tend toward a similar picture, but at present we have not a one to one correspondence between the three methods of approach. There are great areas of uncertainty, especially regarding the arrangement in space and the physical properties of the stars. At present we cannot satisfy everyone. I think the scheme of OORT an extremely useful one; it is, in general, a kinematic one, though it has a bearing on the physical characteristics and location of the different classes of objects in space. I should like to suggest again an allocation of the six columns into three groups retaining OORT's terminology, perhaps with a qualification including "halo", "disk" and "arm" descriptions, so that those working on the physical characteristics (of which our knowledge is much coarser) may describe things in a compatible manner.

BLAAUW

It would not be entirely justified to call column five spiral arms; A-type stars have an irregular distribution, but this may not be

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(*) With regard to the table see the footnote on p. 419.

spiral arm distribution. We may expect more information from RAMBERG's survey.

LINDBLAD

There is evidence from RAMBERG's work that we have, in the spiral arm in Cepheus, A-type stars and late-type giants associated with reddening agreeing with 21-cm line results. This indicates that A stars are associated with spiral arms.

BLAAUW

This may then be considered as sufficient evidence to put column 5 under the general heading of spiral arms, but it is much weaker than the evidence for the location of O and B stars in the spiral arms.

SCHWARZSCHILD

Could column 2 be properly called halo?

OORT

Yes, it contains long-period variables with periods less than 240 days and high-velocity stars with velocity dispersion in the z direction of the order of 25 km/sec.

BAADE

So far we have observed few long-period variables in the halo though they may be there. Otherwise, the long-period variables and high-velocity stars show a concentration towards the galactic plane in their velocity vectors.

It would be better to leave the well defined halo alone till we get more evidence about short-period cluster variables.

OORT

If the mean distance from the galactic plane of short-period RR Lyrae variables is everywhere as small as it is in the nuclear region according to BAADE's observations, they form a thin disk, while for intermediate population II we have something really in between the halo, with its subdwarf velocities, and the disk with its small velocities like those of planetary nebulae. Long-period variables with periods shorter than 250 days have high velocities and so are not true disk objects; so I put them in column 2, not 3.

BAADE

High-velocity stars are concentrated towards the plane. Do they go beyond the disk?

OORT

Only a little, but, as with the long-period variables they would be distinguished from true disk objects like planetary nebulae by their velocities parallel to the plane. The high-velocity population is probably small relative to the true disk population, but we do not know much about this latter in our neighbourhood.

HOYLE

I should like to raise a different point; the different degree of emphasis to be attached to the lines dividing the columns. Could we divide the table of six groups into three strong groups with subdivisions?

OORT

I suggest the strong divisions after the second and third columns.

SCHWARZSCHILD

How strong is the evidence for the division between columns 3 and 4? MORGAN's spectra for the centre of M 31 would put it presumably in column 4. When BAADE talks about the disk between the arms further out in M 31, he means 4 rather than 3. Disk stars in the solar neighbourhood belong to column 4.

OORT

But all the unobserved low luminosity stars are in column 3.

HOYLE

Should we put the second line after column 4?

SCHWARZSCHILD

The term "disk" should apply to 4 as well as 3 on the basis of MORGAN's spectra.

BAADE

HOYLE said this morning in his summary that the disk population of the galactic centre could be like that of M 67. I believe with SCHWARZSCHILD that column 4 corresponds to the integrated spectrum and that column 3 makes little contribution to the light from the nucleus. I believe that HOYLE's suggestion that the RR Lyrae variables in the nucleus fit the M 67 type horizontal branch depends on an unverified assumption.

OORT

Do we know enough about the spectrum of the nucleus?

BAADE

We have MORGAN's data on Sb spirals.

LINDBLAD

If Andromeda is a barred spiral as is indicated, even the central parts are greatly flattened and the population cannot be shifted too much to the left in the table.

OORT

I would think that column 3 would correspond to the population of the thin disk.

MORGAN

As far as the light contribution in ordinary Sb spirals is concerned, from the violet to the green the principal contribution is from giant K stars which have not greatly weakened metallic lines; it is not like M 92, nor even like M 3, but having stronger lines than either, like the strong-line globular clusters near the galactic centre.

O'CONNELL

What are we agreed upon so far? I take it that we agree that the six divisions of OORT are significant, that the transition from column 1 to 2 is gradual, that between 2 and 3 we have a clear division. Are there any comments on the division between 3 and 4?

MORGAN

Everyone looks at it from his own point of view. We do not know enough to come to a detailed decision.

BAADE

Stars within 20 pc of the Sun studied by EGGEN, which are turning off the main sequence, have a colour-magnitude diagram like M 67. These are "normal" stars and seem to constitute the disk.

SPITZER

There are really three questions: how many categories should be used, what they ought to be called, and what the typical contents of each ought to be. I think that it is best to define the categories empirically by their contents rather than by age, stellar composition or spectra.

OORT

Some weight ought to be attached to the theoretical argument that there is a difference between the disk population in column 3 which is concentrated towards the nucleus and disk population in column 4, which has no such concentration. This must mean physically that column 3 was formed at an early stage and column 4 after the ironing out of the large variation of density with distance from the centre that apparently existed in the beginning.

HECKMANN

Let me speak in a parable: At the time of SECCHI there were four spectral subdivisions; now we have ten subdivisions, and side branches. In our present discussion we are trying to go back to SECCHI's types in spite of the fact that our knowledge is much more advanced than SECCHI's.

OORT

But at the time of SECCHI no one knew anything about the significance of the division.

HECKMANN

So his procedure was justified, not ours.

SANDAGE

Would OORT put the stars that contribute to the total light of the disk in column 3?

OORT

Yes.

SANDAGE

Then, if the disk stars are like M 67, would you class M 67 as population II?

OORT

There is no difficulty in this from the age point of view.

SANDAGE

But since M 67 forms the end of a continuum in the colour-magnitude diagram of galactic clusters of population I, does not this lead, on the basis of the present definition, to a population type which changes with time? This would seem to be an unhappy conclusion. Perhaps M 67 belongs in column 4 or slightly toward column 5.

MORGAN

I wish to support SPITZER's recommendation that we define the subdivisions empirically by objects contained in them.

(Discussion continued on the fine points of the following classification with the meeting in agreement on the order of the following table).

1. *Halo population II*: Subdwarfs; Globular Clusters (M 3 to M 92); RR Lyrae variables (periods over 0.4 d).
2. *Intermediate population II*: Long-period variables of spectral type M5e and earlier, or of period less than about 250 days; high velocity stars (Z 25 to 40 km/sec).
3. *Disk population II*: Planetary Nebulae; Novae; probably also RR Lyrae variables with period less than 0.4 days.
4. *Transitional population*: Miss ROMAN's weak-line stars.
5. *Intermediate population I*: Miss ROMAN's strong-line stars, A-type stars.
6. *Extreme population I*: Gas, O and B stars, all other supergiants, T Tauri stars, and galactic clusters of Trumpler's type 1.

SPITZER

This list is meant to include characteristic objects but not to be complete.

SANDAGE

Do columns 3 and 4 differ only in the degree of concentration to the nucleus?

OORT

Yes.

BAADE

I am convinced columns 3 and 4 go together. Column 3 represents only the stellar population II of the Andromeda nebula in which we can see bright stars resolved. I would like to call 2), 3) and 4) "disk" population.

MORGAN

Can column two be considered disk? Should it not be left in the halo?

BAADE

If we call column 4 population I we go beyond our present knowledge.

MORGAN

Call columns 3 and 4 disk.

SPITZER

Let us unite columns 3 and 4 and call this category disk population, with optional subdivisions I and II.

OORT

I am sure column 3 is a theoretically important stage although at present observationally indistinguishable from column 4.

SANDAGE

It seems to me that there is no observational evidence for division between columns 3 and 4 unless MORGAN can distinguish the spectra of the centre and outer parts of the Andromeda nebula.

BAADE

In the disk there are two populations, one closely related to halo population II and another of M 67 type, which makes the main contribution to light in our neighbourhood.

(The amalgamation of columns 3 and 4 under the general name "Disk population" was agreed upon).

HOYLE

I propose that column 4 (the second last column) be called "Older Population I", rather than "Intermediate Population I".

(*This proposal was adopted by the meeting, with several members dissenting*).

STRÖMGREN

We now pass on to consider suggestions for future research. I invite comments on those made by OORT and HOYLE in their summaries this morning and any additions.

O'CONNELL

These summaries contained a great many proposals. Will you agree to accept in general terms the conclusions and recommendations for future research contained in HOYLE's and OORT's summaries? If you agree, the precise formulation can be left until later and then submitted to each of you for your approval.

(*This proposal was agreed to unanimously*).

HOYLE

It would be very useful if the meeting would recommend the suggestion about the importance of securing computing time with high speed electronic computers for work on theoretical aspects of stellar evolution.

(*The meeting expressed unanimous agreement*).

BAADE

One very important fact that has emerged is the need for further studies of the Magellanic Clouds in connection particularly with the ages of population I stars.

O'CONNELL

We should like to express our strong support of the work that THACKERAY has described to us.

BAADE

I should like to propose two motions, one supporting research on the Magellanic Clouds, and another urging the need for a new large observatory for work in the southern hemisphere.

(*Both motions were approved unanimously*).

MORGAN

I should like to move the following resolution:

Resolved: That this Conference express its gratification at the installation at the Vatican Observatory of a new, powerful, reflecting telescope of the Schmidt type — a telescope so well suited to attack-ing some of the problems of stellar evolution discussed by this Conference over the past week.

(*The motion was seconded and carried unanimously*).

O'CONNELL

I am very appreciative of this motion which will set the stamp of approval on the type of problem we are dealing with, and I shall be happy to convey this motion to HIS HOLINESS, to whose generosity we owe the new telescope which is now on its way to us.

STRÖMGREN

We have now to present the conclusions of our discussions and I ask for any comments or additions to the summary of these conclusions given this morning by HOYLE and OORT.

If there are no further comments I take it that you are fully satisfied with the conclusions already reached which will be drafted in a suitable form by the Committee and circulated for final approval.

O'CONNELL

I should like to take this opportunity to express my deep gratitude to all those who have helped to make such a success of this conference. For nearly two years, from the time of the IAU meeting at Dublin, our organizing committee, BAADE, BLAAUW, NASSAU, OORT and SCHWARZSCHILD, has worked extremely hard to prepare the programme. Others of you have helped greatly by your advice and consultations with various members of the Committee, and all the members have given of their very best in preparing their papers and in our very lively and enlightening discussions. On behalf of you all I wish to thank the Academy, its President, Padre GEMELLI, and particularly the Chancellor, Dr. SALVIUCCI, for the very efficient arrangements which have been made for our comfort and convenience, the excellent hotel accomodations and the very efficient transport service to and from the hotel, all of which have contributed greatly to the smooth running of the programme and to keeping us fresh for our intensely strenuous labours. A very special debt of gratitude is owing to the secretarial staff for their devoted and strenuous and most efficient assistance, without which the conference could not have succeeded so well as it has.

STRÖMGREN

We have come to the end of our meeting, which all are agreed has been a tremendously successful one, from which we have all profited very much. We have already expressed our thanks to the Organizing Committee and we all wish to join in expressing our gratitude for the splendid week we have had here and for all those concerned with its preparation. We also wish to thank the Secretariat who worked so hard and well to make it possible to have our discussions so excellently recorded, and especially Father TREANOR for dealing with the heavy work of reporting the discussions. Particularly we would like to express our thanks to Father O'CONNELL. The success of this meeting is a tribute to your organization and preparatory work.

NASSAU

Father O'CONNELL, on behalf of the members of this Conference, I present to you a very small gift, expressing our sincere thanks for your kindness to us during the last ten days.

O'CONNELL

Your expression of thanks has moved me very deeply. It has been a great pleasure to have you here. However hard the work may have been, it has been well worth while.

SUPPLEMENT
AUX
CONCLUSIONS

CONCLUSIONS

The conclusions reached during the meeting are set forth in the summaries prepared by HOYLE and OORT (pp. 491-516). It was not possible to submit these conclusions in writing to the meeting before it ended, but, in accordance with the resolution passed during the final session (p. 525), proofs of the summaries were sent in due course to the members, who have expressed their approval of the conclusions contained in them. One point, however, requires further elaboration and explanation — the classification of the stellar population types.

Classification of Stellar Population Types

One of the most important results of the meeting was the agreement on the classification of types of stellar populations. The classification finally approved by the Conference is given in the table on page 533. Professor OORT's Table 2 (p. 419), which served as the basis for the classification, was discussed at great length (pp. 426-33, 517-24). Some minor modifications were adopted e.g. OORT's original columns 3 and 4 were combined to form column 2 of the final table under the heading "Disk Population". Nevertheless, the table as finally formulated is essentially that prepared by OORT.

On one point there remained a divergence of opinions — the heading of column 4. The question was put to the vote (p. 524) and the majority decided on the heading "Older Population I", whereas a considerable minority preferred the term originally proposed by OORT "Intermediate Population I". Apart from this small difference of opinion the classification given in the table was approved unanimously by the meeting.

The five-fold division shown in the table is based on the observed properties of the various objects, rather than on theoretical considerations. The five types of stellar population are, in fact, defined empirically by their representatives as listed in the table. It was thought inadvisable to introduce criteria of age, composition, etc., until the precise influence of these factors is better understood.

Suggestions for Future Research

HOYLE's proposals for further work are given on pp. 503-506 and OORT's on pp. 515-516. These suggestions have received the unanimous endorsement of the participants in the conference.

ARMELLINI, BAADE, BLAAUW, BRÜCK, CHALONGE, FOWLER, HECKMANN, HERBIG, HOYLE, LEMAÎTRE, LINDBLAD, MORGAN, NASSAU, O'CONNELL, OORT, SALPETER, SANDAGE, SCHWARZSCHILD, SPITZER, STRÖMGREN, THACKERAY.

Classification of Stellar Populations

Halo Population II	*Intermediate Population II*	*Disk Population*	*Older Population I*	*Extreme Population I*
				Gas
Subdwarfs	High-velocity stars with z-velocities >30 km/sec	Stars of galactic nucleus	A-type stars	Young stars associated with the present spiral structure
Globular clusters of high z-motion	Long-period variables with periods <250 days and spectral types earlier than M5e	Planetary nebulae	Strong-line stars	Supergiants
		Novae		Cepheids
				T Tauri stars
RR Lyrae stars with periods longer than 0.4 days		RR Lyrae stars with periods <0.4 days		Galactic clusters of Trumpler's class I
		Weak-line stars		

CONCLUSIONS

Dans les résumés préparés par Hoyle et Oort (pp. 491-416) on trouvera les conclusions adoptées par la conférence. Le temps n'a pas permis de soumettre ces conclusions par écrit aux participants avant la fin de la Semaine, mais, conformément à la résolution prise au cours de la dernière session, les épreuves des sommaires ont été envoyées aux participants, et ceux ci ont approuvé les conclusions. Il semble néanmoins utile d'insister un peu et de fournir un supplément d'explications sur un point — la classification des types de populations stellaires.

Classification des Types de Populations Stellaires

L'accord sur la classification des types de populations stellaires est un des résultats plus importants des travaux de la Semaine. Le tableau de la page 533 présente la classification qui a été finalement approuvée par la conférence. Le point de départ de cette classification a été le Tableau 2 du Professeur Oort (p. 419). Ce tableau a été longuement examiné et discuté (pp. 426-33, 517-24). Quelques modifications mineures y ont été apportées; par exemple, les colonnes 3 et 4 du tableau d'Oort ont été réunies pour devenir la colonne 3 du tableau définitif sous la dénomination de « Disk Population ». Mais le tableau définitif reste essentiellement celui proposé par Oort.

Sur un point cependant a subsisté une divergence d'opinions — la dénomination de la colonne 4. Quand la question fut mise aux voix, la majorité choisit la rubrique « Older Population I », tandis qu'une minorité considérable préférait la dénomination initiale d'Oort « Intermediate Population I ». À part cette petite divergence des opinions, la classification des populations stellaires données dans le tableau de la page 533 a reçu l'approbation unanime de la conférence.

Le tableau est divisé en cinq colonnes. Cette division est basée sur les caractères observationnels des objets classés, plutôt que sur des considérations théoriques. Le cinq types de population stellaire sont en effet définis empiriquement par quelques représentants typiques enumérés dans le tableau. Il n'a pas paru opportun d'introduire des critères d'âge, de composition chimique, etc., avant que l'on comprenne mieux l'influence précise de ces facteurs.

Recommandations pour les Recherches Futures

On trouve, pages 503-6, les suggestions de M. Hoyle pour travaux ultérieurs, et, pages 515-6, celles de M. Oort. Les participants à la conférence ont souscrit à l'unanimité à ces recommandations.

Armellini, Baade, Blaauw, Brück, Chalonge, Fowler, Heckmann, Herbig, Hoyle, Lemaître, Lindblad, Morgan, Nassau, O'Connell, Oort, Salpeter, Sandage, Schwarzschild, Spitzer, Strömgren, Thackeray.

SCHLUSSFOLGERUNGEN

Die während der Woche erzielten Endergebnisse finden sich in den beiden zusammenfassenden Referaten von HOYLE und OORT (S. 491-516). Es war allerdings nicht mehr möglich, diese Zusammenfassungen den Teilnehmern noch vor Schluss der Versammlung schriftlich vorzulegen. Doch wurden sie gemäss einer Entschliessung während der Schlusssitzung allen Mitgliedern noch rechtzeitig zur Begutachtung vorgelegt. Alle haben diese Endergebnisse gutgeheissen. Ein Punkt jedoch bedarf noch der weiteren Klärung und Ausarbeitung: die Klassifikation der Sternpopulationen.

Classifikation der Typen von Sternpopulationen

Eines der bedeutendsten Ergebnisse der Woche war die Einigung über die Klassifikation der Typen der Sternpopulationen. Die von der Versammlung endgültig angenommene Klassifikation findet sich in der Tabelle S. 533. OORTS Tabelle 2 (S. 419), die ausführlich diskutiert wurde (S. 426-33, 517-24), diente dabei als Vorlage. Einige geringfügige Änderungen wurden angebracht. So wurden z.B. die Spalten 3 und 4 der OORTschen Tabelle zu Spalte 3 der endgültigen Form zusammengelegt unter dem Titel « Disk Population ». Doch ist die endgültige Tabelle wesentlich die von OORT vorgeschlagene.

Über einen Punkt konnte allerdings keine Einingung erzielt werden, nämlich bezüglich der Überschrift zu Spalte 4. Es wurde über die Frage abgestimmt (S. 524), und die Mehrheit entschied für die Überschrift « Older Population I », während eine ansehnliche Minderheit den von OORT vorgeschlagenen Ausdruck « Intermediate Population I » vorgezogen hätte. Mit Ausnahme dieser geringfügigen Meinungsverschiedenheit wurde die in der Tabelle niedergelegte Klassifikation einstimmig angenommen.

Die Unterscheidung der fünf in der Tabelle zusammengestellten Klassen gründet sich mehr auf die beobachteten Eigenheiten der einzelnen Objekte als auf theoretische Überlegungen. Die fünf Klassen von Sternpopulationen sind also nur empirisch definiert durch ihre in der Tabelle aufgeführten Vertreter. Man hielt es für unerwünscht, Kriterien einzuführen, wie Alter, chemische Zusammensetzung, u.s.w., bevor nicht die Tragweite dieser Faktoren besser erkannt ist.

Anregungen für weitere Untersuchungen

HOYLES Vorschläge für weitere Untersuchungen finden sich auf S. 503-6, die OORTschen auf S. 515-6. Alle diese Vorschläge und Anregungen wurden von der Versammlung einstimmig befürwortet.

ARMELLINI, BAADE, BLAAUW, BRÜCK, CHALONGE, FOWLER, HECKMANN, HERBIG, HOYLE, LEMAÎTRE, LINDBLAD, MORGAN, NASSAU, O'CONNELL, OORT, SALPETER, SANDAGE, SCHWARZSCHILD, SPITZER, STRÖMGREN, THACKERAY.

INDEX DES NOMS

Les chiffres précédés d'un *P* indiquent les pages initiales des travaux présentés pendant la Semaine. Ceux précédés d'un *D* indiquent la participation aux discussions publiées en cet endroit (page initiale).

Abell, G.O., 23.
Adams, W.S., 245, 262, 343.
Ajzenberg, F., 278.
Albada, G.B. van, 172, 180.
Albers, H., 180, 184, 189.
Aller, L.H., 245, 246, 262.
Alpher, R.A., 278.
Ambartsumian, V.A., 81, 90, 105, 106, 120, 141, 142.
Arp, H.C., 5, 14, 21, 62, 69, 82, 90, 181, 246.

Baade, W., 21, 85, 88, 133, 140, 141, 171, 172, 174, 180, 278, 315, 491, 502, 508-10, 512, 526. *P*: 3, 165, 303. *D*: 22, 38, 57, 73, 91, 121, 159, 168, 181, 203, 215, 241, 283, 299, 316, 328, 381, 426, 459, 473, 517.
Babcock, H., 433.
Bailey, S.I., 10, 49.
Baillet, A., 380.
Barbier, D., 365, 380, 385, 410.
Baum, W.A., 5, 21, 87-90, 246, 262, 303, 315, 331, 332.
Becker, W., 304, 307, 315, 400, 410.
Bell, B., 262.
Belzer, J., 482, 486.
Berger, J., 345, 350, 354, 359, 371, 377, 380.
Bergh, S. van den, 79, 81, 90, 234, 240.
Berman, L.A., 304, 315, 316.
Bernstein, S., 82, 90.
Bertiau, F.C., 112, 120, 401, 410.
Bidelman, W.P., 121, 194.
Biermann, L., 170, 446, 449, 458.
Biesbroeck, G. van, 95, 99.
Blaauw, A., 120, 128, 140, 235, 401, 410, 450, 458, 492-4, 526. *P*: 105, 333. *D*: 73, 91, 100, 121, 143, 168, 181, 190, 203, 241, 263, 299, 316, 344, 381, 426, 473, 517.
Blackler, 124.
Blanco, V.M., 172, 184, 185, 186, 188, 189.

Böhm, K.H., 141.
Bok, B.J., 453, 454, 458.
Bonsack, W.K., 120.
Borght, R. van de, 486.
Brayton, A.M., 262, 343.
Bueren, H.G. van, 293, 388, 404, 410.
Burbidge, E.M., 23, 55, 56, 142, 272, 278.
Burbidge, G.R., 55, 56, 142, 272, 278.

Cameron, D.M., 172, 180, 188, 189.
Chalonge, D., 247, 380, 385, 393, 410, 411, 465, 509, 511. *P*: 345. *D*: 215, 381.
Chamberlain, J.W., 245, 246, 262.
Chandrasekhar, S., 44, 46, 56, 66, 81, 83, 90, 208, 215, 216, 233, 451, 458.
Christie, W.H., 83.
Christy, P.F., 278.
Code, A.D., 170, 329.
Coffeen, M.F., 82, 90.
Cojan, J., 380.
Cook, C.W., 278.
Coryell, C.D., 270, 278.
Cowan, C.L., 278.
Crawford, D., 387, 398, 402, 405, 407, 410.
Cuffey, J., 307, 315.

Darwin, G., 96.
Delhaye, J., 120, 133, 141, 333, 342, 343.
Deutsch, A.J., 178, 180, 447, 458.
Deutsch, A.N., 70, 72, 209, 323.
Diamond, H., 275, 278.
Dieckvoss, W., 65, 66.
Divan, L., 218, 345, 352, 354, 359, 362-4, 380, 410.
Dyer, E.R., 141.

Eddington, A.S., 124.
Eggen, O.J., 41, 159, 288, 290, 293, 294, 298, 314, 315, 404, 410, 521.
Einstein, A., 483, 484, 486.

Feast, M.W., 70, 71, 73, 202.
Fermi, E., 269, 451, 458.
Fields, P.R., 278.
Fleischer, R., 120.
Fong, P., 270, 278.
Fowler, W.A., 56, 278, 498-500. *P*: 269. *D*: 57, 121, 143, 168, 190, 215, 283, 426, 459.
Fresa, A., 97, 99.
Friedmann, A., 475, 477.
Fringant, A-M., 345, 350, 352, 354, 359, 380.

Gamow, G., 6, 44, 269, 270, 272, 283, 284, 482, 486.
Gaposchkin, S., 99, 171, 172, 174, 180, 309.
Gascoigne, S.C.B., 197.
Gent, H. van, 311, 315.
Gliese, W., 141.
Greenstein, J.L., 120, 141, 142, 246, 262, 272, 278, 296, 298, 302, 381, 453, 458.
Gyldenkerne, K., 410, 411.

Halliday, I., 239, 240, 241, 385, 410.
Härm, R., 226.
Haro, G., 135-8, 140, 141, 171, 493.
Harris, D.L., 251, 255, 256, 258, 264, 288, 290, 297, 298, 400, 404, 405, 410.
Harrison, F.B., 278.
Haselgrove, C.B., 124, 225, 278.
Hayashi, C., 270, 278.
Heckmann, O., *D*: 22, 38, 57, 100, 168, 190, 316, 328, 344, 426, 459, 473, 487, 517.
Heeschen, D., 27, 30.
Helmholtz, H. von, 152, 153, 493.
Henize, K.G., 195, 199.
Henyey, L.G., 142, 149, 152, 153, 158, 207.
Herbig, G.A., 90, 98, 141, 186, 492, 493, 512. *P*: 127. *D*: 22, 100, 121, 143, 159, 190, 215, 263, 299, 459.
Herk, G. van, 93, 319.
Herman, R.C., 278.
Herschel, J., 71.
Hertzsprung, E., 47, 57, 58, 65, 209, 210, 214, 231, 233, 342.
Hill, E.R., 417.
Hiltner, W.A., 396, 400, 410.
Hindman, J.V., 19, 21.
Hogg, H.S., 49.
Holmberg, E., 8, 21, 86, 87.
Hossack, W.R., 385, 410.
Houck, T.E., 462.
Howard, R., 226, 297, 298.
Hoyle, F., 6, 8, 10, 21, 54, 56, 237, 249, 262, 272, 273, 278, 420, 421, 440, 456, 507, 508, 531-2, 535-8. *P*: 223, 279, 435, 491. *D*: 22, 57, 121, 143, 159, 190, 215, 228, 283, 299, 441, 459, 487, 517.
Huang, S.S., 96, 97, 99.
Hubble, E., 13, 475, 476, 482.
Huizenga, J.R., 275, 278.
Hulst, H.C. van de, 16, 21, 27, 30, 120, 448, 455, 458.
Humason, M.L., 192, 262, 313, 314, 315, 343, 416.
Hunger, K., 145.
Hynek, J.A., 403, 410.

Jeans, J., 96.
Johnson, H.L., 5, 7, 8, 21, 41, 55, 56, 157, 158, 201, 210, 246, 251, 255, 257, 262, 288, 293, 297, 298, 365, 380, 381, 393, 395, 396, 400, 404, 410, 496.
Johnson, H.M., 220, 334, 343.
Joy, A.H., 97, 140, 141, 143, 166, 167, 217, 245, 262, 316, 319, 323, 343.

Kapteyn, J.C., 75, 105, 120.
Keenan, P.C., 188, 189, 190, 245-7, 262, 323.
Keller, G., 246, 247, 262, 482, 486.
Kellman, E., 262.
Kelvin, Lord, 130, 132, 133, 143, 147, 149, 493.
Kerr, F.J., 19, 21, 30.

Kholopov, P., 141.
Kienle, H., 382.
King, I., 65, 66.
Knuckles, C.F., 255, 257, 262, 297, 298, 365, 380, 410.
Koelbloed, D., 196.
Kopal, Z., 97, 98, 99.
Kourganoff, V., 142.
Kramers, H.A., 160.
Krat, V.A., 98.
Kron, G., 83.
Kruse, H.W., 278.
Kuiper, G.P., 78, 90, 96, 131, 133, 219, 245, 262.
Kukarkin, B.W., 304, 315.
Kushwaha, R.S., 125, 210, 216, 228.

Labs, D., 382.
Langebartel, R.G., 34, 37.
Lauritsen, C.C., 278.
Lauritsen, T., 278.
LeLevier, R., 142, 149, 152, 158.
Lemaître, G., 486, 505. *P*: 475. *D*: 283, 441, 487.
Levée, R.D., 142, 149, 152, 158.
Lilley, A.E., 453, 458.
Lindblad, B., 37, 246, 262, 385, 386, 410, 505. *P*: 33, 467. *D*: 38, 121, 190, 215, 263, 299, 316, 328, 344, 381, 411, 426, 473, 517.
Lindsay, E.M., 196.
Lohmann, W., 306, 315.
Luyten, W., 75, 78, 90, 91, 95, 105, 110, 113.

Maanen, A. van, 319, 380.
McCarthy, M.F., 180, 184, 189.
McCuskey, S.W., 75, 78, 79, 90, 172, 184, 189.
McGuire, A.D., 278.
McKellar, A., 194.
McLaughlin, D.B., 304, 315.
MacRae, D.A., 120.
Martynov, D.J., 98.
Mathis, J.S., 221.
Mayall, N.U., 21, 304, 305, 307, 313, 315, 325, 460, 516.
Menneret, C., 345, 350, 359, 380.
Merrill, P.W., 188, 189.
Mestel, L., 457, 458.
Michard, R., 298.
Miller, W.J., 22.
Milne, E.A., 480.
Minkowski, R., 30, 188, 189.
Mitchell, R.J., 404, 410.
Morgan, W.W.: 7, 17, 21, 41, 85, 87, 88, 140, 188, 189, 201, 245, 247, 255, 262, 288, 293, 303, 305, 307, 313-5, 393, 400, 410, 411, 503, 505, 510, 511, 513, 516. *P*: 323, 325. *D*: 22, 57, 91, 100, 143, 168, 181 ,190, 203, 263, 299, 316, 328, 426, 459, 517.
Muller, C.A., 120, 455, 458.
Muller, W., 124.
Münch, G., 120, 381.
Münch, L., 184, 185, 186, 189.

Nail, V. McK., 71, 72, 73.
Nassau, J.J., 180, 189, 526. *P*: 171, 183. *D*: 57, 121, 143, 159, 181, 190, 263, 316, 381, 459, 517.

Naur, P., 251, 262.
Neckel, H., 382.
Nishida, M., 270, 278.

O'Connell, D.J.K., 99, 505. *P*: 95. *D*: 22, 31, 38, 100, 203, 316, 426, 459, 517.
Odgers, G.J., 96, 99.
Öhman, Y., 385, 410.
Oort, J.H., 19, 30, 120, 282, 455, 456, 458, 491, 497, 526, 531-2, 535-8. *P*: 25, 63, 415, 507. *D*: 31, 57, 73, 91, 121, 143, 168, 190, 215, 241, 299, 316, 411, 426, 441, 459, 473, 487, 517.
Oosterhoff, P.T., 49, 56, 317.
Öpik, E.J., 44, 231, 232, 456, 458.
Osterbrock, D.E., 120.

Parenago, P.P., 55, 56, 142, 149, 158.
Pavlovskaya, E.D., 55, 56.
Petrie, R.M., 265, 385, 410.
Poincaré, H., 96.
Popper, D.M., 246, 262.
Poveda, A., 30.

Raimond, E., 26, 30, 415.
Ramberg, J.M., 518.
Reines, F., 278.
Reiz, A., 248, 262.
Rhijn, P.J. van, 75, 78, 81, 83, 88-91, 105, 110, 113, 494.
Roberts, M.S., 51, 52, 56, 87-90, 107, 120, 492, 506.
Robinson, B.J., 19, 21.
Roman, N.G., 218, 220, 245-7, 255, 256, 258, 262-4, 323, 333-5, 342, 343, 352, 362-4, 379, 380, 394, 410, 427, 432, 511.
Rougoor, W., 30.
Rudkjöbing, M., 216.
Russell, H.N., 209, 210, 214.

Sahade, J., 97, 99.
Salpeter, E.E., 57, 76-9, 81, 88, 90, 105, 109, 110, 112, 113, 120, 149, 151, 158, 159, 208, 240, 273, 287, 423, 494, 495, 512. *P*: 231. *D*: 91, 121, 143, 228, 241, 426, 441, 459, 487.
Sandage, A.R., 5-8, 21, 51, 52, 55, 56, 79, 82, 90, 105, 109, 110, 112, 113, 120, 210, 225, 233, 234, 236, 237, 239, 240, 246, 334, 342, 343, 493, 494, 496, 500, 502, 509-12. *P*: 41, 75, 149, 287. *D*: 22, 57, 91, 143, 159, 168, 181, 190, 215, 228, 241, 263, 299, 316, 328, 381, 426, 459, 517.
Savedoff, M.P., 5, 455, 456, 458.
Schatzman, E., 216.
Schmidt, M., 30, 418, 425.
Schönberg, M., 44, 46, 56, 208, 233.
Schwarzschild, B., 247, 262.
Schwarzschild, M., 6, 8, 21, 44, 54, 56, 82, 90, 120, 226, 237, 247, 249, 260, 262, 297, 298, 303, 315, 331, 418, 419, 423-5, 445, 446, 449, 450, 452, 458, 478, 495-8, 503, 508, 526. *P*: 207. *D*: 22, 57, 100, 121, 143, 159, 168, 190, 203, 215, 228,

263, 283, 299, 316, 328, 344, 381, 411, 426, 441, 459, 473, 517.
Searle, L., 297, 298.
Seeliger, H. von, 75.
Shapley, H., 48, 61, 62, 69, 71-3, 195, 199, 317.
Skumanich, A., 214, 454, 458.
Smith, E.v.P., 185, 186, 189.
Smith, H.J., 185, 186, 189.
Sobolev, W.W., 138.
Spitzer, L., 81, 90, 120, 247, 262, 420, 423-5, 451, 458, 494, 501. *P*: 445. *D*: 22, 31, 57, 73, 91, 121, 143, 159, 168, 215, 228, 241, 263, 283, 299, 328, 411, 426, 441, 459, 487, 517.
Stebbins, J., 16, 21, 83, 85, 313, 315, 329.
Stewart, R.W., 96, 99.
Stibbs, D.N., 316.
Stock, J., 68.
Stromberg, G., 231, 232.
Strömgren, B., 54, 64, 410, 452, 509, 511. *P*: 245, 385. *D*: 31, 57, 143, 168, 215, 228, 241, 263, 328, 381, 411, 426, 459, 517.
Struve, O., 95, 96, 97, 99, 140, 301.
Suess, H.E., 270, 276, 278.
Swihart, T.L., 248, 262.
Swope, H., 10, 86, 87, 88, 512.

Tayler, R.J., 82, 90.
Teller, E., 272.
Thackeray, A.D., 19, 21, 202, 505, 513. *P*: 69, 195. *D*: 73, 121, 143, 159, 203, 263, 316, 426, 441, 459.
Thiessen, G., 100.
Trumpler, R.J., 44, 63, 68, 240, 424, 425.
Tukey, J., 451, 458.
Tulder, J.J.M. van, 308.
Turkevich, A., 269.

Urey, H.C., 270, 276, 278.

Van't Veer, F., 345, 362, 365, 380.
Vassy, E., 385, 410.
Vaucouleurs, G. de, 30.
Velghe, A.G., 180, 185, 189.
Volders, L.M.J.S., 26, 30.
Vyssotsky, A.N., 141, 214, 334, 343.

Wachmann, A.A., 22.
Walker, M.F., 5, 139, 142, 150, 151, 155, 157-9, 210, 246, 464, 493.
Weaver, H.F., 240, 350, 380.
Weitbrecht, R.H., 408, 410.
Weizsäcker, C.F. von, 457, 458.
Wesselink, A.J., 19, 21, 69-71, 196, 197, 199, 202.
Westerhout, G., 27, 30.
Westerlund, B., 180, 345, 362, 380, 385, 410.
Whitford, A.E., 16, 21, 62, 85, 313, 315, 502.
Wildt, R., 247, 262.
Wilson, O.C., 82, 90, 241.
Woerden, H. van, 30.
Woltjer, L., 460.
Wood, F.B., 98.

Zwicky, F., 193, 416, 423.

INDEX

PAGE

INTRODUCTION IX

LA SEMAINE D'ETUDE SUR LE PROBLÈME DES POPULATIONS STELLAIRES XV

L'AUDIENCE ET LE DISCOURS DU SAINT PÈRE XXIX

LA SÉANCE ORDINAIRE DE L'ACADEMIE LI

LES SEMAINES D'ETUDE ET LEUR RÈGLEMENT LVII

I. LES GALAXIES ET LEURS POPULATIONS STELLAIRES

1. W. BAADE: Galaxies and their Stellar Populations. (A Review of the Present State of Affairs) 3
   Discussion 22

2. J.H. OORT: Neutral Hydrogen in Galaxies 25
   Discussion 31

3. B. LINDBLAD: The Population Types and the Evolution of Barred Spirals 33
   Discussion 38

II. AMAS STELLAIRES DE NOTRE GALAXIE COMME REPRESENTANTS DES POPULATIONS STELLAIRES

PAGE

1. A. SANDAGE: The Color-Magnitude Diagrams of Galactic and Globular Clusters and their Interpretation as Age Groups 41
Discussion 57

2. A.D. THACKERAY: 47 Tucanae - an Interim Report . . 69
Discussion 73

3. A. SANDAGE: Luminosity Function of Galactic Clusters, Globular Clusters and Elliptical Galaxies 75
Discussion 91

4. D.J.K. O'CONNELL: Note on Binaries and Theories of Stellar Evolution 95
Discussion 100

III. ETOILES JEUNES DE LA POPULATION I DANS LES BRAS SPIRAUX DE NOTRE GALAXIE

1. A. BLAAUW: Stellar Associations 105
Discussion 121

2. G.H. HERBIG: T Tauri Stars, Flare Stars, and Related Objects as Members of Stellar Associations . . . 127
Discussion 143

PAGE

3. A. SANDAGE: NGC 2264 and M 8 as Examples of Very Young Stellar Associations which are Still Partly in the Stage of Kelvin Contraction 149
Discussion 159

IV. ETOILES VARIABLES PHYSIQUES ET POPULATIONS STELLAIRES. QUELQUES TYPES SPECIAUX D'ETOILES

1. W. BAADE: Physical Variable Stars and Stellar Populations 165
Discussion 168

2. J.J. NASSAU: M-Type Stars and Red Variables in the Direction of the Galactic Centre 171
Discussion 181

3. J.J. NASSAU: Carbon and S-Type Stars 183
Discussion 190

4. A.D. THACKERAY: The Magellanic Clouds and Stellar Populations 195
Discussion 203

V. L'EVOLUTION STELLAIRE ET L'ABONDANCE DES ELEMENTS

1. M. SCHWARZSCHILD: Theory of Stellar Evolution and the Age Sequence of Stellar Populations 204
Discussion 215

2. F. HOYLE: Remarks on the Computation of Evolutionary Tracks 223
Discussion 228

PAGE

3. E.E. SALPETER: Statistics of Stellar Evolution 231
Discussion 241

4. B. STRÖMGREN: Composition Differences Between Stellar Populations 245
Discussion 263

5. W.A. FOWLER: Nuclear Processes and Element Synthesis in Stars 269

6. F. HOYLE: The Astrophysical Implications of Element Synthesis 279
Discussion of the two preceding papers 283

VI. POPULATIONS STELLAIRES DE NOTRE GALAXIE

1. A. SANDAGE: The Stars Within 15 Parsecs of the Sun . . 287
Discussion 299

2. W. BAADE: The Population of the Galactic Nucleus and the Evidence for the Presence of an Old Population Pervading the Whole Disk of our Galaxy 303
Discussion 316

3. W.W. MORGAN: Some Characteristics of the Strong and Weak-Line Stars 323

4. W.W. MORGAN: Some Features of Stellar Populations as Determined from Integrated Spectra 325
Discussion of the two preceding papers 328

PAGE

5. A. Blaauw: Kinematic Properties of the Strong and Weak-Line Stars 333
Discussion 344

6. D. Chalonge: Classification Spectrophotométrique des Populations Stellaires 345
Discussion 381

7. B. Strömgren: Spectrophotometric Classification of the Population Groups 385
Discussion 411

VII. GROUPES DE POPULATIONS ET FONCTIONNEMENT CINEMATIQUE DANS NOTRE GALAXIE.

ÉVOLUTION DE NOTRE GALAXIE

1. J.H. Oort: Dynamics and Evolution of the Galaxy, in so far as Relevant to the Problem of the Populations . 415
Discussion 426

2. F. Hoyle: On the Formation of Galaxies and Type II Stars 435
Discussion 441

3. L. Spitzer: Mass Exchange with the Interstellar Medium and the Formation of Type I Stars 445
Discussion 459

4. B. Lindblad: The Vertex Deviation of the Velocity Ellipsoid and the Evolution of Type I Stars in our Galaxy 467
Discussion 473

PAGE
5. G. Lemaître: Instability in the Expanding Universe and its Astronomical Implications 475
Discussion 487

VIII. RESUME DES DISCUSSIONS ET CONCLUSIONS

1. F. Hoyle: Summary - From a Physical Point of View 491
2. J.H. Oort: Summary - From the Astronomical Point of View 507
Discussion of the Summaries 517
Supplement aux Conclusions 531
INDEX DES NOMS PROPRES 539