PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA

25

SEMAINE D'ETUDE

SUR

LE PROBLEME DU RAYONNEMENT COSMIQUE DANS L'ESPACE INTERPLANETAIRE

(1-6-X-1962)

PONTIFICIA
ACADEMIA
SCIENTIARVM

EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA

MCMLXIII

PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA

25

SEMAINE D'ETUDE

SUR

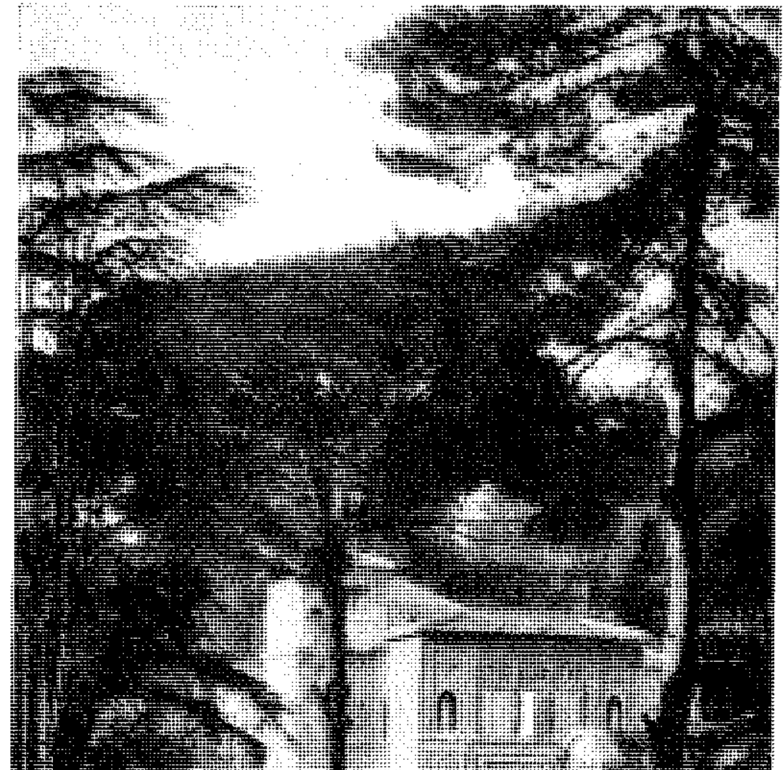
LE PROBLEME DU RAYONNEMENT COSMIQUE DANS L'ESPACE INTERPLANETAIRE

(1 - 6 - X - 1962)

PONTIFICIA
ACADEMIA
SCIENTIARVM

EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA

MCMLXIII



LE PROBLEME DU RAYONNEMENT COSMIQUE DANS L'ESPACE INTERPLANETAIRE

Avant la découverte du rayonnement cosmique par Victor Francis Hess à la veille de la première guerre mondiale et la découverte des ondes électromagnétiques d'origine spatiale faite presque simultanément, la lumière visible représentait le seul moyen pour l'observation de l'univers dans lequel nous vivons.

Depuis, ces deux découvertes sont devenues de puissantes sources d'information et elles ont contribué, toutes les deux, à augmenter énormément le volume de nos nouvelles connaissances.

En particulier, la première de ces découvertes nous a fourni un moyen efficace pour l'étude interplanétaire et de l'espace plus lointain.

Le lancement des satellites artificiels et des véhicules spatiaux munis d'instruments de mesure très sensibles, a donné un nouvel élan à l'étude des rayons cosmiques avant leur arrivée sur la terre et avant leur passage à travers l'atmosphère terrestre.

Ceci a mené à la découverte de ceintures de radiations qui entourent la terre et qui sont composées de particules d'énergie moyenne captées par le champ géomagnétique.

L'émission de particules par le soleil, qui coïncide surtout avec l'apparition de grandes éruptions solaires et qui a été découverte au cours d'expériences avec des ballons volant à grande altitude, a été confirmée.

Simultanément, avec l'émission de particules avec charge électrique et d'autres formes de radiations, le soleil émet de grands nuages de plasma qui affectent le champ magnétique terrestre extérieur et qui modulent l'intensité du rayonnement cosmique.

Toutes ces découvertes ont donné naissance à un grand nombre de problèmes nouveaux.

Désormais le temps est mûr pour une fructueuse discussion de certains de ces nouveaux problèmes.

Une question cruciale est certainement de déterminer quels sont les composants solaires, galactiques et extra-galactiques des rayons cosmiques; en d'autres termes quels sont, parmi eux, les rayons vraiment cosmiques (galactiques ou extra-galactiques) et quels sont les rayons solaires.

Quels sont les critères qui permettent de les distinguer les uns des autres? Quelles recherches doivent être faites encore pour pouvoir répondre à ces questions? Quel est le rapport entre les ceintures de grande intensité découvertes par VAN ALLEN et les rayons cosmiques, en tant que différents des rayons solaires? Quelle est l'influence du plasma solaire sur le champ magnétique terrestre extérieur? Quel est le mécanisme de la modulation de l'intensité des rayons cosmiques?

Voici quelques-uns des problèmes qui ont été discutés au cours de la présente Semaine d'Etude.

PIETRO SALVIUCCI
Chancelier de l'Académie

LA SEMAINE D'ETUDE

SUR

LE PROBLEME DU RAYONNEMENT COSMIQUE DANS L'ESPACE INTERPLANETAIRE

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

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

« Un tel procédé semble devoir être particulièrement utile sous ce rapport: 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 du rayonnement cosmique dans l'espace interplanétaire » (1).

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

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

---

(1) Cette « Semaine d'Etude » sur « Le Problème du rayonnement cosmique dans l'espace interplanétaire » est la cinquième 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 7ème volume des « Scripta Varia » de l'Académie; ils représentent un volume de 364 pages.

La deuxième « Semaine d'Etude » a eu lieu du 19 au 26 novembre 1951; elle a été dédiée au « Problème des Microséismes », et a été présidée par l'Académicien Pontifical S. E. FRANCESCO VERCELLI, Directeur de l'Institut Thalassographique et de l'Observatoire Géophysique de Trieste; y ont participé personnellement 15 savants tandis que 4 autres ont envoyé des mémoires. Les comptes-rendus de la « Semaine d'Etude » ont été publiés dans le 12ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 466 pages.

La troisième « Semaine d'Etude » a eu lieu du 24 avril au 2 mai 1955; elle a été 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

A cet effet ont été invités par l'Académie des experts qualifiés en physico-chimie, en physique théorique, cosmique et nucleaire, en géophysique, radiophysique et radioastronomie, qui, grâce à leurs études spécifiques, ont contribué à la connaissance différentielle du rayonnement cosmique dans l'espace interplanétaire.

La présidence de cette « Semaine d'Etude » sur « Le Problème du rayonnement cosmique dans l'espace interplanétaire » a été confiée par le Président de l'Académie Pontificale des Sciences, S.E. le Rév.me Monseigneur GEORGES LEMAÎTRE, à l'Académicien Pontifical S.E. VICTOR FRANCIS HESS, Professeur émérite de Physique à l'Université Fordham de New York, et l'organisation générale au Chancelier de l'Académie Pontificale des Sciences Dr. PIETRO SALVIUCCI.

Malheureusement l'Académicien VICTOR FRANCIS HESS, l'insigne savant qui découvrit l'existence des rayons cosmique, n'a pas pu, en

---

végétale de l'Université de Madrid, Secrétaire Général du Conseil Supérieur des Recherches Scientifiques d'Espagne; y ont participé personnellement 10 savants tandis qu'un autre a envoyé un mémoire. Les comptes-rendus de la « Semaine d'Etude » ont été publiés dans le 14ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 630 pages.

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

La cinquième « Semaine d'Etude » a eu lieu du 23 au 31 octobre 1961; elle a été dédiée au « Problème des macromolécules d'intérêt biologique avec référence spéciale aux nucléoprotéides », et a été présidée par l'Académicien Pontifical S.E. ARNE TISELIUS, Professeur de Biochimie à l'Université de Uppsala; y ont participé personnellement 28 savants. Les comptes-rendus de la « Semaine d'Etude » ont été publiés dans le 22ème volume des « Scripta Varia » de l'Académie; ils forment un volume de 544 pages.

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

raison de son état de santé, être présent et c'est le Président de l'Académie, lui-même, S.E. GEORGES LEMAÎTRE qui dirigea les études.

Ont été invités à la réunion les savants suivants:

Prof. Dr. EDOARDO AMALDI, Professeur de Physique à l'Université de Rome et Président de l'Institut National de Physique nucléaire. - *Rome* (Italie).

S.E. Prof. Dr. HERMANN ALEXANDER BRÜCK, Académicien Pontifical Astronome Royal pour l'Ecosse et Professeur d'Astronomie à l'Université d'Edimbourg. - *Edinburg* (Grande-Bretagne).

Prof. Dr. LUDWIG BIERMANN, Professeur honoraire de l'Université de Münich, et Membre de l'Académie Internationale d'Astronautique. - *München* (Allemagne).

Prof. Dr. LUCIEN BOSSY, Directeur de la Station ionosphérique de Dourbes, de l'Institut Royal Méteorologique de Belgique. - *Uccle - Bruxelles* (Belgique).

S.E. Sir Prof. Dr. JAMES CHADWICK, Académicien Pontifical, Professeur de Physique à l'Université de Liverpool, Prix Nobel 1935 pour la physique. - *Cambridge* (Grande-Bretagne).

Prof. Dr. GIUSEPPE COCCONI, Professeur de Physique à la Cornell University. - *Ithaca, N.Y.* (U.S.A.).

Prof. Dr. JEAN FRANÇOIS DENISSE, Astronome titulaire de l'Observatoire de Paris, Directeur de la Station de Radioastronomie de Nançay, Président de la Commission de Radioastronomie de l'Union Astronomique Internationale. - *Paris* (France).

Prof. Dr. RENÉ DE VOEGELAERE, Professeur de Mathématiques au Department of Matematics, University of California. - *Berkeley, Calif.* (U.S.A.).

Prof. Dr. HENRY ELLIOT, Professeur de Physique à l'Imperial College of Sciences and Technology de l'Université de Londres et Chef de la Section pour les Rayons cosmiques. - *London* (Grande-Bretagne).

Prof. Dr. ISMAEL ESCOBAR VALLEJO, Directeur du Laboratoire de Physique cosmique de l'Université de La Paz et Directeur de la Commission Nationale pour l'Energie nucléaire. - *La Paz* (Bolivie).

Prof. Dr. SCOTT ELLSWORTH FORBUSH, Président de l'Analytical and Statistical Geophysics de l'Institut Carnegie de Washington. - *Washington* (U.S.A.).

S.E. Rev. Prof. ERNESTO GHERZI, Académicien Pontifical, Directeur des recherches à l'Observatoire Géophysique du Collège « Jean de Brébeuf ». - *Montréal* (Canada).

Prof. Dr. THOMAS GOLD, Professeur d'Astronomie à la Cornell University, Directeur du Centre pour la Radiophysique et pour les Recherches spatiales. - *Ithaca, N.Y.* (U.S.A.).

Prof. Dr. SATIO HAYAKAWA, Professeur de Physique à l'Université de Nagoya. - *Nagoya* (Japon).

S.E. Prof. Dr. VICTOR FRANCIS HESS, Académicien Pontifical, Professeur émérite de Physique à l'Université Fordham, Prix Nobel 1936 pour la Physique. - *New York, N.Y.* (U.S.A.).

S.E. Mgr. Prof. Dr. GEORGES LEMAÎTRE, Président de l'Académie Pontificale des Sciences, Professeur de Mécanique et de Méthodologie mathématique à l'Université Catholique de Louvain - *Louvain* (Belgique).

S.E. Prof. Dr. LOUIS LEPRINCE-RINGUET, Académicien Pontifical, Professeur de Physique nucléaire au Collège de France. - *Paris* (France).

Prof. Dr. HENRY VICTOR NEHER, Professeur de Physique au California Institute of Technology à Pasadena. - *Pasadena, Calif.* (U.S.A.).

Prof. Dr. EDWARD PURDY NEY, Professeur de Physique à l'Université de Minnesota. - *Minnesota, Minn.* (U.S.A.).

S.E. Prof. Dr. JAN HENDRIK OORT, Académicien Pontifical, Professeur d'Astronomie à l'Université et Directeur de l'Observatoire de Leiden, Président de l'Union Astronomique Internationale- *Leiden* (Pays-Bas).

Prof. Dr. EUGÈNE NEWMAN PARKER, Professeur de Physique à l'Université de Chicago. - *Chicago, Ill.* (U.S.A.).

Prof. Dr. BERNARD PETERS, Professeur de Physique théorique à l'Université de Kobenhavn. - *Kobenhavn* (Danemark).

Prof. Dr. ERNEST C. RAY, du « Goddard Space Flight Center ». - *Greenbelt, Md.* (U.S.A.).

Prof. Dr. BRUNO BENEDETTO ROSSI, Professeur de Physique au Massachusetts Institute of Technology et Directeur du Laboratoire de Physique de l'espace. - *Cambridge* (U.S.A.).

S.E. Prof. Dr. MANUEL SANDOWAL VALLARTA, Académicien Pontifical, Professeur de Physique théorique au Colegio Nacional et à l'Université de Mexico, Chargé de la recherche scientifique à la Commission Nationale de l'Energie Nucléaire du Mexique. - *Ciudad de Mexico* (Mexique).

Prof. Dr. JOHN ALEXANDER SIMPSON, Professeur à l'Institut pour les Etudes nucléaires « Enrico Fermi » de l'Université de Chicago. - *Chicago, Ill.* (U.S.A.).

Prof. Dr. FRED SINGER, Professeur de Physique à l'Université de Maryland, Inspecteur de recherches auprès du Jet Propulsion Laboratory à l'Institut Technologique de Californie. - *Pasadena, Calif.* (U.S.A.).

Tous les invités, à l'exception de l'Académicien J. CHADWICK, du Prof. G. COCCONI et de l'Académicien V.F. HESS qui n'ont pas pu intervenir, ont participé à la Réunion.

Le Président de la « Semaine d'Etude » a fait appel à son collègue l'Académicien S.E. MANUEL SANDOVAL VALLARTA pour l'organisation scientifique de la réunion à laquelle ont participé comme Secrétaires scientifiques: Prof. Dr. FRANCESCA ROMANA BACHELET, Prof. Dr. ANNA MARIA CONFORTO, Dr. ERIK DYRING et Dr. GUIDO PIZZELLA.

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

Ont aussi participé à la réunion: en qualité d'interprète et chef de Secrétariat Mme VALENTINE PRÉOBRAJENSKI; en qualité de sténographes polyglottes de séance Mlles MAURA BALOCCO et PAMELA SUTTON; en qualité de sténo-dactylographes polyglottes chargées des Procès-verbaux: Mlle VALERIA CRAJA, Mlle JOSÉPHINE LUCAS et Mme PAULETTE ROSSALDI; en qualité de technicien pour l'enregistrement et la projection, Mr MAURO ERCOLE, assisté par des opérateurs de Radio-Vatican. Le Bureau de Presse était confié au Dr. FRANCESCO SALVIUCCI, Coadjuteur du Chancelier de l'Académie.

Le Comité de Réception pour les Dames dirigé par Mlle MARIA LUISA LOTTI, était composé de la Comtesse KARINA CALVI DI COENZO, Mlle GIOVANNA LOTTI, Mlle ANNA MARIA MILAZZO, Mlle SANDRA ORLANDI, Mlle MARILENA VALLETTI.

Le vendredi 5 octobre tous les Participants ont été reçus en Audience Solennelle par le Souverain Pontife qui leur adressa un discours et après l'Audience a eu lieu, au Siège de l'Académie Pontificale des Sciences, une séance extraordinaire de l'Académie, à laquelle ont été invités également les Participants à la « Semaine d'Etude ».

Pendant la Semaine, qui se déroula jusqu'au soir du samedi 6, les travaux scientifiques se poursuivirent sans interruption. Les discussions des différents 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 Participants qui, à la fin de leurs travaux, ont tenu à exprimer au Saint Père leur profonde gratitude et leur très sincère admiration pour cette manifestation scientifique si réussie, en envoyant à l'Auguste Pontife, animateur et mécène de l'Académie, le télégramme suivant:

« *Sa Sainteté le Souverain Pontife* JEAN XXIII - *Cité du Vatican. — Les Participants de la Semaine d'Etudes sur le problème du rayonnement cosmique dans l'espace interplanétaire prient Sa Sainteté de daigner accepter l'expression de leur admiration et de leur gratitude pour les conditions idéales de quiétude et d'indépendance qui leur ont permis de travailler à l'approfondissement de problèmes de grande actualité et d'avoir eu, en pleine liberté, des échanges de vues hautement profitables au progrès de la science et de l'humanité.* — AMALDI, BIERMANN, BOSSY, BRÜCK, DENISSE, DE

VOGELAERE, ELLIOT, ESCOBAR, FORBUSH, GHERZI, GOLD, HAYAKAWA, LEMAÎTRE, LEPRINCE RINGUET, NEHR, NEY, OORT, PARKER, PETERS, RAY, ROSSI, SANDOVAL VALLARTA, SIMPSON, SINGER ».

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

« *Prof. Dr.* PIETRO SALVIUCCI, *Chancelier Académie Pontificale des Sciences Cité du Vatican. — Saint-Père très touché déférent message Participants récente Semaine Etudes sur problème rayonnement cosmique dans espace interplanétaire se réjouit heureux déroulement savants échanges de vues invoque tout coeur sur distingués signataires abondance divines Bénédictions.* — AMLETO GIOVANNI *Card.* CICOGNANI ».

A la fin de la Semaine d'Etude l'Academicien Pontifical S. E. LOUIS LEPRINCE RINGUET qui tenait la présidence de la dernière séance a été prié par ses collègues de dire quelques mots de clôture.

Nous reproduisons ici son improvisation telle qu'elle a été enregistrée pour en conserver toute sa sympathique spontaneité.

« Vous m'avez demandé de faire quelques remarques pour clôre cette excellente Conférence. Je suis très peu capable de faire des remarques sur le sujet en cause, parce que je suis un transfuge des rayons cosmiques que j'ai abandonnés, maintenant, depuis beaucoup d'années, sous la pression des machines, sous la pression des syncrotrons qui eux sont sur terre. J'ai été obligé à celà à cause de la proximité du syncrotron de Saclay, et du syncrotron du CERN, et aussi à cause du désir de mes collaborateurs d'orienter notre activité vers les machines.

« Je suis donc très heureux aujourd'hui de me retrouver avec beaucoup de mes anciens amis des rayons cosmiques et de voir quel énorme chemin a été parcouru depuis la Conférence de Bagnères de Bigorre en 1953 ou à côté du sujet principal, les mèsons lourds et les interactions nucléaires, il y eut un petit congrès avec DAUDIN sur l'ensemble des effets que l'on étudie ici aujourd'hui: congrès dont les membres continuèrent et continuent de s'interésser aux rayons cosmiques.

« Parmi les anciens, il y a d'une part ceux qui ont quitté les rayons cosmiques pour devenir un peu les esclaves des machines, et les autres — je vois — qui sont restés dans des groupes qui peuvent encore réfléchir, se poser des problèmes, ne pas aller trop vite, faire des hypothèses sur des modèles, et celà est excellent. Ces anciens qui ont eu la sagesse de rester les seigneurs des rayons cosmiques, eh bien, ils ont maintenant des groupes plus importants, avec la possibilité d'utiliser des techniques nouvelles; par exemple, des techniques de très grandes gerbes ne pouvaient se concevoir il y a dix ans. Elles se développent maintenant grâce aux perfectionnements des scintillateurs, des électroniques, etc. Des même, les techniques utilisées avec les satellites permettent et permettront d'avoir des réponses à beaucoup de problèmes.

« Si bien que, maintenant, je m'aperçois et je remarque que le soleil, l'environnement solaire, la région interplanétaire, est devenue un véritable laboratoire. C'est un laboratoire dans lequel on peut accéder grâce à beaucoup d'expériences possibles, que l'on peut et que l'on va faire, de plus en plus précises, sur le champ magnétique, sur les particules, sur les directions, etc. Celà va permettre d'expliquer beaucoup des phénomènes caractériques de cette région. C'est très important pour les connaissances des espaces plus lointains, car, par exemple, on a parlé des électrons de la nébuleuse du Crabe qui peuvent être observés par les moyens, eux aussi nouveaux, de la radio-astronomie.

« On ne peut rien dire maintenant des particules nucléaires qui accompagnent ces processus dans la nébuleuse du Crabe ou dans le voisinage. Mais si l'on étudie les émissions du soleil à l'échelle des distances entre le soleil et la terre, on pourra probablement avoir des explications meilleures sur ce qui se passe beaucoup plus loin, et en particulier sur l'origine des rayons cosmiques.

« Il y a d'autre part quelque chose qui m'a beaucoup impressionné. Comme Peters est parti, je peux parler de lui. Notamment on peut, maintenant, unir les expériences des grands syncrotrone et des satellites. Les problèmes que Peters posait, sur la composition du rayonnement cosmique, sur le beryllium 10, sur le temps pendant lequel les rayons cosmiques voyagent avant d'être recueillis, peuvent se résoudre grâce à l'utilisation simultanée des satellites et de la machine du CERN. Autrement dit, cela correspond à des possibilités nouvelles, des possibilités de connection entre les deux anciennes branches, très jumelles, des rayons cosmiques, qui se retrouvent ainsi pour des problèmes nouveaux.

« Je voudrais souligner maintenant l'intérêt des Semaines d'Etudes: l'intérêt de *cette* Semaine d'Etudes en particulier. Qu'est ce que nous avons comme réunions entre physiciens? Nous avons des petites réunions qui sont des séminaires de laboratoire, faites dans l'intérieur d'un laboratoire sur le sujet qui correspond au travail même du laboratoire, et puis nous avons de grands meetings, de grandes réunions. Dans notre domaine il y a le fameux Congrès de Rochester, *extrêmement* sélectionné, et cette sélection — il y a une pression, un peu comme la pression magnétique — fait que le nombre de cinq cents personnes de cette année va augmenter et devenir huit cents personnes au prochain Congrès de Rochester. Par conséquent, celà n'est plus une réunion très intime, il faut parler pendant un temps parfaitement défini, il y a des lumières rouges qui s'allument, une sonnette qui fonctionne, on coupe la parole, les exposés doivent être envoyés un mois à l'avance, etc. C'est déjà une chose beaucoup plus compliquée. Ce n'est pas très confortable; c'est intéressant, mais pas très confortable. Et puis il y a encore d'autres réunions; il y a les meetings de l'American Physical Society, et là on est deux mille, peut-être davantage, et l'on fonctionne en parallèle, avec un grand nombre de sessions qui se tiennent en même temps. Chacun a droit à dix minutes pour parler et pas une de plus: après huit ou neuf minutes une lampe rouge s'allume, et après dix minutes le suivant prend la parole et celà pendant plusieurs jours.

« Alors, cette Semaine d'Etudes d'aujourd'hui, organisée par l'Académie Pontificale des Sciences, est merveilleuse, puisque les discussions ont été très nombreuses, les exposés longs, et personne ne les a coupés. Le Chairman n'a pas arrêté Gold, n'a pas arrêté... (*rires*)... n'a pas arrêté... n'a arrêté personne, et finalement tout est très intéressant. On a groupé les principaux chefs et les principaux spécialistes des différents Pays et je crois que l'ensemble des exposés et des discussions a été tout-à-fait remarquable, tout-à-fait excellent. Chacun a pu parler, recommencer certaines discussions, nous étions très bien dans ce cadre, nous n'avons pas été pressés. On a la certitude d'avoir bien compris les choses, les problèmes, les difficultés, ce qui est sûr et ce qui n'est pas sûr, beaucoup plus que dans un grand congrès. En outre, l'absence de tout public permet de nous sentir comme en famille, de parler avec la certitude d'être parfaitement compris et cela porte aux conclusions plus sûres et plus rapides. Donc, je crois qu'il est très bon d'avoir de temps en temps des réunions comme ces Semaine d'Etudes et il n'y en a pratiquement pas d'autres.

« Aussi cette Semaine d'Etudes qui s'est faite dans ces conditions très favorables, a été excellente et, je crois, très fructueuse pour tout le monde. De cela nous avons déjà exprimé au Souverain Pontife notre profonde et respecteuse gratitude par le télégramme que nous venons de lui adresser.

« Je voudrais aussi remercier l'Académie Pontificale des Sciences dans la personne de son Président, Monseigneur GEORGES LEMAITRE, qui est jeune et actif, et qui a présidé cette Semaine d'une manière admirable qui sera certainement très appréciée par notre collègue VICTOR FRANCIS HESS qui devait la présider, mais qui en a été malheureusement empêché par son état de santé. Je voudrais remercier essentiellement aussi le Prof. MANUEL SANDOVAL VALLARTA qui a eu la très lourde charge de choisir les participants et d'organiser les sessions scientifiques. Je voudrais remercier d'une façon spéciale le Chancelier PIETRO SALVIUCCI pour toute l'organisation de ce congrès et avec lui toutes les personnes qui l'ont aidé dans cette oeuvre et ont travaillé avec lui pour permettre à la Conférence de se développer parfaitement; mais je crois que son travail n'est même pas terminé maintenant, malheureusement pour lui. Et puis il faut remercier naturellement aussi tous ceux qui ont fait des exposés — tous ceux qui ont eu le courage de parler assez longtemps calmement, tranquillement, de discuter, de recommencer les discussions. Je crois qu'il faut les remercier beaucoup, et notamment ceux qui ont préparé les trois dernières revues synthètiques, les "review papers".

« Enfin, je voudrais dire un mot de plus: je crois que nous nous réjouissons tous du fait que, dans ce beau lieu de la pensée spirituelle qu'est Rome et qu'est ce petit coin des jardins du Vatican derrière Saint-Pierre, la voix scientifique soit invitée à s'élever; que nous soyons invités, nous scientifiques, à parler et à manifester les caractères de la science que nous connaissons bien et que nous aimons beaucoup.

« Certainement il y a dans toutes les études que nous faisons, que nous dirigeons, que font nos collaborateurs, une énorme somme, une très grande quantité de travail. Dans la vie scientifique et technique très moderne — nous utilisons les développements les plus récents de la technique avec enthousiasme — il nous faut également, nous le savons bien, beaucoup de patience pour aboutir. Il nous faut beaucoup d'imagination créatrice, aussi, pour envisager les expériences et pour pouvoir les discuter. Nous avons besoin aussi d'une scrupuleuse honnêteté et les scientifiques sont en effet terriblement honnêtes dans leurs expérimentations et dans leur travail.

« Nous avons également la certitude — l'assurance — que nous sommes très loin de tout connaître, et cela nous procure une grande fermeté dans notre travail, pour aller plus loin, et également une grande humilité. Je crois qu'on peut dire vraiment que les scientifiques — contrairement à l'idée que l'on se fait souvent — sont des gens très humbles. Il faut une humilité pour pouvoir changer la théorie que l'on avait envisagée et pour pouvoir s'adapter et suivre la réalité expérimentale qui doit toujours nous guider.

« Si bien que tout cela ce sont des qualités, ce sont aussi des valeurs — et même des valeurs spirituelles dans notre vie professionnelle.

« Je suis très heureux, et je pense que nous partageons tous cette satisfaction de voir encourager (hier, par exemple, cela a été encouragé par le Pape) cette fondamentale et merveilleuse activité qui est proposée aux hommes de toutes tendances depuis les temps les plus réculés, à savoir: la science ». (*Applaudissement*).

Dans les pages qui suivent, après le compte-rendu de l'Audience du Saint-Père et du « Règlement des Semaines d'Etude », sont imprimés les rapports originaux présentés à la Réunion, et les discussions qui les ont suivis, mis en ordre et publiés par les soins du Prof. Dr. FRANCESCA ROMANA BACHELET et du Dr. ERIK DYRING.

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

Pendant la Semaine, les travaux scientifiques se poursuivirent sans interruption sauf le matin du jeudi 4 pour visiter les Musées Pio-Clementino, Chiaramonti, Etrusque, Egyptien; le Braccio Nuovo; les Galeries des tapisseries, des cartes géographiques; les Chambres et les 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.

Les Participants ont aussi visité la Bibliothèque Apostolique Vaticane et les Archives Secrètes Vaticanes sous la conduite des Rév.mes Préfets Mons. MARTINO GIUSTI et Père ALPHONSE RAES, S.I. et la Station de Radio-Vatican qui leur fut présentée par le Directeur, le Rév.me Père ANTONIO STEFANIZZI S.I.

L'après-midi du vendredi 5, les Participants et leurs épouses visitèrent l'enceinte extraterritoriale suburbaine du Vatican à Castelgandolfo, où les savants étaient attendus par le Dr. Gr. Off. EMILIO BONOMELLI, Directeur des Villas Pontificales, qui leur a fait visiter en détail le Palais des Papes, les ruines de la villa romaine de Domitien, l'ex-Palais des Barberini, et les autres dépendances.

Enfin, le soir du même samedi 6 octobre, un dîner d'adieu a été offert par l'Académie, selon la coutume, aux savants participant à la « Semaine d'Etudes ».

L'AUDIENCE

ET

LE DISCOURS DU SAINT-PERE

Le matin du vendredi 5 octobre, 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 du rayonnement cosmique dans l'espace interplanétaire » tenue par l'Académie même. Ont participé aussi à l'Audience de nombreux hauts personnages.

Etaient présents Leurs Eminences les Cardinaux: EUGÈNE TISSERANT, Président honoraire de l'Académie; AMLETO GIOVANNI CICOGNANI, Secrétaire d'Etat et GIUSEPPE PIZZARDO, Académiciens honoraires; GIUSEPPE FERRETTO, GIACOMO LUIGI COPELLO, FERNANDO CENTO, CARLO CONFALONIERI, GIUSEPPE DA COSTA NUNES, EFREM FORNI, MICHELE BROWNE, ANSELMO ALBAREDA.

De nombreux Académiciens Pontificaux sont intervenus, et spécialement Leurs Excellences: le Rév.me Monseigneur GEORGES LEMAÎTRE Président, JOSÉ MARIA ALBAREDA-HERRERA, MARCELLO BOLDRINI, GIOVAMBATTISTA BONINO, HERMANN ALEXANDER BRÜCK, FREDRIK JACOBUS JOHANNES BUYTENDIJK, CARLOS CHAGAS FILHO, GUSTAVO COLONNETTI, EDWARD JOSEPH CONWAY, JOHN CAREW ECCLES, JOSÉ GARCIA-SIÑERIZ, ERNESTO GHERZI, GIORDANO GIACOMELLO, WERNER CARL HEISENBERG, CYRIL NORMAN HINSELWOOD, SVEN HÖRSTADIUS, ALBERTO HURTADO, LOUIS LEPRINCE-RINGUET, SAN-ICHIRO PAULO MIZUSHIMA, PAUL NIEHANS, JAN HENDRIK OORT, ENRICO PISTOLESI, LEOPOLD RUZICKA, MANUEL SANDOVAL-VALLARTA, HUGH STOTT TAYLOR, ARNE WILHELM KAURIN TISELIUS, THEODORE VON KARMAN; les Académiciens Pontificaux Surnuméraires; Rév. P. DANIEL JOSEPH

KELLY O'CONNELL S.I., Rév. P. JOSEF JUNKES S.I., Rév. P. ALPHONSE RAES S.I., Mgr. MARTINO GIUSTI, Rév. P. MICHAEL SCHULIEN S.V.D.; le Chancelier de l'Académie Prof. Dr. PIETRO SALVIUCCI et le Coadjuteur du Chancelier Dr. FRANCESCO SALVIUCCI.

Parmi le groupe des Académiciens assistaient les savants spécialistes « Participants » à la Semaine d'Etude sur « Le Problème du rayonnement cosmique dans l'espace interplanétaire » MM. les Professeurs: EDOARDO AMALDI, LUDWIG BIERMANN, LUCIEN BOSSY, JEAN FRANÇOIS DENISSE, RENÉ DE VOGELAERE, HENRY ELLIOT, ISMAEL ESCOBAR-VALLEJO, SCOTT ELLSWORTH FORBUSH, THOMAS GOLD, SATIO HAYAKAWA, HENRY VICTOR NEHER, EDWARD PURDY NEY, EUGENE NEWMAN PARKER, BERNARD PETERS, ERNEST C. RAY, BRUNO BENEDETTO ROSSI, JOHN ALEXANDER SIMPSON, S. FRED SINGER et les Secrétaires Scientifiques: Prof. Dr. FRANCESCA ROMANA BACHELET, Prof. Dr. ANNA MARIA CONFORTO, Dr. ERIK DYRING, Dr. GUIDO PIZZELLA.

Etaient également présents: Son Excellence Rév.me Monseigneur ANGELO DELL'ACQUA Substitut de la Secrétairerie d'Etat et le Chef du Protocole Rév.me Monseigneur IGINO CARDINALE; Son Excellence Rév.me Monseigneur CARLO GRANO Nonce Apostolique en Italie; 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, PIETRO SIGISMONDI, PRIMO PRINCIPI, BENIAMÍNO NARDONE, et autres personnalités de la Curie et de l'Etat de la Cité du Vatican.

Au complet le Corps Diplomatique accrédité près le Saint Siège, dont les Membres étaient reçus par le Gr. Uff. Dr. MARIO BELARDO.

Le Saint Père a fait son entrée dans la Salle du Consistoire à 9 heures, accompagné par sa Noble Antichambre avec LL.EE. Nosseigneurs FEDERICO CALLORI DI VIGNALE Majordome et MARIO NASALLI ROCCA DI CORNELIANO Maître de Chambre, par son Secrétaire Particulier Monseigneur LORIS CAPOVILLA, ses 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 donna son assentiment au Président LEMAÎTRE qui s'adressa alors au Souverain Pontife en ces termes:

« Très Saint Père, je vous présente respecteusement mes hommages et ceux de l'Académie Pontificale des Sciences, en ce jour où Votre Sainteté daigne nous recevoir.

« C'est pour nous l'occasion de Lui exprimer notre reconnaissance pour la munificence avec laquelle Elle nous permet de poursuivre nos travaux.

« La Session Plénaire de l'Académie et la Semaine d'Etude sur les Rayons cosmiques dans l'Espace interplanétaire qu'Elle nous a permis d'organiser sont de magnifiques réalisations de l'idéal tracé par Sa Sainteté Pie XI et poursuivi avec tant de bonté par ses illustres successeurs.

« En daignant remettre Elle-même la médaille Pie XI que l'Académie a été heureuse de décerner au Professeur BENGT ERIK ANDERSSON, Votre Sainteté confère à cette récompense une valeur inestimable.

« Nous Lui en sommes infiniment reconnaissants ».

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

A la fin de l'Audience le Souverain Pontife daignait remettre au Prof. BENGT ERIK ANDERSSON, de l'Ecole des Infirmières de Médecine Vétérinaire, la grande médaille d'or qui porte le nom auguste de Pie XI, Fondateur de l'Académie Pontificale, et adressait au Prof. ANDERSSON, qui était accompagné du Président et du Chancelier de l'Académie des paroles de satisfaction et des félicitations.

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

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

Messieurs,

Il Nous est très agréable de recevoir aujourd'hui le Président et les membres de l'Académie Pontificale des Sciences, ainsi que les savants venus du monde entier pour participer à la semaine d'études sur « le problème du rayonnement cosmique dans l'espace interplanétaire ».

L'an dernier Nous avions adressé Nos voeux à l'Académie Pontificale, à l'occasion du vingt-cinquième anniversaire de sa fondation par Notre prédécesseur, le grand et docte Pie XI.

Gentlemen,

It is Our pleasant task to-day to receive the President and Members of the Pontifical Academy of Sciences, together with the scientists who have come from all over the world to take part in the Semaine d'Etudes on « The Problem of Cosmic Radiation in Interplanetary Space ».

Last year We conveyed to the Pontifical Academy our good wishes on the occasion of the twenty-fifth anniversary of its foundation by Our predecessor, the great and learned Pius XI. This year, We have the joy of personally and gladly bidding you welcome to Our house.

For in your persons, Gentlemen, permit me to say, it is science itself which the Church welcomes, that science which the scholars

Cette année, Nous avons la joie de vous souhaiter en personne et de grand coeur la bienvenue dans Notre demeure.

Car en vos personnes, Messieurs, laissez-Nous vous le dire, c'est la science que l'Eglise accueille chez elle. La science que les savants du monde entier, unis dans une pacifique recherche, s'efforcent de faire progresser en mettant en commun les résultats de leurs travaux.

Et c'est pourquoi Nous sommes heureux de pouvoir remettre au Professeur BENGT ERIK ANDERSSON, *jeune et insigne physiologiste de l'Ecole Supérieure Royale de médecine vétérinaire à Stockholm, la médaille d'or qui porte le nom auguste du fondateur de Notre Académie Pontificale.*

L'Eglise encourage volontiers les recherches qui sont faites dans le monde, et qui tendent à mieux connaître l'homme et l'univers, suivant la mission donnée par Dieu à Adam dans les premières pages de la Genèse (cfr. Ge., 9, 7). *C'est ainsi que Nous félicitons de tout coeur ce jeune savant dont les études*

---

of the whole world, united in peaceful research, strive to advance by pooling the results of their labours.

On that account We are happy to be able to present to professor BENGT ERIK ANDERSSON, the young and distinguished physiologist of the Royal Institute of Veterinary Medicine at Stockholm, the gold medal bearing the revered name of the founder of Our Pontifical Academy.

The Church gladly encourages the researches which are being carried on the world over, and which lead to more complete knowledge of man and the universe, according to the command given by God to Adam in the first pages of Genesis (cf. Genesis 9, 7). Thus We congratulate with all Our heart this young scientist, who is an authority on the nervous mechanisms of hunger, thirst and *font autorité sur les mécanismes nerveux de la faim, de la soif, et de la température corporelle. Et Nous formons les meilleurs voeux pour la fécondité de sa carrière scientifique, pour le meilleur service de l'humanité.*

Comment ne pas relever aussi avec une particulière satisfaction l'opportunité du thème choisi, Messieurs, pour votre semaine d'études: « Le problème du rayonnement cosmique dans l'espace interplanétaire »? Il est superflu d'en souligner l'actualité. Mais qu'il Nous soit au moins permis de vous dire combien l'Eglise s'intéresse de près aux problèmes qui retiennent à bon droit l'attention des hommes de notre temps, et qui font l'objet de l'examen scientifique des meilleurs spécialistes. Et vous savez combien Nous faisons Nôtre la joie qui salue avec émotion les éclatantes réalisations des techniciens et des savants d'aujourd'hui, dont les prouesses permettent de domestiquer la nature d'une manière qui naguère encore paraissait un défi à l'imagination la plus riche.

---

body temperature, and We express Our best wishes for the fruitfulness of his scientific career, in the service of humanity.

We must also point out, Gentlemen, with particular satisfaction, the timeliness of the theme chosen for your Semaine d'Etudes « The Problem of Cosmic Radiation in Interplanetary Space ». While it would be superfluous to emphasise its appropriateness, permit Us at least to mention the close interest that the Church takes in those problems which are rightly engaging the attention of the men of our time, and which are the object of scientific investigation by leading specialists. You know how much We share the delight and satisfaction deriving from the brilliant results obtained by the scientists and technicians of our day, who have succeeded in taming

Nous le disions récemment:

« *Oh! Comme Nous souhaiterions que ces entreprises assument une signification d'hommage rendu à Dieu, créateur et législateur suprême. Puissent ces événements historiques, de même qu'ils figureront dans les annales de la connaissance scientifique du cosmos, devenir l'expression d'un véritable et pacifique progrès, contribuant à fonder solidement la fraternité humaine* » (« Osservatore Romano », 24 *août* 1962).

Grâce à Dieu, nous sommes entrés dans une époque où, espérons-le, l'interrogation sur les oppositions entre les conquêtes de la pensée et les exigences de la foi, se fera moins fréquente. Le premier Concile du Vatican a lumineusement affirmé, en 1869-1870, *les rapports de la raison et de la foi. Les exaltantes découvertes et réalisations du vingtième siècle, loin d'en remettre en cause le bien-fondé, aident au contraire l'esprit à mieux en comprendre la valeur. Le progrès des sciences, en permettant de mieux connaître l'extraordinaire richesse*

---

nature in a way which, but lately, would have seemed impossible to the most fertile imagination.

We said recently « Oh! How we wish that these undertakings would signify a homage rendered to God, Creator and supreme Legislator. May these historic events, which will have their place in the annals of the scientific knowledge of the cosmos, likewise become the expression of a true and peaceful progress, contributing their share to the solid foundation of the brotherhood of man » (*Osservatore Romano*, 24 August 1962).

We have entered, thank God, upon an epoch when, let us hope, questions about opposition between the conquests of the human mind and the demands of faith will become less frequent. The first Vatican Council, in 1869-1870, stated clearly the relations between *de la création, enrichit singulièrement la louange que la créature fait monter en action de grâces vers son créateur, qui est aussi le rédempteur de nos âmes. Et toujours, le coeur humain demeure avide, ainsi que son intelligence, d'atteindre l'absolu et de s'y donner.*

Aussi, comment ne pas évoquer devant vous, Messieurs, à la veille de l'ouverture, désormais toute proche, du Concile Oecuménique, cette grande Assemblée, et les promesses qu'elle porte, et qui sont soutenues par les prières des catholiques et l'attente du monde entier. Vision fraternelle, pacifique, spirituelle, d'une rencontre qui se veut toute à la louange de Dieu et au service de l'homme, dans ses aspirations les plus nobles à connaître le vrai, à chercher à l'atteindre, et à l'embrasser de son amour.

Telles sont, Messieurs, les pensées que Nous suggère la présence de votre illustre et savante Assemblée. Heureux d'avoir pu Nous entretenir avec vous, pour vous dire tout l'intérêt que

---

reason and faith. The exciting discoveries and achievements of the twentieth century, far from casting doubt on these solidly based truths, helps the mind to a deeper appreciation of their value. The progress of science, while permitting us to understand better the extraordinary richness of creation, enriches the praise which the creature renders in thanksgiving to his Creator, who is the Redeemer of our souls. The heart of man, as also his intelligence, remains ever eager to reach the absolute and to surrender himself to it.

On the eve of the opening, now close at hand, of the Ecumenical Council, We cannot but call to your mind, Gentlemen, this great Assembly and the promises that it holds out, supported by the prayers of Catholics and by the expectation of the whole world. It

Nous portons à vos travaux, c'est de grand coeur que Nous appelons sur votre semaine d'études, sur vos personnes et sur vos familles, l'abondance des divines grâces, en gage desquelles Nous vous accordons une particulière Bénédiction Apostolique.

---

presents to us the vision of a gathering, at once fraternal, pacific and spiritual, which should be devoted entirely to the praise of God and to the service of man, in his noblest aspirations to know the truth, to seek to attain it and to embrace it lovingly.

Such are the thoughts, Gentlemen, suggested to Us by the presence of your illustrious and learned assembly. We are happy to have been able to meet you and to let you know the great interest that We take in your labours. With all Our heart We invoke the abundance of divine graces on your Semaine d'Etudes, on yourselves and on your families, in token of which We impart to you a special Apostolic Benediction.

LES « SEMAINES D'ETUDE »

ET

LEUR REGLEMENT

Lorsque l'Académie Pontificale des Sciences fut fondée par le Souverain Pontife 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

---

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.

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

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 ».

In his immortal « Motu Proprio » of October 28, 1936, Pope Pius XI, on the contrary, solemnly proclaimed the dignity of the search for truth 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 interna-

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

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

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.

* * *

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

---

tional press of the time and by the innumerable individual tributes paid by scientists and by the greatest scholars of the world.

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

For all these reasons, the foundation of the Pontifical Academy of 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.

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-

---

* * *

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

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

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

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.

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:

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.

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

---

The scholars invited to these meetings undertake in advance to concentrate their efforts on this.

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

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

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

b) 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.

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

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

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.

---

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;

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
ET
DISCUSSIONS

publiés par les soins du prof. Francesca Romana Bachelet et du dr. Erik Dyring

SOME PROBLEMS CONNECTED WITH THE CHEMICAL COMPOSITION OF GALACTIC COSMIC RADIATION

B. PETERS

Institute for Theoretical Physics, University of Copenhagen
Copenhagen - Denmark

Abstract — Progress in the investigation of some of the most basic problems in cosmic ray physics presupposes a knowledge of the chemical and isotopic composition of primary particles, which is more detailed and accurate than can be obtained with existing techniques, but which will probably be soon within the technical competence of space research. Such problems include a study of the degree of chemical fractionation occurring during the initial stages of particle acceleration, the question whether cosmic ray particles of different energy follow similar trajectories in interstellar space, the time scale involved in transferring particles of different energy from the source to the solar system, and the question whether the particles observed here and now can be attributed to a small number of distinct, strong sources or must be considered as a mixture from many sources whose individual peculiarties have become obliterated. The relations of these questions to the composition of primary cosmic radiation are discussed in this paper. Apart from aiding the solution of such specific problems, a very detailed knowledge of primary composition is a prerequisite for hitherto inconclusive efforts to relate abundance anomalies in cosmic radiation to those observed in « peculiar » stars or to particular phases of the process of nucleogenesis.

1. Introduction

A detailed chemical and isotopic analysis of the nuclear component of primary cosmic radiation has been rendered extremely difficult in the past by an unavoidable layer of atmosphere above the experimental equipment and, more important still, by limitations on the aperture of detectors which could be used for measuring small particle fluxes and by the briefness of the period for which these detectors could be maintained and operated at great altitude. In all experiments performed to date it has been necessary, therefore, to correct for chemical changes produced by spallation reactions in the upper atmosphere and to sacrifice resolving power in the interest of gathering adequate statistics. As a result, the relative abundance of elements has been determined so far only for a few of the most prominent nuclear species or groups of elements and even those measurements are confined to a comparatively narrow energy interval.

Since space technology is well on the way of providing opportunities for using more elaborate equipment with greater resolving power which can collect data continuously for months or even years, it is possible to contemplate measuring the relative abundance of all the 28 elements lighter than copper, as well as the isotopic composition of hydrogen and helium with an accuracy of a few percent. To achieve such accuracy, flux values for each of the nuclei would have to exceed a few particles per square meter, second and steradian. This condition is probably fully satisfied for all elements lighter than copper because fragmentation processes in interstellar space will generate even those which are absent or very rare in the source region. The same may be true for particles coming from the sun, but this is not certain. Little is known as yet about the probability for nuclear collisions near the solar surface during or after acceleration. It would be important to measure to what extent the rarity of an element manifests itself as gap in the charge spectrum of solar particles.

A substantial progress in measuring techniques will also make it possible to extend flux measurements to lower and (for the more abundant elements in the galactic nuclear components) also to higher energies than has been possible heretofore.

Although technically such a programme ought to become feasible soon, it will be both difficult and costly. Presumably it will involve the installation of elaborate electronic equipment of large aperture (and therefore large dimensions) in space ships or on a lunar base and possibly also the launching of large stacks of emulsions and their return to earth after having been processed in situ. Such a programme will find itself in competition with many other scientifically worth-while objectives. The justification for undertaking the very large effort which would be required to improve the available crude analysis of primary nuclear composition to the extent indicated, must be found in the variety and the fundamental nature of as yet unanswered questions which are likely to remain unanswered until such data become available.

A few questions of this kind are discussed; they illustrate the scientific urgency of a research programme devoted to these objectives.

One of the basic difficulties which one faces when trying to derive from measurements on the particle beam information on the chemical composition of the regions where cosmic rays originate, is the uncertainty to what extent the process of acceleration itself modifies the original abundance ratios. Fractionation effects, *i.e.* preferential acceleration of certain kinds of particles could depend on molecular properties of the gases, on the electronic structure of the gas atoms (in particular their ionization potential), on the mass, or on the charge to mass ratio of the stripped nuclei. As discussed in Sect. 3, it is possible to arrive at partial answers by a detailed chemical analysis of the galactic component. However, such fractionation effects could also be studied by making very detailed chemical analyses of particles accelerated at the sun and then comparing the abundance ratios found in different flare events with each other as well as with those obtained spectroscopically. While it is not certain that the accelerating processes occurring at the sun are the same as those operative in the initial stages of the acceleration of galactic nuclei, it seems reasonable to expect that fractionation processes which could occur in cosmic ray sources will have their counterpart on the sun.

Another scientifically most urgent, perhaps not too difficult, problem is that of establishing some kind of time scale for the transfer of particles from the source to the solar system. This involves studying breakup products from collisions in the interstellar gas which are either radioactive or recognizable as deriving from radioactive spallation products. It is shown in Sect. 4 that, f.i., the ratios Be/Li and Be/B are very sensitive to the time scale involved in transit through interstellar space if it lies somewhere in the interval of 1 to 10 million years, but statistics of existing measurements would have to be improved by a factor of order 5 or 10 before conclusions can be drawn from them.

Also other important problems related to the transport of particles through space can be investigated as soon as extended, statistically significant measurements on the flux of nuclides of low abundance can be carried out in widely different energy intervals. Given accurate cyclotron data on spallation cross sections in collisions of protons with light and medium weight targets, it seems possible to determine the thickness of the gas layer traversed by the average cosmic ray nucleus with an accuracy of the order of 10% provided that the abundance of spallation products among primary nuclei has been measured roughly one order of magnitude more accurately than at present. Technically, this seems feasible in a space programme designed for the purpose. It would permit a decision as to whether low and high energy particles traverse equal amounts of interstellar matter, *i.e.* verify whether the composition is compatible with their following essentially similar trajectories. Tacitly this has generally been assumed to be true, although it is not at all obvious.

In the high energy region a study of chemical composition as a function of particle energy may reveal detailed features of the primary radiation for which there are as yet only weak and indirect indications. It is conceivable (and if one accepts the supernova theory of cosmic ray origin perhaps even probable) that there are at present only a small number of distinct sources strong enough to contribute to the observed particle flux. If that is so, their spectra are likely to extend to different high energy limits. Presumably these upper energy limits are functions either of particle velocity or of magnetic rigidity, in which case the superposition of such sources can produce in the corresponding energy regions very characteristic identifiable shifts in the ratio of light and heavy nuclei [1].

Finally, there is the general problem as to whether or not cosmic rays exhibit strong abundance anomalies of a « non-trivial » kind, *e.g.* induced neither during acceleration nor in transit, whether such anomalies, if they exist, can be related to those observed in « peculiar » stars and whether the overall pattern of cosmic ray abundances can be related to specific stages in the process of nucleo-genesis. These questions have been discussed from time to time, but inconclusively because of the lack of reliable experimental data. The validity of various views on this subject can be tested only against a large number of well measured abundance ratios more detailed and more accurate than those obtainable by the techniques employed in the past.

When considering these and similar questions, it appears that even a comparatively modest improvement in our ability to analyse the chemical composition is likely to yield great rewards by deepening our understanding of galactic cosmic radiation. One may expect substantial, and perhaps even radical, modifications of present views regarding the nature of sources as well as the mechanism of acceleration and propagation.

2. The Traversal of Interstellar Matter

Determining the amount of matter traversed by primary nuclei is closely related to the well-known problem of determining how much lithium, beryllium and boron is present in the primary cosmic radiation. After much labour this question has been answered at least approximately. Until better measurement techniques become available, one should probably use the ratio given by O'Dell et al. [2],

$$\frac{L}{S} = 18\% \pm 4\% \quad ,$$

where L denotes the flux of Li, Be and B-nuclei and S denotes that of carbon and heavier nuclei with the same energy per nucleon. The value was derived from measurements which required smaller corrections for atmosphere effects than earlier ones and is acceptable to most investigators who have worked on this problem. It applies to particles in the energy region lying roughly between 1.5 and 6 GeV/nucleon. What the ratio is at other energies is not yet known, although there are some indications that it increases with decreasing primary energy.

Generally it is assumed that these three light elements are so rare in the interstellar gas and any stellar object in which nuclear reactions take place that, whatever flux is observed, must be the result of spallation reactions which occur in the interstellar medium. From the point of view of cosmic ray analysis this remains true as long as these elements are at least one hundred times rarer than heavier ones, *i.e.* even if

[1] *Peters I* - pag. 6

they were more abundant in the source than on stellar surfaces by several orders of magnitude. Therefore, by measuring spallation cross sections in the laboratory for proton-nucleus collision in the appropriate energy region as well as the flux of light nuclei incident on the atmosphere, one can find how much material primaries have traversed after having been accelerated to an energy value at which nuclear interactions become important. A detailed analysis of this problem by BADHWAR et al. [3] shows that the amount of matter required to produce Li, Be and B fragments is fairly independent of the exact composition of the injected beam. If λ_A denotes the interaction mean free path in hydrogen of a fast nucleus with atomic weight A, the average numbers of Li, Be and B isotopes produced in traversing one g/cm² of hydrogen has the following values:

$$\text{for} \qquad A = 50; \quad \frac{P_{A,L}}{\lambda_A} = 0.048 \ (g/cm^2)^{-1}$$

$$A = 27; \quad \text{»} = 0.067 \ (g/cm^2)^{-1}$$

$$A = 14; \quad \text{»} = 0.078 \ (g/cm^2)^{-1}.$$

If a mixture of particles is injected in which the nuclei of atomic weight of carbon or heavier occur in the same proportions in which they are observed at the top of the atmosphere, a traversal of 2.5 ± 0.5 g/cm² of hydrogen is required for the creation of $18 \pm 4\%$ of Li, Be and B fragments. If one assumes that only very heavy nuclei are accelerated at the source, then about 3.5 g/cm² are necessary. In any case the amount of matter traversed corresponds to about one or two mean free paths of iron in hydrogen and, therefore, it is not negligible. The thickness of the gas layer is comparable with the amount of air the particles must traverse in the atmosphere in order to reach an altitude corresponding to the best performance of present day balloons. In studying effects of spallation reactions in interstellar space with traditional techniques, one is still forced to work in a region where background and signal are comparable. Therefore, no significant improvement in accuracy can be expected until more powerful experimental techniques can be brought to bear on this problem. Only then will it become possible to make careful comparisons of the chemical composition in different energy ranges and to arrive at a conclusive answer to the question whether primaries in different energy ranges have traversed different thicknesses of interstellar gas. If such differences in chemical composition exist, it ought to be possible to distinguish possible causes, *i.e.* whether the particles originated in different sources, or followed different trajectories between the source and the solar system.

3. Fractionation Effects in the Accelerating Region

Even on the basis of the inaccurate data now available, it seems possible to exclude certain types of fractionation processes, f.i. the possibility that a very strong preference exists in the source for accelerating the heaviest nuclei available. In a recent review article, Ginzburg and Sarovatsky [4] consider very seriously the possibility of a source emitting only heavy nuclei. They show that the necessary bias in favour of heavy particles can be achieved by a mechanism which works essentially as follows. In an acceleration process like that proposed by Fermi, a process which gives to a particle an energy increment proportional to its energy (including rest mass), a heavy particle will *gain* energy much faster than a light one of equal velocity. At the same time, for particles of a given velocity the energy *loss* due to ionization does not depend critically on particle mass as long as the temperature is low enough, so that multiply charged ions are rare. Thus in the initial stages of acceleration, only heavy nuclei may have a net gain and become accelerated. Having once attained a suprathermal velocity, the particles may be favoured in the main acceleration process even though by that time they will begin to lose electrons in atomic collisions. It seems possible then to have a source which is selective and only permits iron and other very heavy nuclei to reach very high energy and escape. But, as shown below, the evidence provided by the relative abundance of elements represented in cosmic radiation is against it.

There is a certain group of primaries named H_2-nuclei by DANIEL et al. [5] comprising atomic numbers 16 to 19, which appear to be very rare or even absent in the source region. If one takes the observed flux of nuclei of atomic number $Z \geqslant 20$ and lets them traverse 2-3 g/cm^2 of hydrogen, one produces by ablation in nuclear encounters as many H_2-nuclei as are actually observed. At the same time one produces an approximately equal number of nuclei with atomic nnmbers between $Z = 10$ and 15 (which are called H_3-nuclei in DANIEL's nomenclature). Therefore, the number of H_3-nuclei observed should be equal to the number of H_2-nuclei observed if the radiation which leaves the source consists of H_1-nuclei ($Z \geqslant 20$) only. Actually, however, $H_2/H_1 = 0.15$, while $H_3/H_1 \approx 2$, *i.e.* larger by at least an order of magnitude.

From this one must conclude that the assumption that only H_1-particles leave the source is untenable; most of the H_3-group also has to be included in the truly primary cosmic radiation.

Once one accepts the emission of both H_3 and H_1-nuclei from the source region, one needs the traversal of about 3 g/cm^2 to produce the observed flux of L-group nuclei. One can calculate then how many medium nuclei (C,N,O,F) are produced in the interstellar medium on the assumption that only two groups (namely H_3 and H_1) leave the source. It turns out that one cannot account for more than 20% of the flux of medium group nuclei by means of interstellar spallation reactions. Thus one is led to the conclusion that also most of the observed nuclei belonging to the medium group must be accelerated at the sources and are truly primaries. It appears that the data available at present make it quite clear that it is not possible to get the composition of the primary radiation as observed near the earth, from a source which puts out only or predominantly heavy particles. One needs a source which puts out approximately the composition observed at the earth. In other words, one is observing a charge spectrum which is very closely related to the chemical composition of the matter accelerated at the source.

The light elements are not the only ones which can be used for checking whether or not most of the observed nuclei have undergone nuclear collisions in space. For instance, one finds comparable numbers of neon and potassium fragments when bombarding iron with protons, while in the universe the abundances of these elements differ by several orders of magnitude. Existing measurements of this ratio in cosmic radiation are not yet reliable, but apparently the ratio is large and not of order unity. If this result can be verified in more accurate experiments, it will imply that also in this case three is no agreement between the expected spallation products of iron and the actual composition of the primary radiation, supporting the evidence against a strong fractionation during acceleration which is based on nuclear mass.

One can also show, though again not yet in an entirely convincing manner, that the acceleration mechanism does not strongly favour elements with low ionization potentials. For instance, the abundance ratio Mg/He is not abnormal in cosmic radiation indicating that magnesium, which has a comparatively low ionization potential, is not accelerated preferentially, compared to helium which has a very high one.

These then should be considered to be only the first tentative answers to the question of fractionating effects during particle acceleration. Progress depends to some extent on better analyses of the galactic charge spectrum, but much more can also be learned about this important problem by studying the composition of high energy nuclei emitted by the sun during flare activity. Deviations of the composition from spectroscopically determined abundances in the gases of the photosphere and in particular possible variations in the composition from event to event and their correlation with flare type are likely to provide new and valuable experimental data.

4. The Time Scale of the Diffusion Process

No methods exist as yet for measuring the time it takes for an average particle to reach the neighbourhood of the earth after acceleration. In principle such a question can be answered, although in a very approximate manner, by studying the composition of radio-active nuclei or their decay products in the primary cosmic radiation. This seems difficult but not at all hopeless, as one can illustrate by an example:

After determining as accurately as possible the cross sections for the fragments produced in interstellar space in 2.5 g/cm^2 of hydrogen (using laboratory cross sections for proton bombardment of elements of various atomic numbers) one studies the changes produced by the decay of the unstable fragments. Proceeding in this manner, Badhwar et al. [3] find that the relative number of fragments belonging to the groups of light (Li, Be, B), medium (C, N, O, F) and heavier elements ($Z \geqslant 10$) does not change appreciably by subsequent decay of radio-active elements, but that measurable changes occur within the light group of elements. Particularly the ratios Be/B and Be/Li are subject to considerable changes which depend on the age of the fragments.

According to these calculations, beryllium and boron nuclei should be produced in spallation reactions in the ratio

$$\text{Be} : \text{B} = 1 : 2$$

and beryllium, lithium in the ratio

$$\text{Be} : \text{Li} = 1 : 1.3 .$$

In calculating these ratios, the fragments, B^8, Be^8, Li^8, which lead quickly to α-particles, and B^{12} which decays to carbon in less than a fraction of a second have been neglected. On the other hand, the contribution of fragments which decay rapidly into one of the L-group elements (C^{11}, Li^9, He^6) have been included.

The chemical composition within this group of fragments will then change with time as a result of the decay of long lived radio-active isotopes. These long term changes will be due entirely to the transformation of beryllium fragments. According to the best available estimates [3], the isotopes of beryllium are produced in the ratio

$$Be^7 : Be^9 : Be^{10} = 1.5 : 2.2 : 1,$$

i.e. more than half of the beryllium fragments produced in space are radioactive.

Be^7 decays to Li^7 by electron capture with a mean life of 77 days,

Be^9 is stable,

and Be^{10} decays to B^{10} with a mean life of 4×10^6 years.

Be^7 cannot decay in the absence of orbital electrons; however, a detailed calculation is needed in order to decide whether or not the chance of capturing an orbital electron in flight through space and then keeping it till the transformation to Li^7 takes place is significant in a period of order of a few million years. Depending on which beryllium isopotes survive, one expects the following ratios for primaries at the top of the atmosphere:

	Be/B	Be/Li
Only Be^9 survives	0.21	0.29
Only Be^9 and Be^{10} survive . .	0.34	0.42
Only Be^7 and Be^9 » . .	0.36	0.61
Be^7, Be^9, and Be^{10} survive	0.50	0.77

[1] *Peters I* - pag. 12

It lies within present day experimental technology to measure these ratios in the primary cosmic radiation with the requisite accuracy and to improve the estimates based on fragmentation processes. The observed ratios as reported at the Kyoto Conference [2], [3] (which refer to particles with a mean energy of about 7 GeV/nucleon), are Be/B = 0.3 and Be/Li = 0.45. Hitherto, the data are not accurate enough to permit a decision as to whether or not the mean age of cosmic rays observed near the earth exceeds the lifetime of Be^{10}. (The experimental data available seem to favour the conversion of Be^7 fragments to Li^7 due to electron capture in flight, an effect which, if it exists, should be very energy sensitive).

If one assumes tentatively a mean age for primaries shorter than the mean life of Be^{10} and combines it with the best available estimate for the average amount of matter traversed suggested by the ratio of the entire group of Li, Be, B nuclei to primaries of atomic number $Z \geqslant 6$ (*i.e.* 2.5 ± 0.5 g/cm^2), one finds a mean gas density $n_g \geqslant 0.3$ atoms of hydrogen per cm^3 along the average cosmic ray trajectory. This is acceptable if the particles which we observe have spent all their life within the galactic disc, but too high if the particles spend most of their life in the halo.

It seemed worth while to go into this question of abundance ratios in light elements in some detail in order to show that, in this case, a comperatively small improvement in the accuracy of experimental data on primary cosmic radiation and on proton induced spallation reactions may provide much more detailed information on the history of cosmic radiation than is obtainable at present.

It seems also necessary to investigate theoretically the probability that a Be^7 nucleus captures an electron in space. The basic process is the inverse of the photo-ionization of a hydrogen-like atom of charge 4. Once the electron has been captured by the beryllium nucleus, it is not likely to be stripped off again for several months at least, so that the transformation to lithium should take place. Since the capture probability will depend on particle energy as well as on gas temperature and on the amount of material traversed by the particles before arrival in the solar system, the calculation may create the possibility for new experimental tests and provide a check as to whether one begins to approach a selfconsistent picture of the history of primary radiation.

5. Particular Features in the Nuclear Composition of the Source

Considerable changes in the chemical composition of primary cosmic radiation as a function of energy could arise in the following hypothetical, but not necessarily improbable situation.

Let us assume that the solar system is so close to a particular source of cosmic ray nuclei that this source dominates the observed flux in the present epoch. At the same time, let us assume that this neighbour source accelerates particles only up to some energy limit, which is lower than the highest cosmic ray energies which have been measured so far, *e.g.* $\sim 2 \times 10^{19}$ eV. Presumably the upper energy limit for particles emitted by the dominant source will be a function of the magnetic rigidity. Particles above the critical rigidity would then have to be supplied by other, weaker and presumably more distant sources. For the purpose of this discussion it is irrelevant whether we think of the close and the distant sources as supernovae in different parts of the galaxy or whether we think of galactic and extragalactic sources as contributing the two components. (One could also think of Alfvén's picture of two sources representing the solar and the galactic contributions, respectively). In any case, while the particle flux above a certain magnetic rigidity (or *energy per nucleon*) will decrease sharply, there will be no such rapid change in the flux of particles as a function of their *total energy*; here α-particles will contribute the major part of the flux beyond the point where the contribution from protons ceases, and beyond the limit to which α-particles can be accelerated, there will be still heavier nuclei with similar rigidity but much higher total energy.

Assuming that the observed chemical composition and energy spectrum in the region of several GeV are characteristic of the dominant source, the integral energy spectrum of primaries supplied by this source will change from a power spectrum with exponent $\gamma = 1.5$ to one with exponent $\gamma \approx 2$ when the cut-off value for protons is reached. Beyond this rather gentle breack in the slope of the spectrum, the flux contributed by the closer source will continue to decrease with slope $\gamma = 2$ until it has reached a value nearly 700 times lower than the flux at the point where cut-off effects become noticeable. At still higher energies only nuclei heavier than iron could make contributions, but such nuclei are probably rare in the dominant source. Throughout this steeper part of the spectrum, the mean atomic weight of primaries must increase with energy. However, before the flux has fallen by a factor of order 700, another « distant » source with a higher energy cut-off may well become dominant, and at this point of the energy scale the predominance of lighter elements among the primaries will presumably be reestablished. Such quite dramatic changes in composition as a function of particle energy as are predicted on the basis of the hypothesis seem to be absent in the region where the primary composition has already been measured, *i.e.* below a magnetic rigidity $p/e\ Z = 10^{11}$ V. However, some evidence seems to accumulate in favour of a cut-off in the magnetic rigidity spectrum of the particles supplied by the locally dominant source in the neighbourhood of $p/e\ Z \approx 10^{15}$ V [1].

Another much better established feature of the primary chemical composition which may be of special astrophysical significance is an apparent scarcity of nitrogen nuclei among the primaries. The experimental facts are not yet entirely clear.

[1] *Peters I* - pag. 15

In the earliest papers on the subject [6] nitrogen was found to be less abundant than carbon and oxygen by a factor of about 3. The observed nitrogen flux was an upper limit because the value was not yet corrected for nitrogen produced in spallation reactions in the atmosphere above the balloon. For many years afterwards most experimenters, using methods with somewhat lower charge resolution, found nitrogen as abundant as carbon. But in more recent investigations the minimum has shown up again clearly [7].

It is not yet quite certain what should be chosen as the best experimental value for the N/C ratio, but in any case it is smaller than one. A reliable value for this ratio would put further restrictions on possible theories of the origin of cosmic rays. In the well-known paper by BURBIDGE, BURBIDGE, FOWLER and HOYLE on the origin of elements [8], the authors discuss the ratio N/C in relation to stellar evolution and show a graph giving the abundance ratio as a function of the age of the star. According to their theory, this ratio is always larger than one except during a comparatively brief period proceeding instability (supernova phase). The explanation for this behaviour is that during most of the stellar life the energy balance is maintained by (p, p) reactions and the carbon cycle:

$$C^{12}\ (p, \gamma)\ N^{13}\ \beta^{+}\ C^{13}\ (p, \gamma) N^{14}\ (p, \gamma)\ O^{15}\ \beta^{+}\ N^{15}\ (p, \alpha)\ C^{12},$$

in which helium is synthesized and C^{12} acts as catalyst. Since in the relevant energy range (80-120 KeV) the cross section for the (p, γ) reaction on N^{14} is much smaller than the cross section for the (p, γ) reaction on C^{12}, the process tends to build up a large N/C ratio. Only in the last stages, when the hydrogen supply is exhansted and the helium burning phase has set in, will large amounts of C^{12} be synthesized. At that time, the ratio N/C can fall to a very low (but unknown) level. (Hydrogen burning near the surface in the subsequent white dwarf stage raises the ratio again to an estimated value of about 160).

If this behaviour of the relative abundance of nitrogen and carbon during stellar evolution is assumed to be correct, a low ratio N/C in cosmic radiation lends a certain amount of support to the supernova theory of origin and its exact value could be interesting from the point of view of nucleo-genesis.

Peculiar features seem to occur also in the isotopic composition of primary helium. APPA RAO et al. [9] reported that about one third of the primary helium with energy between 0.2 and 1.5 GeV/nucleon consist of the light isotope He^3. This surprisingly high abundance of He^3 has not yet been verified by other experimenters. In view of the importance of the problem, one would like to see this point clarified because the implications are very far reaching. He^3 is one of those nuclei which have a very large cross section for capture of neutrons, so that it cannot live long in the hot atmosphere of a star and therefore ought to be rare in the source region. Three ways suggest themselves for producing He^3 cosmic ray primaries:

a) Spallation reactions on heavy nuclei. The difficulty with this explanation lies in the fact that one cannot permit a large number of fragmentation collisions, because they would produce too much Li, Be, B. One way out of the apparent contradiction would be to assume that He^3 occurs only in the low energy region of the primary spectrum where it has been observed and where the abundance ratio L/S has not yet been measured with sufficient accuracy. If this is the correct explanation, then it means that primary particles in the $\sim$ 500 MeV/nucleon region and $\sim$4 GeV/nucleon region go through different amounts of matter. But if low and high energy particles follow different trajectories in space, then the whole problem of diffusion of cosmic rays is more complicated than hitherto considered. New and more accurate experiments are required to verify whether He^3 is present at low energies and rares at high energies, and whether the ratio L/S increases with decreasing primary energy. The presence of a large flux of He^3 among the primaries would raise basic questions related to the diffusion of cosmic rays in the Galaxy.

b) It is also conceivable that He^3 is produced in a proton gas by successive neutron captures, perhaps in a neutron burst at the time of a supernova explosion. In such a hypothesis it is essential that the explosion pushes the hydrogen and neutron interaction products out, so that they cannot interact again. The gas must cool and expand quickly. In such a process, deuterons would be formed first and then, after another neutron capture, tritons would be formed which later decay to He^3. This is not an attractive hypothesis because the neutron capture cross section of deuterons is very low. It would become more attractive if a very large deuteron flux were found in the same energy region where He^3 is present, but whatever evidence for primary deuterons exists is negative [10].

c) Another possibility would be to produce He^3 from the He^4 by (γ, n) reactions, perhaps in a γ-ray burst, such as might occur during a supernova explosion. Simultaneously some boron must be formed by (γ, n) reactions on carbon, boron being the only element of the light group which is likely to be enhanced in such a hypothetical γ-ray burst. Such an effect may show up in a careful study of the Be/B ratio, discussed in Sect. 4.

Interesting new problems may arise also from careful flux measurements of the nuclei in the neighbourhood of the iron peak or from detailed investigations in other regions of the charge spectrum.

Practically all the problems discussed in this paper require an analysis of the primary charge spectrum which is more accurate than present day values by about an order of magnitude which takes most of them outside of the range which can be studied with techniques which have dominated the field till now, *i.e.* balloons and emulsions. Satellites and electronic detectors with high resolving power appear to be essential for future progress in this field.

REFERENCES

[1] B. Peters, *Nuovo Cim.*, *22*, 800, 1961.

[2] F.W. O' Dell, M.M. Shapiro and E. Stiller, *J. Phys. Soc. Japan*, *17*, Suppl. A III, 23, 1962.

[3] G.D. Badhwar, N. Durga Prasad and B. Vijayalakshmi, ibid., p. 55 (and private com.).

[4] R.R. Daniel and N. Durga Prasad, *Nuovo Cim.*, *23*, 82, 1962.

[5] V.L. Ginzburg and S.I. Syrovitsky, *Progr. Theor. Phys.*, Suppl. *20*, 1, 1961.

[6] H.L. Bradt and B. Peters, *Phys. Rev.*, *77*, 54, 1950.

[7] K. Kristiansson, O. Mathiesen and A. Stenman, *Techn. Report Univ. of Lund*, June 1962.

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

[9] M.V.K. Appa Rao and M.F. Kaplon, *J. Phys. Soc. Japan*, *17*, Suppl. A III, 48, 1962.

[10] M.V.K. Appa Rao and P.J. Lavkare, NYO-10231, Univ. of Rochester, 1962.

DISCUSSION

Chairman: G. LEMAÎTRE

SIMPSON

I might comment on the experimental side of the problem as I have viewed it. In the last two or three years we have been interested in designing instrumentation which could investigate the problems which Prof. PETERS has discussed here and one can see immediately where some of the difficulties lie. First, there is no question that we must carry out these measurements in space, free from any overlying atmosphere. Secondly, for high energy particles, existing techniques are available for measuring energy loss and total energy which use scintillation crystals and photomultipliers. The real difficulty arises when one begins to ask questions regarding the charge and isotopic composition of the particle flux at lower energies. By low energies I mean the range 500 KeV to order 100 MeV/nucleon. Over part of this energy range conventional detectors cannot be used. It is, therefore, readily seen that the best approach at this time is to use solid state detectors. Some of the characteristics of a typical solid state detector are as follows. First, solid state devices are extremely fast in response so there is no problem about time resolution and the pick-up of charge. Secondly, their linearity as a function of nuclear charge exceeds that of most scintillation crystals. Thirdly, since they are cut from single crystals of silicon, the detector thickness lies in the range 50 μ to 500 μ. We are presently working in the range 200 to 300 μ to construct telescopes measuring energy loss, total energy, etc. These telescopes will be used to study the light and intermediate nuclei, and possibly the heavy nuclei. I mention these developments because the technology has only recently evolved.

PETERS

I wonder whether we might be able to get information on the isotopic distribution of beryllium.

SIMPSON

At the present time it is not possible to look for any isotope ratios beyond helium with the possible question mark of whether one could separate Li^6 and Li^7.

PETERS

Maybe one more remark on this: would it be possible to measure the ratio Be/Li and Be/B with an accuracy of the order of 5% or better which is necessary in order to answer these questions of time of flight?

SIMPSON

It is possible to achieve this accuracy in measuring these ratios for chemical composition, but we do not know whether presently planned experiments will achieve this precision at low energies.

NEY

The figure that you gave us of 3×10^{-1} atoms/cm^3 would be, I think, extremely important astrophysically if one were sure that it were right. Now this is based on two assumptions: that Be^{10} survives till the time of flight is 4 million years and that hydrogen is the principal constituent of the space.

BIERMANN

With respect to the last point there is some evidence that the interstellar material has quite a considerable proportion of helium, possibly something like 40% by mass or so. I wonder how that will affect your argument and the figures which you give.

PETERS

Even now the spallation reactions (which are all in the range of present accelerators) of hydrogen on materials of the same composition as the cosmic ray beam, are not good enough to rely on the numbers I quoted. The measurements would have to be extended of course to the α-reactions on carbon, nitrogen, oxygen and heavier elements. There is no difficulty in principle in doing this; it is just work that has not been done yet.

HAYAKAWA

I want to make a small comment on the pick-up process of Be^7. I have made some estimates; as far as I remember I think that Be^7 would not become Li^7 within travels in interstellar matter. See: S. HAYAKAWA, K. ITO, Y. TERASHIMA, *Progr. Theor. Phys. Suppl.* No. 6, 1 (1958), p. 19-20, Eqs(23)-(24); the velocity dependence is also given there. The second point I would like to make is the N/C ratio. It is certainly difficult to have the small N/C ratio but in the supernova explosion there may be some layer which has a very high temperature and will be ejected into interstellar space. The nuclear reaction rates therein are very high and the cycle goes to oxygen, namely CNO cycle; then most of nitrogen will be destroyed and C and O become more abundant than N.

AMALDI

May I ask one more point about your argument on Be^{10}? Did I understand correctly that from the fact that the average density of matter traversed is 0.3 atoms per cm^3 one can deduce that this part has not crossed the halo of the Galaxy? Or did I misunderstand?

PETERS

The argument is this. The production ratio of beryllium and boron can be studied. It will change with time in a period of the order of 4 million years. The present data indicate that perhaps the ratio is such as to suggest that Be^{10} had no time to decay. If you combine this fact with 2.5 g/cm^2 of material traversed then you get a minimum value for the density of material along the trajectory of the order of 0.3 atoms per cm^3 based on the assumption that the gas is hydrogen (which would be modified by what Prof. NEY and BIERMANN said) and on the assumption that the data which we have and which we know are not very good, were accurate. Such a density would be acceptable if the particles moved in the galactic disc, but too high if most of the trajectory lies within the halo.

SINGER

I gather from your remarks that you don't feel that the results can be accepted yet; but assuming that the He^3 that has been measured is genuine, then there must be a concomitant result in the sense that deuterium and tritons (H^3) would be produced by spallation. Would you give your opinion concerning the ease with which the resulting tritons can be measured?

PETERS

Tritons would of course not be present in the galactic component because they would decay to He^3. But whether or not deuterons should be present depends on the mechanism by which He^3 is believed to be made: if it is spallation or neutron-capture what Prof. SINGER says is right; if it is a γ-ray burst and it is produced

[1] *Peters I* - pag. 24

from He^4, then we would expect an increase of B and He^3 to go hand in hand and no deuterons. At the moment the evidence against deuterons is rather strong, and so personally I am inclined to think that if the presence of He^3 should be verified then the part which cannot be accounted for by spallation reactions, that is a fraction comparable to the Li, Be and B produced, needs to be explained in terms of γ-ray reactions on He^4.

SINGER

Concerning this question of presence of tritons, I imagine that this would depend very much on where the cosmic rays have spent their last several half lives, say 50 years. If they indeed have been in the interplanetary region where the density is fairly high, then the triton intensity would be correspondingly higher and perhaps measurable.

PETERS

Did I understand your point of view correctly that you think it possible that the galactic particles in the energy range of a few GeV spent 50 years in the interplanetary system? Because then of course one is tempted to think of a situation rather close to what Prof. ALFVÉN has been suggesting. One cannot speak any more very well of galactic particles with confidence if the sun can store them for 50 years; if they can be stored for 50 years, solar particles may very well dominate the flux.

SINGER

I did not use the word galactic, I was really trying not to prejudice the discussion one way or the other; it is just a matter of whether the component might be detectable from an experimental point of view. It is quite difficult of course, to detect tritons and I am ready to welcome the opinion particularly with respect to detection in emulsions.

PETERS

I think that at high energy it is possible to distinguish deuterons from protons if the flux is as high as 5 to 10%. That comes from the fact that a certain fraction of the interactions are stripping reactions where there is a proton proceeding without any measurable transfer of momentum in the original direction. Reactions where this appears to happen by accident, *i.e.* a fast particle comes out accurately in the forward direction, have been studied at proton energies of a few GeV and they are so rare that if the same beam had contained deuterons one would have detected them. The accuracy could be about 10%. Tritons would behave in much the same way in the high energy region; I do not see any way, at the moment, of distinguishing tritons from deuterons among the singly-charged primaries. At low energies of course, techniques are, as you know, a little bit difficult. Deuterons and tritons have been looked for among very low energy particles, and have not been found. And I don't have any opinion on how safe these results are at present.

[1] *Peters I* - pag. 26

EXTENSIVE AIR SHOWERS AT 5200 METRES ABOVE SEA LEVEL AND SEARCH FOR HIGH ENERGY PRIMARY GAMMA RAYS (*)

G. CLARK (1), I. ESCOBAR (2), K. MURAKAMI (3) and K. SUGA (4)

Laboratorio de Física Cósmica, Universidad Mayor de San Andrés
La Paz - Bolivia

Abstract — We report here the preliminary results obtained by our group during first six months of the operation of the Bolivian Air Shower Joint Experiment (BASJE) at Chacaltaya. The report is presented in two parts.

Part I of the report describes the chief characteristics of EAS observed at 5200 m above sea level. The main result of this study are:

a) the observed showers having sizes in the range $\sim 10^5$ to $\sim 10^6$ are near their maximum development;

b) the fluctuations in the number of muons in the observed showers is only one third of that observed at sea level;

c) the lateral distribution of the observed showers, follows N.K.G. function with best 's' value slightly less than unity;

(*) This research is being supported, in part, by the United States Air Force, under Contract No. AF 49(638)-922.

(1) *Laboratory for Nuclear Science, Massachusetts Institute of Technology* - U.S.A.

(2) *Laboratorio de Física Cósmica, Universidad Mayor de San Andrés* - La Paz, Bolivia.

(3) *Institute of Physical and Chemical Research* - Tokyo, Japan.

(4) *Institute for Nuclear Study, University of Tokyo* - Tokyo, Japan.

d) there exists an indication of a 'knee' in the size spectrum of the showers in the range 2×10^5 to 5×10^5.

Part II of the report mainly outlines the approach of our group for the search for high energy primary gamma rays. Our results, pertaining to this study, indicate that there exist a group of showers having an extraordinarily small proportion of muons. The ratio of the frequency of this group of showers to that of ordinary showers is $\sim 3 \times 10^{-4}$ for energies above 10^{15} eV. It is suggested that this group of showers may have as their parent high energy primary gemma rays although we can't yet rule out the possibility of this group of showers having been produced by an extreme fluctuation of a few neutral pions. Further there is some indication of a possible excess of the muonless showers coming from the plane of galaxy though this result has not been established with high enough statistical precision.

PART I

GENERAL CHARACTERISTICS OF EAS

The Bolivian Air Shower Joint Experiment (BASJE) has been in operation since January of this year. The altitude of the site at Chacaltaya where the equipment is located is 5,200 m above sea level (atmospheric depth, 530 g/cm^2). The geographic location of this site is 16°19'S, latitude and 68°10'W, longitude.

The experiment has been designed for the following main purposes:

1) To search for showers generated by primary cosmic γ-rays of energy greater than 10^{14} eV.
2) To search for evidence of high Z primaries.
3) To study the character of ultra high energy nuclear interactions.

Since the basic approach to these goals has been outlined at the Kyoto and Mexico Conferences [1], [2], the present

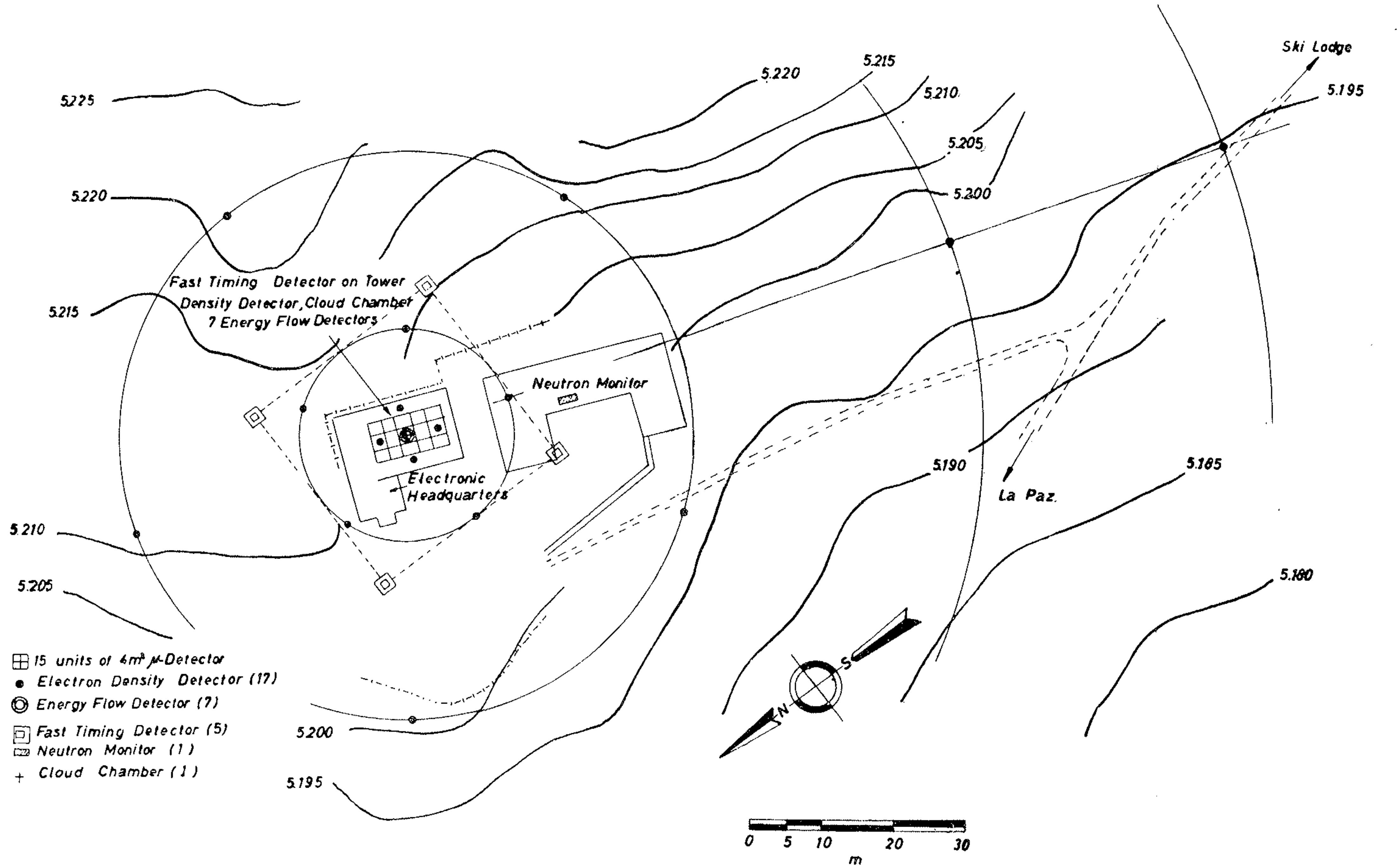


FIG. 1 — The arrangement at CHACALTAYA. Figures attached to contours indicate altitudes in m above sea level.

report will be limited to a brief description of the apparatus and a summary of the preliminary results obtained in the first six months of operation.

As reported at the Kyoto Conference, the equipment consists of seventeen 0.9 m^2 electron density detectors to determine the size and lateral distribution of the air showers, five scintillators to determine their arrival direction by the fast timing method, 60 m^2 of scintillation detector (fifteen 4 m^2 units) under heavy shielding, and seven 0.2 m^2 lead glass Čerenkov detectors, each of 12 radiation lengths thickness, forming an energy flow meter. The whole arrangement is shown in Fig. 1. Except for the fast timing array, the method of displaying the signals from all these detectors is to use a pulse-height to logarithmic pulse-length conversion that gives a wide dynamic range of four decades with good accuracy. For instance, the usable response of the density detectors ranges from 0.5 to about 5×10^3 incident particles.

The 60 m^2 detector is presently under a shielding of concrete and lead ore of about 320 g/cm^2 total thickness. The arrangement is shown in Fig. 2. In the search for γ-ray primaries, the efficiency of both the detector and the shielding must be carefully investigated. The details will be explained in the second part of this report. As has been already mentioned each of the 4 m^2 units comprising this detector has a usable response of from 0.3 to about 5×10^3 penetrating particles. The inefficiency because of the loss of pulses corresponding to less than 0.3 particles is only 1.5% of the total frequency of single penetrating particles.

Four scintillators of the fast timing array are on a horizontal plane at the vertexes of a square, 30 m on a side. The fifth fast timing detector is located on a tower 9.7 m above the center of this horizontal plane. The accuracy in the determination of the arrival direction is about 5°.

The basic triggering requirement used was that any one of the five central density detectors record thirty or more shower

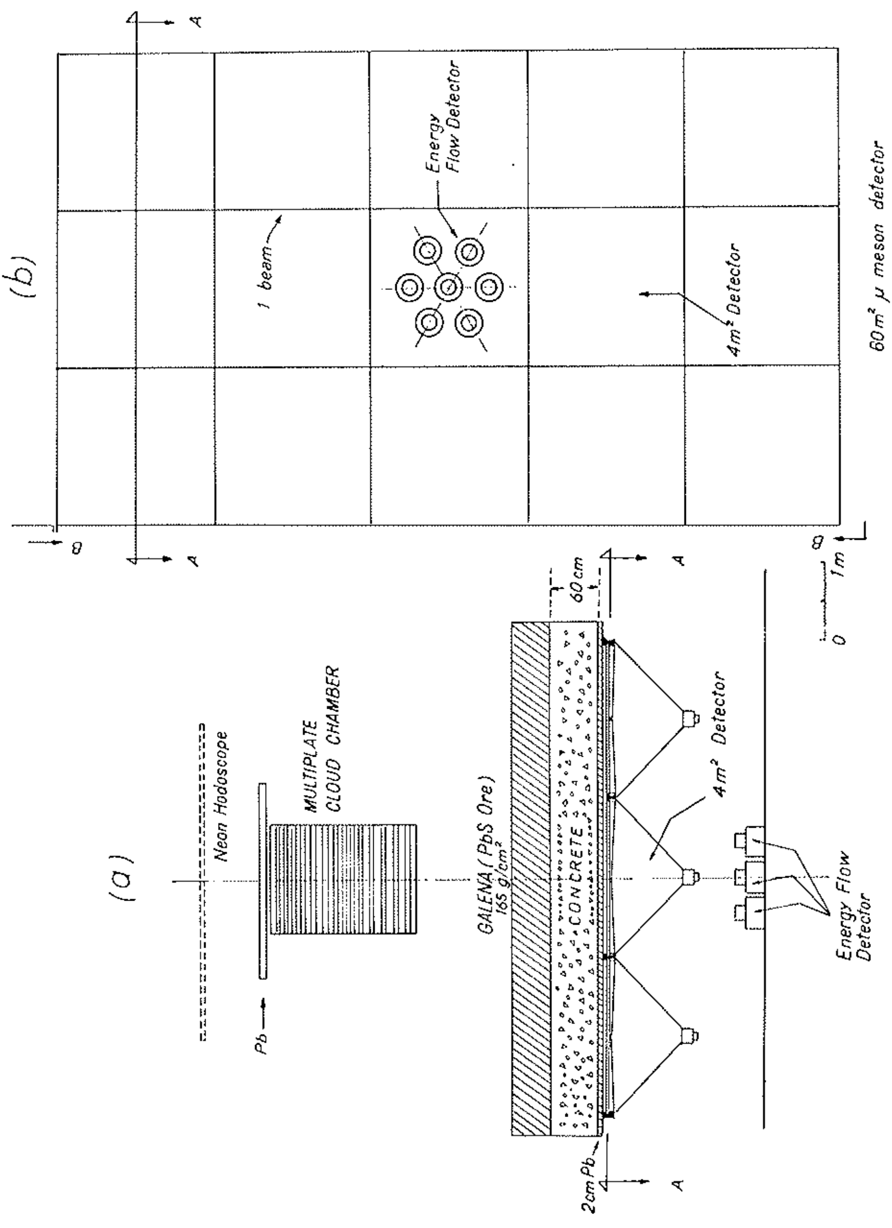


FIG. 2 — *a*) Side view of the arrangement of 60 m² mu-meson detector. The right and left side of the detector also are completely covered by enough thick galena. *b*) Top view of the arrangement.

particles and that each of the five detectors located in the 15 m ring be struck by 3 or more particles. The counting rate with this requirement is about 250/hour at Chacaltaya.

During the first six months of operation interesting results have been obtained. Some of these results, which are related to gamma ray astronomy, will be presented later. This report will be confined to describing some of the features of air showers as observed at Chacaltaya.

1. *Zenith Angle Dependence*

The shower frequencies as function of zenith angle were obtained for two size groups. Fig. 3 shows the relative change of frequency per unit solid angle with atmospheric depth corresponding to zenith angle. The upper curve is for showers with an average size of a few times 10^5. The lower curve refers to showers whose average size is a few times 10^6. There is no significant difference in the attenuation lenght for the two size groups and the maximum frequency seen near 600 g/cm^2 in both cases shows that almost all of the showers observed at Chacaltaya are near their maximum development in the atmosphere.

2. *Fluctuations in the Number of μ-mesons*

Considering the efficiency for the detection of air shower, it is expected that fluctuations in the height of the first nuclear interaction decrease as the observation point approaches the altitude of maximum air shower development [3], [4]. As a result, the fluctuations in the number of μ-mesons should also decrease as one approaches that altitude. Fig. 4 shows the observed ratio of the μ-meson density ($\geqslant$500 MeV) to the electron density for showers of a few times 10^6 size. As may be seen in this figure, the magnitude of the fluctuation in the number of μ-mesons is about three times smaller than that observed at sea level [5].

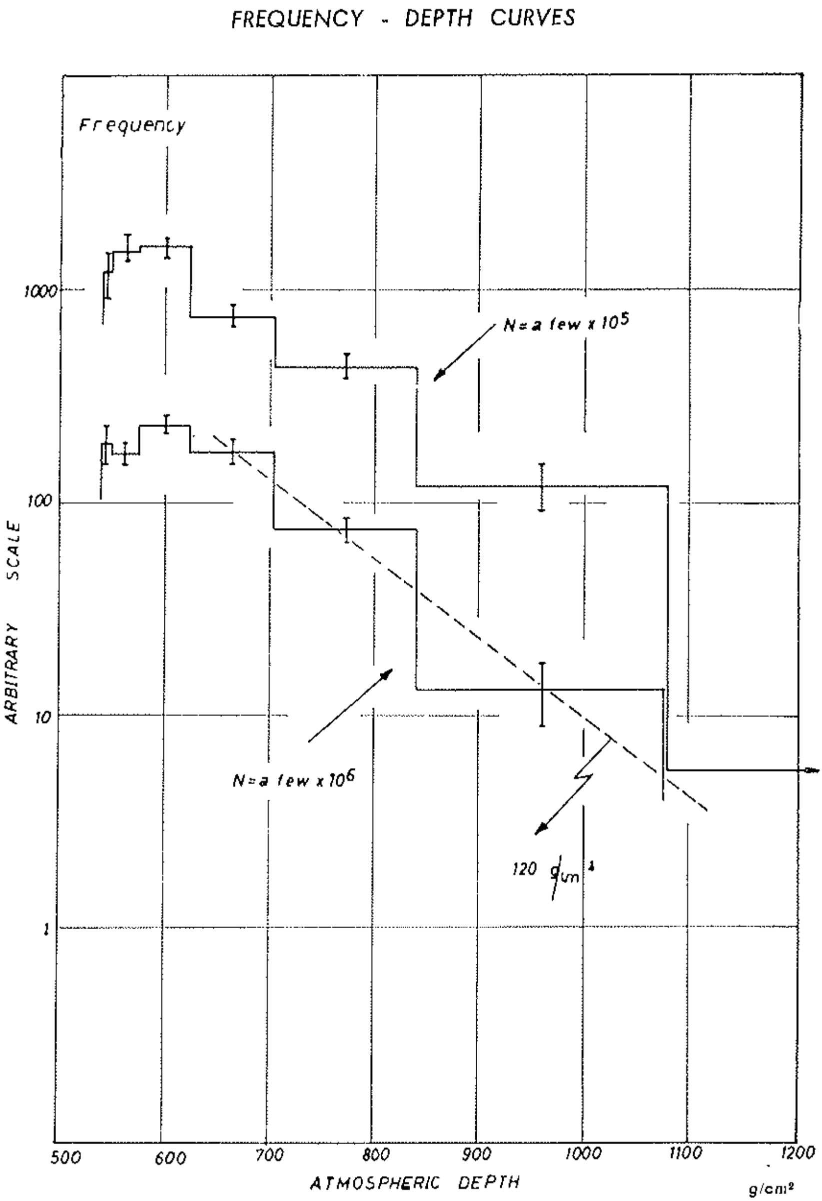


Fig. 3 — Frequency-depth curves. Upper curve is for the showers of the size of a few times 10^5. Lower one is for the size of a few times 10^6. Both curves are not normalized to the absolute intensity.

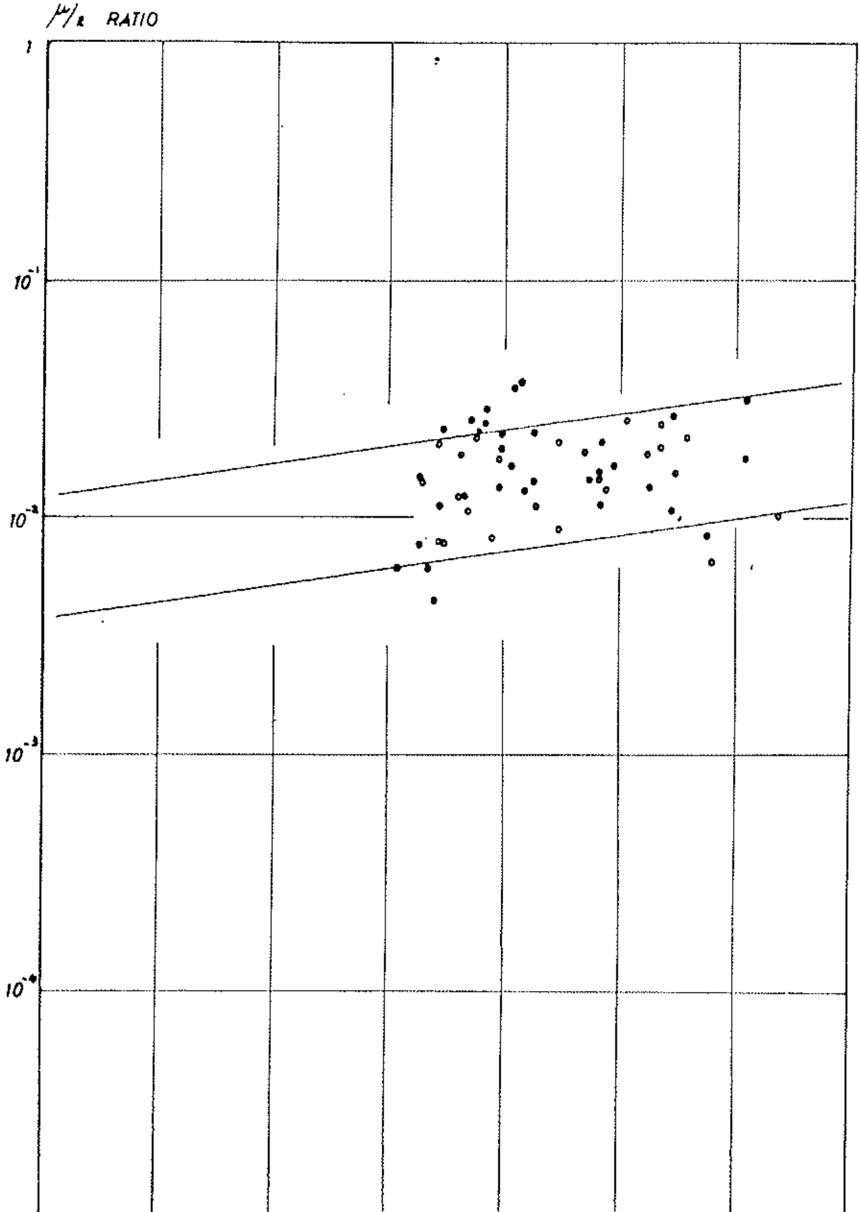


Fig. 4 — Ratio of mu-meson density to electron density. The energy of mu-mesons is more than 500 MeV and the size is estimated as about 10^6.

3. *Lateral Distribution*

The data from the density detectors were analyzed by an I.B.M. 7090 computer to determine the lateral density distribution of the shower particles. The trial functions used were the N.K.G. distribution for $s=0.6$ and $s=1$. The deviations of the observed densities from those predicted by these functions were examined by the χ^2 method and it was determined that the observed values agreed much better with the distribution for $s=1$ rather than that for $s=0.6$. The average size of the showers used in this determination is a few times 10^5. A closer examination of the deviations indicates that the distribution with a value of s slightly less than 1 would give an even better agreement. This result is fairly consistent with the above mentioned zenith angle dependence which indicates also that the showers are near their maximum development.

4. *Size Spectrum*

Currently, one of the more interesting features in air shower work is the change in the exponent of the power law representing the size spectrum. This change which occurs at about a few times 10^5, has been observed at mountain altitudes as well as at sea level [6], [7], [8]. In order to determine whether this change in the exponent represents a change in the primary spectrum or a change in the nature of the nuclear interaction, a size spectrum determination at Chacaltaya is very important. When showers are near their maximum development, the effect of the fluctuation in the height of the first interaction on the shower size is less important and the size spectrum more accurately reflects the energy spectrum.

A spectrum obtained from the data taken at Chacaltaya is shown in Fig. 5. The intensity, expressed in $cm^{-2}sec^{-1}$, should be divided by the effective solid angle, 1.8, to obtain the vertical intensity in $cm^{-2}sec^{-1}ster^{-1}$. Although the present data is too poor to determine the size spectrum precisely, there

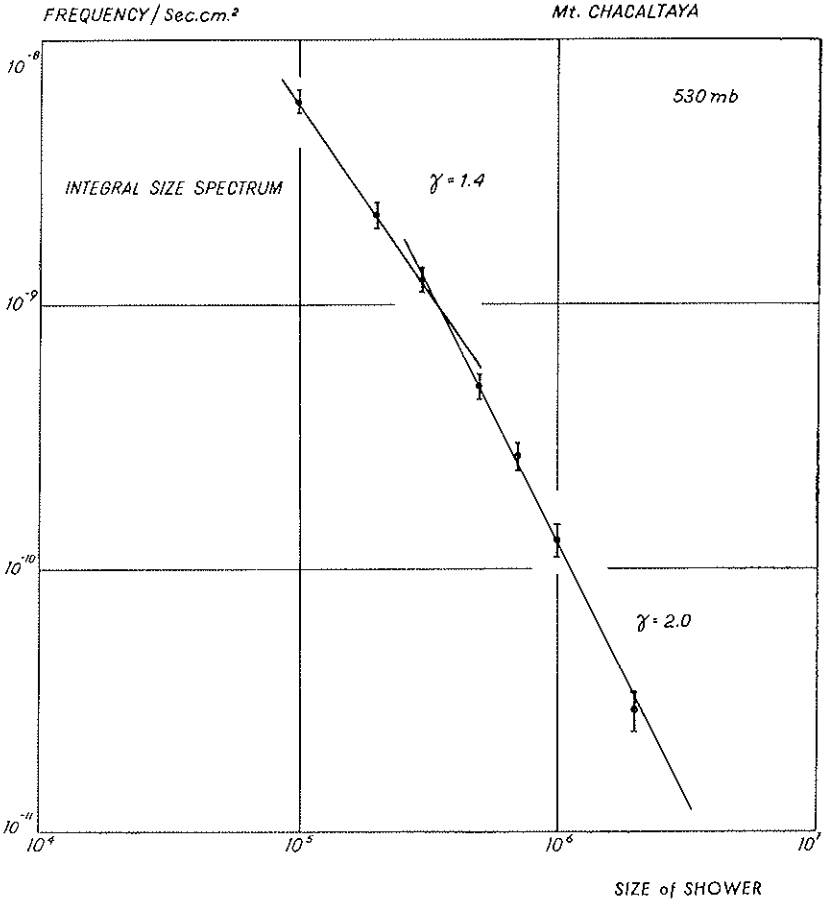


FIG. 5 — Size spectrum observed at CHACALTAYA.

does seem to be a change in the spectrum at a few times 10^5. If we plot a straight line over the whole range, the best value of the exponent would be 1.8. But if a knee is assumed to occur in this spectrum, it would doubtless occur within the range of from 2×10^5 to 5×10^5.

If we are able to substantiate the existence of a change in this region, it would be of great importance when compared with the results obtained at lower altitudes. In the following months of operation, special consideration will be given to obtaining a precise size spectrum.

Part II

Primary Gamma Ray Observations by EAS

We shall report on a preliminary analysis of the existing data which was made for the purpose of searching for showers generated by primary γ-rays. The criterion used in looking for such events is that showers produced by primary γ-rays must not contain appreciable numbers of μ-mesons and nuclear-active particles. The experimental arrangement has been described previously. Here, we shall briefly describe those features of the equipment that should be familiar for an understanding of the analysis.

1. *Experimental Arrangement and Classification of Showers*

a) The accuracy of the determination of the arrival direction by the fast timing array is about $\pm 5°$ for both the zenith and azimuthal angle.

b) The shielding material above the 60 cm^2 detector consists of 165 g/cm^2 of galena (PbS ore), 60 cm of reinforced concrete (132 g/cm^2), and 2 cm of lead. Also, the sides of this detector are enclosed by about 500 g/cm^2 of galena. The lowest energy of μ-mesons able to penetrate this shielding from above is about 500 MeV. When a nuclear-active particle of 10^{12} eV undergoes a nuclear interaction in the concrete, it produces a pulse in the 60 m^2 detector which corresponds, on the average, to 500 relativistic particles.

In order to determine whether there might be a confusion between nuclear showers with an appreciable number of μ-mesons and a γ-ray shower with few μ-mesons, one must question the efficiency of the 60 m^2 detector. Experimental results show that the inefficiency in detecting single μ-mesons is as small as 1.5%. If, because of inefficient absorption of electromagnetic components by the galena and the concrete, survival of γ-rays were to produce Compton electrons in the scintillation material, a true γ-ray shower with no μ-mesons might be mistaken for a nuclear shower which, because of extreme fluctuations, contained very few μ-mesons. Experimental information on the pulse-height distribution at the lower end indicates that the distribution is inconsistent with that which would be obtained from Compton electron due to this survival of γ-rays. However, the spectrum obtained from showers whose cores strike more than 20 m from the 60 m^2 detector is consistent with that of single μ-mesons. Therefore, confusion in the nature of the showers that is due to the above mentioned effects is expected to be very small.

The triggering requirement used was that a least 30 particles strike any one of the five central, unshielded detectors above 60 m^2 detector and three or more particles strike each of the five unshielded detectors in the ring of 15 m radius. The counting rate with this requirement is about 250 per hour. During most of the running time an anticoincidence requirement was added so as to only pick up events in which the number of relativistic particles in the 60 m^2 detector is less than eight. We classified the showers obtained with the above triggering requirement as shown in the following table.

TABLE I

	Distance Between Core and Center of $60 m^2$ Det.	Range of Size	Average Size
A-Showers	$R \leqslant 10$ m	$5 \times 10^4 \sim 5 \times 10^5$	$1 \sim 2 \times 10^5$
B-Showers	$10 \text{ m} \leqslant R \leqslant 30$ m	$10^5 \sim 10^6$	5×10^5
C-Showers	$30 \text{ m} \leqslant R$	$>8 \times 10^5$	$1 \sim 2 \times 10^6$

2. *Results*

a) Recognition of separate groups of showers.

Fig. 6 shows some of the features of showers that were observed without the anticoincidence requirement. Each point, representing an individual shower, gives the relationship between the total number of relativistic particles recorded by the $60 m^2$ detector and the total number of shower particles in the five unshielded detectors above the $60 m^2$ detector. The A, B and C-showers have been grouped individually. 10, 100 and 1000 on the abscissa should be read as 134, 1340 and 13400, respectively, to obtain the total number of shower particles above the $60 m^2$ detector. The diagonal lines (μ/e) in the figures represent constant ratios of particles recorded by the $60 m^2$ shielded detector to the number of particles above the shield.

For the A-showers the points scatter so widely that it must mean that the nuclear-active component contributes appreciably. However, for the C-showers the magnitude of the spread is only about three. The main contribution for these showers comes from the μ-mesons. The ratio μ/e is about $1 \sim 3 \times 10^{-2}$. From these figures it can be seen that the proportion of showers with few μ-mesons (*i.e.*, the possible candidates for γ-ray showers) is quite small.

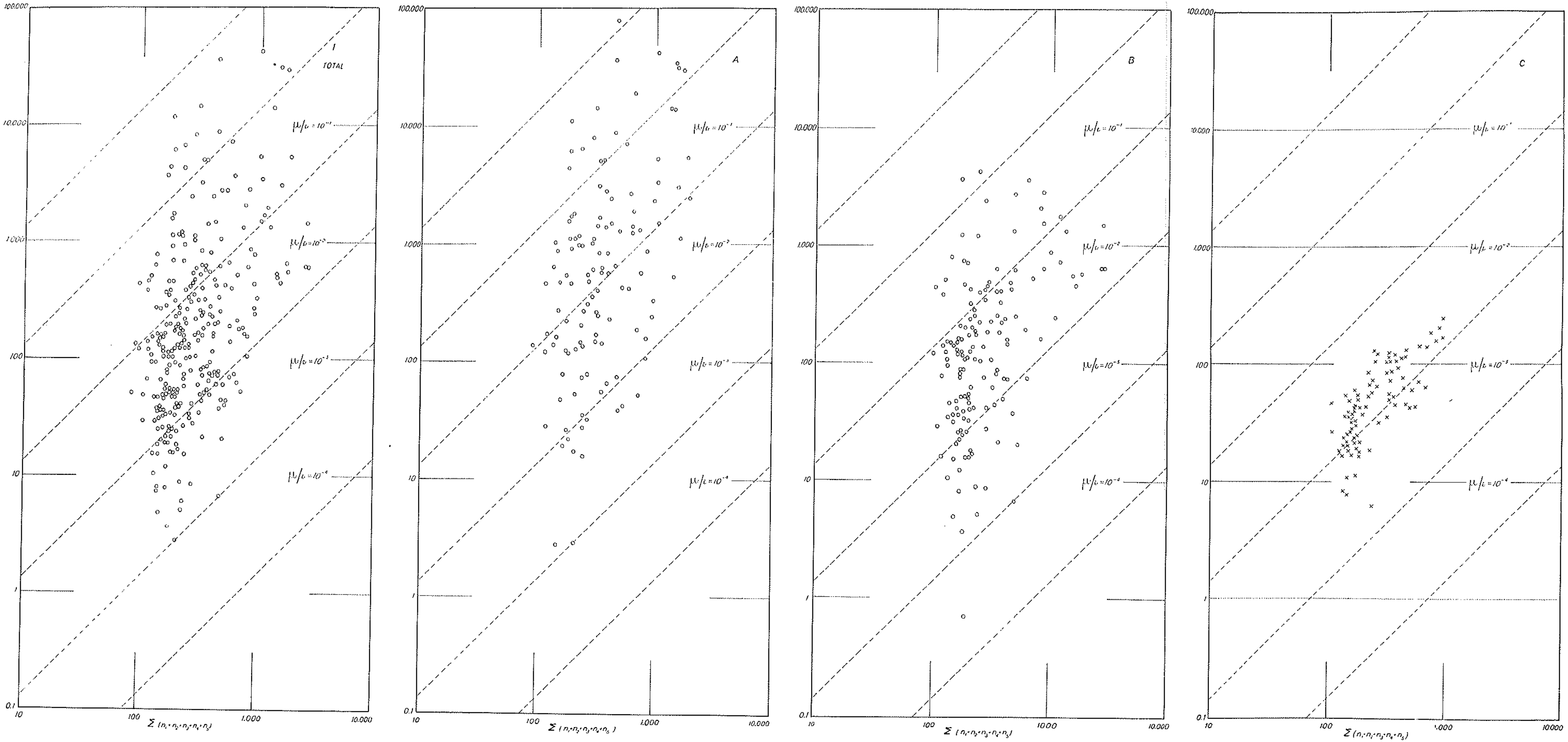


FIG. 6 — Diagrams which show relationship between total number of relativistic particles in 60 m² shielded detector and total number of particles in five unshielded detectors just above 60 m² detector.

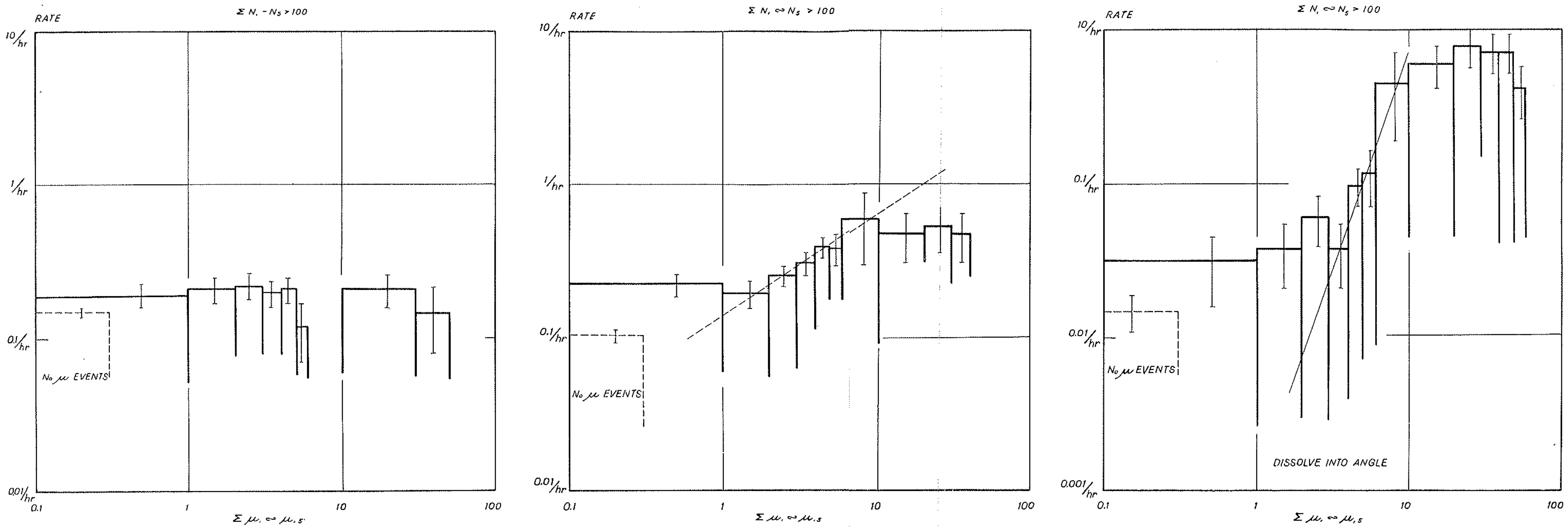


FIG. 7 — Rate of showers with certain number of mu-mesons in 60 m² detector for differential interval of $\Delta\mu = 1$. $\Sigma N_i \sim N_5$ means total number of particles for five unshielded detectors just above 60 m²-detector. 100 for $\Sigma N_i \sim N_5$ should be read as 1,340 for 60 m².

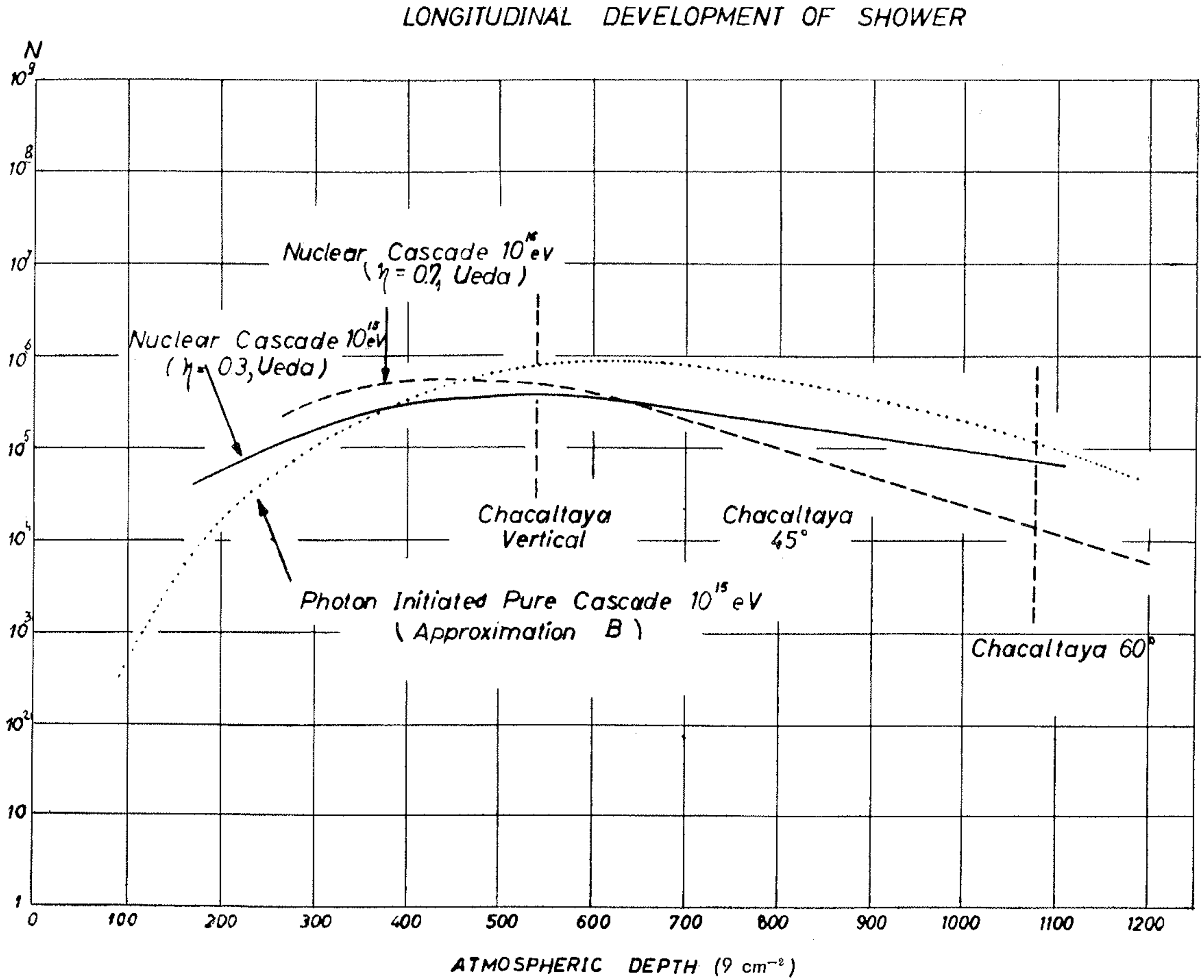


FIG. 8 — Longitudinal development of showers produced by gamma ray and proton through atmosphere.

Fig. 7 is presented to show the relative rates of showers with different numbers of μ-mesons. The abscissa, with a differential interval $\Delta\mu = 1$, gives the summation of the number of relativistic particles traversing the fifteen units which comprise the 60 m^2 detector. Again, the showers have been grouped into the A, B and C core locations. *It is clearly seen that, for the C-showers, there exists a separate group of showers with an exceptionally small number of μ-mesons.* The full line in the figure showing the C-showers represents the Poissonian distribution for an average number of ten μ-mesons. The proportion of the number of showers in this separate group to the total number of showers is about 2×10^{-3} for the same size. Also, the proportion of showers without *any* μ-mesons to the total number of showers is about 3×10^{-4}. This separate group of showers may be a possible indication of showers generated by primary γ-rays but one cannot rule out the possibility that these showers were produced by a nuclear interaction that, because of extreme fluctuation, produced a few neutral π-mesons with great inelasticity.

In the A and B- showers, it is difficult to distinguish a separate class of showers. This seems to be reasonably explained by the fact that the relative amount of μ-mesons to electrons is smaller near the core than far from it. Also, the fluctuation of the nuclear-active component smears out the clear cut separation of these extraordinary showers. By superimposing a distribution (shown by a dotted diagonal line in the case of B-showers) as was done for the C-showers, we can tentatively estimate the relative proportion of extraordinary showers. A value of 1.5×10^{-3} was obtained. This figure is quite consistent with that obtained for the C-showers.

The characteristic of this separate group are those of pure cascades whether produced by a primary γ-ray or primary protons which interact with extreme fluctuations. The longitudinal development of showers produced by γ-rays and by protons is shown in Fig. 8. Approximation B was used for the photon initiated pure cascade and the calculations of UEDA [9] are reproduced for the nuclear showers. The size of a photon shower is about three times larger than that of a proton shower over the range of depth from 530 g/cm^2 (Chacaltaya vertical) to 760 g/cm^2 (Chacaltaya 45°). Assuming that the primary energy exponent is —1.5 to —2.0 for both primary proton and γ-ray *a value* of 3×10^{-4} *is obtained (at the same energy) for the relative proportion of the separate group of showers* instead of 2×10^{-3} at the same size. Table II shows the energy of the primary particles producing the A, B and C- showers observed on Mt. Chacaltaya. For the convenience of discussion, a value of $\eta = 0.5$ has been assumed for the proton showers.

TABLE II

	Range of Primary Proton Energy (eV)	Range of Primary Photon Energy (eV)
A-Showers	$10^{14} \sim 2 \times 10^{15}$	$5 \times 10^{13} \sim 5 \times 10^{14}$
B-Showers	$3 \times 10^{14} \sim 3 \times 10^{15}$	$10^{14} \sim 10^{15}$
C-Showers	$2 \times 10^{15} <$	$8 \times 10^{14} <$

b) Distribution of arrival directions.

The celestials arrival directions of showers with few μ-mesons are shown in Figs. 9a, 9b, 9c. For the C-showers, the black circles and the triangles represent showers with extremely few μ-mesons. There is no striking anisotropy and the points scatter equally over the whole sky. Fig. 9a shows the arrival directions of A, B and C-showers with no μ-mesons. A χ^2 test on this distribution rejects the significance of any lumpy aggregation over the whole sky. A test was made for enhancement along the galactic plane. Points within 5° (10°) of the galactic plane were picked up and counted. The real

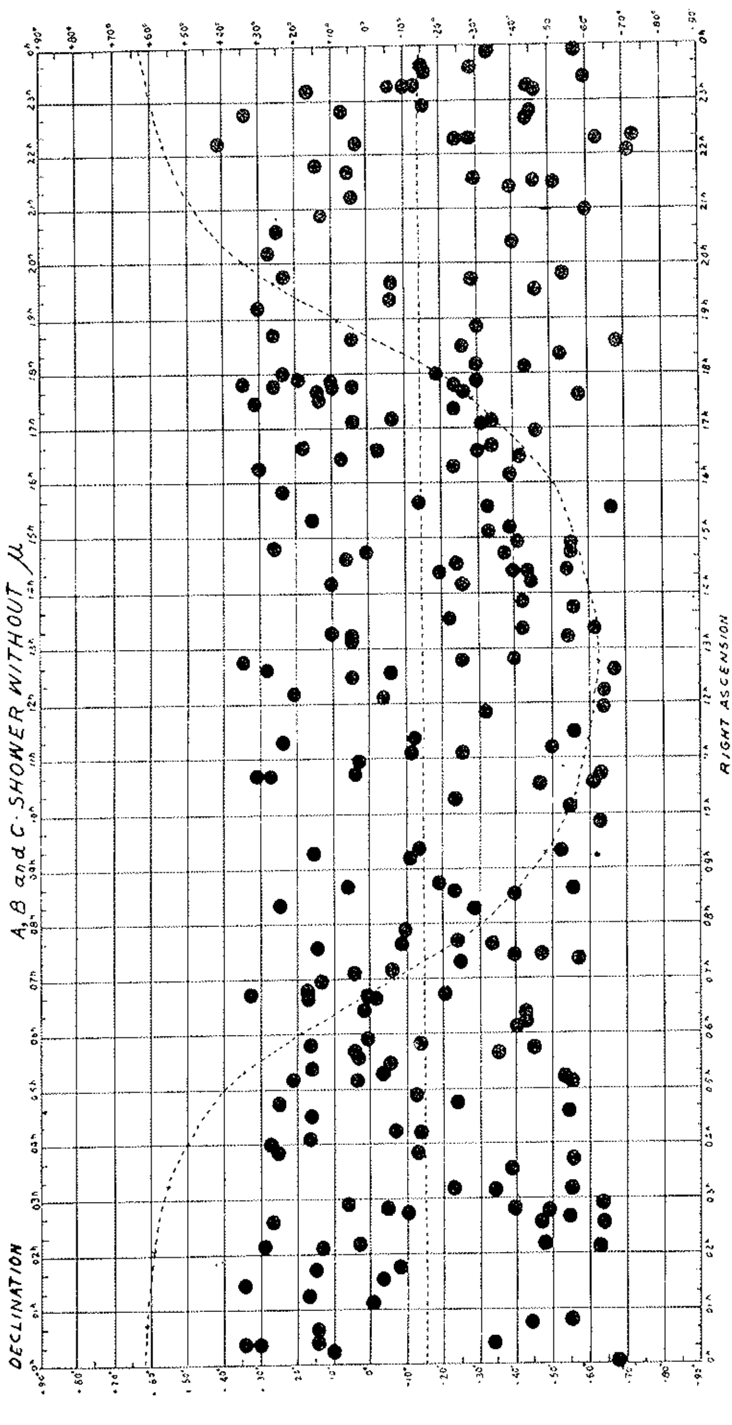


FIG. 9a — The celestial arrival directions of showers with few mu-mesons. Dotted lines indicate the direction of galactic plane.

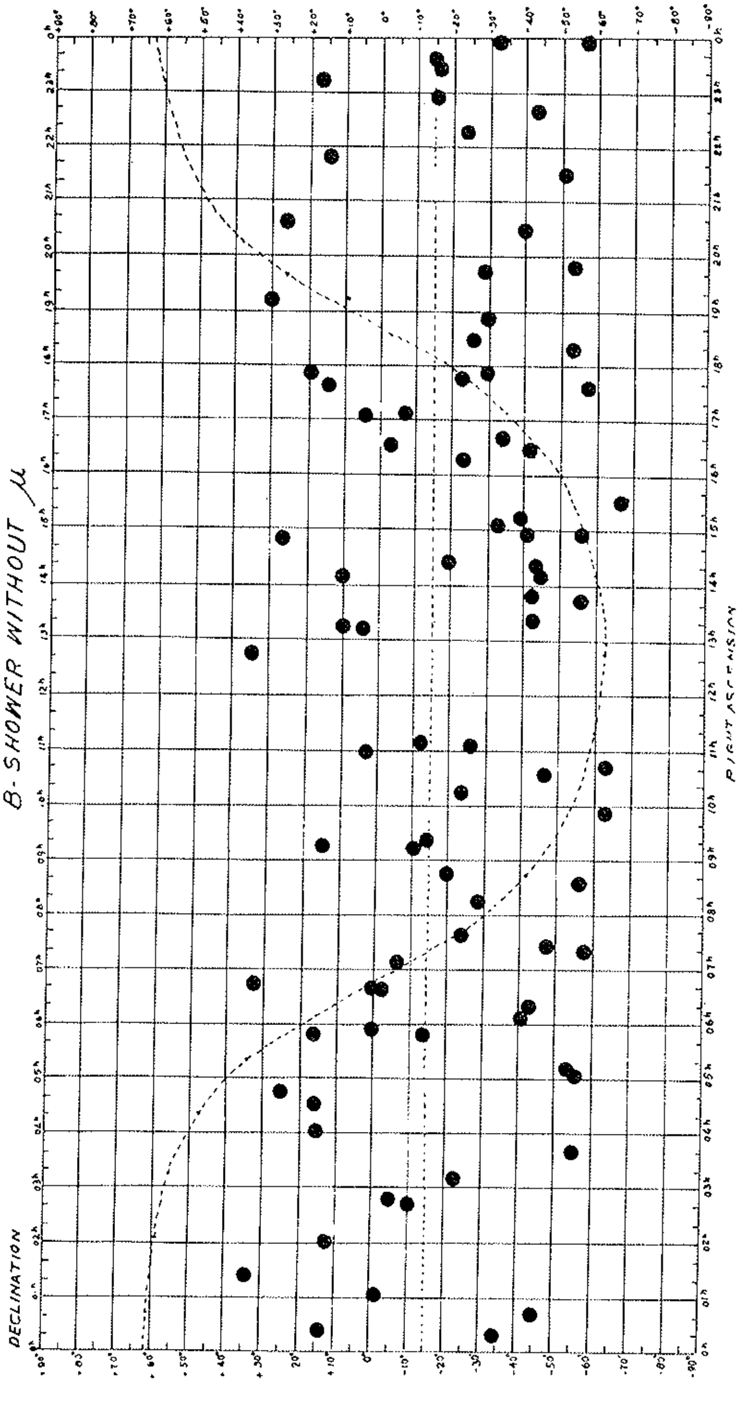


FIG. 9b

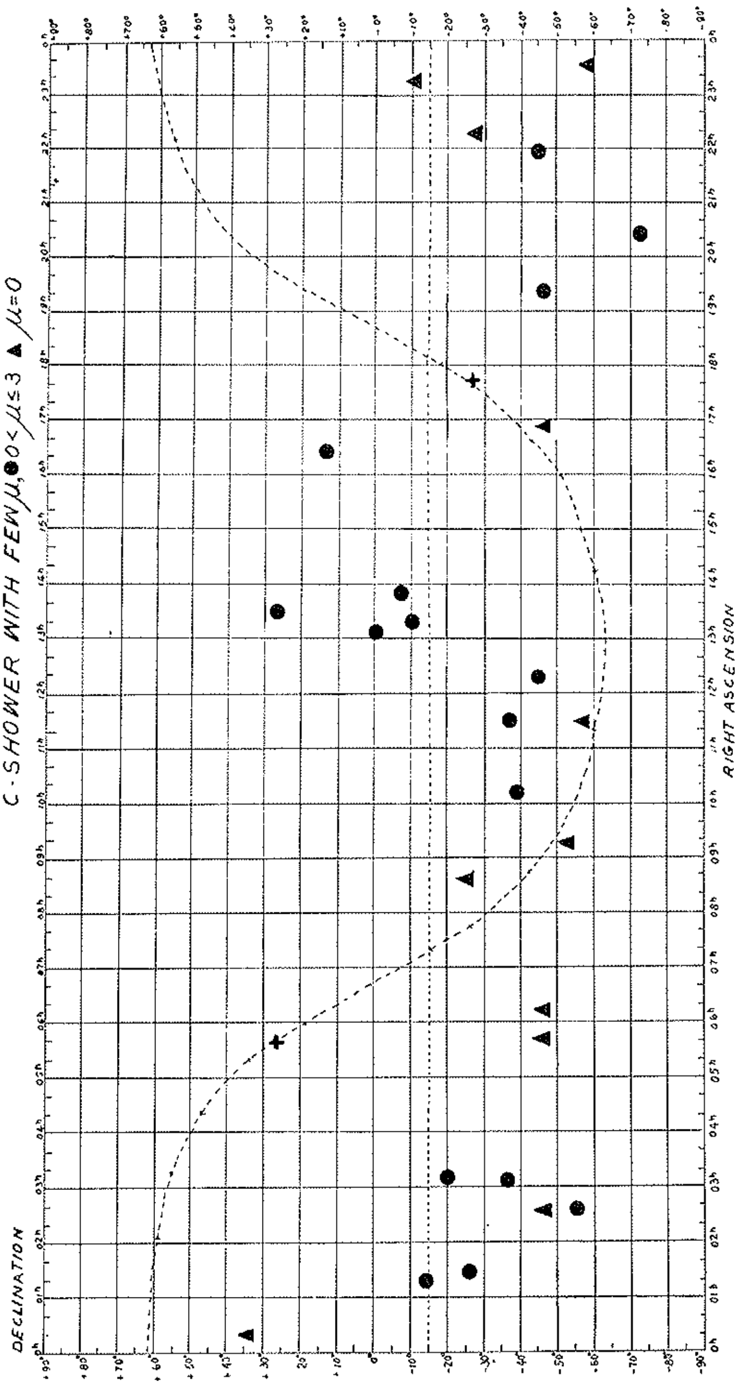


FIG. 9-c

galactic plane with this interval was then shifted by 15° of right ascension and the points now within the 5° (10°) interval were counted. The process was repeated 24 times. Fig. 10 shows the result of this procedure. The ordinate gives the number of showers counted in each shift and the abscissa shows the interval with O being the real galactic plane. There seems to be a slight increase near the galactic plane but the enhancement is not significant. Taking points within 5° of the galactic plane an enhancement of 5×10^{-5} (±60%) over the background of showers of the same energy is obtained under the assumption that the enhancement is due to primary γ-rays.

3. *Conclusions*

The tentative conclusions are the following:

1) There exists a separate group of showers with an extraordinarily small amount of μ-mesons.
2) The frequency ratio of this group to the ordinary showers of the same energy is about 3×10^{-4} (above 10^{15} eV).
3) This group might be a possible indication of the existence of primary γ-rays but the possibility that these showers are the product of nuclear interactions, which, because of extreme fluctuation, have high inelasticity and produce only a few neutral π-mesons.
4) There might be a slight trace of showers without μ-mesons that come from the direction of the galactic plane (above 10^{14} eV).
5) The frequency of this trace of showers is about 5×10^{-5} (±60%) above the background of showers of the same energy.

The first three conclusions came from observation of the C-showers. 4) and 5) came from the observation of A, B and C-showers.

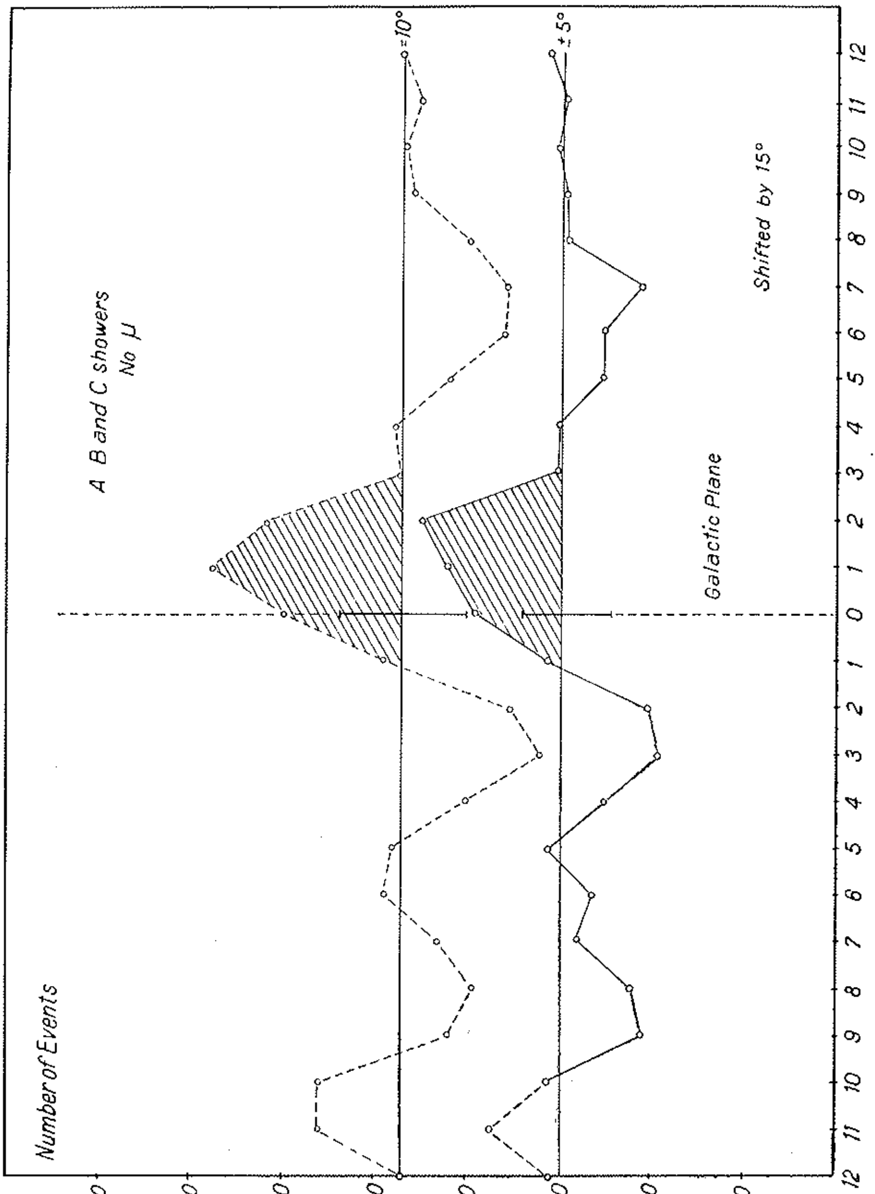


FIG. 10 — Test toward the galactic plane.

Supplementary Remarks

To allow a comparison with these conclusions to be made, the expected ratio of γ-rays will be given:

1) For isotropic γ-rays above 10^{15} eV:

In the halo of the galaxy, the $p+p\rightarrow\pi^0$ process is predominant. The ratio of γ-rays to protons at the same energy is of the order of 10^{-7} under the assumption that the density is $10^{-2}/cm^3$ of hydrogen and that the intensity of cosmic rays is the same as found near the earth. For gamma rays coming from intergalactic space the p + starlight $\rightarrow \pi^0$ is predominant [10]. The ratio is 10^{-4}, if the same intensity of cosmic rays as near the earth is assumed and attenuation by the γ + starlight $\rightarrow e^+ + e^-$ is considered.

2) γ-rays coming from within 5^0 of the galactic plane:

The ratio is of an order of 10^{-6} to 2×10^{-5} if $1/cm^3$ of hydrogen is assumed and if the cosmic ray intensity is constant throughout the whole galactic plane.

Polish and French co-operative groups are also working on the same sort of approach at sea level. They got a value of 3×10^{-3} at same size, as the ratio of abnormal showers with few μ-meson and ordinary showers [11], indicating a consistent result with ours. Results on primary γ-ray with energy more than 50 MeV by KRAUSHAAR and CLARK [12] must be compared with present results. These γ-rays have not a striking anisotropic distribution and the average intensity lies between 3 and 10×10^{-4} $cm^{-2}sec^{-1}ster^{-1}$.

This result appears to indicate the existence of an extragalactic source of γ-rays. If these γ-rays were produced by collisions of cosmic rays with intergalactic matter, and if the density of the latter is taken as $3\times10^{-6}/cm^3$, one would have to assume that the cosmic ray intensity is uniform throughout the Universe.

Equipment to be added in the near future

We are planning to supplement the BASJE installatiou with the following equipments:

a) *A 9′ × 12′ neon hodoscope.*

Placed over the central density detector and the cloud chamber, the device will allow a detailed study of the core structure to he made. Considering that the frequency of shower cores striking the hodoscope will be extremely large on Mt.Chacaltaya, we hope that this device will provide much new information on the character of ultra-high energy nuclear interactions and the constituent of primary particles. When their present purpose has been fulfilled, the energy flow detectors will be clustered underneath the hodoscope to aid in this study.

b) *Image Intensifier System.*

A light detector to record the Čerenkov light produced in the atmosphere by EAS is being planned. This device will be of the type described by PORTER and HILL [13]. Utilizing an image intensifier system and allowing direct photography, the detector will have a high angular resolution. A preliminary experiment was done a few weeks ago at Chacaltaya by HILL and OVERBECK and equipment, suitable for steady operation, is now under construction. The most promising use of this detector is to provide an angular resolution that may be better by a factor of ten over the fast timing method of determining the arrival direction. If so, this additional equipment will provide a powerful method of surveying astronomical objects of small angular size such as the galactic nucleus and intense radio nebulae.

The Authors wish to express their deepest gratitude toward Dr. M. LAPOINTE, Messers. R. SCHULCZEWSKI, A. GARCIA,

I. SARAVIA and J. IPIÑA for their contributions in operating the equipment and in the analysis of the data.

We also want to thank the Japanese Ministry of Education and the Bolivian Government for their support to make this experiment possible.

REFERENCES

[1] K. Suga, I. Escobar, G. Clark, W. Hazen, A. Hendel and K. Murakami, *J. Phys. Soc. Japan*, *17*, Supp. A III, 128, 1962.

[2] I. Escobar, R. Schulezewski, G. Clark, K. Murakami and K. Suga, *Proc. of the IV Interamerican Conference of Peaceful Uses of Atomic Energy*, Mexico, 1962.

[3] S. Miyake, *Progr. Theor. Phys.*, *20*, 844, 1958.

[4] N.L. Gregorov and V. Ia. Shestoperov, *ZETF*, *34*, 1939, 1958.

[5] H. Hasegawa, S. Noranan, T. Matano, I. Miura, M. Oda, S. Shibata, G. Tanahashi and Y. Tanaka, *J. Phys. Soc. Japan*, *17*, Supp. A III, 189, 1962.

[6] C.I. Mitznerv and C.I. Nikolski, *ZEFT*, 38, 257, 1960.

[7] I. Miura and H. Hasegawa, *J. Phys. Soc. Japan*, *17*, Supp. A III, 84, 1962.

[8] N.N. Efimov, D.D. Krasilnikov, M.A. Nifontov and F.K. Shamsutdinova, *J. Phys. Soc. Japan*, *17*, Supp. A III, 232, 1962.

[9] A. Ueda, *Progr. Theor. Phys.*, *24*, 1231, 1960.

[10] S. Hayakawa, *Proc. of the V Interamerican Seminar of Cosmic Rays*, La Paz. Volume 2, 1962.

[11] R. Firkowski, J. Gavin, A. Zawadzki and R. Maze, *J. Phys. Soc. Japan*, *17*, Supp. A III, 123, 1962.

[12] W.L. Kraushaar and G.W. Clark, *Phys. Rev. Let.*, *8*, 106, 1962 and *Proc. of the V Interamerican Seminar of Cosmic Rays*, La Paz, 1962.

[13] N.A. Porter and D.A. Hill, *J. Phys. Soc. Japan*, *17*, Supp. A III, 112, 1962 and D.A. Hill and J.W. Overbeck, *Proc. of the V Interamerican Seminar on Cosmic Rays*, La Paz, 1962.

DISCUSSION

Chairman: G. Lemaître

Ney

We know that there are electron primaries in cosmic rays at 10^9 to 10^{10} eV to the extent of about 1% of the protons. Why should we not consider the smaller flux at your higher energy to be electrons also?

Escobar

I don't think we shall find many electrons of, say, 10^{15} eV because electrons of this high energy are slowed down rapidly by bremsstrahlung in the magnetic field of the galaxy.

Rossi

In this connection I would like to mention that George Clark has made an interesting remark; this is that the magnetic bremsstrahlung produced by electrons of 10^{14} GeV has a spectrum peaked at a wave length in the X-ray region. I would like also to mention that recently Giacconi and others have found some evidence the X-rays coming from a region near the centre of the galaxy. This is a recent rocket experiment. As we all know, it is very difficult to make precise statements from a single experiment, but the evidence is rather convincing.

PETERS

What is the chance of carrying out measurements of the kind that you have been describing at somewhat lower energies? Presumably, the chance of seeing γ-rays from stellar objects will increase rather rapidly. In the case of the Crab Nebula γ-rays of 10^{12} eV exist almost certainly, 10^{13} probably exists; but 10^{15} is out of the range of these objects.

ESCOBAR

When you go to very low energies then the identification of the type of shower is going to be very difficult, because the main problem is how we are going to make a clear distinction between showers which contain and do not contain any nuclear-active particles or any μ-mesons. I would like to repeat here that one of our main worries is the possibility that nucleons may produce μ-less showers by some extreme fluctuations in the first interaction.

PETERS

Perhaps I should make a remark on what you said last. Evidence collected recently seems to show that if two nucleons collide they rarely appear in the ground state, rather they find themselves in one of the isobaric states. If such an isobaric state decays in the neutral mode you are bound to get a π^0-meson which carries on the average 25%, maximum 70% of the primary energy. This is a normal process in high energy interactions, based on the fact that there are 40 known excited states of the baryon, they can all be populated, and the ground state is relatively rare. So it will be rather difficult to eliminate showers in which a large transfer of energy to a single π^0-meson takes place right at the first interaction. The criterion will have to be rather sharp in order to distinguish γ-ray induced from proton induced showers.

ESCOBAR

This is correct; in fact we shall try to study carefully all parameters of the two types of showers, such as the lateral distribution, size spectrum and directions of arrival, to find out whether there is a possibility of making such a distinction. Furthermore we shall also try to improve the determination of the direction of the arrival in order to see if we are able to detect the ultra-high energy γ-rays from point sources like the Crab Nebula.

ROSSI

I should like to amplify on what Dr. ESCOBAR said. This is really our main worry, trying to find out what these μ-less showers are. I discussed it recently with Dr. CLARK and Dr. ODA who agree with Dr. ESCOBAR's remarks. In particular, there might be a possibility of evaluating the « age » of a shower (and therefore the distance from the point of the first interaction) by studying the density distribution at very small distances from the core, the sort of things that the Tokyo group has been doing. At very large distances the lateral distribution is approximately the same for all showers. However, at small distances there are large fluctuations, which appear to be related to the fluctuations in the depth of the first interaction.

GHERZI

May I ask why did you shield with galena, which is an impure matter, instead of lead?

ESCOBAR

This was for economical reasons only. We get the galena cheaper. It is only for shielding purposes. Provided that it is a very heavy material it will be the same whether it is galena or any other heavy material.

AMALDI

May I ask if you could explain what you said about muon-electron ratio. If I understood correctly, you said that at your high altitude station this μ-e ratio has a spread smaller than that observed at sea level. I believe that you mentioned a factor around 1/3. Do you know what is the reason?

Escobar

At Chacaltaya we are near the maximum of the development of showers. Thus a small change in the position of the first interaction does not change the number of electrons appreciably. On the other hand, the μ-meson component decreases slowly past the maximum.

Hayakawa

I want to emphasize the point made by Prof. Peters, I think it is quite true that we have high energy π^0-mesons which would give us a big amount of electrons. If it would also happen in interstellar gas then the ratio of the primary γ-rays with respect to protons will increase and the number you gave us, about 10^{-7} will go up nearly to 10^{-4}, if such a process emphasized by Prof. Peters really happens. And I would also like to mention other sources of γ-rays. γ-rays are also produced by other galaxies and they are almost nearly uniformly distributed and their intensity is expected to be about 10^{-5} as compared with 10^{-7}. So there are more γ-rays than you expected.

Rossi

These, of course, would be isotropically distributed.

Hayakawa

Yes.

Elliot

I want to make a point concerning Prof. Ney's remark on differentiation between primary electrons and γ-rays as the source of your μ-less showers. If you have an electron of energy of about 10^{17} eV, such an electron loses roughly half its energy coming through the magnetic field of the earth. This would generate a shower of very great lateral extent, because it begins at may be a distance of one earth radius away or something like that. This would presumably lead to a cut-off in the frequency which you observe in these showers if you go to sufficiently high energy. I wanted to ask you, because I wasn't clear, what was the highest energy of μ-less shower that you have observed.

ESCOBAR

Until now the average energy is of the order of 10^{15} eV, as shown in Table II. We could go as far may be as 10^{17} or 10^{18} depending on the system of triggering, but what we are trying now to do is just to study the general characteristics of the showers. For that reason we require a fairly good number of showers every day. With the system of triggering we are now using we get about 250 showers a day.

ELLIOT

But isn't it possible to select higher energy showers from the 250 or so per day which are determined by your triggering level?

ESCOBAR

Of course we might select showers of bigger energy just as if we study the general characteristic of each individual shower but the chance that we are going to get showers of much higher energy with this triggering system will be very small.

AMALDI

May I go back to the point already raised by somebody else and which I think you have already answered, and so has Dr. ROSSI, about the structure of the shower? There is obviously a correlation between what you call the C-shower and the distance from the core. You and also Dr. ROSSI mentioned that there is a plan to do a wide investigation abouth this structure of the shower but at the moment — not in the future but now — I wonder if the frequency that you observe, the number of μ-mesons and their distribution as a function of the distance from the core of the shower could not be just a fluctuation if you take account of decrease of muons or things like that.

ESCOBAR

Actually the proportion of μ-mesons to electrons increases with increasing distance from the core. If we selected showeis whose core strikes some distance from the μ-meson detector we increase the probability of detecting μ-meson. Another reason why the data relative to those showers are more specificant is that near the core there may be electrons and photons at much high energy to produce secondary showers that penetrate the shield.

GOLD

The synchrotron radiation of the electrons in the primary cosmic ray beam would seem to be a possible further criterion on the process of origin of cosmic rays if one could measure the electron spectrum carefully. Electrons above 10^{12} eV or so will be treated in their passage through space in exactly the same way as protons and other particles except for the synchroton radiation loss. Therefore if one could measure the spectrum exactly, then one would have a criterion of the rate of energy loss in a given field strength; one would know at what rate cosmic rays must be accelerated if one assumes a value for the field strength, or conversely one would have a value for the field strength in which the cosmic ray fluxes have lived if one had an idea of the rate of acceleration that has happened.

PETERS

May I just for a moment come back to the mention which was made of the work on Explorer XI, because I don't know whether this will be the subject of another talk or come up again. Is there any evidence yet for γ-rays of an energy so high that they could not be produced by annihilation of protons, whereas the γ-rays in the galaxy either originate from π^0 production of fast particles or from annihilation of anti-gas and gas and the γ-ray spectrum of the latter ends at about 150 MeV or so?

ROSSI

There is no energy measurement in Explorer XI. All that KRAUSHAAR and CLARK can say is that the energy is of the order of 100 MeV or more.

BIERMANN

I would also like to come back to the result from Explorer XI. I agree that they are quite relevant to the subject of this conference, but I do not see any place in the programm where they are supposed to come up. As far as I see the KRAUSHAAR and CLARK results can be understood by saying that you get first contributions from the galactic disc, then, second, contributions from the halo, and thir some contributions from other parts of the Universe; the general run of the figures if I remember correctly is such, that the contributions decrease the more the sources are distant. There is another source which is identical, I think, with one mentioned by Dr. PETERS that you should allow for, the contribution from processes on stellar surfaces. This might very well be of the same order. To sum up, I do not see any strong reason for assuming a universal theory of the origin of cosmic rays on the basis of the Explorer XI results.

HAYAKAWA

May I come back to the question of high energy electrons and ask whether or not the X-ray intensity will be consistent with the electron intensity at high energy taking into account the synchrotron loss?

ROSSI

I have not made the calculation myself but I am told that the flux of X-rays is consistent with the flux of γ-rays of energy greater than 10^{14} eV, if μ-less showers observed in Bolivia are indeed produced by such γ-rays.

HAYAKAWA

Then I should like to remark that I think that for X-ray production the inverse Compton effect is more effective than the synchrotron radiation and actually the energy loss due to this process is about the same as the synchrotron energy loss. Moreover, in the inverse Compton effect the spectrum of the scattered photons has a high mean energy so that it will contribute to X-rays even if the energy of electrons is, say, about 1 GeV (1).

ROSSI

I do not think that inverse Compton effect was taken into account. Thank you for pointing this out. One will have to look into this matter.

(1) Note added in proof. Later investigation has shown that the inverse Compton X-rays due to galactic electrons are weaker than X-rays produced by the synchrotron radiation, atomic excitation and the innerbremsstrahlung of knock-on electrons, but that, due to intergalactic electrons, could be strong enough if their intensity is considerable. See: S. HAYAKAWA and M. MATSUOKA, *Progr. Theor. Phys.* (to be published); COSPAR Symposium (1963); G. CLARK, preprint; J.E. FELTON and P. MORRISON, *Phys. Rev. Letters*, *10*, 453 (1963).

EXPLORER X PLASMA MEASUREMENTS

A. BONETTI [1], H.S. BRIDGE, A.J. LAZARUS,
B. ROSSI and F. SCHERB

Physics Department and Laboratory for Nuclear Science [2]
Massachusetts Institute of Technology
Cambridge, Mass. - U.S.A.

Abstract — Plasma measurements were made with a detector aboard the Explorer X satellite, launched on a highly elongated elliptical trajectory with the line of apsides about 33° to the anti-solar direction. Magnetic field measurements were also carried out on Explorer X by the Goddard Space Flight Center of NASA. A plasma moving with a velocity of about 300 km sec^{-1} was first observed when the satellite reached a distance of about 22 earth radii. During the remainder of the observations (which terminated about 40 hours later, at a distance of 42 earth radii) periods in which substantial plasma fluxes were recorded alternated with shorter periods in which the plasma flux was below or just above the detection limit. There was a striking correlation between the plasma flux and the magnetic field: in the absence of plasma the magnetic field direction was nearly radial from the earth, while in the presence of plasma, the field was irregular and generally formed large angles with the earth-satellite direction. The plasma probe did not provide accurate information on the direction of the plasma flow, but placed the direction within a « window » of about 20° × 80°. This window includes the direction pointing radially away from the sun.

---

(1) Presently at the Istituto di Fisica, Università di Bari - Bari, Italy.

(2) This work was supported in part by the National Aeronautics and Space Administration and the United States Atomic Energy Commission.

The flux densities of the positive ions (presumably protons) corresponding to the observed currents were of the order of a few times 10^8 cm^{-2} sec^{-1}. They fluctuated over a range of about a factor of two during the periods when plasma was observed.

1. Introduction

The purpose of this paper is to present the results of plasma measurements performed by Explorer X (1961 Kappa) in the near-by interplanetary space and to discuss them in relation to the magnetic field measurements made aboard the same vehicle. A full report on the latter measurements has appeared recently [1]. It what follows, we shall refer to this paper as HNSS. Preliminary reports on both experiments have been presented at various scientific meetings [2-9].

At the time when the instrumentation for Explorer X was being planned, there were no direct observations of interplanetary plasma and the only indications for its existence came from arguments based on various kinds of indirect evidence. Such evidence included the behavior of comet tails, the scattering of solar light from the distant solar corona and the zodiacal cloud, the occultation of point-like radio sources passing in the general vicinity of the sun, correlations between solar phenomena and geophysical effects, and cosmic-ray observations indicating the existence of an interplanetary magnetic field which was difficult to explain in the absence of a plasma.

For a review of evidence based on the observations mentioned here, the reader may consult, for example, a paper by Rossi [6].

While it was generally accepted that at least the inner part of the solar system should be filled with a dilute plasma, presumably of solar origin and consisting mainly of fully ionized hydrogen, the estimates concerning the density of this plasma varied over a very wide range, from a few particles to several thousand particles per cm^3. Similar uncertainties existed with regard to the magnitude and direction of the plasma velocity, to its temperature, etc. Thus, the over-riding requirement in the design of our instrument was that it should be capable of providing meaningful results under a great variety of possible situations. This requirement, together with severe limitations in weight, power, and telemetering capability, made it necessary to sacrifice accuracy for reliability and dynamic range.

While the preparations for Explorer X were under way, Soviet scientists flew plasma probes on a number of space vehicles, specifically Lunik I (launched in January, 1959), Lunik II (launched in September, 1959), Lunik III (launched in October, 1959) and Venusik (launched in February, 1961). These probes could be operated so as to detect either positive ions of all energies, or electrons with energies above 200 eV. Their construction consisted essentially of a collector plate with two grids in front of it. The inner grid carried a negative potential intended to suppress photoelectric current from the collector; the outer grid was given different positive or negative potentials with respect to the body of the satellite in order to obtain some information on the energy of the plasma ions. The observations made during these flights were published partly before, partly after the flight of Explorer X [10-14]. Most directly pertinent to our problem are the following points:

a) Lunik II was fired away from the sun. Radio contact with this vehicle was maintained from take-off to a distance of about 30 earth radii (R_e), and then again from 39 R_e to impact on the moon. In the early part of the flight (up to about 4 R_e) positive-ion currents were observed, indicating the presence of a stationary plasma, swept into the probes by the motion of the vehicle. No positive-ion currents above background were detected from 4 R_e to 30 R_e. From 39 R_e

to the end of the flight, the probes indicated a flux of positive ions with a density of about 2×10^8 particles cm^{-2} sec^{-1}. Measurements made with different voltages on the outer grid showed that the energy of these ions was greater than 15 eV, but did not allow a more precise determination. No information about the direction of the ion flux was obtained;

b) Lunik III was launched in the general direction of the sun. An observation made at about 20 R_e revealed a flux density of about 4×10^8 positive ions cm^{-2} sec^{-1}; the ions appeared to have energies considerably greater than 20 eV. Other readings, taken at larger distances, did not reveal any detectable ion flux;

c) Venusik was launched in the general direction of the sun. On at least one occasion, when the vehicle was at a distance of 297 R_e, definite evidence for a positive ion flux was obtained; the density of this flux was about 10^9 particles cm^{-2} sec^{-1}.

It should be noted that, even though the suppressor grid eliminated « direct » photoelectric currents from the collector, « inverse » photoelectric currents (see section 2-B) were still present. In most of the measurements, these currents seem to have placed a lower limit of the order of 10^8 cm^{-2} sec^{-1} to the detectable flux density of positive plasma ions.

2. Instrumentation

A. *Particle fluxes in a moving plasma.*

The primary purpose of the plasma measurements performed by Explorer X was to provide data on the density of the plasma, on the direction of its bulk motion and on the magnitude of its bulk velocity, V_0. The bulk velocity is here defined as the velocity (relative to the satellite) of the frame of reference in which the total momentum of the ions and electrons contained in a volume element of the plasma vanishes. It was also hoped that some information would be obtained concerning the random velocities of the plasma particles in this frame of reference. We shall refer to these velocities as « thermal » velocities, without thereby implying that the plasma fulfilled the conditions required for the definition of a temperature (Maxwellian velocity distribution for each kind of particle, equipartition of energy between the various components).

In general, the shape of the signal from the plasma probe is determined by the directional distribution and the energy spectrum of the charged particles in the moving plasma. Let us consider one of the components of the plasma, *e.g.*, the electrons or the positive ions. If the « thermal » velocities of the particles in question are very small compared with the bulk velocity V_0, then the particles form a practically parallel beam having a single energy E_0 given by $E_0 = ½\ mV_0^2$. If the « thermal » velocities are very large compared with V_0, then the particles have an energy spectrum which practically depends only on their « temperature », and a directional distribution which is practically unrelated to the direction of motion of the plasma as a whole. If the « thermal » velocities are small, but not negligible compared with the bulk velocity, then the particle beam, while no longer parallel, is still strongly collimated in the direction of $\mathbf{V}_0$. Likewise, the beam, while no longer monoenergetic, has an energy spectrum strongly peaked near the energy $E_0 = ½\ mV_0^2$. More precisely, the mean angular spread of the beam will be of the order of

$$\Delta\omega = \pm v_{\perp} / V_0 , \tag{1}$$

where $v_{\perp}$ is the average magnitnde of the « thermal » velocities perpendicular to the bulk motion. Similarly, the mean fractional energy spread will be of the order of

$$\Delta E/E_0 = [(V_0 \pm v_{\parallel})^2 - V_0^2] / V_0^2 \simeq \pm 2\, v_{\parallel}/V_0 \,, \qquad (2)$$

where $v_{\parallel}$ is the average magnitude of the « termal » velocities parallel to the bulk motion. If the distribution of « thermal » velocities is isotropic, then $v_{\perp} = v_{\parallel}$, and Eqs. 1 and 2 establish a connection between the angular spread and the energy spread of the observed plasma particles.

If there were equipartition of energy between electrons and positive ions, then the « thermal » velocities of the two kinds of particles would be inversely proportional to the square root of their masses (*e.g.*, protons would be moving 43 times more slowly than electrons). Although, as noted above, there is no reason to believe that such an equipartition is actually achieved, it is still reasonable to assume that the « thermal » velocities of the heavy positive ions are much smaller than those of the electrons. Thus, we might expect that the bulk motion of the plasma is much more clearly recognizable in the directional distribution and in the energy distribution of the positive ions than in the corresponding distributions of the electrons.

Actually, it turns out that measurements on the electron component would not provide reliable information on the bnlk motion of the plasma, even if the « thermal » velocities of the electrons were small compared with the bulk velocity V_0. This is because the kinetic energy of electrons corresponding to reasonable values of V_0 is of the order of several eV at most (2.5 eV for $V_0 = 1000$ km sec^{-1}) and because the unknown electric charge of the satellite introduces serious difficulties in the interpretation of flux measurements at these very low energies (see section 4-A below).

Another reason why measurements of electrons are of less direct value than measurements of positive ions is that, presumably, the satellite is surrounded by a cloud of photoelectrons ejected from its surface by the solar radiation. These electrons may not easily be distinguished from those belonging to the plasma.

It is clear, therefore, that the quantity of most immediate interest for our purposes is the flux of positive ions rather than the flux of electrons.

B. *Description of the plasma probe.*

The instruments used aboard Explorer X to measure the flux of positive ions has already been described in some detail in previous publications [15], [16]. It is a device which separates the positive ions from the electrons in the plasma beam entering the instrument and measures directly the current I carried by the positive ions. If the ions are singly charged, this current is given by:

$$I = (\text{elementary charge} \times \text{ion flux}), \qquad (3)$$

where the ion flux is the total number of ions that arrive upon the collecting electrode per second.

During the planning of our experiment, we were concerned about background currents produced by the photoelectric effect. Estimates available at that time [17] indicated that ultraviolet rays incident on a metal plate facing the sun would produce a photocurrent of the order of 10^{-8} A cm^{-2}. This current was near the upper limit of the expected plasma currents; unless suppressed to a very large extent, it would have probably made it impossible to detect a plasma flowing from the direction of the sun.

The probe, whose schematic design appears in Fig. 1, consisted of a metal cup containing several plane grids (G_1, G_2, G_3, G_4) and a plane collector plate (CP). The cup was mounted

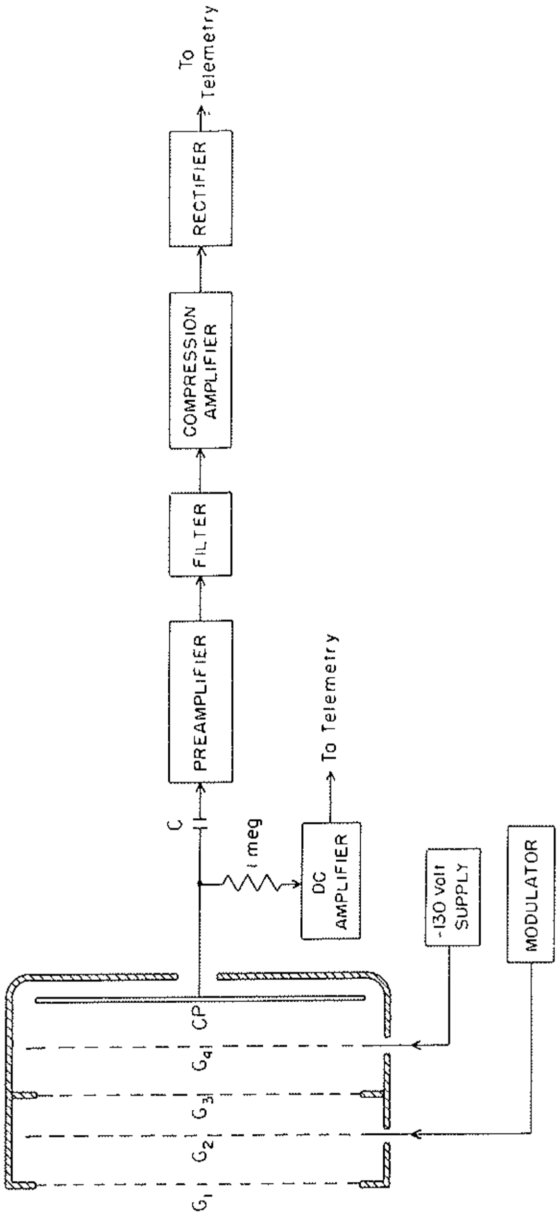


FIG. 1 — Schematic diagram of the plasma probe and block diagram of the electronic system.

in a hole on the outer wall of the satellite, in such a way that grid G_1 (which closed the cup) was part of the satellite's skin. Grids G_1 and G_3 were directly attached to the body of the vehicle, whose potential we shall take as zero. The collector plate CP also connected, through a resistor, to the body of the vehicle. Grid G_4 was kept at a constant negative voltage of 130 V.

In order to understand the operation of the probe, suppose first that grid G_2 is at zero potential, and consider what happens when a neutral plasma flows into the probe. The plasma electrons cannot traverse G_4 unless they have energies greater than 130 eV. Therefore, they flow to another grid or to the walls of the cup. The positive ions, on the other hand, go through G_4 and strike the collector, producing a current I as given by Eq. 3.

The negative potential of G_4 not only stops the plasma electrons but also prevents the escape of photoelectrons emitted by the collector CP when it is exposed to sunlight. Thus, G_4 suppresses the so-called « direct photoelectric current » which otherwise would add to the plasma current (in addition, it suppresses secondary electron emission due to the impact of charged particles on CP). However, sunlight reflected by the collector onto the rear surface of G_4 does produce a photoelectric current, usually referred to as « reverse photoelectric current », which subtracts from the plasma current (as already noted, this current appears to have been a serious background effect in the measurements made by means of the Soviet probes).

Suppose next that, keeping the other grids at the fixed voltages specified above, we apply to G_2 a voltage that varies rapidly and periodically between zero and a positive value sufficiently high to stop the positive ions. The positive ion flux is periodically interrupted, whereas the inverse photoelectric current is not affected in any way. Thus, the collector current will contain a d.c. component which depends both on the positive ion flux and on the inverse photoelectric current, and an a.c. component which depends only on the positive ion flux. By sorting out the a.c. component of the collector current we can now measure the positive ion flux without interference from photoelectric currents.

Any capacitive coupling betwen the modulating grid G_2 and the collector plate CP would cause a spurious signal to appear on CP. Grid G_3 (made of close-spaced bronze mesh) was added to reduce this effect to a negligible value. This grid also prevented modulation of the inverse photoelectric current between CP and G_4.

We have neglected so far a possible contribution of electrons with sufficiently high energy to overcome the retarding potential of G_4. The positive pulsating voltage of G_2 will not stop these electrons; however, it may slightly change the number of electrons reaching the collector CP because the transmission properties of the grid system may depend on the electric field distribution between the grids. Thus, the electron flux on the collector may be slightly modulated and it will then contribute to the observed a.c. component of the collector current in proportion to the degree of modulation. This question was investigated experimentally and the results are described below.

The use of a pulsating positive voltage to modulate the positive ions not only eliminates unwanted background effects, but also affords the possibility of measuring the energy of the ions. In fact, it is clear that if singly-charged ions with energy equal to E eV are incident perpendicularly upon the probe, the minimum amplitude of the pulsating voltage needed for their modulation is $V_m = E$. In other words, the a.c. current produced by a modulating voltage V_m is a measure of the total flux of singly charged ions with energy $E < V_m$. If, on the other hand, the beam is incident at an angle δ with respect to the normal to the probe, the pulsating voltage necessary to modulate ions of energy E is

$$V_m = E \cos^2 \delta \, . \qquad (4)$$

In our probe the collector CP had an area of 121 cm^2, and the combined transparency of all the grids was 23% (the shield grid G_3 by itself had a transparency of 36%). Thus, the effective area of collection for normal incidence was 28 cm^2.

For oblique incidence, the effective area of collection A is a decreasing function of the angle δ between the ion beam and the normal to the cup. We computed the dependence of A on δ from the geometry of the probe and the estimated variation of the grid transparencies. The result of this computation is shown in Fig. 2 (dotted curve). It is seen that the probe was completely insensitive to ions incident at angles greater than 63° to its normal.

The modulating voltage was applied in the form of a square wave with a frequency of 1400 cycles per second. Six different amplitudes were used; *i.e.*, 5, 20, 80, 250, 800 and 2300 V. (Since it was inconvenient to obtain pulsating voltages varying over such a wide range from a single supply, we used, in place of G_2, two separate modulating grids connected to two separate supplies, one providing the lower three modulating voltages and the other one providing the higher three modulating voltages).

A block diagram of the electronic system appears in Fig. 1. The collector CP was capacity coupled to a wide-band a.c. preamplifier which had an input impedance of 15,000 ohms. This was followed by a narrow-band filter tuned to the modulation frequency, by a compression (non-linear) amplifier with a dynamic range of about 5,000, and by a rectifier. The rectified signal, in the range from 0 to 5 V, was applied to the imput of the telemetering system.

The lower limit of the measurable a.c. current (determined by the amplifier noise) was about 2×10^{-11} A. The upper limit (determined by saturation of the amplifier) was about 10^{-7} A. Thus, for perpendicular incidence, the minimum

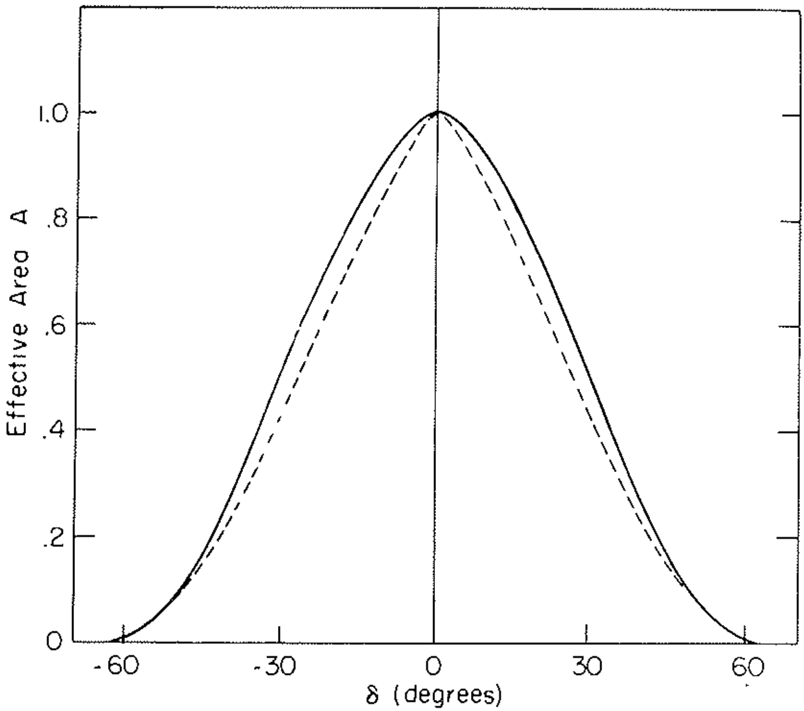


FIG. 2 — Angular response of the probe for a parallel beam of particles. The abscissa is the angle δ between the normal to the cup and the direction of the incident beam. The ordinate is the effective area of collection, normalized to unity for perpendicular incidence. The dotted curve is the result of a computation based on the geometry of the cup; the solid curve is the result of a direct measurement made by means of a well collimated electron beam.

detectable flux density (flux per unit area) was about 4×10^6 singly charged particles cm^{-2} sec^{-1}; the maximum measurable flux density was about 2×10^{10} particles cm^{-2} sec^{-1}.

The collector CP was also directly coupled to a d.c. amplifier through a 1 M Ω resistor. The useful range of this amplifier was from about 10^{-7} A to 5×10^{-7} A.

C. *The Explorer X configuration.*

Fig. 3 shows the structure of Explorer X and the location of the various instruments aboard this satellite.

The instruments used for measurements of the magnetic field included a rubidium vapor magnetometer and two flux-gate magnetometers (see HNSS).

The satellite spun around its axis of symmetry (see Fig. 3) with a rotation period of 548 milliseconds. A sun-earth-moon aspect sensor, instrumented by the Goddard Space Flight Center, provided information on the orientation of the spin axis

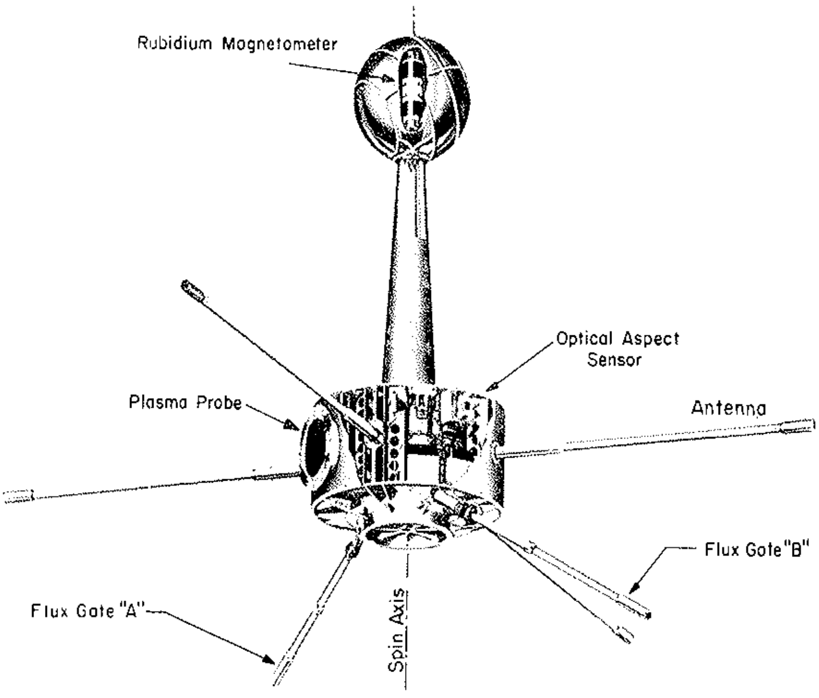


FIG. 3 — Explorer X (from the paper by HEPPNER, NESS, SEARCE and SKILLMAN [1]).

and on the instantaneous angular position of the various instruments with respect to a plane passing through the spin axis and the sun.

The normal to the plasma probe was perpendicular to the spin axis. Thus, during each rotation it swept out a plane which we may call the « equatorial » plane of the satellite. As explained above, the probe was only sensitive to ions incident at angles smaller than 63° above or below this plane.

If the « thermal » velocities of the ions are not large compared with the bulk velocity V_0, the current recorded by the probe varies periodically with the rotation of the satellite. One should expect that it reaches a maximum at the time when the angle δ between the normal to the probe $\mathbf{n}$ and the vector $\mathbf{V}_0$ has its minimum value; *i.e.*, when the probe looks as closely as possible into the plasma stream. In order to express δ as a function of time, it is convenient to introduce the angles defined in Fig. 4, *i.e.* the angle α between $-\mathbf{V}_0$ and the equatorial plane of the satellite, and the angle β between $\mathbf{n}$ and the projection of $-\mathbf{V}_0$ onto this plane. As the satellite rotates, α

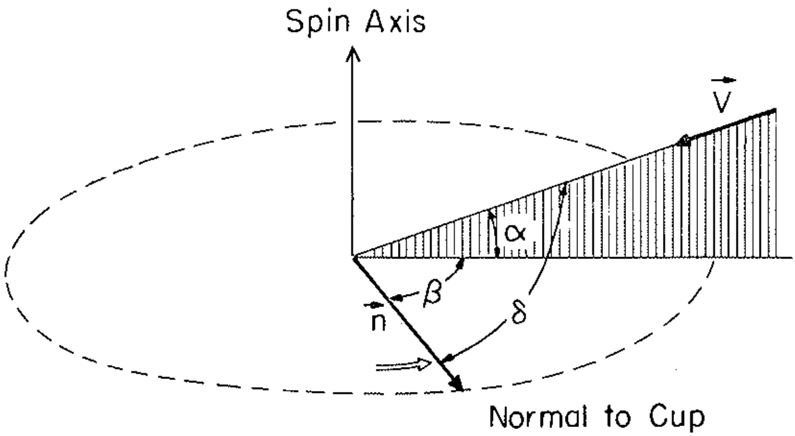


FIG. 4 — Showing the spin axis of the satellite, the normal to the cup $\mathbf{n}$, the plasma velocity vector $\mathbf{V}_0$ and illustrating the angles α, β, δ.

remains constant, β increases uniformly with time, and the instantaneous value of δ is given by:

$$\cos \delta = \cos \alpha \cos \beta \,. \tag{5}$$

The shape of the current signals from the probe (collector current I vs. β) depends on the degree of collimation of the ion beam and on the value of the angle α. As an example, let us consider the case of a parallel beam. If $\alpha = 0^\circ$, then $\delta = \beta$ and the computed signal is illustrated by the dotted curve in Fig. 2. Using this curve and Eq. 5, one can easily compute the expected height and shape of the signals produced by parallel beams incident at any angle α between 0° and 63°.

We have considered thus far a situation in which the modulating voltage V_m is higher than the kinetic energy E of the ions; in this case, full modulation occurs at all angles of incidence. However, if $V_m < E$, modulation occurs only when the angle of incidence is greater than the angle defined by Eq. 4 (provided δ is smaller than 63° — the maximum angle of acceptance of the probe). Thus, for $\cos^2 63^\circ < V_m/E < \cos^2 \alpha$, the current signal obtained during the rotation of the satellite will have a characteristically « horned » shape such as illustrated in Fig. 5 for the case of $\alpha = 0^\circ$.

D. *Laboratory tests.*

Prior to the flight, we subjected the probe and the associated electronic circuits to extensive laboratory tests, and other tests were made after the flight on a duplicate of the flight unit.

The probe was placed in a vacuum system and exposed to parallel beams of protons of various energies and at various angles of incidence. We thus verified that for each energy and for each angle, there was a sharp lower limit, V_m, for the amplitude of the voltage necessary to modulate the proton beam, and that V_m agreed with the value given by Eq. 4.

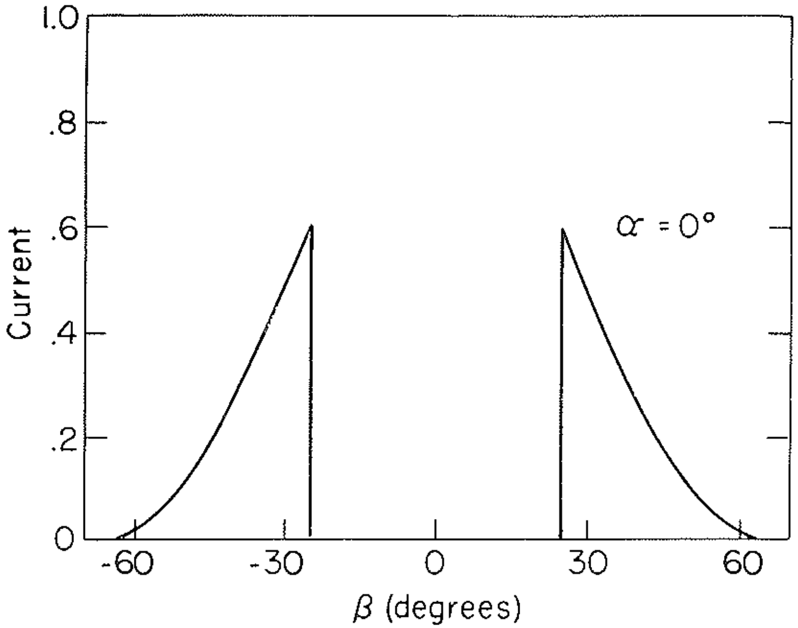


FIG. 5 — Computed current signal for a parallel beam of singly charged ions whose energy (in eV) is 1.2 times the modulating voltage. The velocity vector lies in the equatorial plane of the satellite ($\alpha = 0°$). The abscissa is the angle of rotation β (see Fig. 4) and the ordinate is the magnitude of the current relative to that corresponding to a fully modulated beam incident perpendicularly upon the probe.

Above this limit, the a.c. signal was found to be independent of the modulating voltage.

It was also verified that even the highest modulating voltages did not produce a detectable signal through capacity coupling of the modulating grid to the collector plate.

In order to determine the importance of photoelectric effects in the cup, we placed in the vacuum system a source of ultraviolet rays whose intensity at the probe was about one third the intensity of solar ultraviolet rays. At the beginning of the test, a small signal was detected, but it disappeared when the probe had been thoroughly outgassed. We attribute this signal to photoionization of the residual gas.

The probe was exposed to a beam of electrons of sufficient energy to overcome the retarding potential of G_4. An a.c. signal was observed corresponding to a partial modulation of the electron flux, the degree of modulation depending somewhat on the electron energy and on the modulating voltage. The modulated component was usually one to three percent of the total flux, in no case larger than 5%. Thus, the probe, when operated as described, detects only a small fraction of the high-energy electrons that may be present in the plasma.

Using a well-defined narrow beam of electrons, and keeping G_2 at zero potential, we tested the geometrical response of the probe, *i.e.*, the dependence of the effective area of collection A on the angle of incidence δ. The solid curve in Fig. 2 represents the results of these measurements. This curve may be compared with the computed response curve (dotted in Fig. 2), both curves having been normalized to $A=1$ at normal incidence. While there is no difference in the cut-off angle, the experimental curve is about 10° wider than the computed curve at half height. In what follows, we shall refer to the solid curve in Fig. 2 as the *geometric response curve* of the probe and we shall use this curve in the analysis of our data.

The geometric response curve and Eq. 5 can be used to compute the effective area of collection A as a function of the angles α and β (see Fig. 4). Curves showing A vs β for various values of α, normalized to $A=1$ for perpendicular incidence, appear in Fig. 6. To bring out more clearly the differences among the shapes of these curves, we have replotted them in Fig. 7 after normalizing each curve to $A=1$ at $\beta=0°$ (1).

We also used the narrow electron beam and a deep Faraday

(1) These curves differ somewhat in shape from those shown in Figs. 10-14 of our previous communication [2] because of a plotting error in the earlier curves.

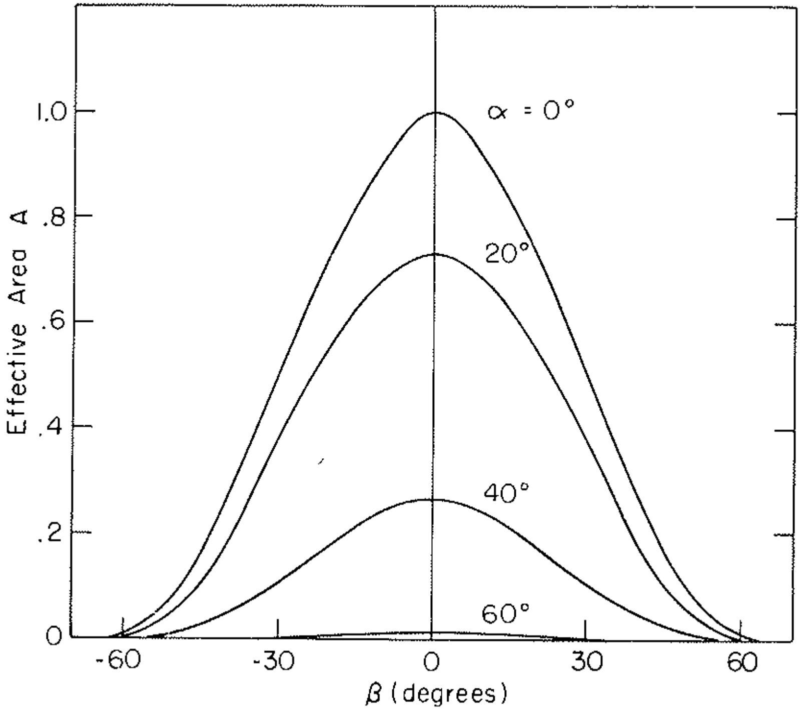


FIG. 6 — Response curves of the probe for fully modulated parallel beams of ions forming different angles α with the equatorial plane of the satellite. The ordinate is the effective area of collection A normalized to unity for perpendicular incidence ($\delta = 0^0$).

well to make an absolute calibration of the probe for normal incidence.

Finally, we tested the effect of the electronic circuits on the signals by putting in pulses of known shape and recording the corresponding output pulses. Some of the results thus obtained are shown in Fig. 8. The input signals are those computed for parallel ion beams incident at different angles to the equatorial plane of the satellite. They are represented by curves identical to those shown in Fig. 7, with the time scale adjusted to the period of rotation of the satellite. There

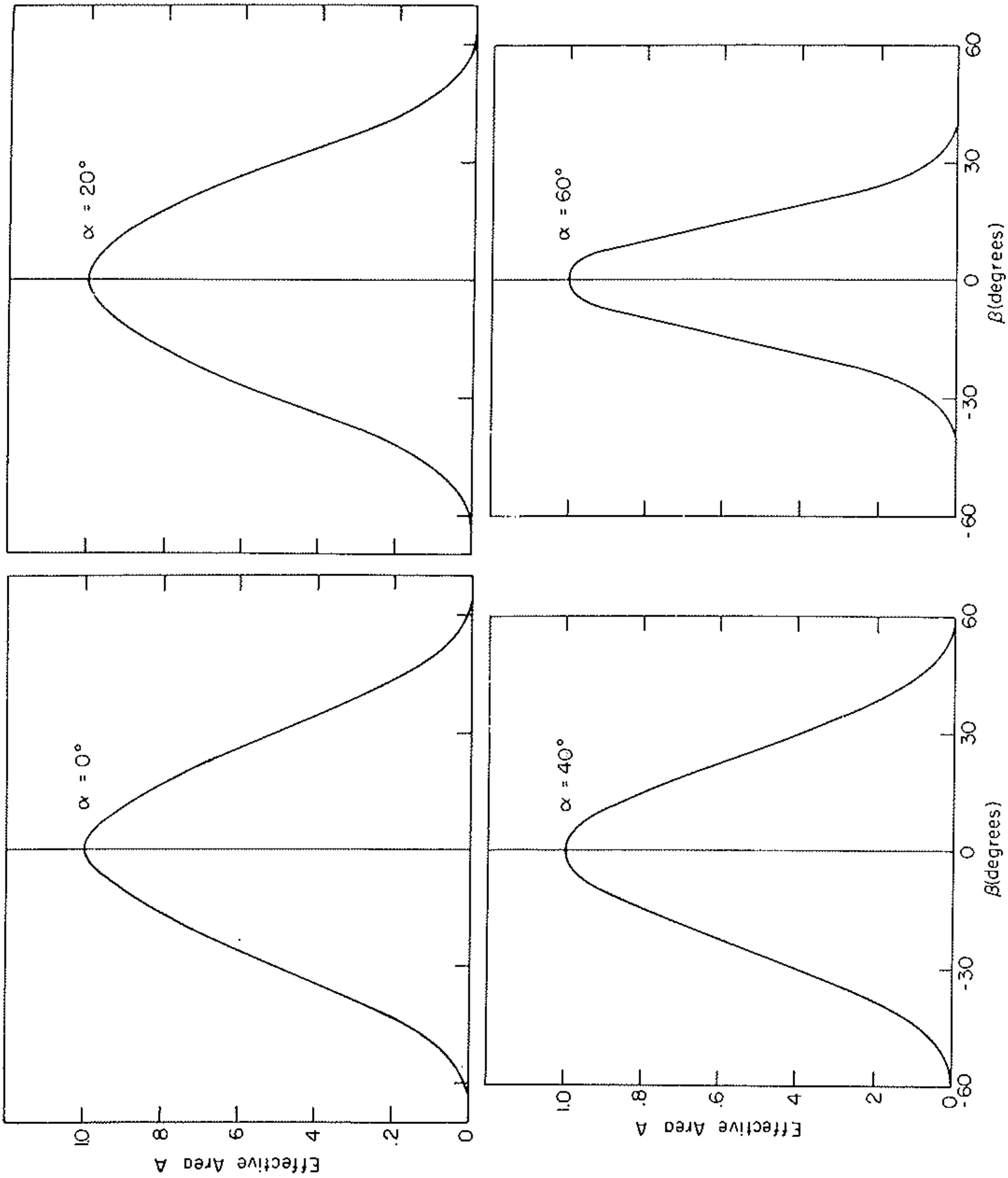


FIG. 7 — Same as Fig. 6, with the effective area of collection normalized to unity at $\beta = 0°$.

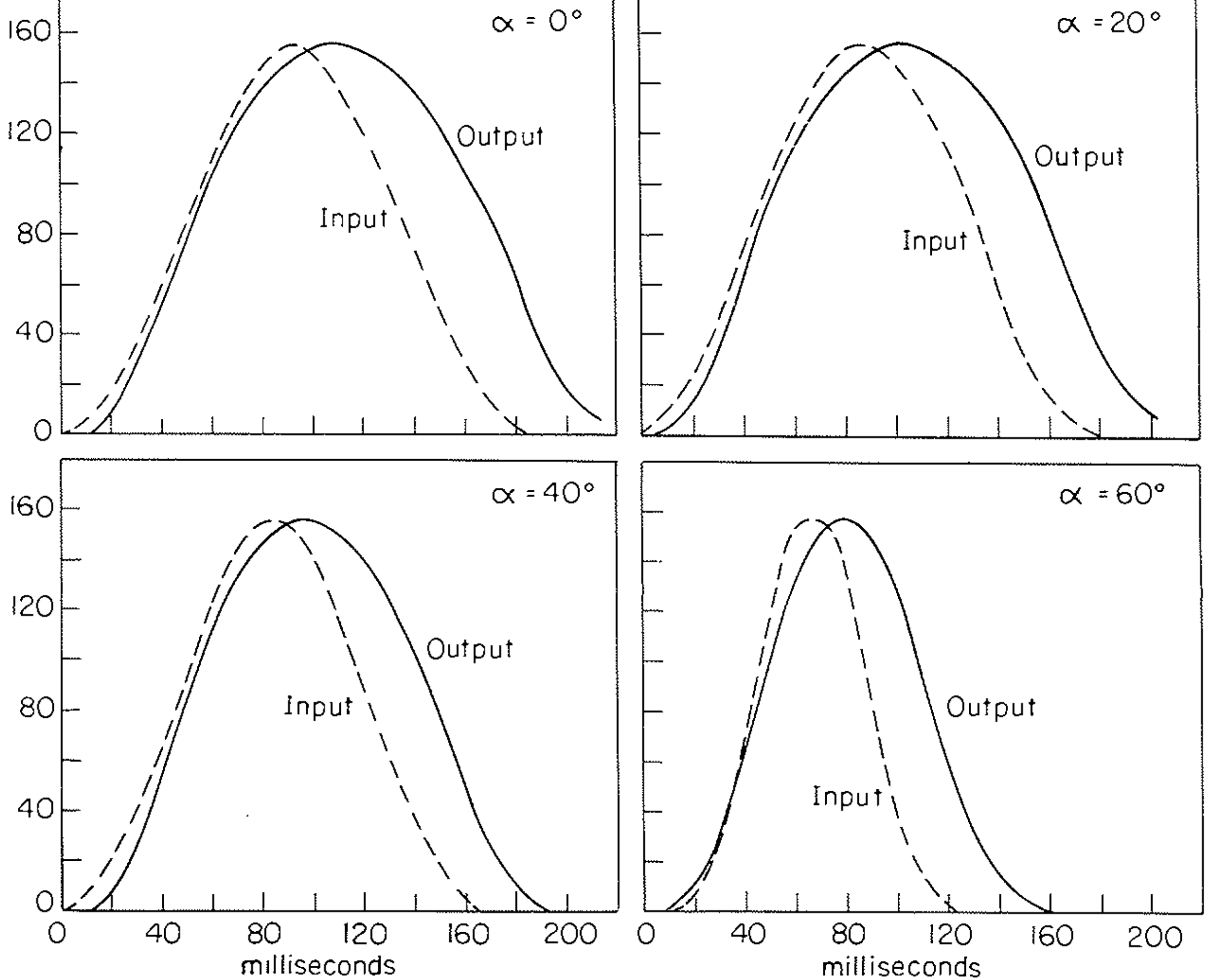


FIG. 8 — Distortion due to the non-linearity of the amplifier and the finite time delay of the electronic circuits. The dashed curves correspond to the computed response curves for $\alpha = 0°$, $\alpha = 20°$, $\alpha = 40°$, $\alpha = 60°$ (see Fig. 7).

are two main effects produced by the electronic circuits: 1) the pulses are distorted by the non-linear amplifier which tends to increase their width, and 2) the pulses are delayed by about 15 milliseconds (corresponding to $\beta = 10°$) due to the time constant of the rectifier. The non-linear distortion of the pulses increases rapidly with their amplitude, so that large pulses are significantly wider than smaller pulses.

No further significant distortion of the current signals was introduced by the telemetering circuits, or by the data processing equipment on the ground.

3. The flight

The flight of Explorer X is described in detail in HNSS. We recall here its main features.

The satellite was placed into a very elongated elliptical trajectory with an apogee of 46.6 earth radii (R_e). The line of apsides was about 33° to the antisolar direction.

Fig. 9 shows the trajectory in a solar-ecliptic cartesian frame of reference, with one of the coordinate planes parallel to the ecliptic, and another perpendicular to the sun-earth line (which was practically the same as the sun-satellite line). Fig. 10 shows the projections of the orbit onto the three coordinate planes, and Fig. 11 describes the frame of reference that we shall use to specify directions; the angular coordinates are the ecliptic latitude ϑ, and the solar ecliptic longitude φ (measured eastward from the earth-sun line).

Fig. 12 is a Mercator projection of the celestial sphere drawn using φ as absissa and ϑ as ordinate. Shown on this map are:

a) the spin axis orientation « A » (which was fixed throughout the flight);

b) the plane « n » traced by the normal to the probe during the rotation of the vehicle (notice that the sun-vehicle line made an angle of 22° with this plane);

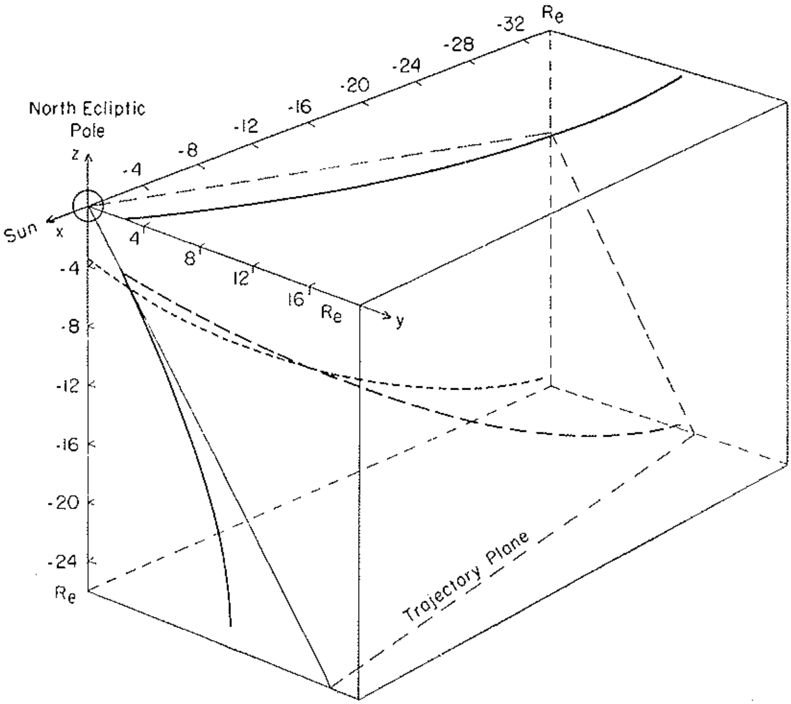


Fig. 9 — Representation of the Explorer X trajectory in a cartesian coordinate system with the origin at the center of the earth, the x-axis toward the sun, the z-axis toward the north ecliptic pole, and, therefore, the x-y plane coincident with the plane of the ecliptic. The distances marked on the coordinate axes are measured in earth radii (R_e). The motion of the earth is in the direction of the negative y-axis.

c) the plane « p » which contained the spin axis and the direction to the sun;

d) the regions (shaded oval areas) for which $\alpha > 63°$. The sensitivity of the probe was a maximum along the plane « n » and dropped gradually to zero at the boundary of these regions.

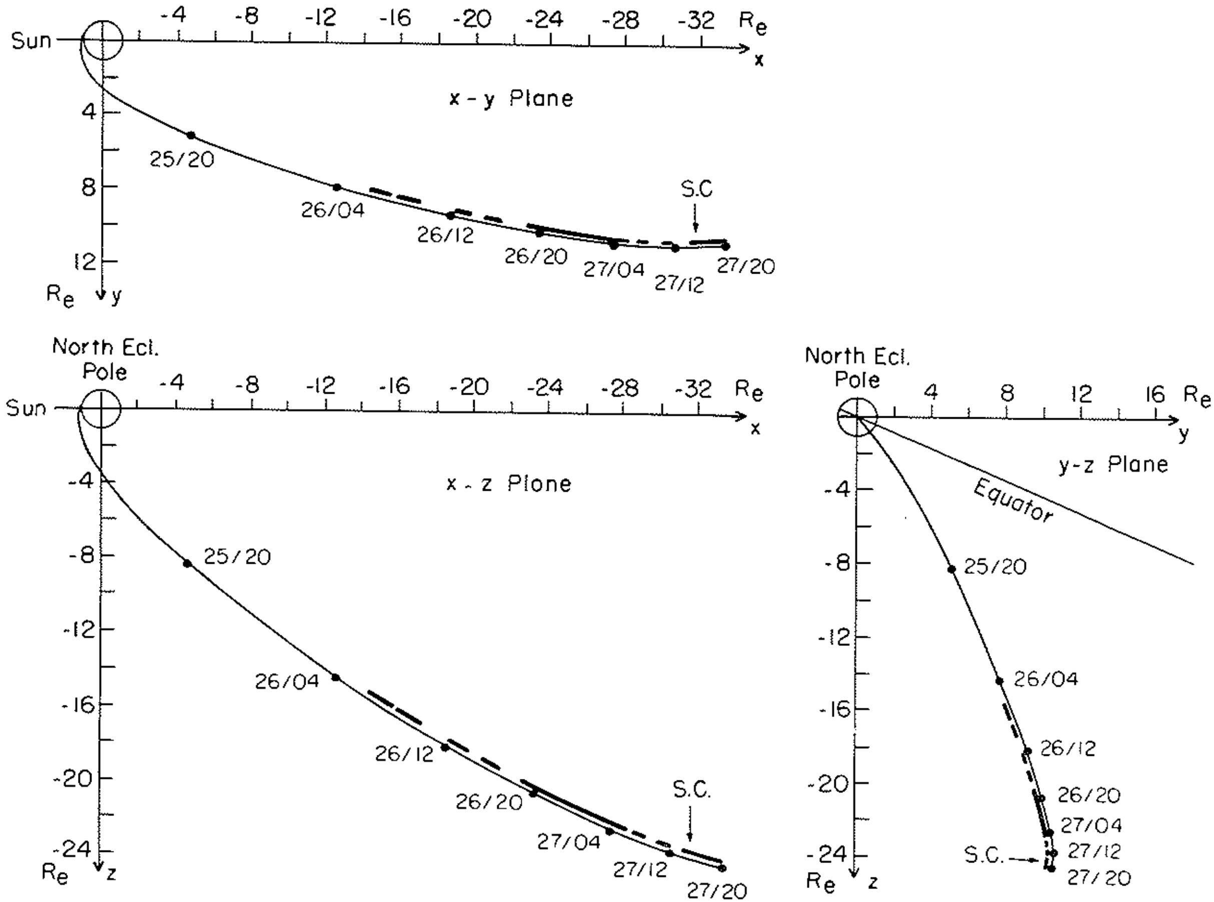


FIG. 10 — Projections of the trajectory of Explorer X on the x-y plane (the plane of the ecliptic), on the x-z plane and on the y-z plane (see Fig. 9). The line marked « Equator » represents the intersection of the y-z plane with the equatorial plane of the earth. Heavy lines by the curves represent sections of the trajectory were substantial plasma fluxes were observed. « SC » represents the position of Explorer X at the time of the sudden commencement. Dots represent positions of the satellite at 8-hr. intervals (25/20 means March 25, $20^h\ 00^m$ UT, *etc.*).

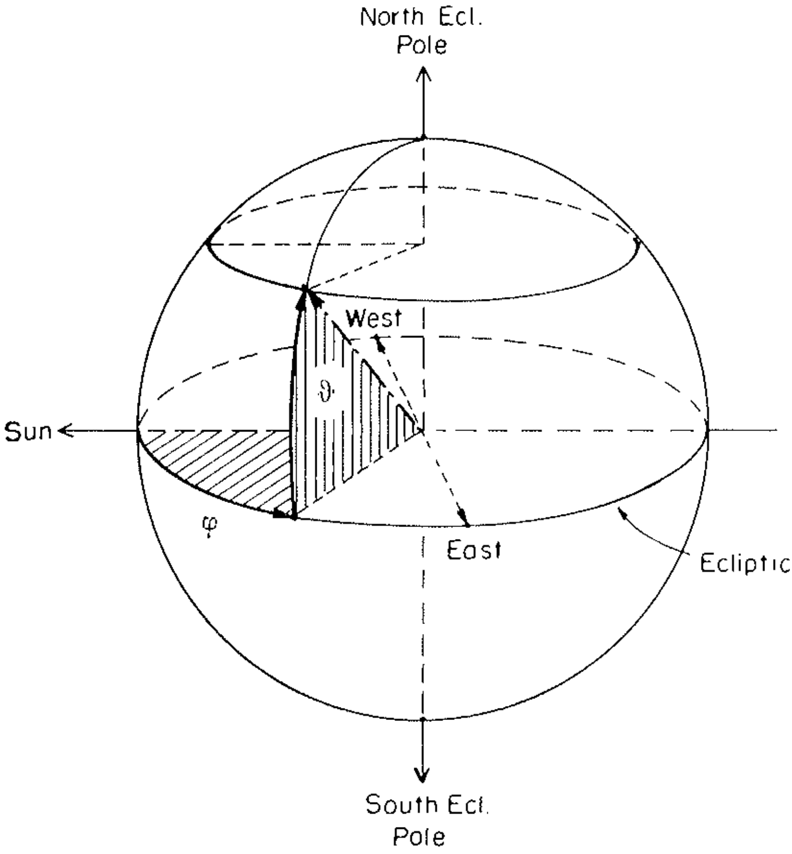


FIG. 11 — Polar frame of reference used to specify directions. The angle ϑ is the latitude measured from the plane of the ecliptic, positive toward the North. The angle φ is the longitude, measured from the solar direction, positive toward the East.

The satellite was powered by chemical batteries, which provided reliable operation for about 50 hours, during which time the satellite reached a geocentric distance of about 42 R_e.

Fig. 13 shows the telemetering sequence One sees that during a telemetering cycle, lasting 148 seconds, 5 seconds

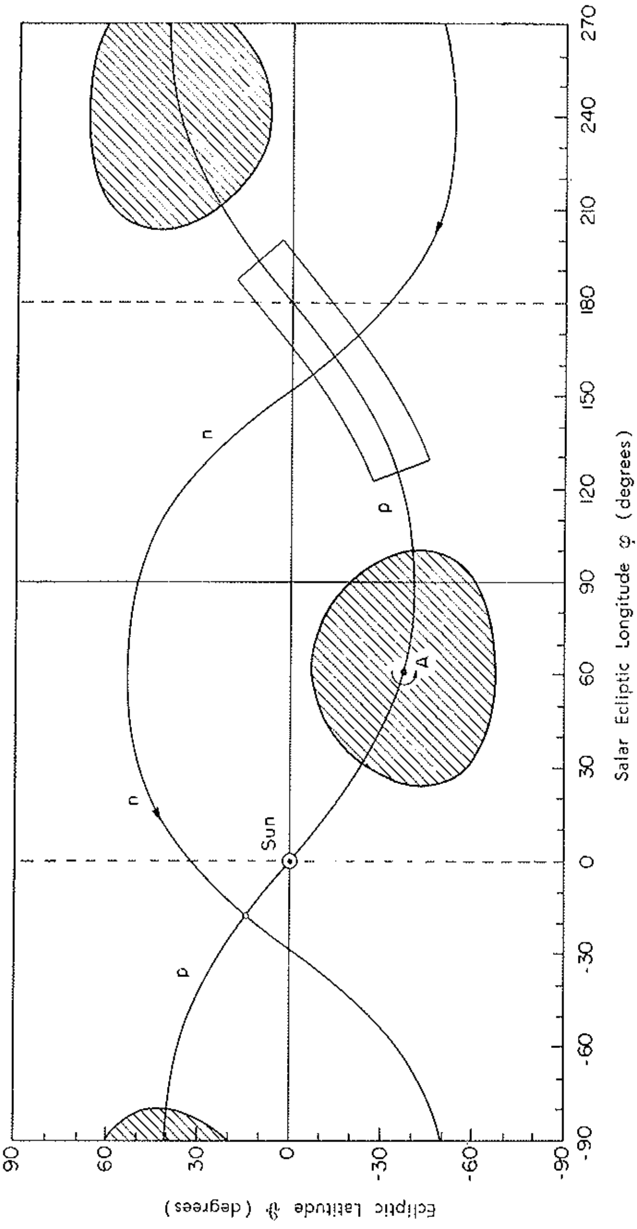


FIG. 12 — Mercator projection showing the following: the direction A of the spin axis; the plane *n* traced by the normal to the probe during the rotation of the satellite; the plane *p* defined by the spin axis and the solar direction; the directions (shaded oval areas) for which the probe was insensitive; the « window » showing directions of the plasma wind consistent with the measurements made beyond 21 R_e.

were assigned to the plasma probe. These 5-second intervals were subcommutated by an internal program and were used to transmit sequentially the following data:

a) a marker signal;

b) the output signal of the d.c. amplifier;

c) the output signal of the a.c. amplifier as the probe was operating with one of the six modulating voltages.

Thus, a complete plasma probe sequence consisted of eight telemetering cycles and lasted $19^m\ 44^s$.

Because of the low sensitivity of the d.c. amplifier, no current measurements were obtained in the d.c. mode.

As explained in HNSS, the rubidium vapor magnetometer operated satisfactorily only during the early part of the flight. Thus, the magnetic field measurements that are of interest for a comparison with the plasma measurements at large geocentric distances were obtained with the flux-gate magnetometers. As seen from Fig. 13, the flux-gate measurements were made immediately before the plasma measurements.

4. General results

The flight of Explorer X may be divided into four periods, characterized by distinctly different conditions of the plasma and the magnetic field.

A. *First Period*

(3-25-1517, $R = 1.0\ R_e$, to 3-25-1629, $R = 3.9\ R_e$).

The first signal from the plasma probe was received at 3-25-1522 (meaning March 25, $15^h\ 22^m$ UT), about 5 minutes after liftoff when the satellite was at an altitude of about 200

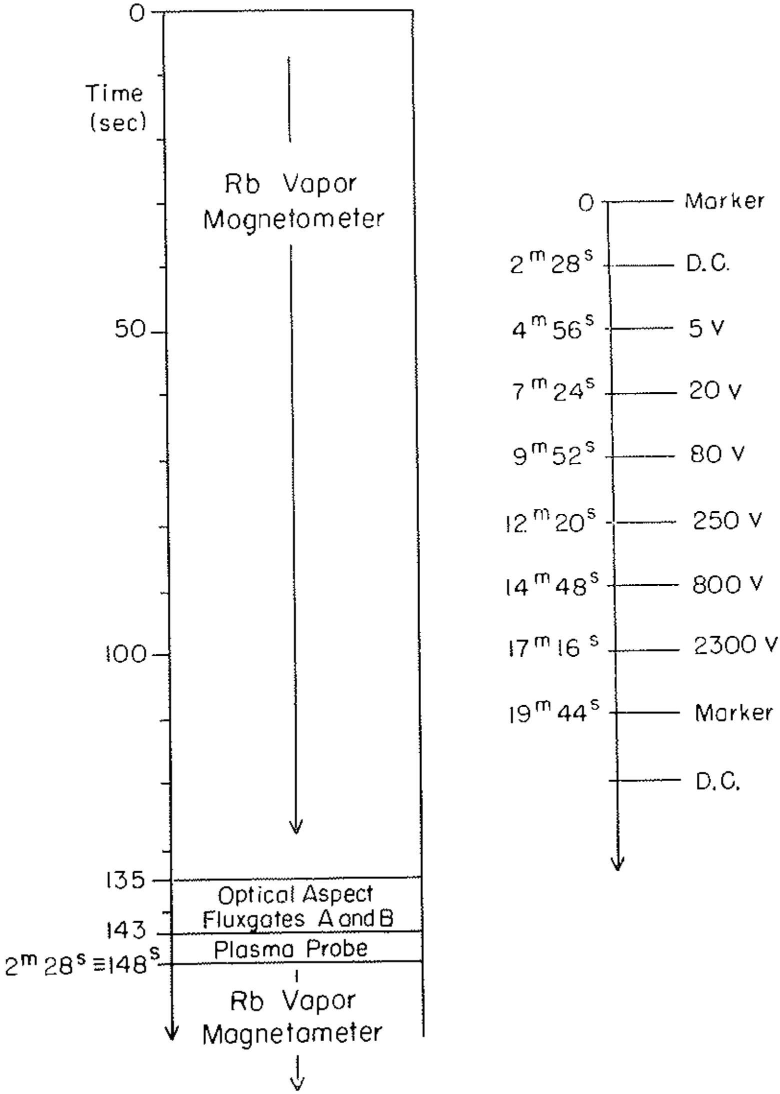


FIG. 13 — Explorer X telemetry sequence.

kilometers (geocentric distance $R = 1.03\ R_e$); the modulating voltage was then 20 V.

From that time until 3-25-1610, when the satellite was at $R = 3.0\ R_e$, a plasma current was detected whenever the probe was operated with any one of the six different modulating voltages (except in two cases, occurring at the 2300 V modulating level, when noise obscured the telemetered signal). During each of the 5-second telemetering intervals, the current varied periodically with the rotation of the satellite, the maximum occurring at the time when the normal to the probe came closest to the direction of motion of the satellite. The current maxima observed with the various modulating voltages, when plotted against geocentric distance, lay close to a smooth curve, indicating that the current was independent of the modulating voltage (from 5 to 2300 V). The current peaks decreased from a value of about 9×10^{-8} A at $R = 1.03\ R_e$ to a value of about 2×10^{-10} A at $R = 3.0\ R_e$.

The above results can be understood if one assumes that during this part of the flight the satellite was moving through a relatively stationary plasma. Up to 3 R_e, the velocity of the satellite relative to the earth varied from about 10 to about 5 km sec^{-1} (the maximum velocity during the acceleration period was 10.9 km sec^{-1}). Protons at rest with respect to the earth would have kinetic energies of a few tenths of one eV, oxygen or nitrogen ions energies of a few eV, with respect to the satellite. These energies are consistent with the observation that full modulation of the plasma current occurred at the 5 V level.

The order of magnitude of the current is consistent with the ion densities deduced from whistler data [18]. There are, however, several reasons why it is difficult to draw firm quantitative conclusions from the observations made during this period:

a) Explorer X reached a distance of 3 R_e in less than one hour;

thus this observation period included less than three complete telemetering sequences;

b) it is known that a satellite in orbit acquires a certain electric potential with respect to the medium as a result of 1) the differential velocity of electrons and positive ions in the surrounding plasma, 2) the photoelectric effect due to solar ultra-violet rays and 3) the secondary electron emission due to bombardement of high-energy particles. The first effect tends to make the satellite electrically negative, the two last act in the opposite direction. Presumably, the resulting potential, which might be of the order of a few Volts changes with altitude; during the flight of Explorer X it might even have reversed its sign. Such a potential would substantially affect the flux of low-energy positive ions into the probe;

c) the probe was not yet completely outgassed. As we had found in the laboratory (see section 2-D), incomplete outgassing makes the probe slightly sensitive to electromagnetic radiation capable of ionizing the residual gas. In fact, toward the end of the first period, small secondary maxima, corresponding to currents of about 10^{-10} A or less, began to appear at the highest modulating voltages. These maxima occurred when the normal to the plasma probe came closest to the solar direction. We are inclined to ascribe them to photoionization by solar U.V. or X-rays. Presumably, photoionization currents had not been observed in the earlier part of the flight because the plasma currents were strong enough to obscure them.

The magnetic field measured by the instruments aboard Explorer X during this period did not deviate much from a reference field defined in HNSS as the « main geomagnetic field » (which is an extrapolation of the field measured near the earth's surface, made under the assumption tbat the field is entirely produced by sources below the region of observation). However, there was some evidence for a small perturbation such as might be produced by a ring current at about 3 R_e.

During the last telemetering sequence of the first period, while the vehicle was moving from 3.0 R_e to 3.9 R_e, the plasma current decreased to a value below the detection limit. This rapid disappearance of the plasma current agrees with the observations of the Soviet scientists (see section 1). However, present uncertainties concerning the electric potential acquired by space vehicles call for some caution in the interpretation of these results.

B) *Second Period*
(from 3-25-1629, $R = 3.9\ R_e$, to 3-26-0408, $R = 20.9\ R_e$).

In this period no currents were observed which could be ascribed to the motion of the satellite through a stationary plasma. However, during the first part of the period the probe continued to give the small signals, due presumably to photo-ionization of the gas, which had already been observed at the end of the first period. These signals gradually faded away because of the progressive outgassing of the probe. During a 4-hour interval extending from 3-26-0001 ($R = 16.3\ R_e$) to 3-26-0408 ($R = 20.9\ R_e$) no currents were recorded at any of the modulating voltages.

For our purposes, the most important result of the observations made during the second period is that, when the probe was sufficiently well outgassed, it became practically insensitive to sunlight, which confirms the results of our laboratory tests. In addition, these observations provided a check on possible disturbances of the electronic equipment. The only disturbances detected were some anomalies appearing occasionally in the 2300 V modulation mode. Such anomalies (which were probably due to the large currents in the circuit supplying power to the modulator) included: 1) an occasional premature termination of the normal 5-second on-time of the probe, and

2) an occasional abnormal shift in the zero level of the output signal. This shift in level may have obscured small plasma currents (corresponding to less than 1.5×10^{-10} A; see section 5-C) (1).

The anomalies noted above persisted throughout the flight; in a number of cases they made it impossible to obtain readings at the 2300 V modulation level.

The measurements of the magnetic field during the second period (see HNSS) revealed a field that deviated more and more from the « main geomagnetic field » until, toward the end of the period, the field lines became nearly radial from the earth. The magnitude of the field decreased gradually, but much more slowly than the « main field ». However, near the end of the period (*i.e.*, beginning at 3-26-0250, $R = 19.5\ R_e$) the field, which had been for some time near 25 γ, began to increase gradually. After one hour, it reached a value of about 32 γ (these field strengths may be compared with a value of 4.5 γ for the extrapolated « main field »).

C. *Third Period*
(from 3-26-0408, $R = 20.9\ R_e$, to 3-27-1437, $R = 41.3\ R_e$).

Beginning at 3-26-0408, when the satellite was at a geocentric distance $R = 20.9\ R_e$, small plasma currents ($< 2 \times 10^{-10}$ A) were observed intermittently. Then at 3.-26-0603 ($R = 22.7\ R_e$) much stronger and more persistent signals appeared.

Though the plasma currents observed earlier during the first period were fully modulated even at the 5 V level, substantial modulation now occurred only at the three highest voltage levels (250, 800 and 2300 V), with an occasional small signal at

(1) In this connection, we note that even under normal undisturbed conditions, the zero level was slightly shifted when the probe was operated at the 2300 V modulation level; we attribute this shift to insufficient electrical isolation of the amplifier from the modulator circuits.

the 80 V level. This means that the positive ions of the plasma had energies of the order of several hundred eV.

Since Explorer X was about 23 earth radii away from the earth, it is reasonable to assume that the observed plasma, whether of terrestrial or solar origin, consisted mainly of ionized hydrogen, with perhaps a small admixture of ionized helium. In discussing our experimental results, we shall assume that the positive ions detected by the probe were protons. Under this assumption, the ion velocities corresponding to the observed energies were of the order of several hundred km sec^{-1}.

The plasma current varied periodically, going through a sharp maximum during each rotation of the satellite, then falling below the detection limit for more than half of the rotation period (Fig. 14). Thus the positive ions formed a reasonably well-collimated beam. In other words, the « thermal » velocities of these ions were substantially smaller than the bulk velocity of the plasma.

After correcting for the time response of the electronic system (see section 2-D), it was found that the current peaks occurred at about the time when the angle between the normal to the probe and the direction of the sun was a minimum. As already mentioned, this minimum angle was about 22°. Making a generous allowance for the experimental errors, we conclude that the vector $\mathbf{V}_0$ describing the bulk velocity of the plasma was within 10° to the plane passing through the spin axis of the satellite and containing the sun-earth direction (plane « p » of Fig. 12).

Since the sensitivity of the probe was zero for $|\alpha|>63°$, the vector $\mathbf{V}_0$ was certainly at an angle smaller than 63° to the equatorial plane of the satellite.

Additional information on the value of the angle α is contained in the shape of the current signals. The possibility of an angular spread in the positive ion beam is a complicating factor in the interpretation of the observed shapes, so that a very detailed analysis is needed to extract from the experimental

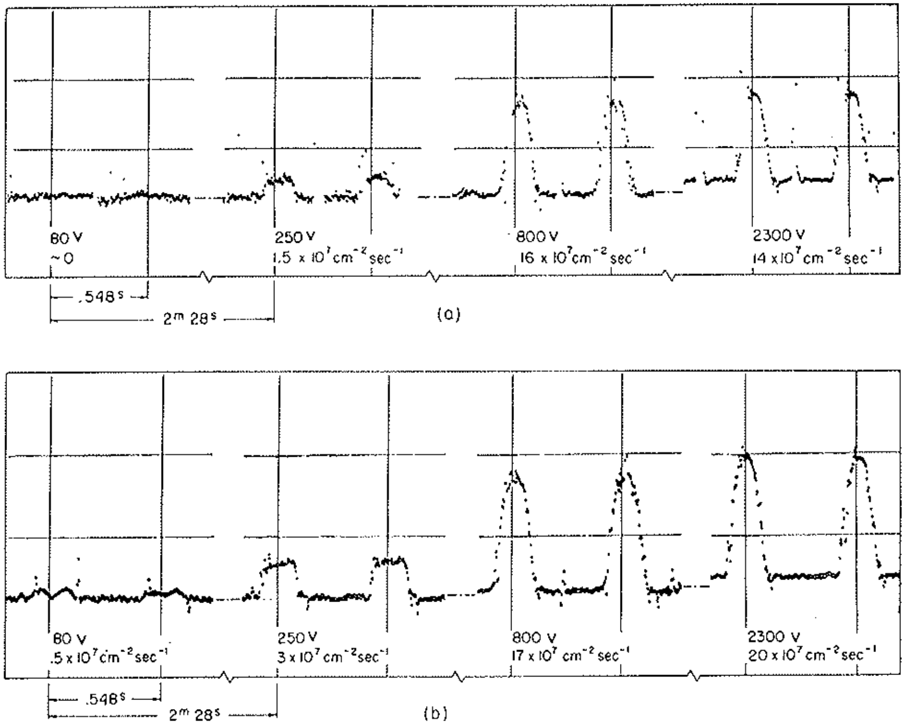


FIG. 14 — Two samples of the telemetry records obtained during the third period at the 80, 250, 800 and 2300 V modulation levels. The figure under each modulation voltage indicates the nominal flux corresponding to the peak of the current signal. Vertical lines represent times when the normal to the probe was closest to the direction of the sun; thus the distance between two consecutive vertical lines represents one rotation period. Notice that the signal at the 80 V level is below the noise level in (*a*) and slightly above the noise level in (*b*).

data all of the potentially available information. Such an analysis has not yet been completed; however, preliminary results place an upper limit of about 40° to the value of α. Thus, the possible directions of the « plasma wind » are restricted to a « window » bounded by the cones corresponding to $\alpha = \pm 40°$ and by the planes at $\pm 10°$ to the plane « p » (see Fig. 12). Notice that the antisolar direction is well within this window.

Notice also that for $\alpha = 40°$ the effective area of collection of the probe is 3.7 times smaller than for $\alpha = 0°$ (see Fig. 2).

The situation described above prevailed for about 75% of the time during the period considered here. However, on several occasions, and for time intervals of the order of hours, the plasma current fell to a value below (or occasionally barely above) the noise level and then later reappeared in full strength (*i.e.*, with a value more than 10 times the noise level). The portions of the trajectory where substantial plasma currents were recorded are marked by the heavy lines in Fig. 10.

During the third period, the magnetic field, as described in HNSS, underwent sharp transitions from a situation where it was nearly radial from the earth (as it had been at the end of the second period) to a situation where it was at a large angle to the earth-satellite line. The changes in the plasma current mentioned above showed a striking correlation with these changes in the field direction. Substantial plasma currents consistently appeared whenever the field changed from radial to non-radial, and disappeared whenever the field reverted to the radial configuration.

D. *Fourth Period*
(from 3-27-1437, $R = 41.3\ R_e$, to 3-27-1800, $R = 42.3\ R_e$).

This period was characterized by magnetic disturbances, which included the sudden commencement of a magnetic storm observed on the earth at 3-27-1503. At about the same time, there was a substantial increase both in the plasma flux and in the magnetic field strength measured by Explorer X. These higher intensities persisted, with some fluctuations, until the end of the observations; *i.e.*, for about 3.5 hours. During the first two hours of the fourth period, there was also a considerable increase in the mean energy of the plasma protons (see Fig. 15). Later, however, the mean energy appeared to return to the prestorm value. At about 3-27-1800, the zero-levels

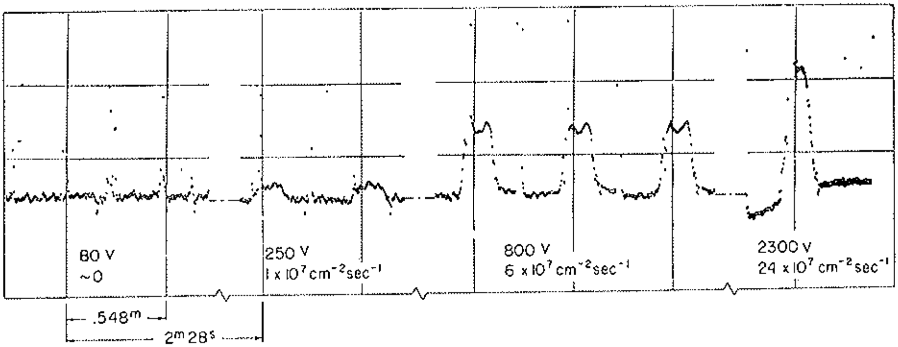


FIG. 15 — Sample of the telemetry records obtained during the fourth period. Notice the « horned » shape of the signal at the 800 V modulation level, indicating the presence of a substantial number of protons with nominal energies somewhat greater than 800 eV.

shifted, due to exhaustion of the chemical batteries, and the data obtained after this time were no longer reliable.

5. Detailed analysis of the experimental data

For the reasons explained in section 4, we have not attempted to carry out a detailed analysis of the data obtained in the vicinity of the earth, but have concentrated our attention on the plasma measurements made in the more distant regions.

The graphs in Fig. 16 provide an over-all view of these measurements and afford a comparison with the magnetometer data obtained by the Goddard group. The vertical bars in the bottom part of this figure represent the « nominal » flux densities corresponding to the maxima of the signals recorded at the various modulation levels. By « nominal » flux densities, we mean the numbers of positive, singly-charged ions per cm^2 per sec, computed from the observed currents assuming normal incidence upon the probe. Above this graph are graphs giving the magnitude B of the magnetic field, and the angles φ and ϑ which specify its direction (see Fig. 11). These data were

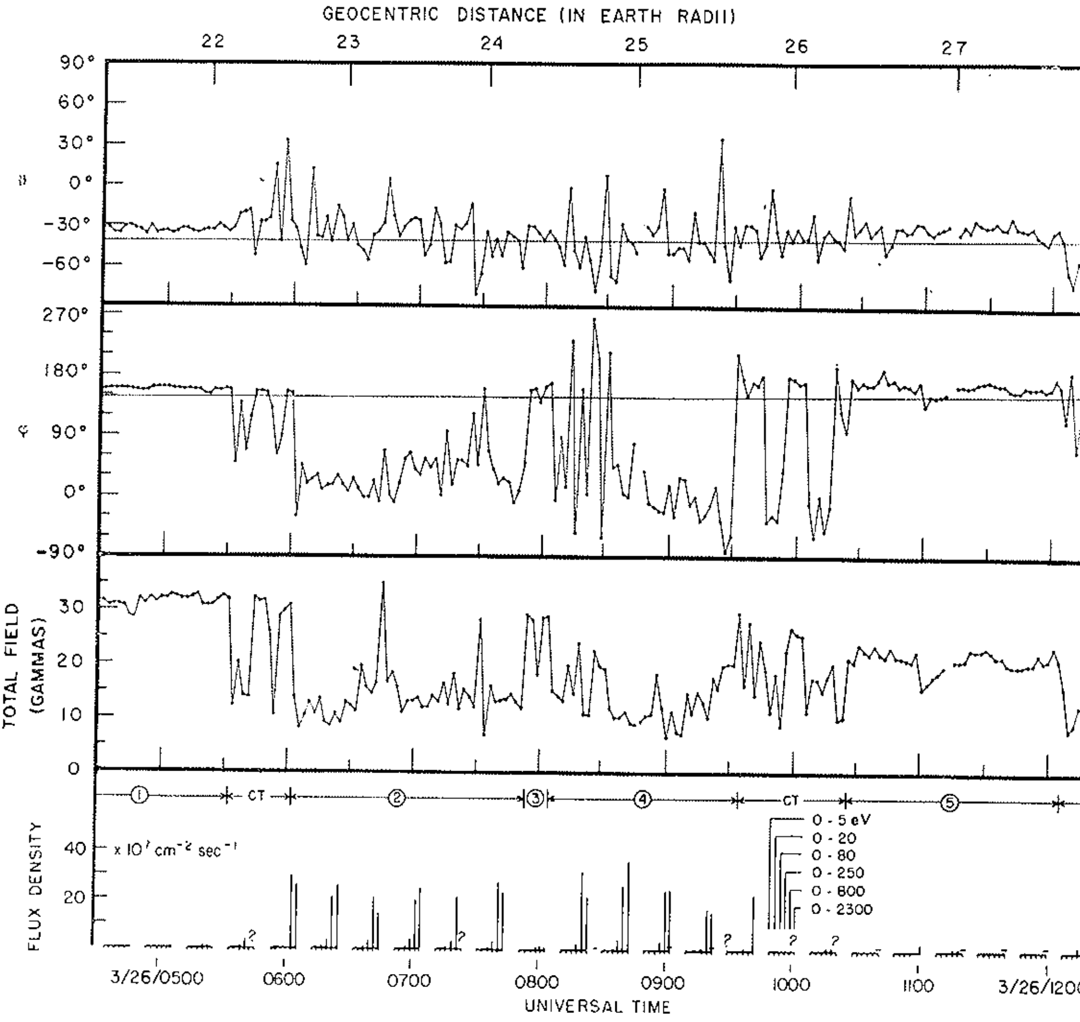


FIG. 16-*a*

FIGS. 16*a*, *b*, *c*, *d*, *e* — Plasma and magnetic field measurements during the third and fourth p riods of the flight. The magnetic field data were provided to us by Dr. J.P. HEPPNER prior their publication (see HNSS). Question marks in the plasma data indicate missing measuremen and the short horizontal bars in many of the 2300 V measurements indicate a shift of the ze level in the amplifier output (see section 4-B). The different intervals listed in Table 1 are in cated by the numbers above the plasma data.

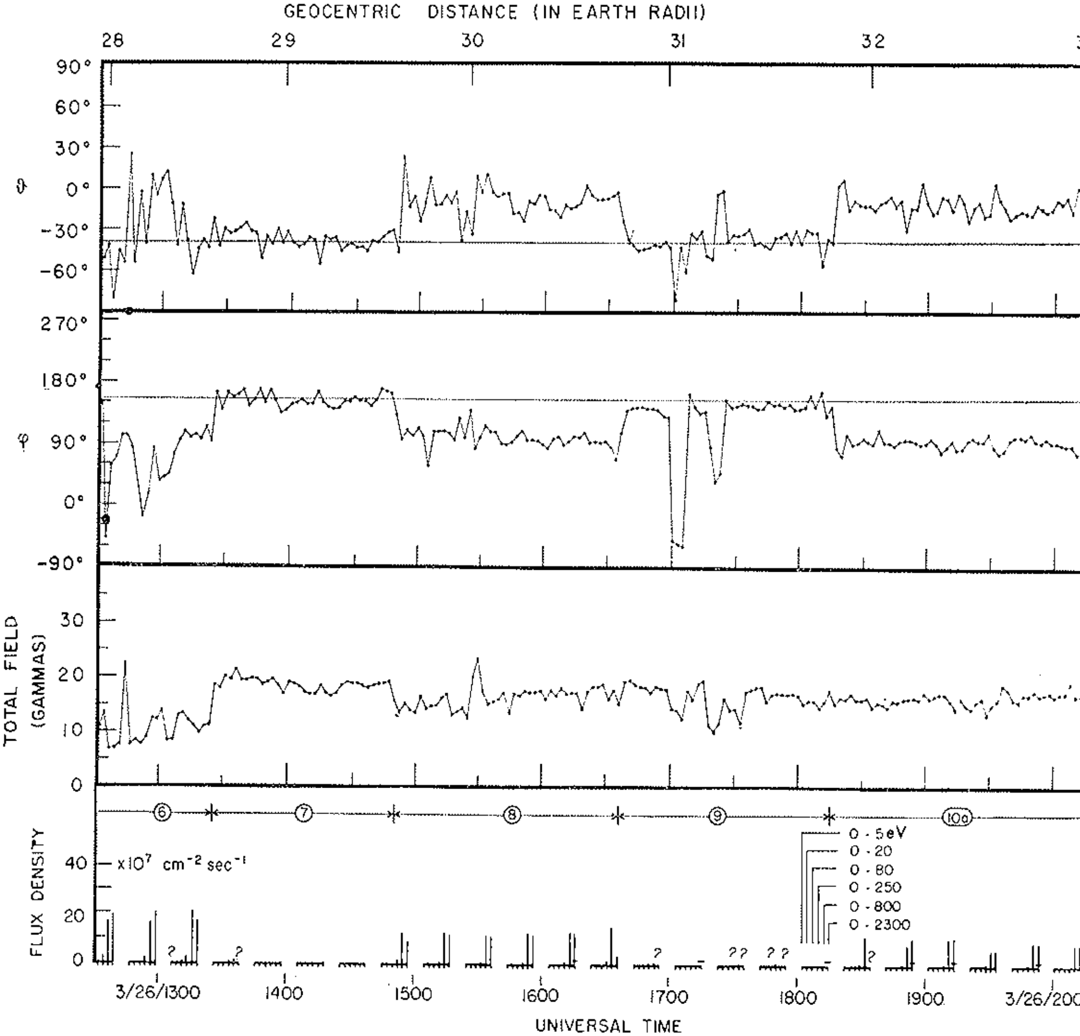
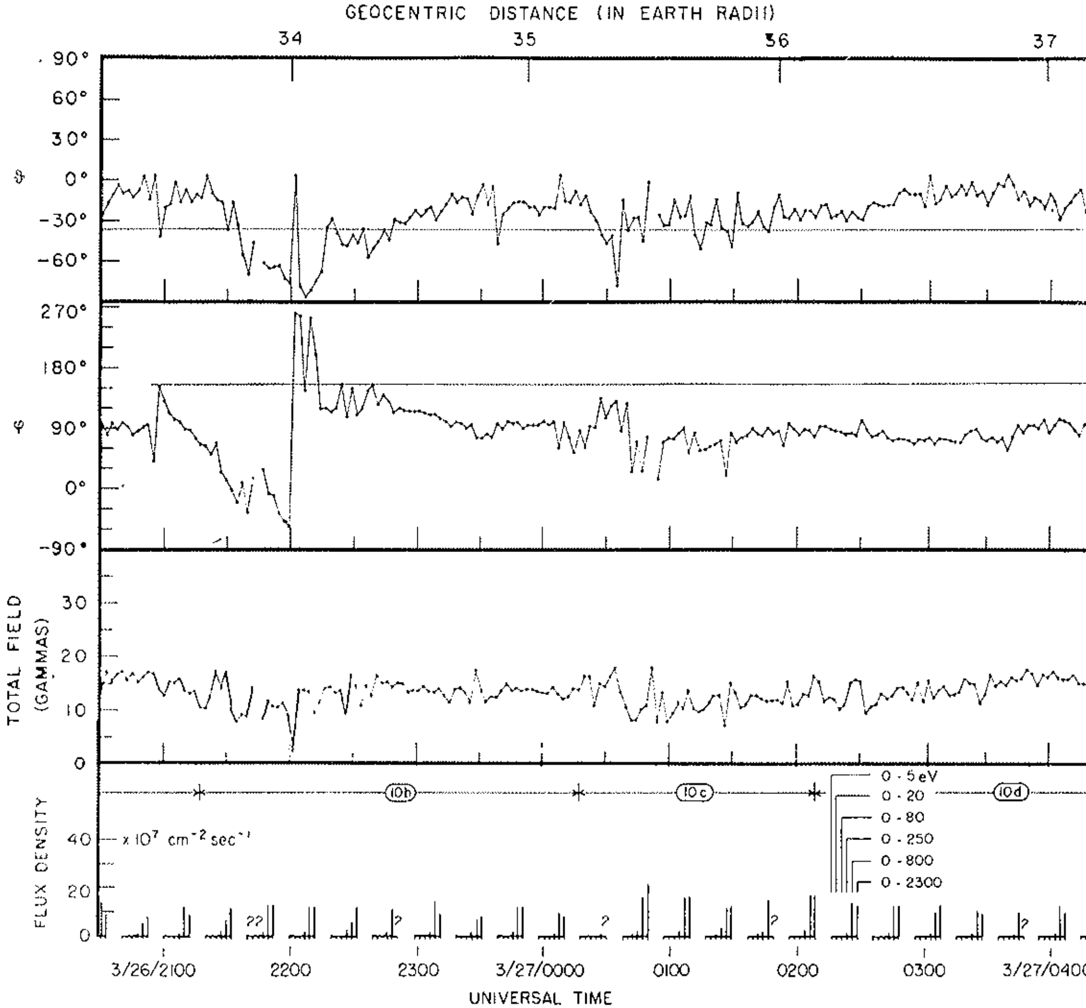


FIG. 16-*b*

[3] *Rossi* - pag. 37



GEOCENTRIC DISTANCE (IN EARTH RADII)
34
35
36
37
90°
60°
30°
0°
-30°
-60°
ϑ
270°
180°
90°
0°
-90°
φ
TOTAL FIELD (GAMMAS)
30
20
10
0
FLUX DENSITY
40
20
0
x 10^7 cm^{-2} sec^{-1}
10b
10c
10d
0 - 5 eV
0 - 20
0 - 80
0 - 250
0 - 800
0 - 2300
3/26/2100
2200
2300
3/27/0000
0100
0200
0300
3/27/0400
UNIVERSAL TIME

FIG. 16-c

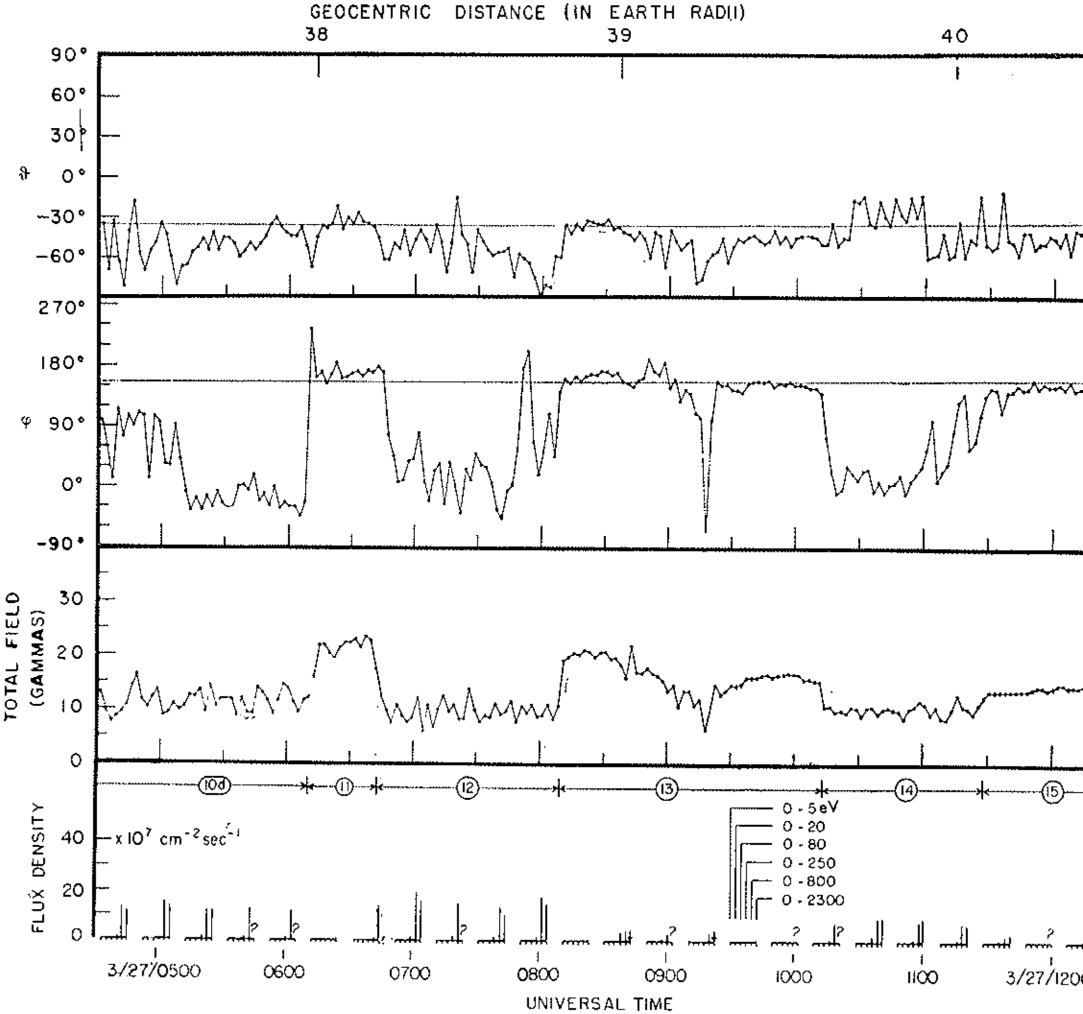

GEOCENTRIC DISTANCE (IN EARTH RADII)
38
39
40
90°
60°
30°
0°
-30°
-60°
270°
180°
90°
0°
-90°
TOTAL FIELD (GAMMAS)
30
20
10
0
FLUX DENSITY
40
20
0
x 10^7 cm^-2 sec^-1
10d
11
12
13
14
15
0 - 5 eV
0 - 20
0 - 80
0 - 250
0 - 800
0 - 2300
3/27/0500
0600
0700
0800
0900
1000
1100
3/27/1200
UNIVERSAL TIME

FIG. 16-*d*

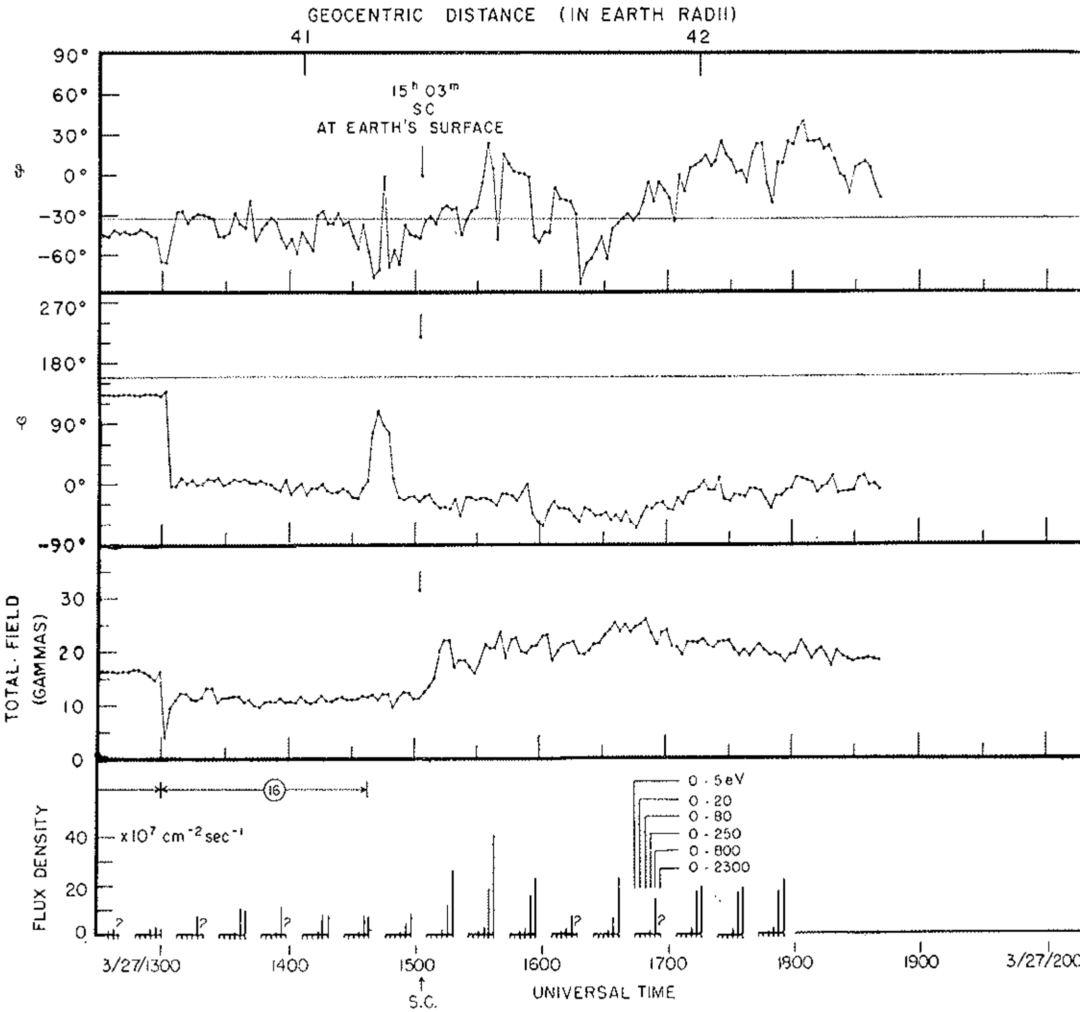

GEOCENTRIC DISTANCE (IN EARTH RADII)
41
42
90°
60°
30°
0°
-30°
-60°
15h 03m
SC
AT EARTH'S SURFACE
270°
180°
90°
0°
-90°
TOTAL FIELD (GAMMAS)
30
20
10
0
16
FLUX DENSITY
x10⁷ cm⁻² sec⁻¹
40
20
0
0 - 5eV
0 - 20
0 - 80
0 - 250
0 - 800
0 - 2300
3/27/1300
1400
1500
1600
1700
1800
1900
3/27/200
S.C.
UNIVERSAL TIME

Fig. 16-e

kindly provided us by Dr. HEPPNER prior to their publication and are identical with those appearing in HNSS.

A. *Third Period - Correlation between plasma and magnetic field.*

The correlation between magnitude of the plasma current and direction of the magnetic field is clearly visible in the graphs of Fig. 16. We shall now examine it in more detail.

Inspection of Fig. 16 shows that during the third period, the current signals obtained at the 800 and 2300 V modulation levels were, on the average, nearly equal. Thus, full or almost full modulation of the plasma protons was achieved at both these levels, so that we may take the heights of the corresponding current signals as a measure of the total « nominal » flux density of plasma protons.

The histogram in Fig. 17 gives the frequency distribution of the flux densities observed during the third period, based on all available readings at the 800 and 2300 V levels.

It is clear from this graph that the observed flux densities fall into two distinct groups; a narrow group, including those cases where the flux density was below or barely above the detection limit (4×10^6 cm^{-2} sec^{-1}), and a broad group peaked somewhat above 10^8 cm^{-2} sec^{-1}. We shall refer to the observations corresponding to the two groups as *weak* and *strong* plasma signals respectively. Because of the small number of intermediate cases, the distinction between weak and strong signals does not depend critically on the choice of the flux density used for the separation of the two groups. In what follows, we shall set this limiting flux density at 5×10^7 cm^{-2} sec^{-1}.

As already noted, each plasma measurement was preceded, within a few seconds, by measurements of the magnetic field made by means of the flux-gate magnetometers. In Fig. 18 we have plotted the directions of the magnetic field measured

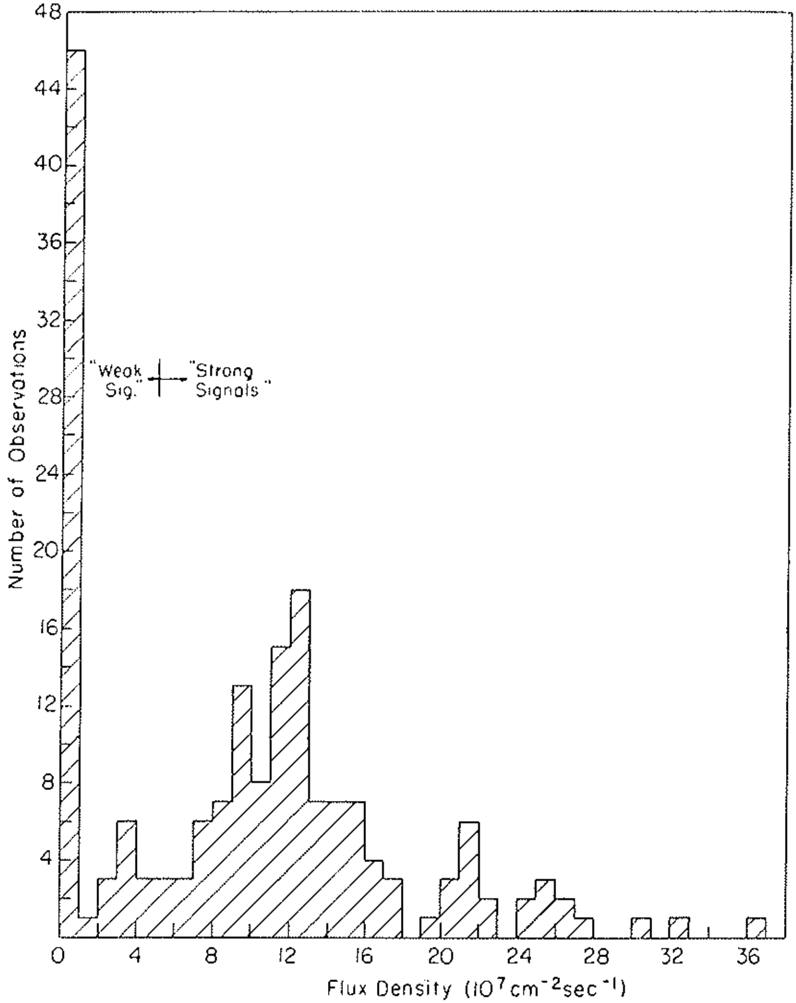


Fig. 17 — Distribution of flux densities observed at the 800 and 2300 V levels during the third period.

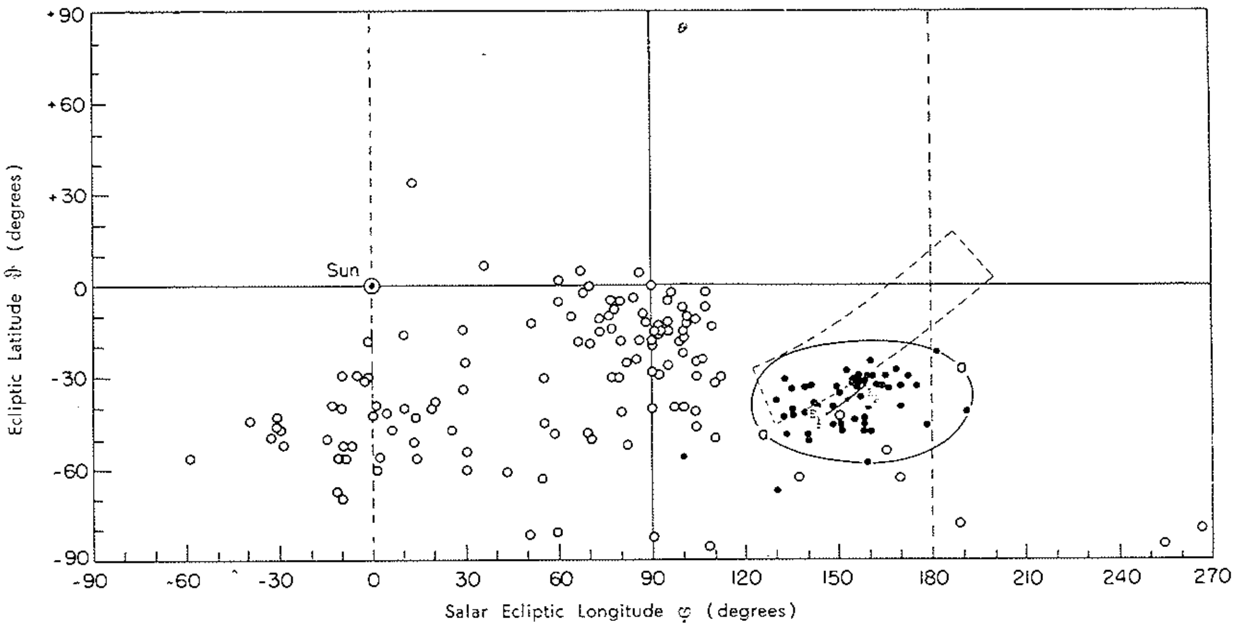


FIG. 18 — Directions of the magnetic field observed immediately before each of the plasma readings at the 800 V and 2300 V levels during the third period. Open circles refer to « strong » plasma signals, solid dots refer to « weak » plasma signals.

before each of the available plasma readings at the 800 V and 2300 V levels. Open circles refer to magnetic fields associated with strong plasma fluxes and solid dots refer to magnetic fields associated with weak plasma fluxes. During the time of observation, the representative point of the vector pointing from the earth to the satellite moved along the short line segment $E_1 E_2$. One sees that practically all the solid dots fall within a restricted area around this segment (enclosed by the line « a » in Fig. 18). The very few exceptions correspond to measurements taken when plasma and magnetic conditions were changing rapidly, or when the plasma signal was close to the limiting value of 5×10^7 cm^{-2} sec^{-1}. On the other hand, practically all the open circles fall outside this area. They are distributed over a wide region, but not at random throughout the map, clustering mainly in the area to the south of the ecliptic plane, between $-30°$ and $+110°$ ecliptic longitude.

These results point to the conclusion that during the third period, Explorer X encountered alternately two distinct physical situations. The first, which shall be called *situation A*, was characterized by weak plasma fluxes, often below the detection limit, and by nearly radial magnetic fields. The second, which shall be called *situation B*, was characterized by strong plasma fluxes, and by non-radial fields. Note that the field directions corresponding to situation A fill the region denoted as « region A » in Fig. 23 of HNSS, while the field directions corresponding to situation B fall within regions « B » and « C » of the same figure.

While measurements of the magnetic field were made during every telemetering cycle (*i.e.*, every $2^m\ 28^s$), significant plasma data were obtained only during the 250, 800, and 2300 V modulation periods or roughly 3/8 of the time during which the plasma probe was turned on. On the other hand, the essentially one-to-one correspondence between the magnetic field and the plasma fluxes, established by all near-simultaneous observations of these two quantities, enable us to use the magnetic field measurements to identify the times at which transitions between situation A and situation B occurred more precisely than we could do by means of the less frequent plasma signals.

As noted also in HNSS, it was usually found that the conditions typical of situation A or B persisted through many observations; then, quite suddenly, often within the $2^m\ 28^s$ separating two subsequent magnetic measurements, a switch to the other situation occurred. We shall call these changes « simple » transitions. Occasionally, however, it appears that situations A and B alternated rapidly during time intervals extending through several magnetic field and plasma measurements. We shall call these « complex » transitions.

The time intervals in the third period during which situations A and B prevailed, and the types of transitions between them, are shown in Table 1. Details of the measurements made in the vicinity of the transitions appear in Table 2. Listed in Tables 3 and 4 are the *average* magnitudes and the *average* directions of the magnetic field observed during the various intervals of type A and type B respectively. The average directions of the magnetic field are also shown graphically in Fig. 19, where solid dots correspond to situations of type A and open circles to situations of type B. The number by each experimental point specifies the time interval to which the point refers, according to the listing in Table 1.

Tables 3 and 4 show that the magnetic field was usually weaker in the presence of plasma (situation B) then in the absence, or near-absence of plasma (situation A). However, the strength of the magnetic field did not correlate with plasma conditions quite as strikingly as did the direction of the field.

We call attention to the fact that, in contrast with the steady behavior of the magnetic field characteristic of situation A, the field in situation B underwent substantial changes during each time interval (the bars crossing at the point No. 2 in Fig. 19 are an indication of the spread in the direction of the

TABLE 1.

Time intervals during the third period of the flight when measurements of the magnetic field and plasma fluxes indicated situations of type A or type B. Geocentric distance is the distance of the satellite from the center of the earth (in earth radii). Lateral distance is the distance from the sun-earth line. During interval No. 10, which was considerably longer than the others, plasma and magnetic conditions underwent substantial changes. Therefore, this interval has been divided into four sub-intervals for the purpose of analysis. The transitions between intervals 1 and 2 and between intervals 4 and 5 are of the « complex » type. All other transitions are of the « simple » type.

The telemetry cycles, times and distances indicated in the table correspond to the first sequence of measurements (optical aspect, magnetic field, plasma flux) made in the respective intervals.

[3] *Rossi* - pag. 46

Interval No.	Telemetry Cycle	Time	Geocentric Distance (R_e)	Lateral Distance (R_e)	Situation
	318	26/0410	21.0	16.7	
1	352	0534	22.2	17.3	A
Complex transition	364	0603	22.6	17.6	
2	409	0754	24.2	18.5	B
3	414	0805	24.4	18.6	A
4	450	0935	25.7	19.3	B
Complex transition	471	1026	26.5	19.6	
5	512	1207	27.7	20.3	A
6	544	1326	28.7	20.8	B
7	578	1450	29.7	21.3	A
8	622	1639	30.9	21.9	B
9	662	1817	32.0	22.4	A
10a	734	2115	33.7	23.6	B
10b	814	27/0032	35.3	24.3	B
10c	854	0211	36.1	24.8	B
10d	952	0613	38.0	25.1	B
11	965	0645	38.2	25.3	A
12	1000	0811	38.8	25.5	B
13	1050	1014	39.6	25.7	A
14	1081	1131	40.1	26.0	B
15	1118	1300	40.6	26.2	A
16	1157	1438	41.3	26.4	B

TABLE 2.

Details of measurements of magnetic field and plasma in the vicinity of transitions. The numbers in the first column specify the telemetering cycle; measurements referring to subsequent cycles are separated by $2^m\ 28^s$. B is the absolute magnitude of the magnetic field vector (in units of 10^{-5} gauss, or gammas); φ and ϑ are the two angles (solar ecliptic longitude and ecliptic latitude) which describe the direction of this vector. The nominal flux densities listed correspond to the currents measured at the 80, 250, 800 and 2300 V modulation levels. These measurements occupy four of the eight telemetering cycles which form a complete sequence (see Fig. 13). Question marks indicate measurements missing because of electronic disturbances. From 26/0534 to 26/0603, and then again from 26/0935 to 26/1026 more frequent changes from situation A to situation B and vice versa took place than during the rest of the flight. We chose to describe these occurrences as « complex transitions » rather than as a sequence of short time intervals of type A and B, although it is not clear that the distinction is physically significant. Notice the isolated occurrence of situation A during one telemetering cycle (No. 419) of time interval No. 4.

Telemetry Cycle	Interval	Magnetic field B (gammas)	Magnetic field φ (degrees)	Magnetic field ϑ (degrees)	Plasma Nominal flux density (10^7 cm^{-2} sec^{-1}) $\Phi(80)$	$\Phi(250)$	$\Phi(800)$	$\Phi(2300)$	Situation
346	↑	31	150	—35	o	—	—	—	A
347		31	150	—36	—	.4	—	—	↑
348	**1**	31	156	—30	—	—	.5	—	
349		32	155	—32.5	—	—	—	o	
350		33	157	—37	—	—	—	—	↓
351	↓	32	156	—32.5	—	—	—	—	A
352	26/0534	12	46	—22.5	—	—	—	—	B
353	↑	20	137	—21	—	—	—	—	A
354		14	65	—19.5	.4	—	—	—	B
355		13.5	115	—55	—	3.0	—	—	B
356	COMPLEX	32.5	152	—28.5	—	—	o	—	A
357	TRANSITION	32	152	—28.5	—	—	—	?	A
358		32	151	—26	—	—	—	—	A
359		26	130	+ 14	—	—	—	—	B
360		10	59	—44	—	—	—	—	B
361		28.5	89	+ 31.5	—	—	—	—	B
362		30	152	—28	o	—	—	—	A
363	↓	31	151	—34	—	o	—	—	A
364	26/0603	14	—33	—49	—	—	30	—	B
365	↑	8	43	—60.5	—	—	—	26	↑
366		10.5	16	+ 11	—	—	—	—	
367	**2**	13	21	—44	—	—	—	—	
368		11	29	—41	—	—	—	—	
369		13.5	3	—25.5	—	—	—	—	
404		14	29	—34	—	—	28	—	
405		14	20	—38	—	—	—	22.5	
406		15	—10	—41	—	—	—	—	
407		13	9	—61	—	—	—	—	↓
408	↓	12	50	—30	—	—	—	—	B
409	26/0754	29	159	—30	—	—	—	—	A
410	↑	28.5	160	—34	o	—	—	—	↑
411	**3**	18.5	140	—40.5	—	1.0	—	—	
412		28.5	162	—33	—	—	1.1	—	↓
413	↓	28.5	169	—40	—	—	—	.7	A

Telemetry Cycle	Interval	*Magnetic field* B (gammas)	φ (degrees)	ϑ (degrees)	*Plasma* Nominal flux density (10^7 cm^{-2} sec^{-1}) Φ(80)	Φ(250)	Φ(800)	Φ(2300)	Situation
414	26/0805 ↑	15	—1	—46	—	—	—	—	B
415		14.5	88	—59	—	—	—	—	↑
416		13.5	13	— 1	—	—	—	—	
417	4	19.5	240	—49	—	—	—	—	↓
418		13.5	—53	—61	0	—	—	—	B
419		24	160	—40	—	2.3	—	—	A
420		11	2	—56	—	—	32	—	B
421		11	266	—80	—	—	—	21	↑
443		13.5	—28	—50	—	.7	—	—	
444		10.5	—11	—56	—	—	16.8	—	
445		17.5	13	+34	—	—	—	15.4	
446		15.5	—36	—46	—	—	—	—	
447		19.5	—83	—71	—	—	—	—	
448		20	—60	—30.5	—	—	—	—	↓
449	↓	20	211	—46	—	—	—	—	B
450	26/0935 ↑	29.5	176	—30	0	—	—	—	A
451		16.5	150	—30	—	.5	—	—	A
452		28	170	—33	—	—	0	—	A
453		14.5	165	—54	—	—	—	22.8	B
454		24	180	—45	—	—	—	—	A (?)
455		19	—39	— 2.5	—	—	—	—	B
456		11.5	—29	—34	—	—	—	—	B
457		18	—36	—52	—	—	—	—	B
458		8.5	38	—34	0	—	—	—	B
459	COMPLEX	22.5	178	—41	—	0	—	—	A
460	TRANSITION	26.5	175	—33	—	—	0	—	A
461		26	168	—40	—	—	—	?	A
462		25.5	169	—40	—	—	—	—	A
463		11.5	—10	—21	—	—	—	—	B
464		17.5	—60	—56	—	—	—	—	B
465		17.5	0	—38.5	—	—	—	—	B
466		15.5	—50	—33.5	0	—	—	—	B
467		18	—17	—40	—	.8	—	—	B
468		20	191	—41.5	—	—	.5	—	A (?)
469		10	128	—48	—	—	—	?	B
470	↓	10.5	98	— 8.5	—	—	—	—	B

[3] *Rossi* - pag. 50

Telemetry Cycle	Interval	*Magnetic field* B (gammas)	φ (degrees)	ϑ (degrees)	*Plasma* Nominal flux density (10^7 cm^{-2} sec^{-1}) Φ(80)	Φ(250)	Φ(800)	Φ(2300)	Situation
471	26/1026	21.5	173	—38	—	—	—	—	A
472		20.5	161	—32	—	—	—	—	
473		24	169	—27.5	—	—	—	—	
474	5	22.5	165	—38.5	0	—	—	—	
475		22	165	—33	—	0	—	—	
476		24	172	—30	—	—	0	—	
506		20.5	161	—38.5	0	—	—	—	
507		22.5	162	—41	—	0	—	—	
508		21	158	—44	—	—	0	—	
509		21.5	160	—35	—	—	—	0	
510		23.5	173	—31.5	—	—	—	—	
511		21.5	162	—40.5	—	—	—	—	A
512	26/1207	16.5	111	—65	—	—	—	—	B
513		8.5	184	—75	—	—	—	—	
514		9.5	69	—57	0	—	—	—	
515	6	13	121	—67	—	2.1	—	—	
516		12	—29	—52	—	—	11.4	—	
517		10	?	—45	—	—	—	11.7	
538		13.5	109	—40	.4	—	—	—	
539		12	100	—64	—	2.3	—	—	
540		11	104	—46	—	—	21	—	
541		10	97	—39.5	—	—	—	17	
542		11	114	—45	—	—	—	—	
543		11	93	—22.5	—	—	—	—	B
544	26/1326	18.5	164	—44	—	—	—	—	A
545		18	140	—30	—	—	—	—	
546		20	162.5	—35	0	—	—	—	
547	7	19.5	158	—32.5	—	.67	—	—	
548		21.5	161	—30	—	—	1	—	
549		19.5	167	—27	—	—	—	?	
571		19	151	—43.5	—	0	—	—	
572		18.5	151	—47.5	—	—	0	—	
573		18	143	—39.5	—	—	—	.4	
574		18.5	151.5	—40	—	—	—	—	
575		19	169	—37	—	—	—	—	
576		19	165	—32.5	—	—	—	—	
577		19.5	161	—30	—	—	—	—	A

Telemetry Cycle	Interval	*Magnetic field* B (gammas)	φ (degrees)	ϑ (degrees)	*Plasma* Nominal flux density (10^7 cm^{-2} sec^{-1}) Φ(80)	Φ(250)	Φ(800)	Φ(2300)	Situation
578	26/1450	16	132.5	—48.5	0	—	—	—	?
579	↑	14	96	+22	—	1.2	—	—	B
580		15.5	109	—13.5	—	—	12.7	—	↑
581	**8**	14	100	— 7	—	—	—	9.0	
582		14	110	—23	—	—	—	—	
583		16.5	100	—11	—	—	—	—	
584		14.5	57	+ 6.5	—	—	—	—	
616		18.5	92	— 9	—	—	—	—	
617		18.5	92	— 9	—	—	—	—	
618		19	92	— 8.5	0	—	—	—	
619		16.5	85	— 6	—	1	—	—	
620	↓	18	68	— 2	—	—	15.7	—	↓ B
621	26/1636	15.5	106	—24	—	—	—	3.4	?
622	26/1639	19.5	138	—38	—	—	—	—	A
623	↑	20	142	—42.5	—	—	—	—	↑
624		19	142	—47	—	—	—	—	
625	**9**	18.5	144	—45	—	—	—	—	
626		18.5	140	—44.5	0	—	—	—	
627		17.5	141	—41	—	.5	—	—	
656		15.5	143	—30	—	—	—	—	
657		16	160	—32	—	—	—	—	
658		16	143	—33	0	—	—	—	
659		15	163	—57	—	0	—	—	
660		16	130	—38	—	—	0	—	
661	↓	18	143	—43	—	—	—	?	↓ A
662	26/1815	15.5	81	+ 2	—	—	—	—	B
663	↑	17	70	+ 7	—	—	—	—	↑
664		16.5	102	—15.5	—	—	—	—	
665	**10**	17.5	88	— 9	—	—	—	—	
666		16	90	—11	0	—	—	—	
667		16	98	—13	—	.5	—	—	
946		15	—27	—43	—	—	—	—	
947		14	—31	—46	0	—	—	—	
948		11.5	—31	—46	—	.7	—	—	
949		9.5	—48	—39	—	—	12.4	—	
950		12	—27	—52.5	—	—	—	?	
951	↓	12.5	233	—69	—	—	—	—	↓ B

[3] *Rossi* - pag. 52

Telemetry Cycle	Interval	Magnetic field B (gammas)	Magnetic field φ (degrees)	Magnetic field ϑ (degrees)	Plasma Nominal flux density (10^7 cm^{-2} sec^{-1}) Φ(80)	Φ(250)	Φ(800)	Φ(2300)	Situation
952	27/0613	16	160	—46	—	—	—	—	A
953	↑	22	169	—37	—	—	—	—	↑
954		22	151	—40	o	—	—	—	
955		20.5	166	—37	—	o	—	—	
956		19.5	181	—22	—	—	o	—	
957		21.5	159	—40	—	—	—	·4	
958	**11**	22.5	161	—30	—	—	—	—	
959		22.5	167	—35	—	—	—	—	
960		23	170	—27	—	—	—	—	
961		21.5	161	—35	—	—	—	—	
962		24	171	—36	o	—	—	—	
963		23	169	—39	—	o	—	—	↓
964	↓	17.5	178	—46	—	—	·5	—	A
965	27/0645	13	169	—63	—	—	—	14.2	B
966	↑	10	77	—63	—	—	—	—	↑
967		8	45	—50	—	—	—	—	
968	**12**	11	8	—54	—	—	—	—	
969		9	9	—40.5	—	—	—	—	
970		8	38	—59	—	—	—	—	
994		11	68	—71	o	—	—	—	
995		9	18	—90	—	1.4	—	—	
996		9.5	50	—81	—	—	15.0	—	
997		11	108	—85	—	—	—	11.1	
998		8.5	46	—60	—	—	—	—	↓
999	↓	11	140	—60	—	—	—	—	B
1000	27/0811	19	160	—35	—	—	—	—	A
1001	↑	20	154	—43	—	—	—	—	↑
1002		21	163	—36	o	—	—	—	
1003	**13**	20.5	157	—40	—	o	—	—	
1004		21.5	163	—33	—	—	1	—	
1005		21	166	—34	—	—	—	·7	
1044		16.5	151	—45.5	—	—	o	—	
1045		16.5	153	—44.5	—	—	—	?	
1046		16	151	—44	—	—	—	—	
1047		16	146	—45	—	—	—	—	
1048		15.5	146	—46	—	—	—	—	↓
1049	↓	15.5	140	—51	—	—	—	—	A

[3] *Rossi* - pag. 53

Telemetry Cycle	Interval	*Magnetic field* B (gammas)	φ (degrees)	ϑ (degrees)	*Plasma* Nominal flux density (10^7 cm^{-2} sec^{-1}) Φ(80)	Φ(250)	Φ(800)	Φ(2300)	Situation
1050	27/1014	11	72	—51	0	—	—	—	B
1051	↑	11	20	—36	—	.4	—	—	↑
1052		10	—10	—52	—	—	8	—	
1053	**14**	10.5	—2	—46	—	—	—	?	
1054		10	30	—47	—	—	—	—	
1055		11	20	—18	—	—	—	—	
1074		10	81	—60	0	—	—	—	↓ B
1075		13	126	—35.5	—	.4	—	—	?
1076		11	137	—62.5	—	—	5.7	—	?
1077		10.5	58	—48.5	—	—	—	4.7	B
1078		9.5	69	—51	—	—	—	—	↕
1079	↓	11.5	106	—16	—	—	—	—	B
1080	27/1128	12.5	134	—53	—	—	—	—	?
1081	27/1131	14	146	—56	—	—	—	—	A
1082	↑	14	142	—54	0	—	—	—	A
1083		14	110	—13	—	.5	—	—	?
1084	**15**	14	140	—49	—	—	1.7	—	A
1085		14	140	—51	—	—	—	3.6	↑
1086		14	149	—60	—	—	—	—	
1112		17	132	—46	—	—	—	—	
1113		17	132	—42	—	—	—	—	
1114		16.5	133	—45	0	—	—	—	
1115		15.5	133	—48	—	2.1	—	—	
1116		14.5	133	—49	—	—	3.2	—	↓ A
1117	↓	16.5	130	—67	—	—	—	2.7	?
1118	27/1302	4	137	—68.5	—	—	—	—	?
1119	↑	9.5	—4	?	—	—	—	—	B
1120		11	—4	—28	—	—	—	—	↑
1121		12.5	7	—28	—	—	—	—	
1122	**16**	12.5	0	—38	0	—	—	—	
1123		11	4	—32.5	—	.4	—	—	
1124		11	—2.5	—31	—	—	7.7	—	↓
1125	↓	11.5	—1	—32	—	—	—	?	B

[3] *Rossi* - pag. 54

TABLE 3.

Average magnetic conditions during the time intervals of type A listed in table 1. $\bar{B}$ is the arithmetic average of the magnetic field strengths measured during each individual interval (in units of 10^{-5} gauss); $\bar{\varphi}$ and $\bar{\vartheta}$ are similar averages for the two angles (solar ecliptic longitude and ecliptic latitude) which describe the direction of the vector **B**.

Interval N.	$\bar{B}$ (gammas)	$\bar{\varphi}$ (degrees)	$\bar{\vartheta}$ (degrees)
1	31	155	- 32
3	27	158	- 36
5	22	164	- 35
7	20	154	- 36
9	17	143	- 38
11	21	166	- 36
13	18	155	- 44
15	15	139	- 48

magnetic field observed in the corresponding time interval). However, the changes were usually gradual and not quite as large as those occurring from one time interval to another. One exception was the long interval No. 10 during which substantial changes of the magnetic field (as well as of the plasma flux) were observed. For this reason, interval No. 10 is divided into four sub-intervals in Tables 1 and 4 and in Fig. 19 ([1]).

([1]) This subdivision, while based on the behavior of the plasma flow and the magnetic field, is admittedly somewhat arbitrary.

TABLE 4

Average magnetic and plasma conditions during the time intervals of type B listed in Table 1. $\bar{B}$, $\bar{\varphi}$, and $\bar{\vartheta}$ have the same meaning as in Table 3. $\bar{\Phi}(80)$, $\bar{\Phi}(250)$, $\bar{\Phi}(800)$ and $\bar{\Phi}(2300)$ are the average values of the nominal flux densities at the 80, 250, 800 and 2300 V modulation levels respectively for each interval. The two sets of figures in the column under $\bar{\Phi}(80)/\bar{\Phi}(800)$ represent minimum and maximum values of this ratio.

Interval N.	Magnetic field			Plasma			
	$\bar{B}$ (gammas)	$\bar{\varphi}$ (degrees)	$\bar{\vartheta}$ (degrees)	$\bar{\Phi}(800)$ ($10^7 cm^{-2} sec^{-1}$)	$\frac{\bar{\Phi}(80)}{\bar{\Phi}(800)}$ (percent)	$\frac{\bar{\Phi}(250)}{\bar{\Phi}(800)}$ (percent)	$\frac{\bar{\Phi}(2300)}{\bar{\Phi}(800)}$ (percent)
2	13	22	—35	24	1.6	12	105
4	15	—24	—44	25	.9-1.6	10	99
6	11	50	—37	17	1.2-2.3	14	105
8	16	100	— 9.2	13	0-2.7	7.4	86
10a	16	88	—11	9.8	0-3.7	5.3	92
10b	14	68	—31	10	0-3.5	14	109
10c	12	77	—34	15	1.9-2.8	15	109
10d	13	39	—34	12	0-2.9	7.4	95
12	9.7	39	—60	16	0-2.2	9.4	81
14	10	38	—37	8.0	0-4.4	6.7	102
16	11	1	—42	9.2	0-3.9	6.0	91

B. *Third period - Properties of the plasma observed in situations of type B.*

From an experiment of the type considered here, one would wish, ideally, to determine the energy spectrum and the total flux of protons per unit area per unit solid angle in any given direction at any given instant of time. Actually, our instrument was not designed to achieve anything approaching this ambitious aim. However, the experimental data contain information of a somewhat more specific nature than the qualitative results presented in section 4-C.

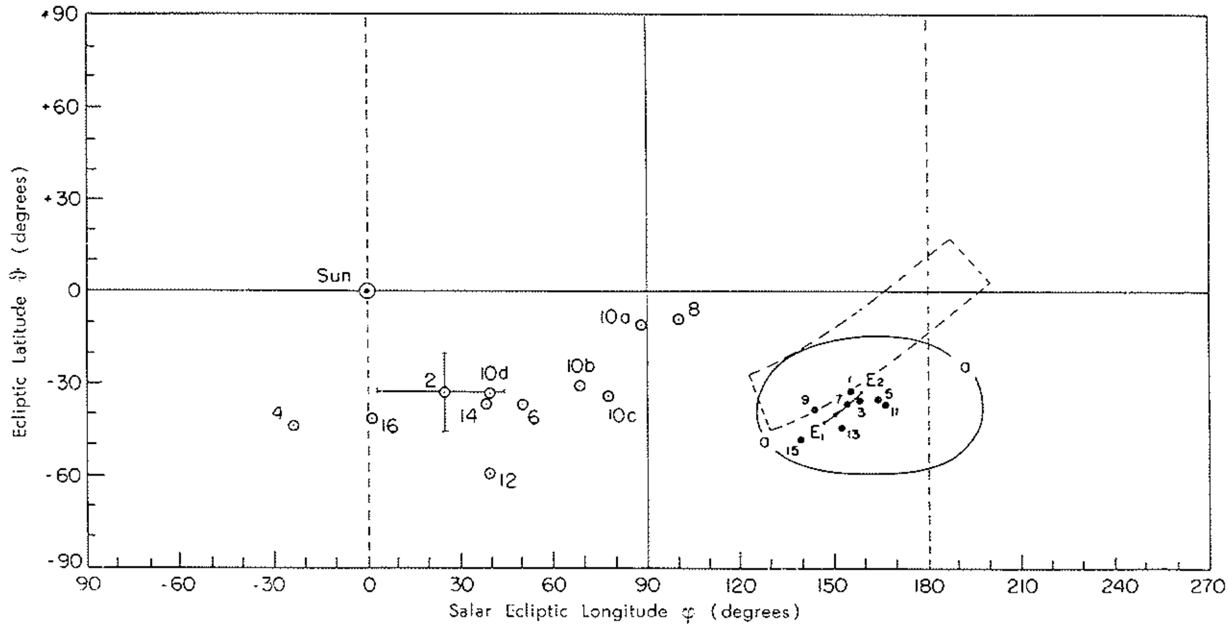


FIG. 19 — Average directions of the magnetic field observed during the various time intervals of the third period. Solid dots refer to situations of type A; open circles refer to situations of type B. The number by each point specifies the time interval to which the point refers, as listed in Table 1. The two bars crossing at point No. 2 represent the spread in the direction of **B** observed during this time interval. The line segment $E_1 E_2$ represents the angular displacement of the earth-satellite line during the time of observation.

1) *Plasma flux densities*

Because of the frequent electronic disturbances which interfered with the measurements at the 2300 V modulation level, we chose to use the measurements at the 800 V level to evaluate the total flux density of plasma protons. As we shall discuss later in more detail, it is possible that a small fraction of the plasma protons did not undergo modulation at this level. We believe, however, that the error introduced by this lack of complete modulation is negligible within the accuracy claimed for the absolute value of the plasma current in the present experiments. The flux densities measured at the 800 V level, which are shown in Fig. 16, are replotted on a condensed time scale in Fig. 20. It can be seen that these flux densities exhibit both short-time fluctuations and long-time changes; moreover, the long-time changes have a larger amplitude than the short-time fluctuations. Therefore, it is meaningful to compare the time averages of the flux densities observed during the individual time intervals of type B. These averages appear in Table 4 under the heading $\overline{\Phi}(800)$.

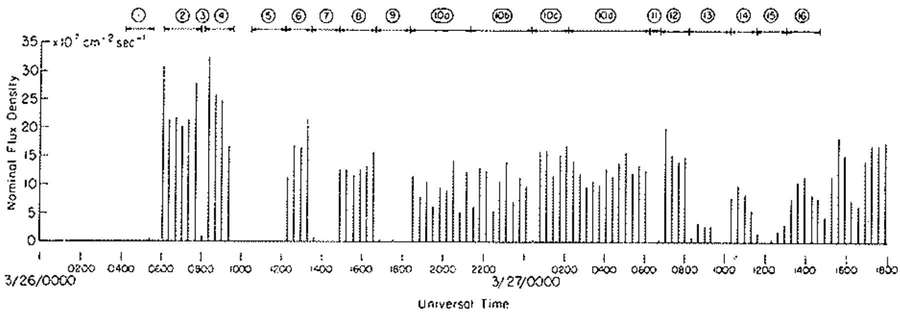


FIG. 20 — Plasma measurements at the 800 V level on a condensed time scale.

2) *Dependence of the plasma current on the modulating voltage.*

The main source of information on the energy spectrum of the plasma protons lies in the relative amplitudes of the current signals observed with the different modulating voltages. However, because of the time fluctuations in the plasma flux, it is not possible to draw firm conclusions from a comparison of consecutive measurements at different modulation levels. A more promising approach is to compare the averages of such measurements for each of the time intervals. This is done in the last three columns of Table 4, where we list the ratios of the average nominal flux densities observed at the 80, 250, and 2300 V levels, $\bar{\Phi}(80)$, $\bar{\Phi}(250)$, and $\bar{\Phi}(2300)$, to that observed at the 800 V level, $\bar{\Phi}(800)$.

As a comment on these data, we note the following: The current signals at the 80 V level were often below the detection limit, particularly during those time intervals when the total flux density was low. The pairs of figures appearing under $\bar{\Phi}(80)/\bar{\Phi}(800)$ represent lower and upper limits for this ratio, computed respectively under the assumptions that the flux density corresponding to a signal below the noise level was *a*) zero, or *b*) equal to the minimum detectable value (4×10^6 cm^{-2} sec^{-1}). We see that during some of the time intervals $\bar{\Phi}(80)/\bar{\Phi}(800)$ was of the order of one or two percent; during other time intervals $\bar{\Phi}(80)/\bar{\Phi}(800)$ might have had any value from zero to several percent.

The values of $\bar{\Phi}(250)/\bar{\Phi}(800)$ listed in Table 4 vary from 5% to 15%. The values of $\bar{\Phi}(2300)/\bar{\Phi}(800)$ oscillate around unity, from a minimum of 81% to a maximum of 109%.

There are two possible interpretations for the variability of these ratios. The first is that it is due to short-time fluctuations in the total proton flux whose effects are not entirely eliminated by the averaging process. The second is that it is due, at least in part, to changes in the energy spectrum of the protons.

If we accept the first interpretation and assume, accordingly, that the proton spectrum was the same during all time intervals listed in Table 4, we do not need to consider these various time intervals separately, but we may take for $\bar{\Phi}$ (250), $\bar{\Phi}$ (800) and $\bar{\Phi}$ (2300) the averages of the measurements made at each modulating voltage during all such time intervals. As for the computation of $\bar{\Phi}$ (80), it is more advantageous to consider only those time intervals when the total flux density was sufficiently high to yield significant data at the 80-volt modulation level (intervals No. 2, 4, 6, 10c). The results obtained in this manner are listed in the first row of Table 5.

At any one instant of time, the ratio Φ(2300/Φ(800) must be greater than or equal to unity because there cannot be more protons with energies below 800 eV than protons with

TABLE 5

Ratios of the average values of Φ(80), Φ(250) and Φ(2300) to the average value of Φ(800) for all time intervals of type B, for those time intervals in which Φ(250)/Φ(800) ≥ .10 and for those time intervals in which Φ(250)/Φ(800) < .10 (corrected values for Φ(2300)/Φ(800) appear in parentheses).

	$\frac{\bar{\Phi}(80)}{\bar{\Phi}(800)}$ (percent)	$\frac{\bar{\Phi}(250)}{\bar{\Phi}(800)}$ (percent)	$\frac{\bar{\Phi}(2300)}{\bar{\Phi}(800)}$ (percent)
Average for all type B intervals	1.5-2.1 ([1])	9.3	97
Average for intervals 2, 4, 6, 10b, 10c	1-2.5	13	104 (113)
Average for intervals 8, 10a, 10d, 12, 14, 16	0-3.3	6.9	92 (100)

([1]) Only time intervals 2, 4, 6, 10c are included here.

[3] *Rossi* - pag. 60

energy below 2300 eV. The ratio of the over-all averages of $\Phi(2300)$ and $\Phi(800)$ is actually close to unity. According to the interpretation discussed here, the reason why $\bar{\Phi}(2300)/\bar{\Phi}(800)$ is less than unity for the averages taken over some of the individual intervals must be found in the short-time fluctuations of the flux.

There are, however, strong arguments against this interpretation.

In the first place, the changes of the ratio $\bar{\Phi}(250)/\bar{\Phi}(800)$ for the individual time intervals were, percentagewise, much greater than those of the ratio $\bar{\Phi}(2300)/\bar{\Phi}(800)$. If both changes were due to finctuations of the total proton flux, they should be approximately equal in relative magnitude.

In the second place, there appears to be a definite correlation between the values of $\bar{\Phi}(250)/\bar{\Phi}(800)$ and the values of $\bar{\Phi}(2300)/\bar{\Phi}(800)$ relative to the same time intervals. For example, in all four cases where $\bar{\Phi}(250)/\bar{\Phi}(800) > .10$, we find that $\bar{\Phi}(2300)/\bar{\Phi}(200 > 1.0$, whereas in five out of seven cases where $\bar{\Phi}(250)/\bar{\Phi}(800) < .10$, we find that $\bar{\Phi}(2300)/\bar{\Phi}(800) \leq .95$. Thus, the experimental data support the interpretation that the proton spectrum did indeed change from one time interval to another, and we shall now analyze our results under this assumption.

Since the accuracy of the data does not warrant a more detailed treatment, we shall group together, for the purpose of analysis, all time intervals for which $\bar{\Phi}(250)/\bar{\Phi}(800) \geq .10$. (No. 2, 4, 6, 10b, 10c) and all time intervals for which $\bar{\Phi}(250)/\bar{\Phi}(800) < .10$ (No. 8, 10a, 10d, 12, 14, 16). The ratios between the average flux densities computed separately for these two groups appear in the second and third rows of Table 5. We see that $\bar{\Phi}(2300)/\bar{\Phi}(800)$ has a value of 1.04 for the first gronp and a value of 0.92 for the second group. As already pointed out, the « true » value of this quantity cannot be smaller than unity. To explain the value 0.92 as a statistical result due to short-time fluctuations in the proton flux would not be consistent with the point of view adopted here. On the other hand, it is possible that we may have slightly misjudged the effective gain of the compression amplifier when the probe was operated at the 2300 V level, because as already noted, the zero line was somewhat displaced in this mode of operation. We can estimate a lower limit for the instrumental error by assuming that $\bar{\Phi}(2300)/\bar{\Phi}(800)$ was actually unity for the time intervals of the second group. This lower limit amounts to 8%; therefore, the minimum value of the correction factor is 1.08. With this correction factor, the value of $\bar{\Phi}(2300)/\bar{\Phi}(800)$ for the time intervals of the first group becomes 1.13.

3) *The proton energy spectrum*

If we neglect the angular spread of the plasma protons and assume that the particles formed a parallel beam, we can relate the flux densities observed at the various modulating voltages directly to the energy spectrum of the protons. The uncertainty in the value of the angle α which the proton beam formed with the equatorial plane of the satellite introduces an uncertainty in the value of the energy because the minimum voltage needed to modulate protons of energy E is $V_m = E, \cos^2\alpha$. In what follows, we shall call the quantity $E \cos^2\alpha$ the « nominal » proton energy.

Fig. 21 shows the values of $\bar{\Phi}(80)$, $\bar{\Phi}(250)$, $\bar{\Phi}(800)$ and $\bar{\Phi}(2300)$ for the two groups of time intervals (see Table 5), normalized to unity at 2300 V. According to our assumptions, these values represent the fractions of protons in the total flux whose nominal energies are less than 80, 250, 800 and 2300 eV respectively. We see that, during the time intervals of the first group, a very small fraction of the protons have nominal energies lower than 80 eV and a somewhat larger fraction have nominal energies greater than 2300 eV. During the time intervals of the second group, the spectrum appears to be

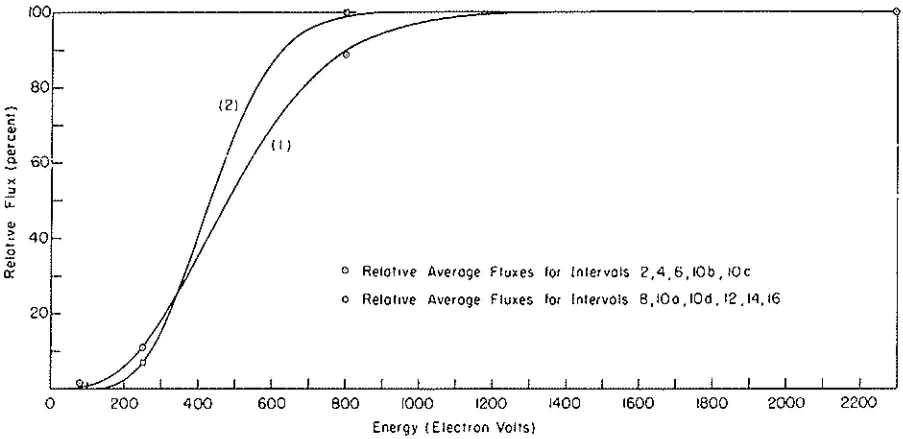


FIG. 21 — « Nominal energy » distribution of plasma protons. The experimental points are obtained from Table 5 [« corrected » values for $\Phi(2300)/\Phi(800)$ are used]. The curves represent theoretical spectra computed under the assumption of a one-dimensional Maxwellian distribution for the « thermal » velocities with the following parameters:

1) $E_0 = 420$ eV, $T = 6.2 \times 10^5$ °K
2) $E_0 = 420$ eV, $T = 2.6 \times 10^5$ °K.

narrower, but is less well defined; the data in fact are consistent with a complete absence of protons with energies less than 80 eV or more than 800 eV, but they do not rule out the possibility that a few percent of the protons may have energies beyond these limits.

The energy spread of the plasma protons may be interpreted in terms of a « thermal » agitation of these particles in the frame of reference of the moving plasma. For the sake of orientation, let us compare the experimental results with the energy spectra computed under the assumption that the « thermal » velocities obey a Maxwellian distribution, corresponding to a certain temperature T, and let us simplify the calculations by neglecting the components of the thermal velocities perpendicular to the direction of bulk motion. (This simplification is consistent with the assumption of a parallel proton beam and is partially justified by the fact that the perpendicular components of the thermal velocities have only a second-order effect on the resultant velocity of the protons, while the parallel components have a first-order effect). The kinetic energy of the individual protons ($E = mV^2/2$), the proton energy corresponding to the bulk motion ($E_0 = mV_0^2/2$), and the mean thermal energy in one dimension ($kT/2$) appear only through their ratios in the results of this computation. Since the experimental spectra are given in terms of the « nominal » energy, $V_m = E \cos^2\alpha$, comparison with the theoretical curves yields information on the « nominal » energy of bulk motion, $E_0 \cos^2 \alpha$, and on the « nominal » temperature, $T \cos^2 \alpha$. The results of this comparison are shown in Fig. 21. One sees that the experimental points for the first group of time intervals fit satisfactorily the theoretical curve corresponding to $E_0 \cos^2 \alpha = 420$ eV and to $T \cos^2 \alpha = 6 \times 10^5$ ^{0}K. Considering the uncertainties of the measurements and the crude character of our analysis, we assign an uncertainty of $\pm 15\%$ for the value of $E_0 \cos^2 \alpha$ and a range of values from 4×10^5 ^{0}K to 1×10^6 ^{0}K for the nominal temperature.

Less definite conclusions can be reached concerning the conditions of the plasma during the time intervals of the second group, except that the spectrum appears to be narrower, and, therefore, the nominal temperature appears to be lower than that of the plasma observed during the time intervals of the first group. The nominal energy of bulk motion, on the other hand, is probably not very different from that estimated above. (The tentative spectrum shown in Fig. 21 corresponds to $E_0 \cos^2 \alpha = 420$ eV and $T \cos^2 \alpha = 2.6 \times 10^5$ ^{0}K; this temperature represents an approximate upper limit for the range of temperatures which could be used to obtain reasonable agreement between the experimental data and the theoretical model).

Another source of information on the proton energy spectrum may be found in the shapes of the current signals. Throughout the third period of the flight, the signals at the

2300 V and at the 800 V modulation levels had round tops, while those at the 250 V level had flat tops (see Figs. 14 *a*, *b*). This is consistent with the tentative spectra shown in Fig. 21, according to which the flux density of protons with nominal energy less than E increases rapidly near E = 250 eV, increases slowly near E = 800 eV and has already reached saturation before E = 2300 eV. (As the rotation angle β increases, the effective area of collection decreases but the energy of the protons which can be modulated by a given modulating voltage increases; if the spectrum is sufficiently steep, the consequent increase in modulated flux compensates for the decrease in collection area, giving rise to a current which is nearly independent of β over a certain range).

The properties of the plasma and of the associated magnetic field, as they emerge from the present discussion, are summarized in Table 6. Note that while the experimental data appear to be consistent with the assumption of a Maxwellian distribution for the random velocities of the protons, they certainly do not prove that this assumption represents more than a crude approximation. Thus, the temperatures in Table 6 are simply an indication of the mean energy of random motion of the protons in the frame of reference of the moving plasma.

4) *Average direction and angular spread of the proton beam*

Since the plasma was fully modulated at the 2300 V level, the shapes of the current signals obtained at this level are independent of the proton energy spectrum; they depend only on the angle α formed by the bulk velocity vector $\mathbf{V}_0$ with the equatorial plane of the satellite, and on the angular spread of the proton beam. The position of their maxima, on the other hand, determines the angle which the plane passing through the spin axis and the vector $-\mathbf{V}_0$ forms with the plane through the spin axis and the solar direction (plane « p » in Fig. 12). We shall call this angle β_0.

TABLE 6

Average properties of the plasma and the magnetic field observed during time intervals of the first group [$\Phi(250)/\Phi(800) \geq .10$] and during time intervals of the second group [$\Phi(250)/\Phi(800) < .10$]. The values labelled « minimum » and « maximum » are respectively the smallest and largest of each group of average values (see Table 4). The proton density n is the ratio of the average flux density Φ to the bulk velocity V_0. All the results given for the plasma were computed for $\alpha = 0^0$ and, therefore, represent nominal values of the corresponding quantities.

	Intervals No. 2, 4, 6, 10b, 10c ($\Phi(250)/\Phi(800) \geq .10$)	Intervals No. 8, 10a, 10d, 12, 14, 16 ($\Phi(250)/\Phi(800) < .10$)
Average proton flux density, Φ (10^7 cm^{-2} sec^{-1})	19 (minimum: 10) (maximum: 25)	11 (minimum: 8) (maximum: 16)
Velocity of bulk motion, V_0 (km sec^{-1})	280 ± 20	280 ± 20
Proton kinetic energy, $mV_0^2/2$ (eV)	420 ± 60	420 ± 60
Proton density, n (cm^{-3})	7 (minimum: 3) (maximum: 8)	4 (minimum: 3) (maximum: 5)
Proton « temperature », T (10^5 ^0K)	6 (between 4 and 10)	$\lesssim 3$
Magnetic field, B (gammas)	13 (minimum: 11) (maximum: 15)	3 (minimum: 10) (maximum: 16)
Energy density of bulk motion, $nmV_0^2/2$ (eV cm^{-3})	2,800 (minimum: 1,500) (maximum: 3,800)	1,600 (minimum: 1,200) (maximum: 2,600)
Energy density of « thermal » motion, $3nkT/2$ (eV cm^{-3})	(between 200 and 700)	200
Magnetic energy density, $B^2/2\mu_0$ (eV cm^{-3})	400 (minimum: 300) (maximum: 600)	400 (minimum: 200) (maximum: 700)

Figs. 22-a and 22-b illustrate the procedure used for the analysis of the observed pulses. The scale on the horizontal axis indicates times in milliseconds measured from the instant when the normal to the cup was closest to the solar direction. The dots in each figures represent superposed measurements of individual current signals obtained during two different telemetering cycles. The solid curves represent the geometrical response of the probe for parallel beams with $\alpha=0^0$ and $\alpha=40^0$, respectively, corrected for the distortion due to the electronic circuits (see Fig. 8). The vertical scales for these curves and their horizontal positions were adjusted so as to obtain the best fit with the maxima of the experimental current signals. The times at which these maxima occur are shown in the figures as t_m. Considering the 15 ms delay introduced by the electronic circuits, the values of t_m shown in Figs. 22a and 22b correspond, respectively, to $\beta_0=-7^0$ and $\beta_0=0^0$ (negative angles indicate directions to the south-east of the plane « p »). Analysis of the various current signals recorded at the 2300 V level gives values of β_0 which cluster around 0^0, with a dispersion of a few degrees. We were unable to determine whether this dispersion is due to actual fluctuations in the direction of the plasma flow or is due entirely to experimental errors. In this connection, we note that the timing signal from the optical aspect sensor had an uncertainty of about 4 ms, corresponding to an uncertainty of about $2{,}5^0$ in β_0, and that a somewhat larger uncertainty is involved in the determination of t_m. In any case, we can safely state that whenever plasma was observed during the third period of the Explorer X flight, the angle β_0 was smaller than 10^0 in absolute value.

The current signals shown in Figs. 22(a) and 22(b) are slightly wider than the curve representing the response of the probe to a parallel beam of particles incident at $\alpha=0^0$. The difference is even greater for $\alpha>0^0$. We shall make a crude estimate of the angular spread of the proton beam needed to account for the observed widening by assuming that both the

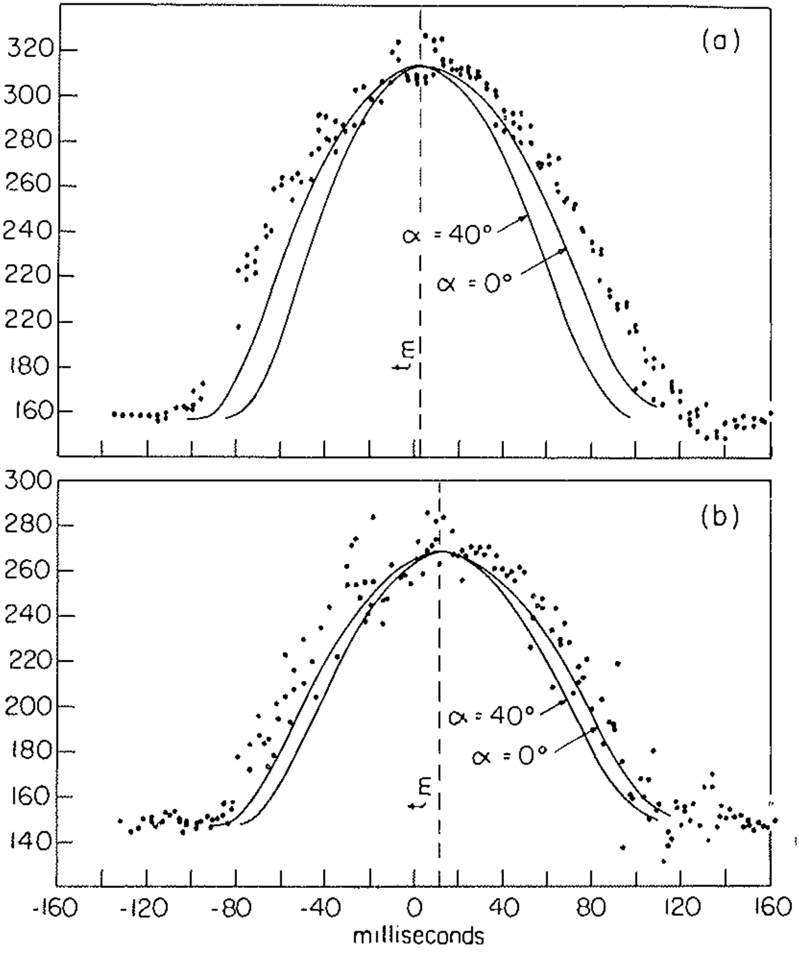


FIG. 22 — Comparison between observed current signals and theoretical curves which represent the response of the probe and electronic circuits for a parallel beam of particles with $\alpha = 0^0$ and $\alpha = 40^0$.

response curve of the probe and the angular distribution of the protons may be approximated by gaussian functions, with root mean square angles equal to $\Delta\beta$ and $\Delta\omega$ respectively. The observed current signal should then be a gaussian function with a root mean square angle $\Delta\beta_e$ given by:

$$(\Delta\beta_e)^2 = (\Delta\beta)^2 + (\Delta\omega)^2 .$$

Comparing the observed signals with the response curve for $\alpha = 0^0$ (corrected for the distortion of the pulses due to the non-linearity of the electronic circuits), and considering that, for a gaussian distribution, the root mean square angle equals the half-width at 0.6 maximum height, we find from Fig. 22(a), a value of $(\Delta\omega)^2$ between .02 and .10, and from Fig. 22(b) a value of $(\Delta\omega)^2$ between .03 and .12.

If we interpret the angular spread in terms of a « thermal » agitation of the protons in the frame of reference of the moving plasma, we have:

$$(\Delta\omega)^2 = kT/2E_0 .$$

Using the above values of $(\Delta\omega)^2$ and a kinetic energy of bulk motion $E_0 = 420$ eV, we obtain « temperature » estimates ranging roughly from 2×10^5 ^{0}K to 1×10^6 ^{0}K in the case of Fig. 21a and from 3×10^5 ^{0}K to 1×10^6 ^{0}K in the case of Fig. 21b.

These results appear to be more or less typical of all current signals obtained at the 2300 V level. Thus, we conclude that the range of possible « temperatures » deduced from the width of the current signals is not in disagreement with that deduced from the proton energy spectrum. Of course, it should be noted that both temperature determinations are very crude. Also there is no *a priori* reason why the two « temperatures » should be identical since the root mean square velocities of agitation parallel and perpendicular to $\mathbf{V}_0$ may well differ from one another.

C. *Third period - Currents observed in situation of type A*

The currents observed at times when the radial configuration of the magnetic field was indicative of a type A situation corresponded always to nominal flux densities smaller than 5×10^7 cm^{-2} sec^{-1}. However, these currents were occasionally distinctly above the noise level. They were modulated by the rotation of the satellite, with the maximum at the time when the normal to the probe was closest to the direction of the sun (as in the case of the currents observed in situations of type B). In many instances, they appeared only at the 2300 V modulation level; in some cases, they appeared also at the 800 V and at the 250 V levels, once even at the 80 V level. Modulation at the latter voltages was observed more frequently toward the end of the flight. The origin of these small currents cannot be established with certainty.

D. *Observations during the fourth period*

During the fourth period, the following sequences of events took place.

Between 3-27-1440 and 3-27-1452, the magnetic field changed direction abruptly (from about $\varphi = 0^0$, $\vartheta = -60^0$ to about $\varphi = 90^0$, $\vartheta = 0^0$) and then returned just as abruptly to approximately the original direction. The next two plasma measurements at the 800 V and 2300 V levels indicate that a substantial increase in the mean proton energy had occurred [$\Phi(2300) \simeq 2\ \Phi(800)$, flat-topped signal at the 800 V level]; while the total flux density had not changed appreciably.

At about 3-27-1500, the magnitude of the magnetic field at the satellite (which had been for some time in the neighborhood of 13 γ) began to increase and reached a maximum of about 25 γ at 3-27-1640, after which time it decreased slightly, oscillating around a value of about 20 γ.

At 3-27-1503, when the satellite was at a geocentric distance of 41.4 R_e, the sudden commencement of a magnetic storm was recorded on the earth. In the next six telemetering sequences (*i.e.*, until 3-27-1655), the signals at the 2300 V level (when available) were about twice the size of those at the 800 V level. Moreover, the latter had a distinct « horned » shape which had not been observed previously (see Fig. 15), while the signals at the 2300 V level still had a round top. There was also a large increase in the total proton flux.

For the remainder of the observation period (*i.e.*, until 3-27-1800, when the satellite was at 42.3 R_e) the proton flux remained at a level about double that observed prior to the sudden commencement. However, there was no longer any marked difference between Φ (2300) and Φ (800), and the signals at the 800 V level again had a rounded top.

The above results show that during the first two hours after the sudden commencement about half of the plasma protons had nominal energies above 800 eV. However, the round tops of the signals at the 2300 V level indicate that the proton spectrum did not extend much beyond 2300 eV. Thus the kinetic energy of bulk motion was of the order of 1000 eV; however, the shape of the proton spectrum does not appear to be consistent with a Maxwellian distribution of the proton velocities in the frame of reference of the moving plasma.

Throughout the fourth period, the positions of the maxima were not appreciably different from those observed during the preceding third period. Thus, there was no evidence for any change in the direction of the plasma flow.

6. Interpretation

There is little doubt that the fast-moving plasma encountered by Explorer X during the third and fourth periods of its flight did not originate from the earth, but was a feature of interplanetary space (however, it is likely, as we shall see, that the presence of the earth might have materially modified the plasma flow in the region explored by the satellite).

It is also difficult to avoid the conclusion that the reason why no fast-moving plasma had been detected in the previous periods is that the geomagnetic field acts as an obstacle to the plasma flow, creating around the earth a « cavity » which the interplanetary plasma cannot penetrate (though the cavity may contain a quasi-stationary plasma representing an extension of the earth's atmosphere). The first appearance of the plasma at the beginning of the third period means that, at that time, Explorer X had traversed the boundary of the geomagnetic cavity.

A. *Theoretical considerations*

The interaction of a moving plasma with the earth's magnetic field was first studied theoretically by CHAPMAN and FERRARO [19-21]. The problem was taken up again by FERRARO [22], [23], whose work led to the prediction of a geomagnetic cavity of the general shape shown in Fig. 23(a). Its characteristic features are a blunt « nose » pointing toward the oncoming wind, and a long « tail » stretching in the downwind direction (see also JOHNSON [24]; more recent developments of the theory are described in a paper by DAVIS and BEARD [25], which also contains a good bibliography of the subject).

This theoretical model is based on a set of highly idealized assumptions, of which the most important are: 1) absence of plasma within the geomagnetic cavity; 2) absence of magnetic field in the moving interplanetary plasma, and 3) absence of random motions of the plasma particles in the rest frame of reference of the plasma (« perfectly cold » plasma).

During the last few years, it has become increasingly clear that none of these assumptions correspond to reality. Thus,

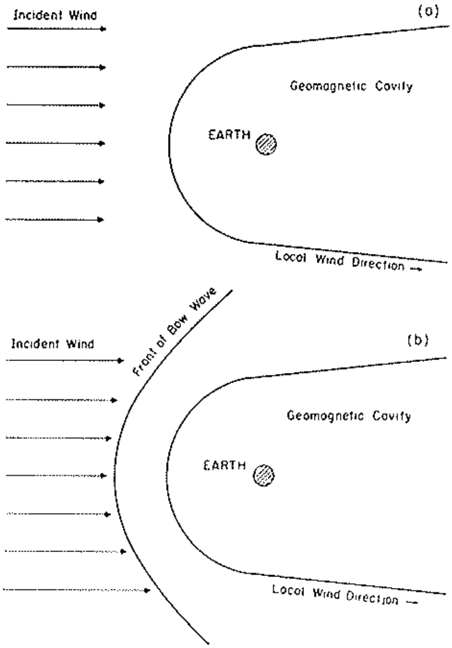


FIG. 23 — (*a*) Schematic representation of the geomagnetic cavity predicted in the case of a moving, perfectly cold interplanetary plasma with no magnetic field.

(*b*) Tentative model for the cavity and the stationary shock front produced by the interaction of the actual plasma wind with the geomagnetic field.

before the flight of Explorer X, even the qualitative validity of the theoretical conclusions was questionable.

On the other hand, the findings of Explorer X showed that the theoretical model was correct in predicting a sharp boundary between the geomagnetic cavity and the surrounding interplanetary plasma. Moreover, another important feature of the theoretical model, *i.e.*, the strong forward-backward asymmetry of the cavity with respect to the direction of the plasma flow, was also experimentally confirmed; while Explorer X crossed the geomagnetic boundary at a distance of about 22 earth radii in the anti-solar region, Explorer XII, moving in the subsolar region, crossed the boundary at about 10 earth radii (see section B below). It is thus reasonable to explore the possibility of interpreting the experimental results on the basis of the theoretical model suitably modified to make it compatible with the properties of the « real » interplanetary plasma.

The irreversible flow, indicated by the asymmetric shape of the geomagnetic cavity, implies dissipative processes such as are likely to occur prominently if the plasma approaches the earth at supersonic speed.

In the idealized theoretical model, the plasma flow is indeed « infinitely » supersonic because in a « perfectly cold » plasma with no magnetic field, the velocity of propagation of small low-frequency disturbances (« sound » waves as well as Alfvén waves) is zero (1).

In the actual interplanetary plasma, on the other hand, both the « sound » velocity and the Alfvén velocity have finite values, and we must examine the experimental data to determine whether these velocities are actually smaller than the bulk velocity.

In this connection, we note that the properties of the plasma wind observed by Explorer X may differ substantially from those of the « distant wind ». In fact, it is well known that a supersonic flow cannot be stopped suddenly by an obstacle (in our case, by the geomagnetic cavity), but must first be modified in such a way that, in the region ahead of the stagnation point, the velocity of the flow becomes subsonic. In the case of ordinary fluids, the conversion occurs through a stationary shock front (or bow wave) that forms ahead and around

(1) A collisionless plasma does not propagate ordinary sound waves. However, some of the possible wave modes have propagation velocities that are close to the velocity of sound, defined in the ordinary manner.

the obstacle. It is reasonable to assume that a similar shock front exists in the interplanetary plasma around the geomagnetic cavity (see Fig. 23(b)).

Since collisions do not play any appreciable role in the exceedingly dilute interplanetary plasma, the dissipation processes that occur in the passage of the plasma across the shock front must be due to a mechanism different from that operative in ordinary fluids, a mechanism which is not yet well understood. In any case, it is certainly true that between the shock front and the geomagnetic cavity, plasma and magnetic conditions are different from those beyond the front, where no effect of the earth's magnetic field can be felt. In particular, the plasma in this region will not only move with a smaller speed and in a direction different from that of the distant wind, but it will also have a higher « temperature » and carry a stronger magnetic field. For these reasons, the « Mach numbers » of the local wind relative to both « sound » waves and Alfvén waves will be smaller than the corresponding Mach numbers of the distant wind.

With this in mind, let us consider the Explorer X results. The velocity of bulk motion of the plasma was found to be substantially larger than the mean «thermal» velocity of agitation of the plasma protons. Since the « thermal » velocity is close to the « sound » velocity, we conclude that the velocity of bulk motion was larger than the « sound » velocity.

From Table 6, we see that the ratio of the kinetic energy density of bulk motion to the magnetic energy density was greater than unity. Since this ratio equals the square of the ratio of the bulk velocity to the Alfvén velocity, we conclude that the bulk velocity was also larger than the Alfvén velocity.

The observed plasma wind was thus supersonic with respect to both « sound » waves and Alfvén waves; for the reasons explained above, this conclusion applies *a fortiori* to the distant wind.

Note that a bow wave does not appear in the theoretical model because in the limit of an infinitely large Mach number the bow wave becomes coincident with the boundary of the geomagnetic cavity.

B. *Experimental data relating to the geomagnetic cavity and the bow wave*

Besides Explorer X, several other space vehicles have provided information that can be used to specify some of the parameters characteristic of the interaction region between the interplanetary plasma and the geomagnetic field.

Pioneer I (launched October 11, 1958) and Pioneer V (launched March 11, 1960) both went in the general direction of the sun. They did not carry plasma probes, but they did carry rotating-coil magnetometers which measured, intermittently, the component of the magnetic field perpendicular to their spin axes.

Up to a geocentric distance of about 13 R_e, the observations of Pioneer I indicated a magnetic field which was not very different from that of a dipole; however, in the neighborhood of 13 R_e, the field was decreasing more slowly than a dipole field. Between 13 R_e and 14 R_e, the field became highly disturbed and decreased in strength from about 25 γ to less than 10 γ [26], [27].

The observations of Pioneer V [28] indicated a quiet magnetic field out to 10 R_e. Then between 10 R_e and 14 R_e, the field became highly disturbed. Between 14 R_e and 15 R_e the situation changed again, and after 15 R_e the field became much quieter and decreased in strength, dropping to a value of about 5 γ at 20 R_e.

Explorer XII (which was launched August 15, 1961, on an elliptical orbit with an apogee of about 13 R_e) carried a plasma probe, three flux-gate magnetometers and various high-energy particle detectors. Its measurements refer to the subsolar region. The magnetometers showed that, in this region, the field was regular and had a structure consistent (in strength and direction) with that of a « compressed » dipole field up to a certain distance, beyond which it became highly irregular and its direction changed drastically (by about 180^0). The distance at which the transitions occurred varied between 8 R_e and 12 R_e [29], [30].

The plasma probe aboard Explorer XII did not supply data pertinent to this discussion. However, the high-energy particle detectors showed that the region populated by trapped particles terminated near the point where the magnetic transition occurred [31].

The combined results of Pioneer I, Pioneer V, and Explorer XII support the theoretical model described in Section A. Moreover, they show that the boundary of the geomagnetic cavity (separating the magnetically disturbed region from the magnetically « quiet » region populated by trapped particles) lies, in the subsolar region, between 8 R_e and 12 R_e. They also indicate the presence of a second surface of discontinuity at 14 R_e or 15 R_e, which presumably represents the bow wave, separating the magnetically disturbed region around the geomagnetic cavity from the unperturbed interplanetary field.

Fig. 24 summarizes in graphical form the data mentioned above. This figure was taken from the report presented by one of us at a recent Symposium of IRE-PGNS (Bridge [7]). A similar picture was presented by Cahill at the same symposium.

C. *A tentative model for the geomagnetical cavity*

Making use of the above results, we now attempt to draw a tentative and schematic model for the geomagnetic cavity as it existed at the time when Explorer X crossed the boundary and first detected the plasma wind. For this purpose, we still need to supplement the experimental data with a few hypotheses.

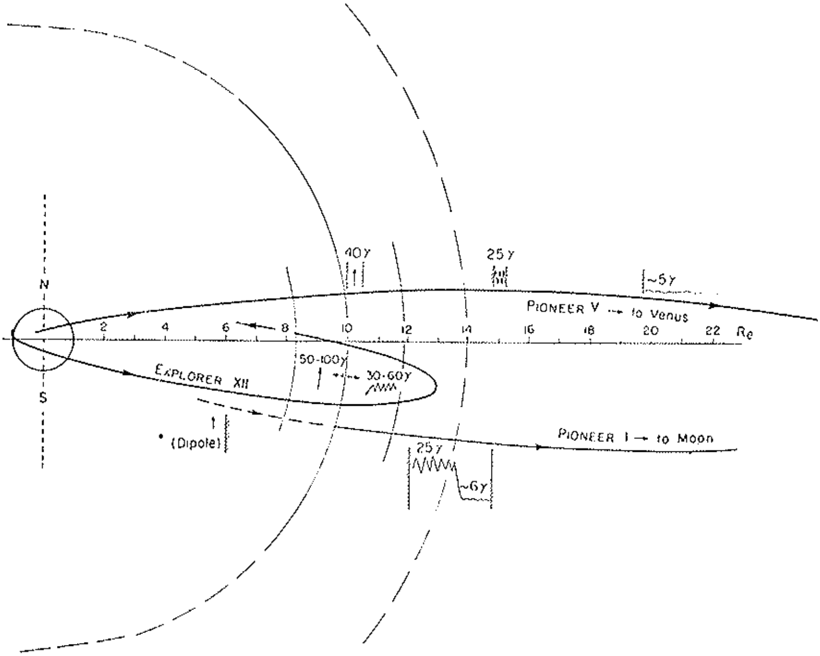


FIG. 24 — Pictorial summary of combined results of Pioneer I, Pioneer V, and Explorer XII concerning the boundary of the geomagnetic cavity and the location of the bow wave.

In the first place, we assnme that the distant plasma wind comes directly from the sun. Then in an earth-bound frame of reference, the plasma wind outside the bow wave arrives at an angle of about 6^0 to the sun-earth direction in the plane of the ecliptic, because of the orbital velocity of the earth.

We assume next that the geomagnetic cavity has axial symmetry around a line parallel to the distant wind and passing through the center of the earth. Moreover, we assume that the boundary of the cavity can be approximated by a spherical cap joining smoothly to a conical surface.

Finally, we take for the radius of the spherical cap a value of 10 R_e, which is the average distance at which Explorer XII detected the termination of the geomagnetic cavity in the subsolar region.

The above assumptions, together with the observed position at which Explorer X first encountered the plasma wind, determine the boundary of the geomagnetic cavity; the conical surface of this boundary has a half-angle at the vertex of about 20^0 (see refs. [32] and [33]).

The assumed shape of the geomagnetic boundary (a spherical cap joining to a conical « tail ») is obviously an oversimplification. Indeed, since the earth's magnetic field is not axially symmetric with respect to the direction of the distant wind, there is no reason to believe that the geomagnetic cavity has axial symmetry. We have also neglected here the complex phenomena that are likely to occur in the vicinity of those singular points of the boundary surface where the magnetic field vanishes (see, for example, DUNGEY [34]). Moreover, the choice of 10 R_e for the geocentric distance of the geomagnetic boundary in the subsolar region is, to some extent, arbitrary. This distance could easily have been 20% larger or smaller; correspondingly, the half-angle of the conical « tail » could have been smaller or greater than 20^0. Finally, one must remember that, as demonstrated hy the Explorer XII results, the boundary of the geomagnetic cavity changes with time. Therefore, our specific model refers only to the geomagnetic cavity at one particular instant of time, *i.e.*, the time when Explorer X left the cavity.

Undoubtedly, the present model will be refined and revised as more experimental data become available. We believe, however, that its general features will not change drastically, and we feel justified in using it as a basis for the interpretation of our data.

D. *Alternate appearances and disappearances of the plasma*

An important feature of the Explorer X observations is the alternate appearance and disappearance of the plasma during the third period of its flight (transitions from situation A to situation B and *vice versa*). There are, in principle, two interpretations of these occurrences. The first is that the interplanetary plasma has a « stratified » structure, in which tubes of force which are essentially empty alternate with tubes of force containing substantial amounts of plasma. The second is that, during the third period of its flight, Explorer X found itself alternately inside and outside the geomagnetic cavity (1).

After examining in detail the results of the magnetic field measurements, we are convinced (as discussed below) that the second interpretation is the correct one (Rossi [6]; other authors such as Piddington [35] have reached the same conclusion independently). These measurements, in fact, strongly suggest that the field corresponding to situations of type A was to some extent modified by the presence of the earth, whereas the field corresponding to situations of type B was not.

In the first place, the field observed in the absence of plasma (situation A), was found to point almost directly away from the earth. This is the expected direction of field lines originating from the earth and contained in the elongated « tail » of the geomagnetic cavity. Only by pure accident would one find field lines with this particular orientation in a region of space where the field arises from sources totally unrelated to the earth.

In the second place, the data summarized in Tables 3 and 4 show that the strength of the magnetic field observed during the intervals of type A decreased with increasing geocentric

(1) We dismiss here, as unlikely, the possibility that during intervals of type A the direction of the plasma flow was within the solid angle where the plasma probe was insensitive ($\alpha > 63°$, see Fig. 12).

distance, whereas no such consistent trend is detectable in the magnetic field measured during intervals of type B. These observations are easily understood if we assume that the field typical of situation A is the geomagnetic field modified by the plasma wind, and that the field typical of situation B is of non-terrestrial origin. On the other hand, if we assumed that the field typical of situation A is also unrelated to the earth, the observed decrease with increasing geocentric distance would be entirely accidental.

A much more detailed and critical analysis of these questions appears in HNSS, to which we refer the reader for further information [1].

The above interpretation of the alternate appearances and disappearances of the plasma is consistent with our model of the geomagnetic cavity. To illustrate this point, Fig. 25 shows the intersection of this cavity with the plane of the satellite's trajectory. One sees that Explorer X kept close to the assumed boundary after leaving the geomagnetic cavity. While we do not claim that the situation depicted in Fig. 25 represents more than a crude approximation, we feel justified in assuming that Explorer X, during the remaindeı of its flight, was never very far from the boundary as it existed at the time of the first crossing. It is thus very likely that fluctuations in the position of the boundary brought the satellite alternately inside and outside the geomagnetic cavity. Such fluctuations are to be expected, since the position of the boundary depends on

---

[1] H. Elliot, in a private communication (October, 1961), first pointed our that the strength of the magnetic field detected by Explorer X prior to the sudden commencement decreased with increasing geocentric distance. He used this observation as evidence that the field was of terrestrial origin (although modified by the interplanetary plasma). When the distinction between « situation A » and « situation B » was clearly established, it became evident that Elliot's argument was valid for situations of the first type but not for situation of the second type. The careful analysis of the magnetic measurements carried out by J. Heppner and his collaborators (see HNSS) has now added considerable strength to the conclusion that the field observed in situations of type A was of terrestrial origin.

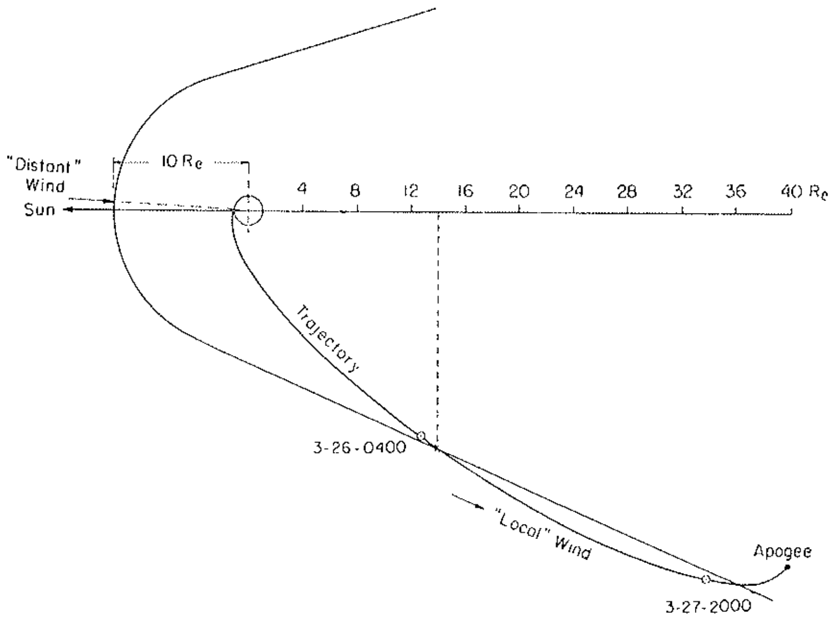


FIG. 25 — Intersection of the geomagnetic cavity with the plane of the trajectory of Explorer X. The cavity is assumed to have axial symmetry around the direction of the « distant » wind (which is at 6° to the solar direction in the plane of the ecliptic), and to consist of a spherical cap joining to a conical tail with a half-angle at the vertex of 20°.

the dynamic pressure of the plasma wind and the Explorer X data obtained outside the cavity reveal appreciable changes in the plasma flux.

It is possible, also, that the boundary surface might be somewhat « wavy », thus allowing several successive traversals even without any temporal changes in the position of the surface.

In connection with the present discussion, it is of interest to recall that on March 26, at 0250 UT, while the satellite was still within the geomagnetic cavity, the magnetic field began to increase in strength without changing direction (see section 4-B). Presumably, this increase was due to a compression of the geomagnetic cavity, caused by an increase in the plasma flux. Possibly, when the plasma wind was first detected a few hours later, the geomagnetic boundary was still moving inward at a speed greater than the outward speed of the satellite. If so, it would be more appropriate to say that the geomagnetic boundary had moved past the satellite, rather than to say that the satellite itself had crossed a relatively stationary boundary.

E. *Properties of the plasma detected by Explorer X during the magnetically quiet third period*

If Explorer X never got very far from the geomagnetic boundary, the local wind detected by the plasma probe must have been practically tangent to this boundary. If, moreover, the boundary was axially symmetric, the wind direction would lie in the plane passing through the axis of the cavity and the point of observation.

Let us assume that at all times when Explorer X detected a plasma wind, the geomagnetic cavity had the shape shown in Fig. 25. We then find that at the point where the satellite's trajectory first crossed the geomagnetic boundary, the plasma wind must have had the direction shown by point L_1 in Fig. 26. We also find that, despite the motion of the satellite, the wind direction changed very little during the remainder of the flight, the representative point moving only from L_1 to L_2. Points L_1 and L_2 are well within the « window » that contains the wind directions compatible with our observations. Thus, the proposed model of the cavity is consistent with these observations.

The directions corresponding to points L_1 and L_2 lie practically in the equatorial plane of the satellite (represented by the line « n » in Fig. 26). Therefore, the angle α for the local

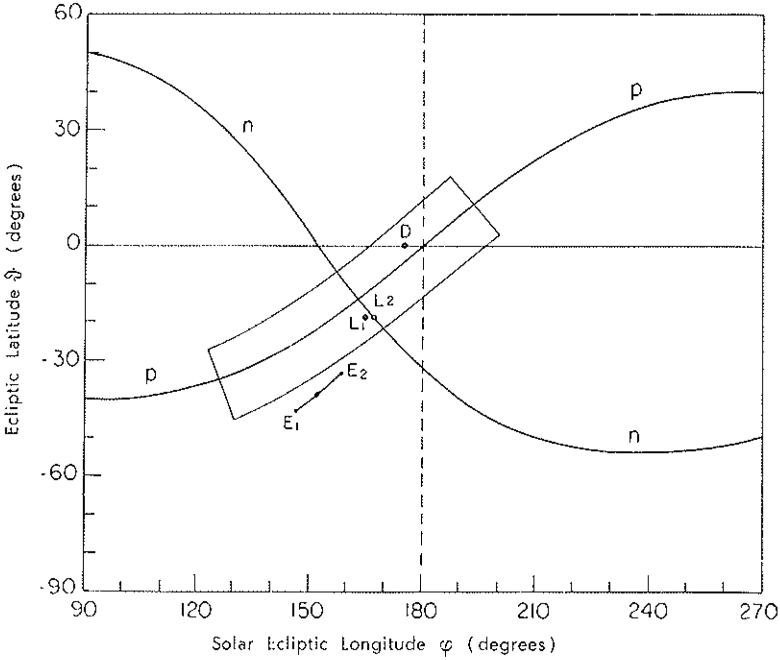


FIG. 26 — Showing the directions of the « local » wind (L_1, L_2) at the time when plasma was first detected and at the end of the observing period. Shown also are the directions of the earth-satellite line (E_1, E_2) at the same times, and the direction of the distant wind (D).

wind is practically zero. Of course the exact value of α thus determined is not significant because the assumed shape of the geomagnetic cavity does not represent more than a crude approximation. However, it would seem that for all reasonable directions of the local wind which are consistent with a distant wind coming directly from the sun, α sbould lie between 0^0 and 20^0 (notice that $\alpha = 20^0$ corresponds to a nearly cylindrical, rather than conical, « tail » of the geomagnetic cavity).

For angles smaller than 20^0, the differences between « nominal » and actual values of the flux and the energy are within the limits of our experimental uncertainties. Thus, we may use the figures listed in Table 6 as a reasonable estimate for the properties of the plasma observed during the third period of the flight.

We wish to note again that, in all likelihood, Explorer X never went out of the stationary shock front which has been assumed to surround the geomagnetic cavity. Presumably, the mechanical and magnetic properties of the plasma undergo a change across the shock front; thus, the experimental data of Explorer X may not represent accurately the properties of the interplanetary plasma at large distances from the earth.

F. *Explorer X observations at the time of the sudden commencement*

As noted in HNSS, a class 3 flare appeared on the east limb of the sun about 29 hours before the sudden commencement observed on the earth and the almost simultaneous increase in plasma flux and magnetic field strength recorded by the instruments aboard Explorer X. If this flare was indeed responsible for these effects, the mean velocity of propagation of the disturbance in interplanetary space was about 1400 km sec^{-1}.

Presumably, the disturbance consisted of a shock wave produced by the solar outburst and travelling over the « normal » solar wind. Immediately behind the shock front, one should expect to find a plasma moving with a bulk velocity smaller than that of the shock front itself (which corresponds to a proton energy of about 11 KeV). The protons detected by the plasma probe had energies below 2300 eV, corresponding to a velocity of less than 640 km sec^{-1}. The shape of the current signals is not consistent with the assumption that the probe was detecting the low-energy tail of a broad distribution peaked at an energy greater than 2300 eV.

Thus, the bulk velocity of the plasma appears to differ from the computed mean velocity of propagation of the shock front by at least a factor of two. However, one must consider: 1) that the velocity of the shock front near the earth might have been smaller than its mean velocity, 2) that passage through the bow wave might have decreased the bulk velocity of the plasma. It is also possible, of course, that the observed magnetic field and plasma flux increases were not caused by the flare referred to above.

G. *Configuration of the magnetic field lines*

In the theoretical model of the cavity produced by the interaction of a moving interplanetary plasma with the geomagnetic field, all of the magnetic field lines originating from the earth return to the earth. This is a consequence of the assumption that the interplanetary plasma does not carry any magnetic field. Even though it is now known that a magnetic field exists in interplanetary space, one might be inclined to believe that the earth's magnetic field is still confined to the geomagnetic cavity. According to this picture, the lines of force of the interplanetary field would spread out in the vicinity of the earth so as to envelope the geomagnetic cavity and remain disconnected from the field lines originating in the earth. The magnetic field vectors on the inner and outer side of the geomagnetic boundary would then be tangent to this surface (without necessarily being parallel to each other).

The general pattern of the experimental data provided by Explorer X does not appear to support this view. In fact, along those sections of the trajectory which were outside the cavity, the average magnetic field formed large angles with the boundary, being often approximately perpendicular to it. Inside the cavity, the average magnetic field (which was nearly radial from the earth) also formed a finite angle with the boundary of the cavity. Thus, it would seem that the field lines originating from the earth do not remain confined to the geomagnetic cavity but connect to the field lines of interplanetary space through the boundary of the cavity (1).

Since the interplanetary plasma flows past the geomagnetic cavity at great speed, while the cavity itself contains a nearly stationary plasma, it seems difficult to reconcile such a magnetic configuration with the generally accepted belief that the magnetic field lines are frozen into the plasma.

In view of this difficulty, it is advisable to exercise great caution in the interpretation of the experimental results.

One possibility is that the geomagnetic cavity is separated from the interplanetary plasma by a boundary layer of finite thickness, and that within this layer violent dissipative processes occur which effectively de-couple the field lines of the interplanetary plasma from those contained in the geomagnetic cavity. The transitions which we have defined as « complex » (see section 5-A) appear to suggest, in fact, the presence of a boundary layer of considerable thickness. However, most of the transitions were not complex. Moreover, it is possible that the rapid changes of magnetic field and plasma flux occurring during the complex transitions may have been due to fluctuations of a thin geomagnetic boundary. The fact that, even during such transitions, the correlation between plasma flux and magnetic field direction persisted, supports the latter point of view. In any case, the character of the fluctuations in the magnetic field observed during the complex transitions does not suggest the kind of turbulence that one would associate with strongly dissipative processes. Thus, there is little experimental evidence to support the view that dissipation of energy within

(1) As noted in HNSS, some uncertainty exists in the direction of the Explorer X spin axis; the extreme values for its ecliptic longitude are 59.5° and 63°, and the extreme values for its ecliptic latitude are −30° and −46.5°. However, these uncertainties do not affect significantly the conclusions stated here concerning the magnetic field directions.

a boundary layer of finite thickness may provide a way out of the difficulties.

Another possibility is that the field lines, both inside and outside the geomagnetic cavity, approach the boundary at a finite angle and then turn sharply so as to become parallel to this boundary.

To test such a possibility, we examined in detail the behavior of the magnetic field in the vicinity of the various transitions which, according to our interpretation, represent traversals of the geomagnetic boundary (see Table 2). We found no evidence that the magnetic field tended to become parallel to such a boundary at the times when any one of the 13 simple transitions occurred, and only a few of the observations made during the two complex transitions might be compatible with magnetic fields parallel to the boundary. A typical example of the changes in the direction of **B** corresponding to a simple transition is illustrated in Fig. 27.

It would be premature, perhaps, to draw any firm conclusion from the above results, in view of the fact that the magnetic field was not measured continuously, but only at intervals of $2^m 28^s$. One must also consider the uncertainties introduced by the arbitrary assumptions on which our tentative model of the geomagnetic cavity is based (see section 6-C). Of these assumptions, the one which affects the predicted orientation of the geomagnetic boundary most critically is the hypothesis that the plasma wind flows radially away from the sun. One might inquire if, by abandoning this assumption, one can construct a reasonable model for the geomagnetic cavity such that its boundary is parallel to the magnetic fields observed near the transitions. It turns out that this is possible, provided one assumes that the distant wind comes from a direction near the plane of the ecliptic at about 45^0 west of the sun (see ref. [8]). The direction of the « local » wind corresponding to this model falls within the « window » containing the allowed directions of the observed plasma flow. However, this model appears

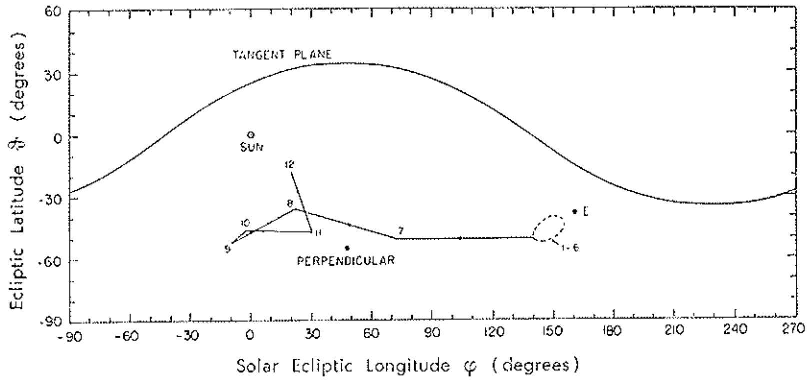


FIG. 27 — Directions of the magnetic field observed in the vicinity of the transition occurring during telemetry cycles No. 1044 to 1055 (see Table 2). Points labelled by consecutive numbers indicate successive measurements, made at intervals of $2^m\,28^s$. All points corresponding to measurements made before the transition (1 to 6) fall within the small area enclosed by the dotted line. The point E indicates the direction from the earth to the satellite. The solid curve represents the plane tangent to the geomagnetic boundary at the moment of the transition, according to the schematic model of the geomagnetic cavity described in section 6-C. The point labelled « perpendicular » is the direction perpendicular to the tangent plane. There is no evidence from these data that during the transition the direction of the magnetic field came near to the tangent plane.

unrealistic on the following grounds: First, it is difficult to imagine a mechanism that would account for the wind coming from that particular direction. Second, considering the intersection of the geomagnetic cavity produced by this wind with the orbital plane of Explorer X, we now find that the satellite, after crossing the boundary at 22 R_e, moved rapidly away from it. Thus, it is no longer possible to explain the alternate disappearances and reappearances of the plasma by expansions and contractions of the geomagnetic boundary, unless these oscillations had a very large amplitude.

In conclusion, we wish to stress the fact that questions of basic importance are still unresolved by present experimental information on the interplanetary plasma and the geomagnetic boundary. It is essential that further experiments be undertaken, designed to provide a detailed description of conditions existing in the immediate vicinity of the geomagnetic boundary and within the boundary layer itself, through continuous recording of magnetic fields and plasma fluxes.

ACKNOWLEDGEMENTS

The Project Manager for Explorer X was Dr. J. P. HEPPNER of the Goddard Space Flight Center; his group was also responsible for the magnetic field measurements reported in HNSS. We would like to acknowledge particularly the essential contribution of this group to the success of our own experiment. In addition, the cooperation and collaboration of NASA personnel too numerous to mention individually contributed to the experiment reported in this paper.

We recall gratefully the important part played by Dr. CONSTANCE DILWORTH OCCHIALINI and Mr. ERVIN F. LYON in the preparation of the experiment and in the early analysis of its results. We are greatly indebted to Dr. S. OLBERT for many suggestions and critical discussions concerning the interpretation of the experimental data.

REFERENCES

[1] J.P. Heppner, N.F. Ness, C.S. Scearce and T.L. Skillman, *J. Geophys. Res.*, *68*, 1, 1963 (referred too in the text as HNSS).

[2] H.S. Bridge, C. Dilworth, A.J. Lazarus, E.F. Lyon, B. Rossi and F. Scherb, *J. Phys. Soc. of Japan*, *17*, Suppl. A-II, 553, 1962.

[3] J.P. Heppner, N.F. Ness, T.L. Skillman and C.S. Scearce, *J. Phys. Soc. of Japan*, *17*, Suppl. A-II, 546, 1962.

[4] J.P. Heppner, N.F. Ness, T.L. Skillman and C.S. Scearce, Space Research III, North-Holland Publ. Co., Amsterdam 1963, p. 553.

[5] B. Rossi, Paper presented at the January, 1961 meeting of the American Physical Society, New York (unpublished).

[6] B. Rossi, Space Research III, North-Holland Publ. Co., Amsterdam 1963, p. 529.

[7] H.S. Bridge, Paper presented at the International Symposium on Space Phenomena and Measurements, Annual Meeting of IRE-PGNS, Detroit, October 16, 1962.

[8] A. Bonetti, H.S. Bridge, A.J. Lazarus, E.F. Lyon, B. Rossi and F. Scherb, Space Research III, North-Holland Publ. Co., Amsterdam 1963, p. 540.

[9] A. Bonetti, H.S. Bridge, A.J. Lazarus, E.F. Lyon, B. Rossi and F. Scherb, *Proc. Fifth Inter-American Seminar on Cosmic Rays*, La Paz, July, 1962.

[10] K.I. Gringauz, V.V. Bezrukikh, V.D. Ozerov and R.E. Rybchinskii, *Doklady Akad. Nauk SSSR*, *131*, 1301, 1960, and L.V. Kurnosova, *Artificial Earth Satellites*, No. 6, p. 122.

[11] K.I. Gringauz, V.G. Kurt, V.I. Moroz and I.S. Shklovskii, *Doklady Akad. Nauk SSSR*, *132*, 1062, 1960, and L.V. Kurnosova, *Artificial Earth Satellites*, No. 6, p. 130.

[12] K.I. Gringauz, V.G. Kurt, V.I. Moroz and I.S. Shklovskii, *Astronomicheskii Zhurnal*, *37*, 716, 1960.

[13] K.I. Gringauz, Paper presented at the Twelfth International Astronomical Congress, Washington, D.C., October, 1961.

[14] K.I. Gringauz, V.V. Bezrukikh, S.M. Balandina, V.D. Ozerov and R.E. Rybchinskii, Space Research III, North-Holland Publ. Co., Amsterdam 1963, p. 602.

[15] H.S. Bridge, C. Dilworth, B. Rossi, F. Scherb and E.F. Lyon, *J. Geophys. Res.*, *65*, 3053, 1960.

[16] H.S. Bridge, A.J. Lazarus, E.F. Lyon, B. Rossi and F. Scherb, Space Research III, North-Holland Publ. Co., Amsterdam 1963, p. 1113.

[17] H.E. Hinteregger, K.R. Damon and L.A. Hall, *J. Geophys. Res.*, *64*, 961, 1959.

[18] R.L. Smith and R.A. Helliwell, *J. Geophys. Res.*, *65*, 2583, 1960.

[19] S. Chapman and V.C.A. Ferraro, *Terr. Magn. Atm. Elec.*, *35*, 77, 171, 1931.

[20] S. Chapman and V.C.A. Ferraro, *Terr. Magn. Atm. Elec.*, *37*, 147, 421, 1932.

[21] S. Chapman and V.C.A. Ferraro, *Terr. Magn. Atm. Elec.*, *38*, 79, 1933.

[22] V.C.A. Ferraro, *J. Geophys. Res.*, *57*, 15, 1952.

[23] V.C.A. Ferraro, *J. Geophys. Res.*, *65*, 3951, 1960.

[24] F.S. Johnson, *J. Geophys. Res.*, *65*, 3049, 1960.

[25] L. Davis and D.B. Beard, *J. Geophys. Res.*, *67*, 4505, 1962.

[26] C.P. Sonett, E.J. Smith and A.R. Sims, Space Research I. North-Holland Publ. Co., Amsterdam 1960, p. 921.

[27] C.P. Sonett, D.L. Judge, A.R. Sims and J.M. Kelso, *J. Geophys. Res.*, *65*, 55, 1960.

[28] P.J. Coleman, C.P. Sonett, D.L. Judge and E.J. Smith, *J. Geophys. Res.*, *65*, 1856, 1960.

[29] L.J. Cahill, Paper presented at the Annual Meeting of the American Geophys. Union, Washington, D.C., April, 1962.

[30] L.J. Cahill and P.G. Amazeen, *J. Geophys. Res.*, *68*, 1835, 1963.

[31] W.G.V. Rosser, B.J. O'Brien, J.A. Van Allen, L.A. Frank and C.D. Laughlin, *J. Geophys. Res.*, *67*, 4533, 1962.

[32] H.S. Bridge, A.J. Lazarus, E.F. Lyon and F. Scherb, Paper presented at the Symposium on Recent Results in Space Physics, American Geophys. Union, Washington, D.C., April 25-28, 1962.

[33] A. Bonetti, S. Olbert, B. Rossi and G. Siscoe, Paper presented at the Symposium on Recent Results in Space Physics, American Geophys. Union, Washington, D.C., April 25-28, 1962.

[34] J.W. Dungey, *Cosmic Electrodynamics*, p. 98 and f.f., Cambridge University Press, London, 1958.

[35] J.H. Piddington, *Planet. Space Science*, *9*, 305, 1962.

DISCUSSION

Chairman: B. PETERS

VALLARTA

Now with regard to this question of the cavity from the action of geomagnetic field we have made some calculations on this based on very unlikely assumptions, so that the results must be considered only as a very rough first approximation. Other people have also made similar calculations; among them I'll mention the paper by LEVERETT DAVIS and MIDGLEY which appeared in the *Journal of Geophysical Research* some time ago, and another paper by SLUTZ which also appeared in the same number of the *Journal of Geophysical Research*. Now there are some small differences in our results, but in the main I think we all agree; the main difference is that we seem to disagree on the cusp that is formed at the pole: according to our results the cusp is much deeper than according either to SLUTZ or to LEVERETT DAVIS and MIDGLEY. Now if I may use the blackboard a moment perhaps I could draw a figure. As I was saying, the assumptions that one makes are obviously all wrong, but one has to start somewhere. The first assumption is that the plasma is stationary, the second is that it has axial symmetry, and the third is that inside the cavity there is only a magnetic field and outside the cavity there is only plasma. Now on those assumptions, by just equating the gas pressure in the plasma to the magnetic pressure inside the cavity one comes out with the following result: if this is now the meridian plane then this is the dipole axis of the earth, let's say pointing in this direction, then if this is the equatorial plane, the cavity has this shape: (draw) more or less, symmetrical of course with respect to the equator.

(Yes, of course, you rotate this whole business round the dipole axis). Now the main difference I will say between the calculations made by MIDGLEY and LEVERETT DAVIS and SLUTZ on the one hand, and by ourselves on the other, is about the depth of this cusp: according to us this cusp is very much deeper than according to them. This distance here is about 13.5 earth radii, this distance here is about 8 earth radii, and inside here they say there is only magnetic field, outside here there is only plasma. Now this is the first result I think one can mention in this connection.

ROSSI

Excuse me, were the computations of DAVIS made under the same assumptions as yours?

VALLARTA

Yes, DAVIS uses the same assumptions essentially and also SLUTZ uses the same assumptions. The size of the cavity according to us is just about the same as according to SLUTZ and LEVERETT DAVIS; the main difficulty comes about this cusp. It is much deeper according to us than according to either one of the others.

ROSSI

Are these numerical computations?

VALLARTA

Yes these are numerical computations as far as the boundary is concerned.

PARKER

I want to add one note to the complications that Prof. ROSSI has already indicated concerning the cavity and the possibility that

[3] *Rossi* - pag. 94

its size may be fluctuating. That is to remember the magnometer data from Pioneer V travelling in the direction of the sun. The magnometer showed perturbations and fluctuations, which one tends to attribute to the presence of the earth, all the way out to about some 150,000 kilometers, some 20 or 25 earth radii. I think one must look forward to some kind of terrible complications outside the cavity boundary at 10 earth radii. Simple models, even including shock waves, do not explain a disturbance 25 R_e into space.

ROSSI

I had forgotten about this. I thought that the perturbations are seen out to about 15 earth radii. Are you sure it is 20 earth radii?

PARKER

The number I remember is about 150,000 kilometers.

ELLIOT

There is one point in connection with this change in direction of the field as you cross the boundary of the cavity. On the slide that you showed, a few hours, if I remember the scale correctly, before the sudden commencement there was a sharp change in the field direction indicating a crossing of the boundary at this time.

ROSSI

Before the sudden commencement do you mean?

ELLIOT

Yes, a few hours before the sudden commencement, there is a sharp change in the field direction which seems to be accompanied by a very sharp downward spike in the scalar value of the field, indicating perhaps that there is a very thin transition layer here with a neutral surface in between.

ROSSI

That's right.

GOLD

I wonder whether the disappearance of the plasma beyond 4 R_e should not be thought of as perhaps a very genuine effect connected with the rotation of the earth. At that distance it needs only a small thermal velocity for the particles to he centrifuged away. So since they are ionized they certainly will be constrained to rotate with the field at that distance and so they certainly will be living in the centrifugal potential superimposed on the gravitational potential of the earth. The region where the vehicle was, it being not on the equator, will be in a very unfavourable place so far as potential is concerned for maintaining the plasma.

ROSSI

It is a very interesting suggestion. Did you work it out quantitatively whether it would?

GOLD

Yes, I can't say that I would place it exactly at 4 earth radii that it must disappear, but that is about the place where the centrifugal potential will already have made a contribution that is of the order of 50%.

SIMPSON

I would like to ask a question. If one imagines the interface of the plasma with the geomagnetic field as a rather thin boundary, then, since the plasma generally flows from the direction of the sun, one might expect some kind of an albedo effect just in the moments before the magnetic boundary passes through the orbit of the space craft. Solar wind particles would be suddenly scattered from another direction. I wonder if there is any evidence that just before passing through the boundary one sees an « illumination » of particles from the direction of the boundary.

Rossi

I am just trying to think if there is anything that can answer this question. I mean, as far as the average direction — that is the position of the maximum of the peak — is concerned, we never found any deviation from solar direction. Now this would probably not produce any shift in the maximum as much as a widening of the curve; and, as I mentioned, towards the beginning of the measurements there was some evidence that the curve was wider. Whether that means something of the kind you describe or whether it means simply a hotter plasma, I don't know. I think we need much more measurements. This was just a first attempt, and I think what is very important in any future measurement is, when you continue recording both the magnetic field and the plasma, trying to catch the situation really at the transition.

Vallarta

I would like to add just one more thing to what I said a moment ago. According to the theory there are particles of plasma that are reflected at the boundary — as there must be — so you must expect something to happen at the boundary of the plasma.

LARGE SOLAR OUTBURSTS IN THE PAST

T. GOLD

Center for Radiophysics and Space Research - Cornell University
Ithaca, N.Y. - U.S.A.

Abstract — The question whether great solar outbursts have occurred in geologic times is discussed. A limitation of the possible severity is given by the consideration of the maximum amount of terrestrial atmosphere that could have been swept away by each such outburst. Evidence in favor of outbursts incomparably greater than those that have been observed in recent times may be contained in solar system nuclear compositions, in the geologic record, and in the record of rock magnetism.

The question I would like to tackle is whether solar outbursts of the present day are representative of all that has happened in geologic times or whether much greater outbursts have occurred from time to time. Our evidence that nothing very violent has taken place in historic times is concerned with such a short span of time only that it cannot answer the question. We should therefore inquire what limits can be placed on the solar violence that may have taken place in geologic times.

In the early phases of the life of the sun it is likely to have contained magnetic fields in its interior resulting from the contraction of the fields in the gas masses forming it. Such fields are likely to be of such a strength that they will interfere with the settling down of the star to the main sequence, and a process of shedding magnetic fields will take place. If this process is slower than the contraction against the thermal energy, the magnetic time-scale will be more important in defining the speed of settling down than the usual Helmholtz time-scale. The ohmic decay of low modes of the field of the sun would have a time constaut of the order of 10^{10} years; in fact, one suspects that most of the field will be lost by instabilities that cause surface disturbance and that act more quickly than ohmic decay.

Fowler, Greenstein and Hoyle [1] have shown from a consideration of the light element nuclear composition of terrestrial material that at least in the early phases in the solar system much high energy proton bombardment must have taken place, and they have associated that with such shedding of internal magnetic energy of the forming sun. This nuclear evidence therefore suggests that at least in the early solar system the sun's activity was much more violent than it is now.

The initial magnetic energy of the sun may have been 10^{48} ergs. The rate of loss at the present time through flares and such surface instabilities is perhaps of the order of 10^{34} ergs per year, and this rate is therefore very small compared with the mean rate in the age of the sun. From this point of view large explosions yielding more energy than ordinary flares, on a long term average could still be taking place now, though no longer as intensely as in the early sun.

The geological evidence is by no means opposed to major disasters. If substantial extra heating took place for a short time every few tens of thousands of years, even to the extent of destroying a lot of plant and animal life, this would not have shown up clearly in the record; on the other hand there are many hints in the record of geology that unusual things have happened from time to time. Substantial climatic changes are clearly implied by the ice ages on a time scale of a few tens of thousands of years, and geologists have often inquired from astrophysicists and astronomers whether they could invoke a variability of the sun for the explanation.

One line of evidence that places a limit on the strength of past outbursts is that of the permanence of the terrestrial atmosphere. The rate at which surplus volatiles may be diffusing out of the material of the earth cannot be estimated very accurately; but it does appear unlikely that the total loss of atmosphere from the earth in the whole of geologic time could have been more than about ten or twenty times the mass of the present atmosphere. This limit is somewhat different for the different constituents of the atmosphere, and is in fact least stringent for the components that tend to separate out at the higher levels, on account of their small molecular weight.

For one big outburst every ten thousand years, for example, it would be permissible to have 2×10^{-5} of the present atmosphere removed every time. That means the outburst could be intense enough to drive down to the 20 μ bar level and blast away everything above that level. The change in atmospheric pressure resulting would only have minor climatic consequences.

It is of interest to consider the magnetic storm effects of such an outburst. The simple rule about the magnetic field-strength generated at a large obstacle in the interplanetary stream is that the magnetic pressure will rise until it equals the stagnation pressure of the flow: $\frac{H^2}{8\pi} = \rho v^2$. The solar gas driving at the earth will thus augment its field on compression, and for the intensity of the stream we were discussing where the stagnation pressure amounts to 20 dynes/cm^2 the field strength would be about 20 gauss.

A magnetic storm of that kind of severity would be a totally different kind of phenomenon from the usual one. The earth's magnetic field could clearly not hold up the incoming gas, and it would indeed drive down to the atmospheric level where the gas pressure can resist the further flow. At that level the atmosphere is dense and the ionization that could be maintained would not result in a good conductivity. The incoming gas bringing its strong field into the virtually insulating atmosphere (Fig. 1) would then result in very large electric fields so directed that the resulting currents would maintain those fields. But in the atmosphere this can be done only by electrical breakdown. Since the ground is a good conductor such a breakdown is likely to take a path of breakdown through the entire thickness of the atmosphere on each side of the magnetic cloud being pressed in, and through the body of the earth from one site of breakdown to the other (Fig. 2). This breakdown would be in the form of a series of sparks, burning for extended periods of time and carrying currents of hundreds of millions of

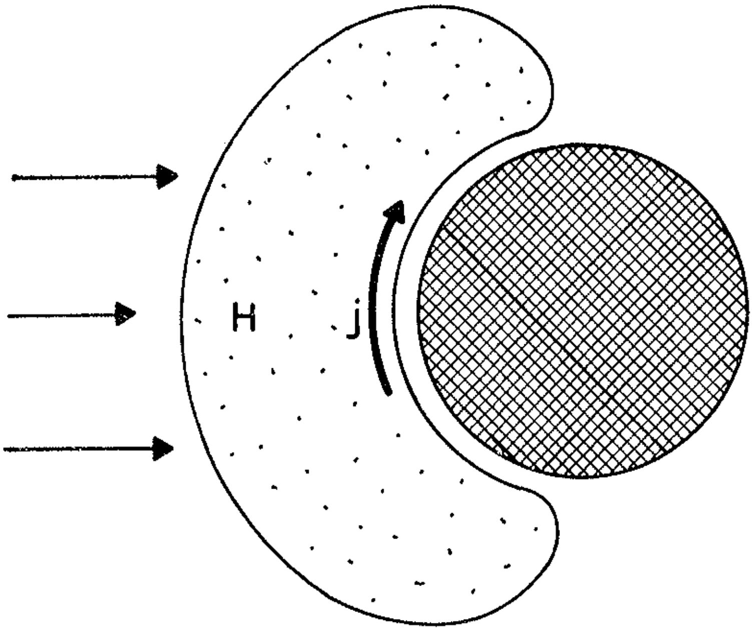


FIG. 1 — Magnetized cloud approaching the earth, showing current above the insulating atmosphere.

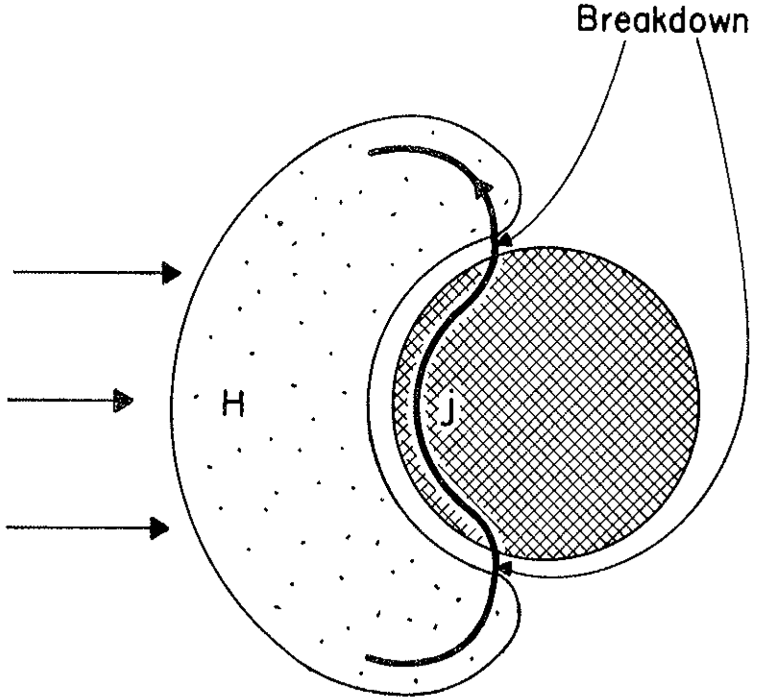


FIG. 2 — Electrical breakdown of the atmosphere that would be caused by a still closer approach. The field will then penetrate into the solid earth.

amperes. One might search whether there is any geological record of surface fusing and vitrification of rock or sand which cannot be accounted for by volcanic or meteoritic events. Large quantities of glass, far too much to be made by ordinary lightning discharges, are indeed found on the surface in a few places, notably in the Libyan desert [2], [3]. Perhaps it might be worthwhile to pursue this clue further.

If fieldstrengths as large as 20 gauss could be brought to the earth, one wonders whether there is no possibility of magnetizing the earth from outside, rather than accounting for the main field of the earth by a self-excited dynamo action in the interior. The magnetic changes that occur in the main field of the earth seem to occur in remarkably short periods of time, for any effects connected with the very long time constants of the earth's interior. The secular changes in the field and the rate of decrease of the dipole moment which is observed at the present time are all effects that have a few thousand years as their time scale and not the millions of years which one would normally associate with any changes taking place in the earth's interior. Evidence from rock magnetism [4], [5], [6] points strongly towards comparatively frequent reversals having taken place at least in the last few million years, with a time scale of only a few tens of thousands of years. The indications there are that the field has changed sign in a short period of time, but has at all times retained a strong tendency to have a direction close to that of the axis of rotation. It is very difficult to think that any process changing the motion in the earth's core could have happened in such, short period of time, and it is equally very hard to invent any way in which a self-exciting dynamo could be caused to reverse the sense of its field. Such explanations are only pursued because one cannot see any other method of accounting for the facts. It seems to me now that one should look very carefully into the possibility that the earth gets magnetized through a solar action and that the field we are seeing now is merely that left by the last magnetization and decaying with the time scale appropriate to the size and conductivity of the earth, which is likely to be 10 or 20 thousand years.

The experimental fact that the time scale of the ice ages and the time scale of the reversals of the field deduced from rock magnetism is rather similar would appear accidental if the magnetic changes were entirely of interior origin. If however they were impressed from outside, then perhaps the same events responsible for the one were responsible for the other.

[4] *Gold I* - pag. 6

One cannot at the present time make a case for occasional giant outbursts on the sun; but on the other hand, one must not ignore the possibility in the discussion of many lines of evidence in astronomy, geophysics and geology.

REFERENCES

[1] W.A. Fowler, J.L. Greenstein and F. Hoyle, *Geophys. J.*, *6*, 148, 1962.

[2] P.A. Clayton, *Bull. Inst. Fouad I du Desert*, *1*, 37, 1951.

[3] A.J. Cohen, *Phys. and Chem. of Glasses*, *2*, 83, 1961.

[4] E. Irving, *Geophys. J.*, *2*, 56, 1959.

[5] A. Cox and R.R. Doell, *Bull. Geol. Soc. Amer.*, *71*, 735, 1960.

[6] C.W.F. Everitt and J.C. Belshé, *Phil. Mag.*, *5*, 683, 1960.

DISCUSSION

Chairman: P. PETERS

PARKER

I think Prof. GOLD's ideas are very interesting. I want to raise two questions, however, the first with regard to the problem of packing an intense field into the core of the earth. Some quick figures here indicate that in order to have sufficient weight the clouds would have to have a density that is comparable to the present ionosphere. The relaxation time for such a system is of the order of minutes or at most hours rather than thousands of years so there seems to be some difficulty in getting the field into the earth.

The second point that I would like to make is that the energy required to eject 2×10^{-5} of the atmosphere from the earth into the space, requires an outburst at the sun of not less than 10^{41} ergs. This is equal to the total luminosity of the sun for a period of somethings in excess of a year, and I wonder therefore if one could not devise an experimental test of this outburst on the sun, by making the assumption that the sun is a typical star. Then ask: if these things come at random do I see outbursts on other stars? We can see thousands and ten of thousands of them. Now, as I said the outburst is the equivalent to doubling the luminosity of the sun for a period of a year; I imagine you have something of a much shorter time in mind, so that the outburst would be a very brilliant flash. In short, I think you are suggesting the sun is a recurrent nova.

Gold

I will take the two things in order: in both cases I think your figures are a little high. So far as the maintenance of field close to the earth is concerned, if you only wanted to maintain the field on the order of a gauss in order to magnetize the earth to half a gauss, then that is only a pressure of 4 hundredths of a dyne. A dyne is a millionth of the atmospheric pressure. So the total weight of atmosphere that you are involved with is only like what it is at the moment in the conducting atmosphere of the earth, and not what is below.

Parker

But we have examples of how long it takes the other part of the geomagnetic field to relax from magnetic storms, and that is less than a day usually. At 4 earth radii the relaxation time is only a day.

Gold

Yes, but this is a different circumstance where new field and gas is put into the earth's domain.

Parker

Well, if you stuff in more gas you decrease the decay time.

Gold

In this case one will be putting in extra field from outside, which will be holding the gas apart and which will be giving it a much greater scale-height. It is then free from the neutral gas and the conductivity is maintained high. I am not sure though that I could maintain such a system against disturbances. But it is a different situation from the usual case. So I don't know...

The second point of the intensity of the outburst — no, I am not thinking of it on the scale of a recurrent nova but the luminosity is not in any very simple way related to the intensity of the plasma outburst. The field strength I have quoted and the amount of atmosphere swept away is concerned with the gas flow from the sun, but if that happens only with the speeds of the present outbursts, only with much more gas involved, it is not clear to me that the sun would be extremely luminous as a consequence. It is the momentum that I have given in this picture, not the extra luminosity of the sun. It may be that you will be able to show that if one tears that quantity of gas away from the vicinity of the sun, a lot of luminosity would be a side effect. That I don't know. I agree that that is a possibility and that could place a limit that I otherwise have not been able to find, on the magnitude of the outburst, because indeed we cannot tolerate an amount of heat to come out of the sun which would really, completely destroy animal life and vegetation. I don't think that you would place the limit so low as to have a stagnation pressure of less than one gauss, and even at that stage it begins to be interesting magnetically.

BIERMANN

I would like to make also some comments along this line. The first is the question of the applicability of the time scale which is given by the cross section and the resistivity and the ratio of magnetic pressure to the gas pressure. This of course plays a great deal in theoretical and experimental work in plasma physics: specifically that connected with the problems of controlled thermonuclear fusion. It became increasingly evident in recent years that the early estimates of this time scale were not quite adequate for several reasons. One reason is that even equilibrium configuration tend to be more complicated than one would think at first sight, and that the actual time scale might differ greatly from simple estimates. It has been found, I think, furthermore. that nearly all experiments in this field have been plagued by a great variety of instabilities. There are the so called hydromagnetic instabilities which are perhaps analogous to those of ordinary hydrodynamics and which are found if one effectively puts the conductivity equal to infinity. More recently, one has recognised instabilities which are based on the distribution in velocity space; even mixed types of instabilities do occur which you cannot describe in every simple terms. These types of instabilities have the consequence that the gradient of almost any quantity such as the pressure, the temperature, the density, the velocity, might eventually lead to instability. It is now somewhat difficult to see how, under the circumstances which you describe, one of these instabilities would not arise just automatically.

GOLD

Since we do not see many, because the sun is rather faint, we ought to look at an awful lot of stars very carefully for a long time, in order to see one outburst every ten thousand years in anyone of them. So even if they are awfully bright outbursts, this is not a very sensitive test. But as to the other point, of the instability, I suppose you meant the internal field of a star like the sun would in any case by now have decayed away pretty completely due to instabilities. Of course, I was specifically talking of these instabilities in so far as I regarded the process of flares and explosions as a process of an instability getting rid of the internal field energy of the sun. I would still suppose that at present these flares are still getting rid of some of the internal energy of the sun. Only, I quite agree with you that in the early phases of the sun there would have been a rush of them, much more of them at a much higher rate, and it would have got rid initially of the field energy at a much faster rate, so one should not take the early decay time as being the genuine decay time for a star like the sun settling down to its final shape. But there will certainly be, initially, a very high rate of decay due to instabilities, and then there will be a long tail, and I suppose that we are still now on this tail and still see, every now and again, a little bit of internal field being got rid of. But how do we known that it has been got rid of at a steady rate of 10^{34} ergs each year?

[4] *Gold I* - pag. 12

A more unsteady rate would still make very big events occur in geologic time, and this cannot be excluded from known data.

SINGER

The small amount of evidence we have about the solar outbursts seems to show that the large outbursts also go with a large mean energy of the particles from the sun. If that is so, then of course these huge outbursts will also carry with them a large number of particles at fairly high energies, let us say GeV. Then I think one would have to look into a variety of other effects. In addition to the purely pressure effect that you discussed here, I am speaking particularly of the effect of meteorites. Now, as far as I am aware there is no positive evidence that the cosmic ray intensity over the last 100 millions of years has been any different from what it is at the present time. In addition there is the evidence of the isotopic constitution of various atmospheric constituents, I think Prof. PETERS knows more about this than I do, which seems to show again that the cosmic ray intensity has been reasonably constant over a million years. I don't know which of these evidences is more firm, but I have not seen any evidence from any of these nuclear effects which would indicate a higher average cosmic ray intensity in the past.

PETERS

May I make just one remark on this? A 10 thousand years period seems to be excluded for these major disturbances because the carbon 14 inventory of the earth, which was taken before the bombs exploded, was in agreement with what is to be expected from the ordinary cosmic ray flux. The data which Dr. SINGER refers to, I think, are a paper by ARNOLD and his group in La Jolla last year, where 21 isotopes in meteorites were investigated ranging in lifetime from 30 days to several million years; they obtained constancy of cosmic rays over this period within a factor of two. Now this is pretty good in the short lifetime region and not so good in a long lifetime region, but I agree with Dr. SINGER that the evidence for very large disturbances, as far as it goes, is negative; there are effects in meteorites which could be studied in more detail with the view of finding evidence for major disturbances.

GOLD

Of course such disturbances would have to be brief, but big disturbances would of course have to contain a vast flux for the integrated flux not to dominate. If we are talking about one big outburst in 10 thousand years, we have to compare the cosmic ray flux of one such big outburst with the integrated flux over this long period of time. What you and Prof. SINGER have said seems certainly very valid and should be calculated to give a limit on the maximum possible number of high energy particles that could have come out. The light or heat radiations should be considered in terms of what the geologic record on the surface of the earth would tolerate for maximum heat flux for a certain length of time.

DENISSE

May I ask you if you consider that such effect could not change appreciably the momentum of rotation of the earth?

GOLD

I have not thought about that. My immediate answer would be yes, they would change the angular momentum of rotation of the earth, of the order of 1 millionth the angular momentum residing in the atmosphere. But that of course is not a very large amount; one could do that very many times and still not beat the mean rates of change of angular momentum due to tidal friction.

VALLARTA

Could the secular change of the earth magnetic field during the last, let's say, 150 years be accounted for by some such mechanism as you have mentioned in your lecture? I mean by the secular change the motion of the earth magnetic centre, the change in the magnitude and the direction of the dipole axis, the change in the magnitude and direction of the quadripole axis and so on. It is known that such secular variation exists. Now, I wonder whether it can be accounted for by such argument as yours.

GOLD

Indeed this is one of the respects in which I think that the present theories of the origin of the earth field are really quite unsatisfactory, in that the earth's field does have a variability which it is very hard to ascribe to a system in the deep interior of the earth. Any of the time constants of dynamics and the thermal time constants are all very long, and even the magnetic time constants are uncomfortably long for the speed of the secular changes. So, one would really quite like to have something that is more variable and can be ascribed to the inside of the earth. If the earth could be magnetized from the outside, then of course we would see in the present magnetization and its changes with time some replica — some distorted replica — of the method of magnetization that occurred in the past. One component of the magnetic field then would behave like heat conduction; so let us think of this in the way of heat condution. It is a problem like putting a blow-torch against a thick wall for a certain period of time, making the intensity of the heat that we apply a certain function of time, and then taking the blow-torch away. If we feel the temperature of the wall, it will change with time in a way which will not be a simple decay, but will be a certain more complex behaviour which will reflect in a distorted way the particular time pattern with which the heat was applied. If we see a variability in the magnetization of the earth now, it could be ascribed then to a variability during the time that an external field was impressed on it.

SINGER

This heated discussion simply shows that the remarks that Dr. GOLD made are really quite stimulating. I agree in a general way with his philosophy that one should try to find upper bounds to the amount of particles which may have come out of the sun, both high energy and ion energy. I should like to mention two particular items: one is the possibility that you might be able to set a limit to the number of protons of about 1 MeV by looking at the amount of nitrogen 15 in the atmosphere, assuming that all of it is produced from nitrogen 14 by p-γ reaction. Now for 1 to 10 KeV protons, you can again set an upper limit by the amount of the erosion which is produced in the meteorites and that is a severe one. It may give an upper limit which is a lot less than the proton flux which Dr. GOLD has been speaking about here.

SOLAR-CYCLE VARIATIONS OF COSMIC-RAY INTENSITY, COSMIC-RAY ACTIVITY AND GEOMAGNETIC ACTIVITY, 1937-1961

S.E. FORBUSH

Carnegie Institution of Washington, Department of Terrestrial Magnetism
Washington 15, D. C. - U.S.A.

Abstract — In the consideration of models to explain the solar-cycle variation of cosmic-ray intensity it seems desirable to know its phase relation relative to that for geomagnetic activity and cosmic-ray activity. Thus, for the period 1937-1961 the amplitudes and phases of the solar-cycle variation were derived for cosmic-ray ionization and cosmic-ray activity at Huancayo, and for geomagnetic activity and sunspot numbers. The best estimates from the limited amount of data available indicate that relative to that for the solar-cycle variation in sunspot numbers, the *maximum* for magnetic activity occurs about three months later while the *minimum* for cosmic-ray intensity occurs about six months later. Thus, the *minimum* of the solar-cycle variation in cosmic-ray intensity occurs about three months later than the *maximum* for magnetic activity. No significant difference was found between the times of maxima for geomagnetic activity and cosmic-ray activity. Estimates are derived of the lower limit for statistical uncertainties in differences between times of maxima. Differences (D-Q), from yearly means on magnetically disturbed and quiet days for cosmic-ray intensity are compared with those for the equatorial geomagnetic field, (ERC), relative to the magnitude, $(S\text{-}C)_q$, of their respective solar-cycle variations for quiet days. For cosmic-ray intensity $(S\text{-}C)_q/(D\text{-}Q)$ is about ten times that for ERC. $(S\text{-}C)_q$ in ERC probably arises entirely from the fact that yearly means of ERC for quiet days generally are not free of the effect of preceding storms. If this effect were comparable for cosmic-ray intensity, for which the recovery from observed

magnetic storm decreases occurs at a rate comparable to that for ERC, then $(S\text{-}C)_q/(D\text{-}Q)$ for cosmic-ray intensity should be comparable to that for ERC. Thus, it seems clear that the $(S\text{-}C)_q$ variation in cosmic-ray intensity is not directly due *per se* to the cumulative effects of cosmic-ray intensity decreases often observed during magnetic storms. Thus, during the solar cycle a state prevails in interplanetary space, or beyond, which results, except near solar minimum, in a persistent lowering of cosmic-ray intensity even on magnetically quiet days, which is not directly due, *per se* to storm-time decreases in cosmic-ray intensity. This appears to be in accord with the apparent lag in the *minimum* of the solar-cycle variation in cosmic-ray intensity relative to the maximum in that for geomagnetic activity.

1. Introduction

In a previous paper [1] it was concluded qualitatively that the *maxima* in the solar-cycle variation of cosmic-ray intensity appeared to occur as much as a year or so after the *minima* in the curve for sunspot numbers. Recently Neher and Anderson [2] examined the correlation between sunspot numbers and the ionization at 15 g cm^{-2} measured at Thule on several days during the summer of most of the years from 1951 to 1961. They concluded that the best correlation (negative) was obtained using sunspot numbers for periods 9 to 12 months prior to the ionization data.

Since the results may be of importance to models for explaining the solar cycle variation of cosmic-ray intensity, it seems desirable to determine as well as possible from the data available the phase relation between the solar cycle variation of cosmic-ray intensity and geomagnetic activity. Geomagnetic activity results from solar streams or plasma striking the earth. Simpson et al. [3] showed from measurements on Explorer VI and Pioneer V that a reduction in cosmic-ray intensity occurred at a great distance from the earth when the front of the solar stream, which resulted in a magnetic storm, enveloped their detector. The reduction of cosmic-ray intensity at the earth during that magnetic storm was thus shown to be due to envelopment of the earth by the solar stream or « magnetic bottle », within which the cosmic-ray intensity was below normal. Since, apart from such rare observations as these, the best indication for arrival of solar streams is geomagnetic activity, we choose to relate the phase of the solar-cycle variation of cosmic-ray intensity to that in geomagnetic activity.

The cosmic-ray data used are those from the ionization chamber at Huancayo, Peru, corrected to constant barometric pressure and for drift, FORBUSH [1], for the period 1937-1961. For magnetic activity we adopt the u-measure of BARTELS which for a given month is the average of the absolute values of the changes from each day to the next in the daily mean geomagnetic equatorial field [4]. Monthly values of u are published in Geomagnetism, CHAPMAN and BARTELS [5] for the period January 1872 to April 1939. Monthly values of u were similarly derived for the period April 1939 to December 1961. Annual means of these u-values are given in Table 1. BARTELS [4] showed that the correlation coefficient between annual means of u_1 and of sunspot numbers for the years 1872-1930 was +0.88. BARTELS derived his u_1-measure by a transformation of u using a variable scale designed to render similar the frequency distributions of monthly means of u_1 and of sunspot numbers. This transformation was particularly important to his demonstration not only of the reality of the equinoctial maxima in the six-month wave in u_1, but also enabled him to show that the maxima in this six-month wave occur close to the equinoxes, March 21 and September 23, and not close to March 5 and September 7 when the sun's axis is most inclined to the sun-earch direction. Since we find that the yearly means of u (not u_1) for the period 1872 to 1961 have a frequency distribution similar to that for yearly means of sunspot numbers, we adopt the annual means of u to measure magnetic activity.

TABLE 1 — *Annual Means 1937-1961: Sunspot Numbers (SS), Magnetic Activity* (u), *Cosmic-Ray Ionization* (1) *at Huancayo (C-R), Cosmic-Ray Activity* (s) *and Magnetic Activity* (A_p).

	SS	u unit: 10γ	C-R 0.1%	s unit: 0.01%	A_p unit: 2γ
1937 . . .	114	1.38	53	43	12
1938 . . .	110	1.41	53	67	15
1939 . . .	89	1.34	55	48	17
1940 . . .	68	1.22	59	38	16
1941 . . .	48	1.20	54	37	17
1942 . . .	31	0.86	60	39	14
1943 . . .	16	0.77	60 (2)	25 (2)	17
1944 . . .	10	0.72	71	24	11
1945 . . .	33	0.84	68	29	10
1946 . . .	93	1.65	48	83	19
1947 . . .	152	1.46	38	61	19
1948 . . .	136	1.14	50	52	15
1949 . . .	135	1.53	54	50	15
1950 . . .	84	1.38	56	38	18
1951 . . .	69	1.21	54	49	22
1952 . . .	31	1.06	59	52	21
1953 . . .	14	0.83	64	28	16
1954 . . .	4	0.64	68	21	11
1955 . . .	38	0.85	68	31	11
1956 . . .	142	1.50	58	55	18
1957 . . .	190	1.82	39	100	20
1958 . . .	185	1.78	41	63	19
1959 . . .	159	1.56	39	90	21
1960 . . .	112	1.63	41	64	24
1961 . . .	54	1.22	53	38	16
Mean . .	84.7	1.24	54.5	49.0	16.6

(1) Corrected for drift (see ref. [1]) and also corrected for adjustments in balance after March 23, 1954 (−1.0%) and October 4, 1957 (+0.4%).
(2) 11-month mean, October 1943 missing.

2. Correlation coefficients and regression lines for selected combinations among sunspot numbers, cosmic-ray intensity, cosmic-ray activity, and magnetic activity, 1937-1961

Annual means, 1937-1961, are given in Table 1 for sunspot numbers, SS, magnetic activity, u, cosmic-ray intensity, C-R, cosmic-ray activity, s, and magnetic activity, A_p. The correlation coefficients $r(x, y)$ between selected pairs (x, y) of the above variables are of some interest *per se*. However, these values of r and the appropriate regression lines which depend on r, are essential for providing some estimate for a lower limit of statistical uncertainties in the harmonic dials for the differences in the solar cycle variation for selected pairs of variables.

Fig. 1(A) shows the regression line for annual means of A_p on SS Nos. and the correlation coefficient, $r(A_p$, SS Nos.$) = +0.47$. The superior correlation $r(u$, SS Nos.$) = +0.90$, between annual means shown in Fig. 1(B) dictated the use of u for a measure of magnetic activity. In Fig. 1(B) in addition to the single line for the regression of u on SS Nos., the data are also fitted with two regression lines (a) and (b) which indicate, as shown by Bartels [4] that changes in u with changes in SS Nos. are greater when SS Nos. are less than 30 to 50.

Fig. 2(A) shows the lines for the regression of C-R on SS Nos. and 2(B) that for the regression of C-R on u. For 2(A) and 2(B) r is essentially the same.

Figs. 3(A) and 3(B) show respectively the regression of cosmic-ray activity, s, on u and of C-R on s for which the correlation coefficients are also similar. Cosmic-ray activity is derived from the yearly pooled standard deviations of daily means of C-R intensity, at Huancayo, from their monthly means [1].

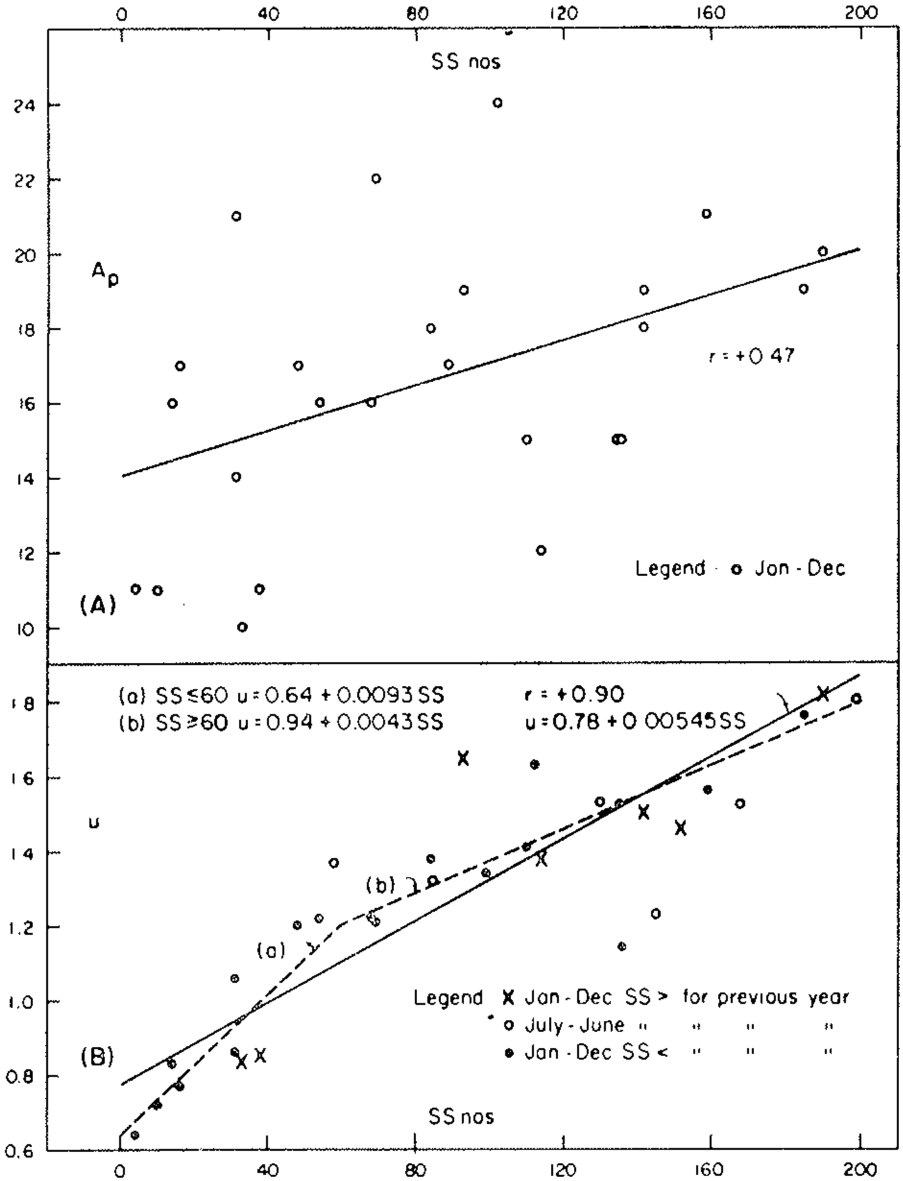


FIG. 1 — Yearly means 1937-1961 and regression lines (A) for A_p on SS nos and (B) for u on SS nos.

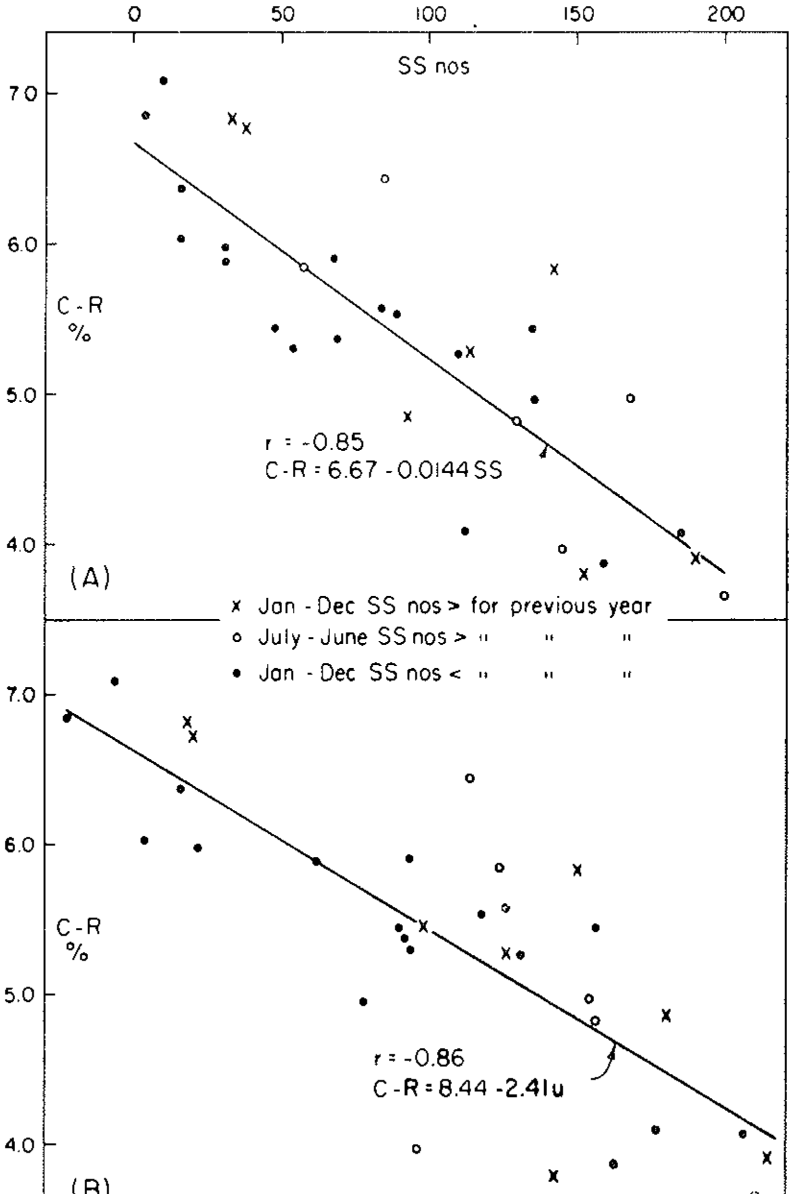


FIG. 2 — Yearly means 1937-1961 and regression lines (A) for C-R on SS nos and (B) for C-R on u.

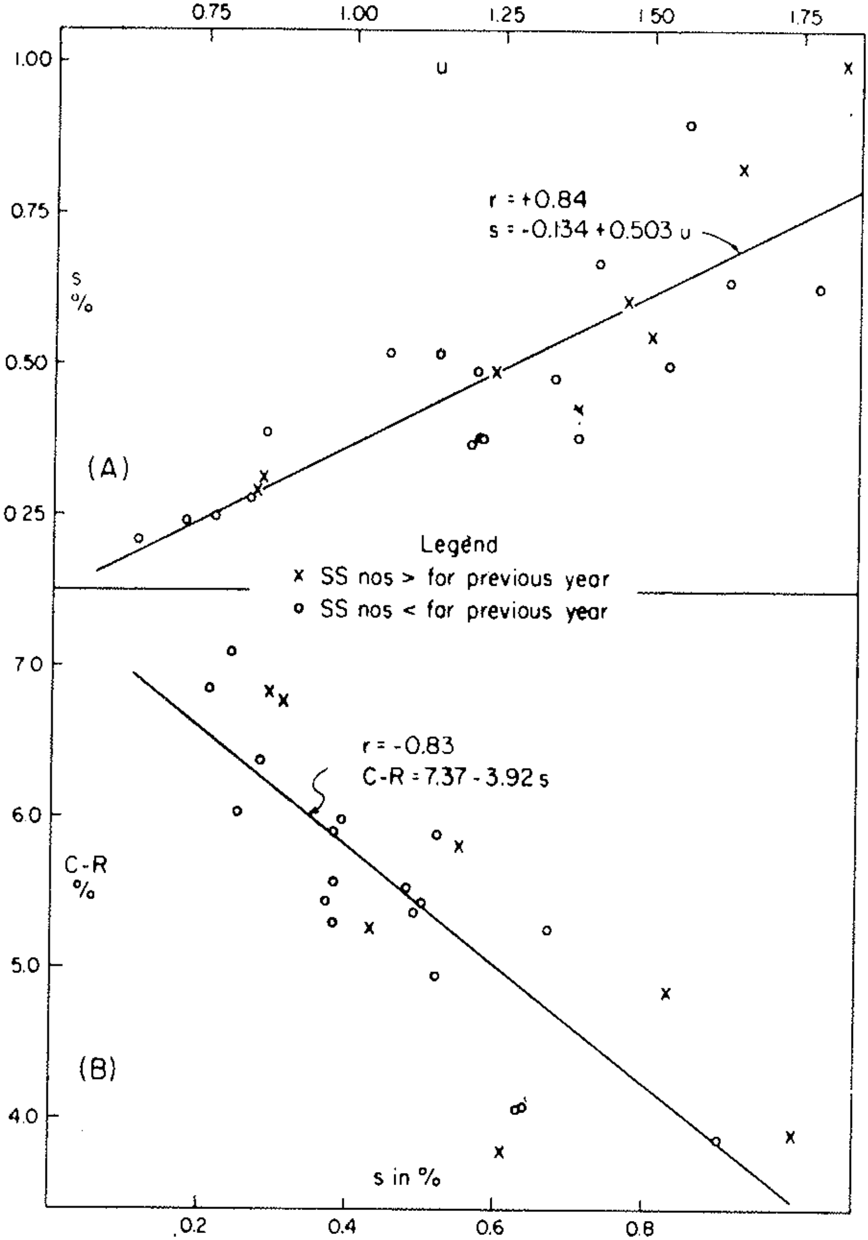


FIG. 3 — Yearly means 1937-1961 and regression lines (A) for u on SS nos and (B) for C-R on s.

3. Curves comparing the solar cycle variation for selected variables

Fig. 4(A) compares the solar cycle variation in SS Nos. and in u. The triangles are annual means of u from Table 1. The solid curve indicates annual means of u calculated, u_c, from SS Nos. using the single regression line in Fig. 1(B) while the dashed curve is for values of u calculated, u_c, from SS Nos. using the two regression lines (a) and (b) in Fig. 1(B). The latter values of u_c agree better with observed values than the values, u_c, calculated from the single regression line. Fig. 4(B) compares observed annual means of cosmic-ray intensity C-R with values $(C\text{-}R)_c$ calculated from u using the regression line of Fig. 2(B). Fig. 4(C) compares observed values of cosmic-ray activity, s, with values calculated from u using the regression line in Fig. 3(B). An inspection of Fig. 4 provides no reliable indication of phase differences between the solar cycle variation in observed and computed values.

4. Harmonic dials for solar cycle variations

To determine whether significant differences exist in the phases of the solar cycle variation for selected pairs of variables harmonic coefficients were derived from the data of Table 1. The resulting coefficients for each of three groups are given in Table 2. Since Fig. 4 indicates the interval between SS minima is close to 10 years, the coefficients are those derived for a period of exactly 10 years. The resulting times of maximum given in Table 1 for SS Nos. show that the intervals between maxima are indeed quite close to 10 years during the period 1937-1961.

The coefficients in Table 2 are obtained from a 10-ordinate schedule using successive differences of the ordinates. This procedure of Bartels [6] was used since it automatically

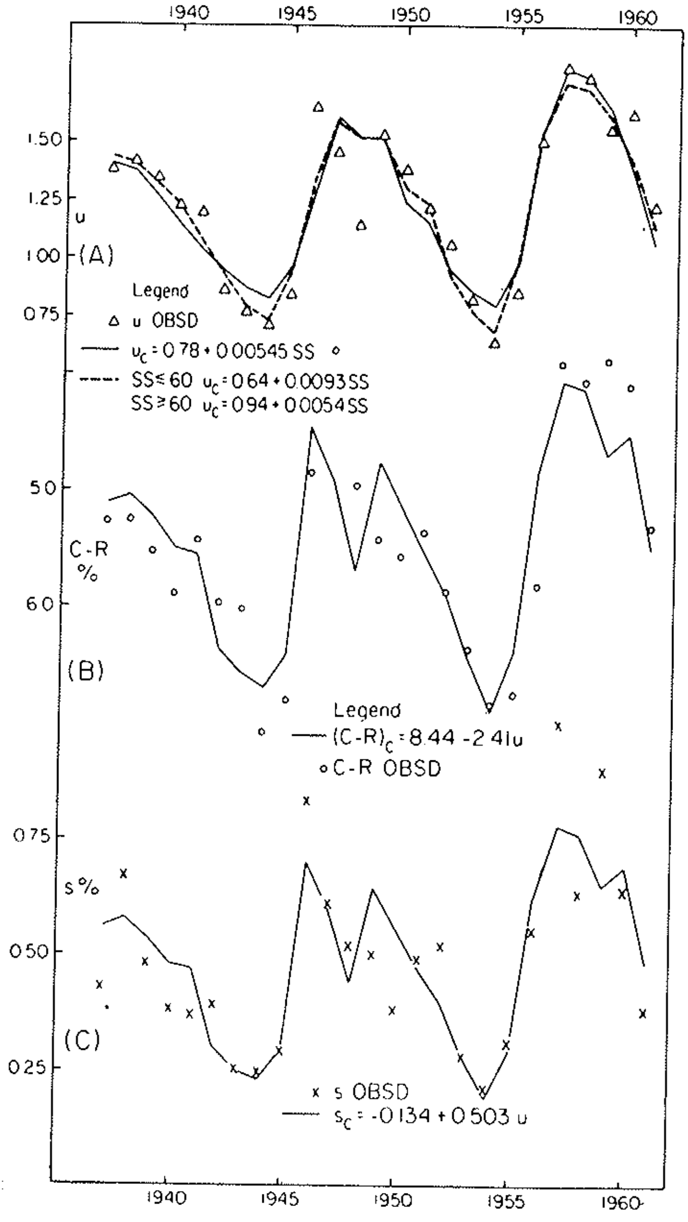


FIG. 4 — 1937-1961 comparison of yearly means
(A) u with u_c computed from SS nos
(B) C-R with C-R computed from u
(C) s with s_c computed from u

TABLE 2 — *Harmonic-Coefficients* (1) *for* 10 *Year Waves Derived from Yearly Means for Sunspot Nos. (SS), Magnetic Activity (u and u'), Cosmic Ray Intensity (C-R), and Cosmic Ray Activity (s).*

Group	1			2			3			
Interval	Jan. 1937 - Dec. 1947			Jan. 1947 - Dec. 1957			Jan. 1951 - Dec. 1961			Weighted (5) mean of c_1
	a_1	b_1	c_1	a_1	b_1	c_1	a_1	b_1	c_1	
SS Nos.	+31.8	+52.2	61.1	+46.6	+69.8	83.9	- 0.3	- 100.6	100.6	78.1
u (2)	+.218	+.324	.391	+.107	+.445	.458	+.114	- .533	.545	.449
C-R %	- .23	- 1.09	1.11	- .35	- .84	.91	- .71	+1.38	1.55	1.12
u' (2) (3)	+.185	+.336	.384	+.240	+.423	.486	+0.37	- .567	.568	.461
s(4)%	+.136	+.165	.214	+.049	+.240	.245	+.077	- .324	.333	.250
Sunspot Maximum from 10-year wave at	1938.63			1948.56			1958.50			

(1) Corrected for non-cyclic change (hence 11 year interval required). Time origin Jan. 1 in each group 1, 2, 3.
(2) In units of 10γ after BARTELS.
(3) Magnetic activity computed from sunspot numbers using two regression lines in fig. 1.
(4) Standard deviation of daily means from monthly means; pooled for each year.
(5) Giving unit weight to 1 and 2 and 1/2 weight to 3.

provides coefficients corrected for any non-cycle (*i.e.*, linear change). The coefficients are also corrected for the use of yearly means, BARTELS [7]. Since group 3, of Table 1, overlapped group 2, group 3 was given half weight in the weighted means. Except for the last row of Table 1, the amplitudes c_1 in each group exceeded that for c_2 (the amplitude for frequency two per 10 years) by factors of 2.5 or more. For s, in the last row each c_1 exceeded c_2 by a factor of 1.6 or more. Thus, only the 10-year waves were used to examine relative phases.

In Fig. 5 are plotted the amplitudes c_1 for pairs of variables shown in Table 2 and the weighted means. These graphs show the values of c_1 were greatest for group 3 and least for group 1, and for each pair the two values of c_1 were somewhat correlated. The ratios of the weighted mean amplitudes (shown in Fig. 5) are about the same as the slopes of the corresponding regression lines shown in Figs. 1, 2, and 3.

In the harmonic dial of Fig. 6(A) the vector from SS. Nos. for each group shown in Table 2 has been rotated through an angle α to zero time of maximum, and each vector for u (and C-R) for the corresponding group has been rotated through the same angle. Thus Fig. 6(A) shows the times of maxima of the u and C-R vectors relative to that for the SS vector. Likewise, Fig. 6(B) shows the times of maxima for the (C-R) vectors relative to that for the u vector, and similarly for Figs. 7 and 8. Also, for convenience, on the amplitude scales in Figs. 6 and 8 (not 7) the weighted mean amplitude (Table 2) for each vector is unity. In addition, the amplitude for each of the rotated vectors was first corrected (using the slopes shown in Fig. 5) for amplitude deviations from the weighted mean amplitude for the vector rotated to zero time of maximum. Thus, for example, for Fig. 6(A), if $c_{1n}(u)_c$, and $c_{1n}(u)_o$ denote respectively the corrected and observed amplitudes from u, for group n ($n = 1$, 2 or 3); and if $\bar{c}_1(\mathrm{SS})$ and $c_{1n}(\mathrm{SS})_o$ denote respectively the weighted mean amplitude

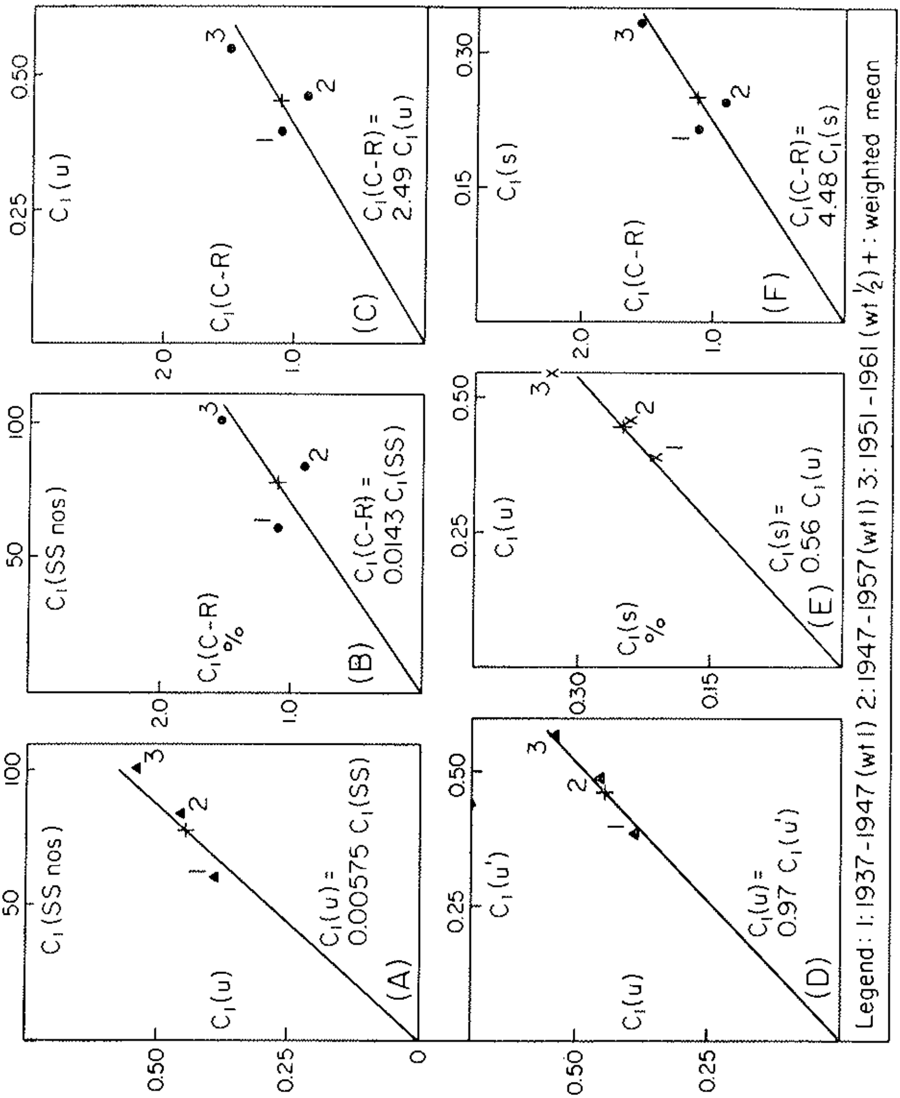


FIG. 5 — Amplitudes 10-year waves C_1 (y) *vs* C_1 (x) for different x and y.

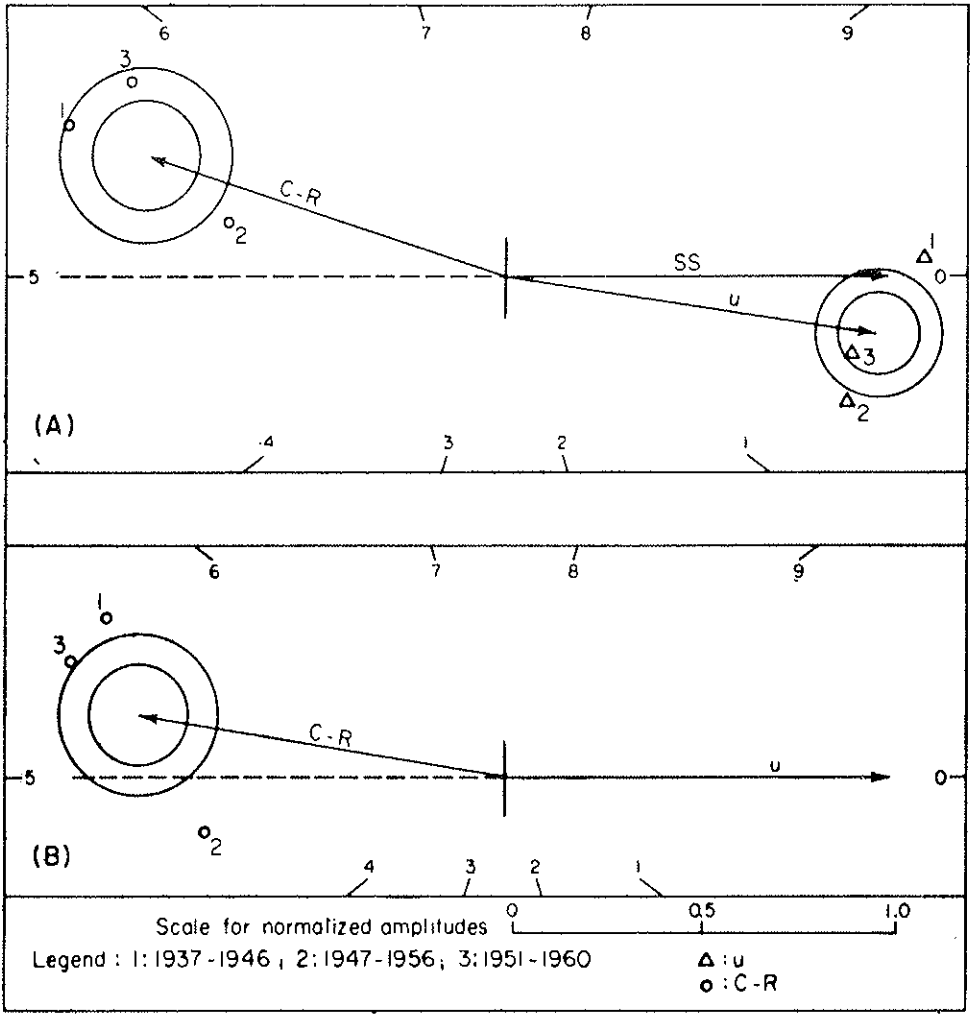


FIG. 6 — Harmonic dials 10-year waves
(A) *u* and C-R relative to SS nos
(B) C-R relative to *u*

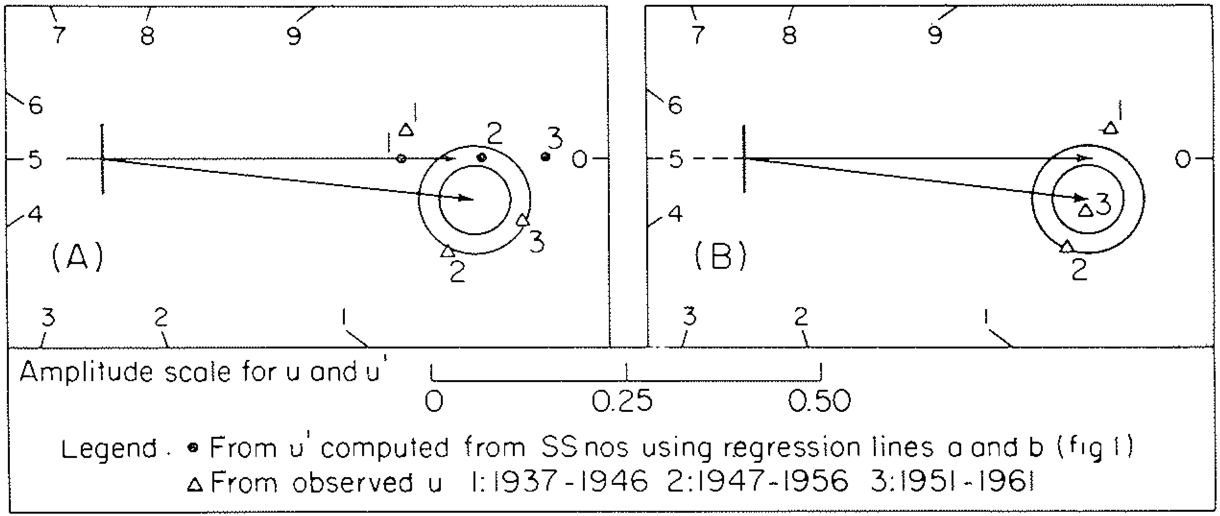


FIG. 7 — Harmonic dials 10-year waves for u and u' (A) before and (B) after correcting amplitudes for u for deviations from weighted mean amplitude for u'.

and that observed from SS Nos. for group n, then $c_{1_n}(u)_c = c_{1_n}(u)_0 + [\overline{c_1(SS)} - c_{1_n}(SS)_0] \times 0.00575$, using the factor shown in Fig. 5(A). The amplitudes of the other (non-zero time of maximum) vectors in Figs. 6, 7 and 8 were similarly corrected.

5. Statistical parameters for harmonic dials

The cosmic-ray data limit the derivation of 10-year waves to 2.5 solar cycles. To determine the statistical reality of the difference between average vectors for 10-year waves from two different variables in the harmonic dial, the « safe » procedure is to determine the dispersion of the cloud of end points for many such vector differences. These safe procedures and the consequences of not using them were thoroughly emphasized by Bartels [7] and in earlier contributions. For a « cloud » of only 2.5 points (1.5 degrees of freedom) the two-dimensional standard deviation derived from it is subject to a large uncertainty. Some estimate for the lower limit of this dispersion can be made. If each of a large number of sets of equally spaced random ordinates is harmonically analyzed, the distribution of end points for the resulting cloud of points in the harmonic dial for frequency, ν, is governed by the expectancy M. Bartels [7] showed that $M = 2\sigma / \sqrt{r}$, in which σ is the standard deviation for the population from which the random ordinates are drawn, and that M is the same for all ν except for the case when r is even and $\nu = r/2$. Thus, from an estimate of the standard deviation for « random » errors in the differences between pairs of ordinates (for corresponding years in our case) an estimate may be derived for the expectancy M, for random vector differences in the harmonic dials for 10-year waves. For example, the line in Fig. 2(A) for the regression of C-R on SS Nos. predicts values of $(C\text{-}R)_c$ from SS Nos. This line minimizes the variance, say

Δ^2, of the residuals or differences, D_i, between the $N=25$ pairs of observed values $(C\text{-}R)_o$ and $(C\text{-}R)_c$ when all error is in the (C-R) values. In Table 3, row 2, this estimate for the standard deviation, Δ, of D_i is listed in the column headed $\Delta(24)$ to indicate 24 degrees of freedom among the 25 differences. The values of $\Delta(24)$ in Table 3 are similarly determined for the other pairs of variables (column 1), the regression lines for which are shown in the indicated figures.

In the harmonic dials of Figs. 6, 7, and 8 the location of the vectors (or their end points) for one variable relative to the vector (which has its time of maximum put to zero) for another variable is in effect determined by the 10-year wave in the residuals, D_i, for the corresponding period (or group in Table 2). If the D_i were completely random there would be no significant difference between the vectors for the pair of variables; in addition, the expectancy, M_1, for single differences between vectors could then be estimated from $M=2\Delta/\sqrt{r}$ with $r=10$ for the number of ordinates, used in the harmonic analysis. It should be noted, for example, in Fig. 6(A) that the differences between the vectors for u (triangles) and SS Nos. are the vector differences between these triangle points and the end point of the SS vector, while the differences between vectors for C-R and SS Nos. are geometrically the vectors from the circles (for end points of C-R vectors) to the end point of the *negative* vector for SS Nos. This remark applies similarly to Figs. 6(B), and 8(A). If the difference between such pairs of vectors is statistically significant, then values of D_i would not be completely random, and there would be a tendency (more or less marked depending on the magnitude of superimposed random errors) for D_i to be correlated with D_{i+10} (with $i=1, 2, 3\ldots10$). To remove the effect of any such tendency, the standard deviation, ε_2, was estimated from the ten differences: $(D_i - D_{i+10})$ with $i=1, 2, 3\ldots10$ and $i=1$ for 1937, using 9 degrees of freedom.

TABLE 3 — *Data for estimation of statistical parameters in harmonic dials*

Regression (constants from fig. No.)	For dial in fig.	Standard deviations (1) $\Delta(24)$	$\varepsilon_1(9)$	M_1	M_1^*	ρ_1^*	ρ^*_{mm}
u on SS Nos. . . . 1 (B, 1 line)	6 (A)	0.151	0.141	0.089	0.198	0.165	0.104
C-R on SS Nos. . 2 (A)	6 (A)	0.515	0.474	0.300	0.268	0.224	0.142
C-R on u . . . . 2 (B)	6 (B)	0.496	0.445	0.282	0.252	0.210	0.133
u on u' . . . . . 1 (B, 2 lines)	7 (A or B)	0.129	0.132	0.084	(0.084)	(0.070)	(0.044)
C-R on s . . . . 3 (B)	8 (A)	0.536	0.339	0.215	0.192	0.160	0.101
s on u . . . . . 3 (A)	8 (B)	0.110	0.070	0.044	0.176	0.147	0.093

(1) Units for s.d. same as for 1st variable in column 1;
$\Delta(24)$ is the s.d. for differences (25) between obsd. values and those computed from regression lines (24 deg. of freedom);
$\varepsilon_1(9)$ is estimated s.d. (9 deg. of freedom) for « random » errors, see text.

*) M_1^*, ρ_1^* are respectively: expectancy, and radius of « p.e. circles » for single « random » vectors in units using which the weighted mean amplitude = 1.00;
$\rho^*_{mm} = \rho_1^*/\sqrt{2.5}$.
For u on u' values in ( ) are in original units for u not normalized to weighted mean amplitude = 1.00.

If these successive differences were random, or statistically independent, then the standard deviation of « random » errors in single values of D_i would be $\varepsilon_1 = \varepsilon_2/\sqrt{2}$. These values of ε_1 are listed in Table 3 in the columns headed $\varepsilon_1(9)$. Most of the values for ε_1 are only slightly less than the values of $\Delta(24)$ indicating that the residuals D_i are not greatly reduced when any systematic waves (the same for 1937-1946 as for 1947-1957) are removed. If the differences $(D_i - D_{i+10})$ were random (statistically independent) the expectancy, M_1, for siugle vector differences (*i.e.*, between the vector with maximum set to zero and that for another variable) could be obtained from the relation $M_1 = 2\varepsilon_1/\sqrt{r}$ of BARTELS [7] referred to above with $r = 10$. These values of M_1 are listed in Table 3. These values of M_1 divided by the appropriate weighted mean amplitude, c_1, from Table 2, gives M_1^* which is the estimated expectancy for single vector differences in units for which the weighted meau amplitude is uuity. In the fourth row of Table 3 the values in parentheses in the last three columns are not so uormalized but are instead in the same units as u. The radius, ρ_1^*, of the so-called probable error circle for single random vector differences is then $\rho_1^* = 0.833\ M_1^*$ [7] and for the vector difference between weighted means of 2.5. vectors, $\rho^*_{mm} = \rho_1^*/\sqrt{2.5}$. In the harmonic dials the larger circles are the « probable error » circles, thus derived, for single vectors and the smaller ones for the weighted means. On the whole, roughly half the points lie inside the larger circle as should be the case for large numbers of points if the radii of the circles have been properly estimated. Deviations, from the weighted mean, as large or larger than that for point numbered 2 in the left side of Fig. 8(A) should occur only for about one point out of 60 in the long run. It must be emphasized that if the differences $(D_i - D_{i+10})$ are not random, then M_1 and the other parameters derived from it are underestimated. BARTELS [7] emphasized that in the harmonic dial even the deviations (from the average) of vectors, derived from suc-

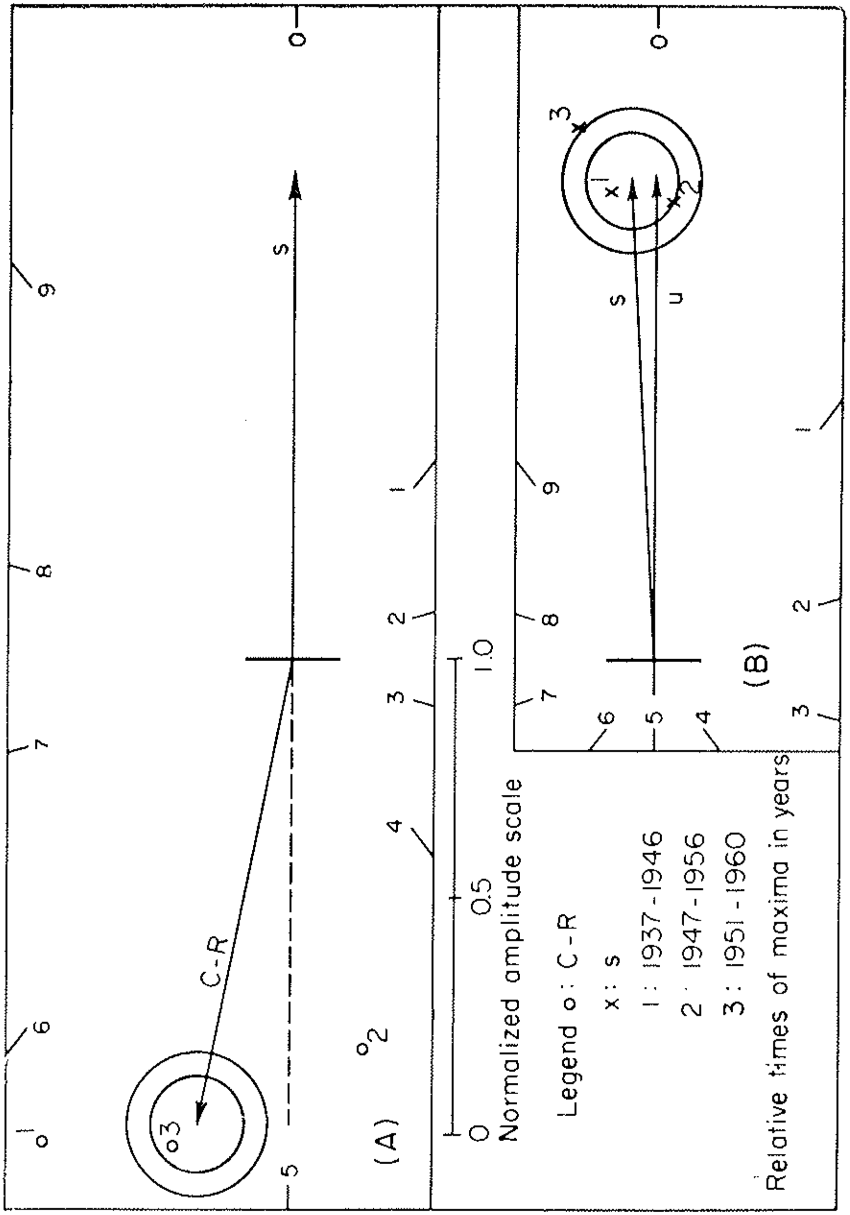


FIG. 8 — Harmonic dials 10-year waves
(A) C-R relative to *s*
(B) *s* relative to *u*

cessive intervals, were in many geophysical cases not statistically independent; and showed how to obtain the effective number of statistically independent values.

In addition to the value $\Delta(24)$, in Table 3, for the standard deviation for single values of D_i, values of the characteristic, $\Delta(h)\sqrt{h}$, were derived for the means of h successive values of D_i, with $h=1$, 2, and 3 (for $h=1$ by definition $\Delta(24)$ and $\Delta(h)\sqrt{h}$ are identical). If successive values of D_i are statistically independant the value of the characteristic is independent of h as shown by BARTELS [7], otherwise the characteristic values increase with h, at least for small values of h. For the D_i from which values of $\Delta(24)$ in Table 3 were determined none of the characteristic values $\Delta(h)\sqrt{h}$ showed any certain tendency to increase with h. With only 25 values of D_i available, such a test is not very reliable. Thus, the statistical parameters which we have derived must be regarded as lower limits since the data are inadequate for testing statistical independence among vector deviations for successive intervals or even among the ten consecutive values for the differences $(D_i - D_{i+10})$. With this reservation, the results may be summarized.

6. SUMMARY OF RESULTS FROM HARMONIC DIALS FOR 10-YEAR WAVES

The time of maximum (or minimum) for the weighted mean 10-year wave for one variable (x) relative to the maximum for the weighted mean for another variable is shown in Table 4 for different pairs. T_1 and T_2 indicate the times between which the maximum (or minimum) in the variable, x, would, from further samples, ordinarily be expected to occur with probability = 0.5 and P ($T<O$) is the probability for the maxima (or minima) in waves from the variable x to occur at $T<O$ (relative to the wave with maximum at $T=O$). The interval

TABLE 4 — *Summary for relative times of maxima for weighted mean 10-year waves*

Figure No.	Wave with T_{max} at zero from	For wave from x: T for	For wave from x: x	T in mos.	T_1 mos.	T_2 mos.	P (T<0)
6 (A) right . . .	SS Nos.	Max	*u*	3.0	1.8	4.2	0.05
6 (A) left . . .	SS Nos.	Min	C-R	6.0	4.5	7.5	0.006
6 (B) . . .	*u*	Min	C-R	3.2	1.7	4.7	0.08
7 (B) . . .	*u′* from SS Nos.	Max	*u*	2.5	1.3	3.7	0.08
8 (A) . . .	*s*	Min	C-R	3.8	2.6	5.0	0.01
8 (B) . . .	*u*	Max	*s*	− 1.0	—	—	—

T_1 and T_2 are limits between which T should occur with probability 1/2.

P (T<0) is the probability for T<0.

between T_1 and T_2 and P ($T<O$) are both too small if the successive differences ($D_i - D_{i+10}$) discussed earlier are not statistically independent. However, the values in Table 4 are the only estimates possible from the data available.

7. Solar-cycle variation on magnetically quiet and disturbed days for cosmic-ray intensity and geomagnetic field

In Fig. 9 yearly means from the five magnetically quiet and from the five magnetically disturbed days of each month are shown for cosmic-ray intensity at Huancayo and for the southward equatorial geomagnetic field, ERC (equatorial ring current field). The values of ERC for 1939-1945 were obtained from those published by Kertz [8]; those for 1960 were computed using the Kertz's procedure. As previously pointed out [1], the solar cycle variation of cosmic-ray intensity is nearly the same for magnetically quiet and disturbed days, although the yearly means for the latter are, except for 1953, always less. The 10-year wave from cosmic-ray intensity for quiet days differs insignificantly in phase from that for all days (used in the harmonic dials) although its amplitude is about 10% less. Fig. 9 shows that the change in ERC for quiet days during the solar cycle is small relative to the difference, (D - Q), for disturbed minus quiet days. For cosmic-ray intensity, however, the ratio of the difference, (D - Q), to the magnitude of solar-cycle variation for quiet days is small; actually it is about ten times smaller than the ratio for ERC. The larger values for ERC on disturbed days are due to magnetic storms and most probably the variation of ERC on quiet days is due to the fact that on many of the quiet days (5 per months) the post-perturbation effects of preceding storms are still present since the time for recovery of the ERC is several days. The recovery time for cosmic-ray magnetic storm as-

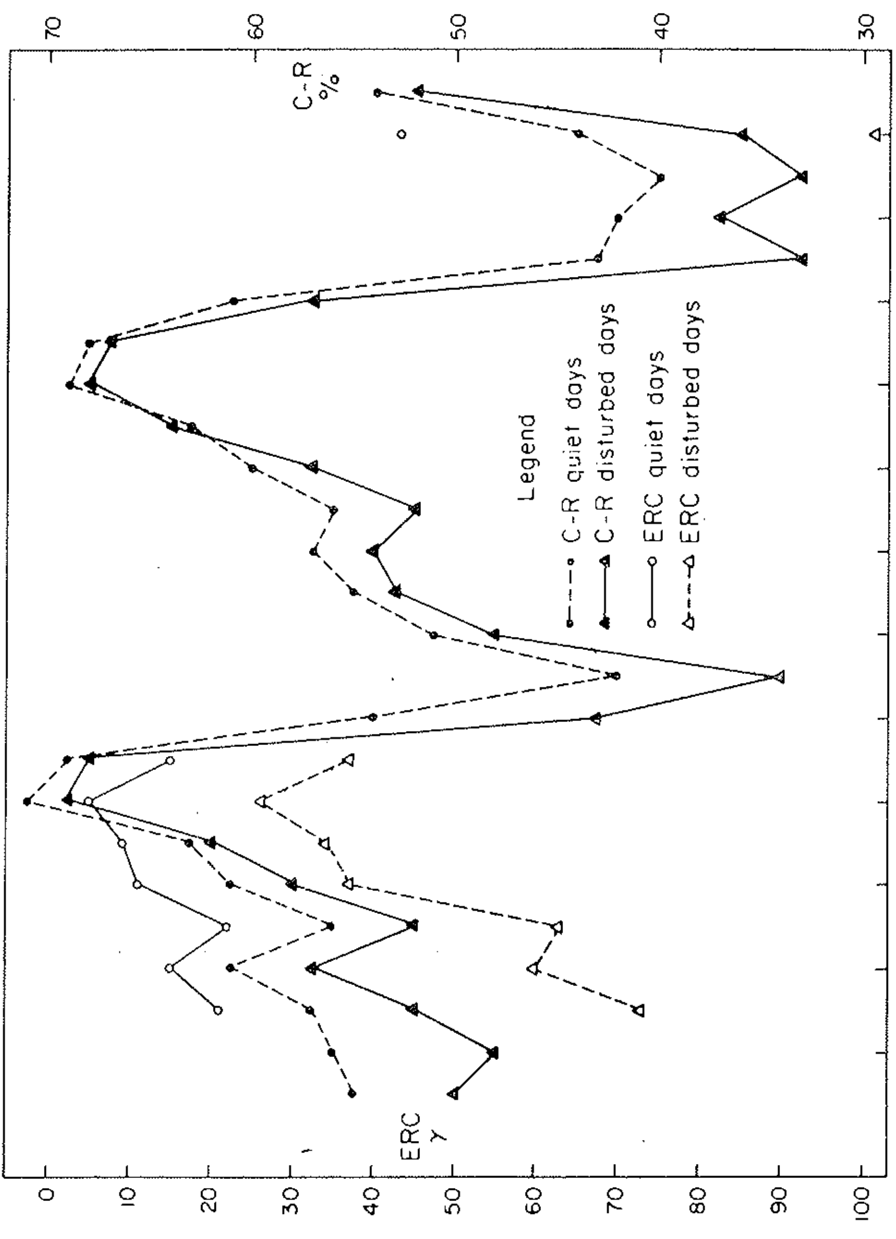


Fig. 9 — Yearly means for magnetically quiet and disturbed days for C-R, 1937-1961 and for ERC 1939-1945 and 1960.

[5] *Forbush* - pag. 24

sociated decrease is about the same as for ERC. Thus, the solar cycle variation of cosmic-ray intensity on quiet days can not arise in large measure from post-perturbation effects from magnetic storms preceding the quiet days (as for ERC) since this would result in a much greater difference in (D - Q) for cosmic-ray intensity than is observed.

This conclusion is also supported by comparing for cosmic-ray intensity the standard deviations: (1) for single days from monthly means pooled for the period 1937-1961; (2) for monthly means from yearly means pooled for 1937-1961; ; and (3) for yearly means from the mean for 1937-1961. These values are for (1) 0.54; (2) 0.57; and (3) 0.95 in per cent of the total intensity. If (3) is derived from yearly means for quiet days, the value is 0.85%. This also shows that the effect of magnetic storm changes on cosmic-ray intensity can not *per se* account for the solar cycle variation in C-R.

8. Comparison of solar-cycle variation in cosmic-ray ionization C-R, at Huancayo with neutron intensity at Ottawa

Fig. 10 compares six-month averages of (C-R) and neutron intensity at Ottawa, values for which were kindly provided pressure-corrected by Rose and co-workers. These solar cycle variations follow rather closely except possibly for the period April 1954 through June 1955, when apparently neutron intensity decreased at Ottawa but not (C-R) at Huancayo. The solar cycle variation of neutron intensity is about five times greater than for (C-R) at Huancayo. During several storms in 1957 the ratio of the percentage decrease in neutron intensity at Uppsala to that in ionization at Huancayo is only about 2.5, as found by Sandström et al. [9]. This also indicates that the solar-cycle variation of neutron intensity is not due *per se* to decreases during magnetic storms. A com-

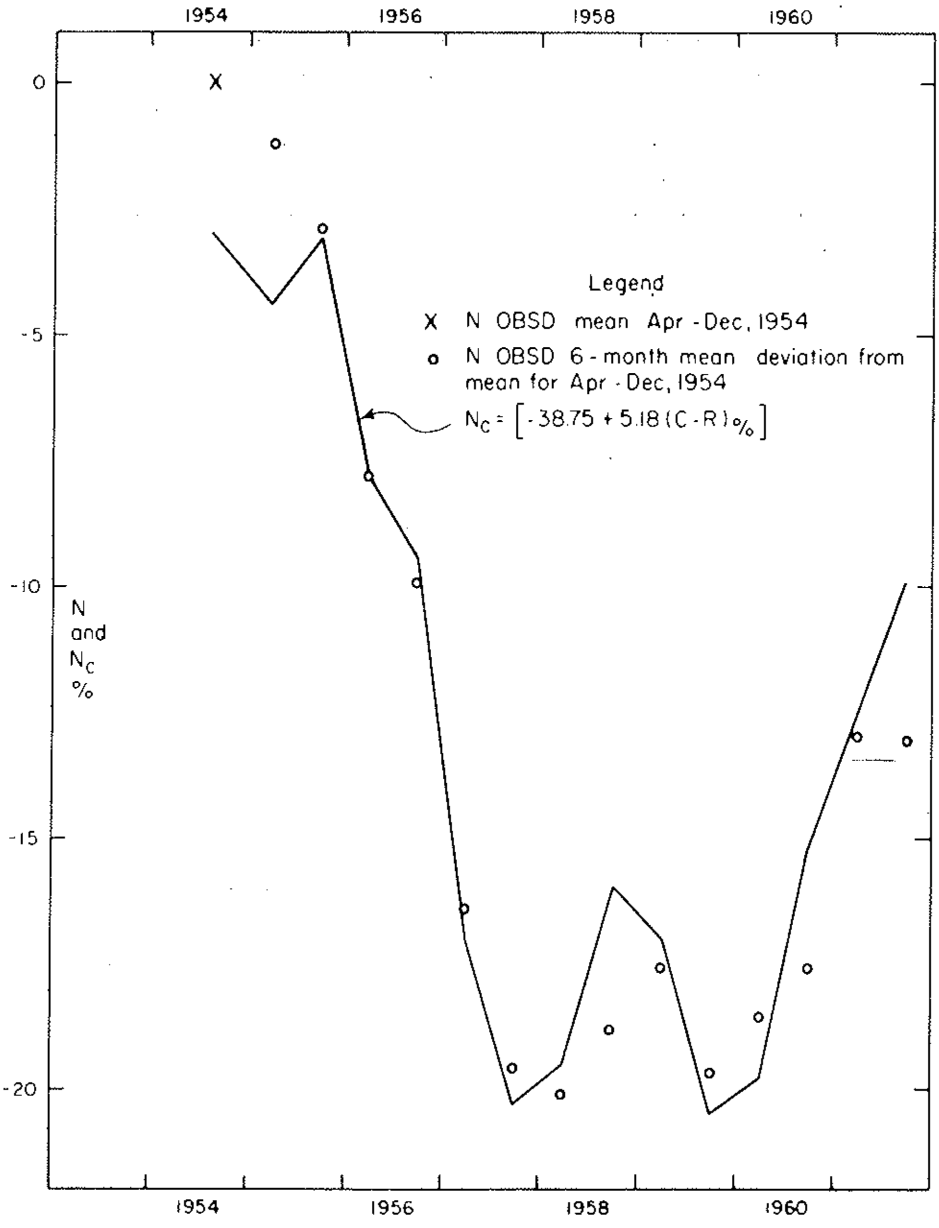


FIG. 10 — Six-month means neutron intensity, N, observed at Ottawa (Rose) and computed, N_c, from C-R ionization at Huancayo Apr. 1954-Dec. 1961.

parison of the results obtained by NEHER [2] for ionization at 15 g cm^{-2} over Thule, with those in neutron intensity at Ottawa indicates that the solar cycle variation in the former is about 2.6 times greater than for neutron intensity at Ottawa.

9. SOME DETAILS OF THE SOLAR CYCLE VARIATION IN COSMIC-RAY INTENSITY AND SUNSPOT NUMBERS

Fig. 11 shows the variation of monthly means of cosmic-ray ionization, C-R, at Huancayo and of sunspot numbers from June 1936 to March 1962. Fig. 11 indicates that the maxima in C-R tend to occur somewhat later than those in SS Nos.; or, in other words, that following SS minima the increase in SS Nos. may continue for some months without an accompanying decrease in C-R. A similar tendency was noted by BARTELS [7] in u.

A conspicuous feature in Fig. 11 is the large decrease in C-R from January to February 1946 and the low values of C-R that prevailed for several months thereafter.

Fig. 12 shows the variation of daily means of C-R and of magnetic horizontal intensity, H, at Huancayo for the period January 1 to April 9, 1946. Conspicuous in this figure is the large decrease in C-R which began after February 3, 1946, and which preceded the magnetic storm which resulted in a low value of H on February 7. The low values of C-R that prevailed for at least two months or more seem to indicate that the earth was for months continually inside one enormous « magnetic bottle of GOLD ».

DISCUSSION

The insignificant difference between the times of maxima for the weighted average 10-year waves in magnetic activity

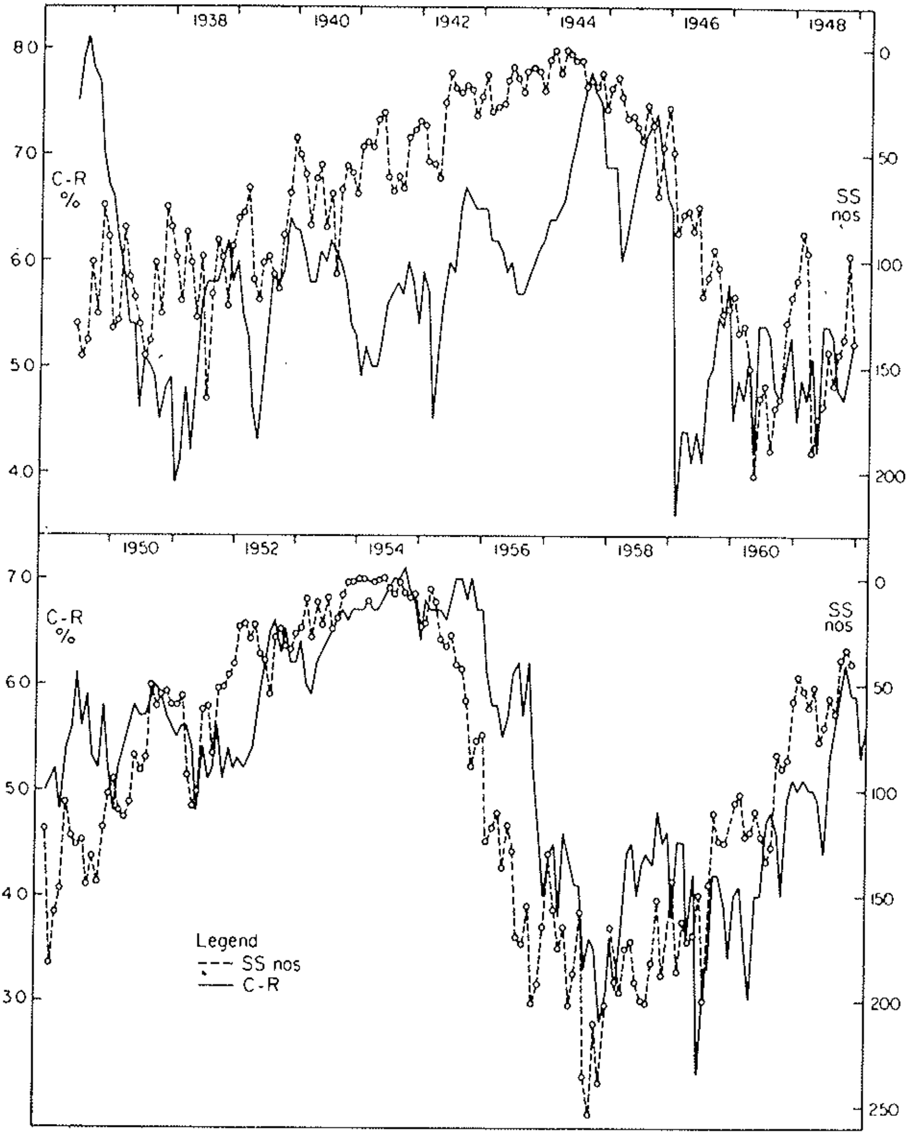


FIG. 11 — Monthly means C - R and SS nos 1937-1961.

[5] *Forbush* - pag. 28

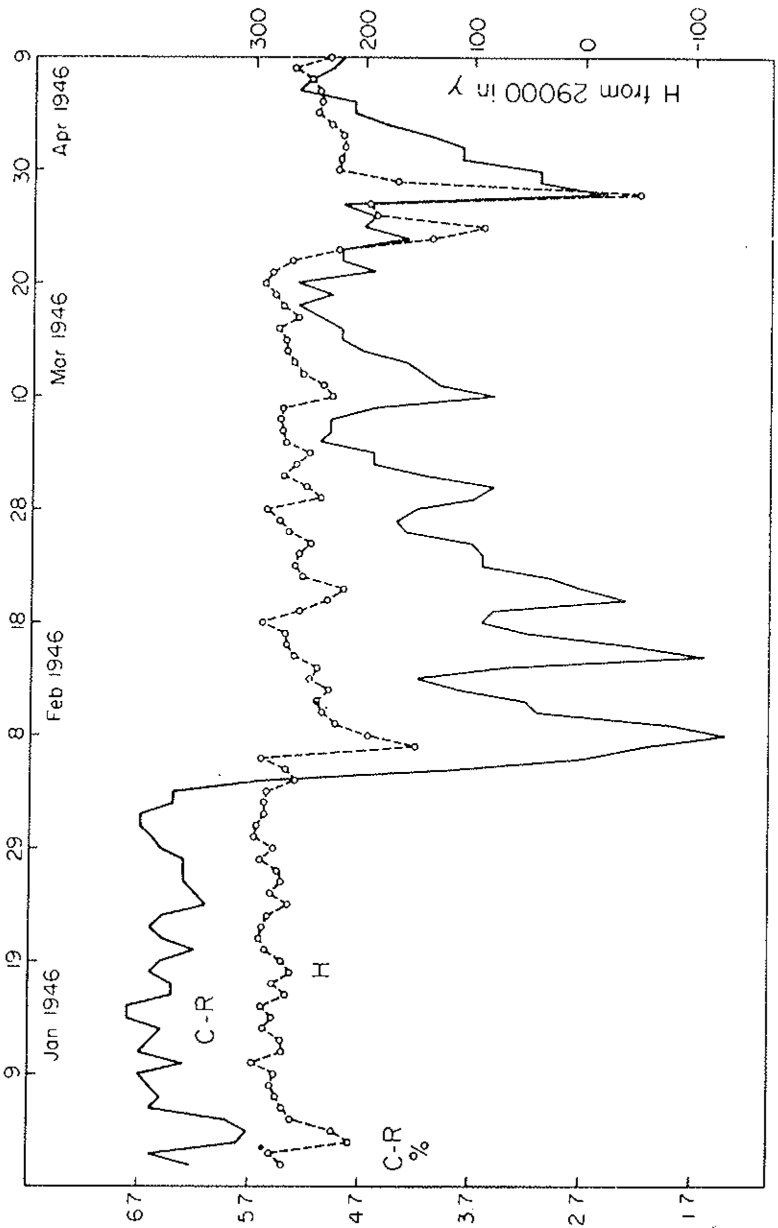


FIG. 12 — Daily means (75° wmt) C-R and H at Huancayo Jan. 1 - Apr. 9, 1946.

u and cosmic-ray activity *s* (Fig. 8 B) would be expected since *s* is due principally to so-called Forbush decreases associated with magnetic storms which account entirely for *u*.

On the other hand the solar cycle variation in cosmic-ray intensity is apparently due to less transient effects. Since the 10-year wave in cosmic-ray intensity appears to lag about 180° plus 3 months behind that for magnetic activity, *u*, this may indicate that the solar cycle variation in cosmic-ray intensity results from magnetic field irregularities, in the planetary system, due to a cumulative effect from many emitted solar plasma clouds which has no counterpart in magnetic activity since once past the earth these plasmas can no longer affect the earth's field.

Acknowledgements

Grateful appreciation is expressed to Dr. D.C. Rose and his staff in the Division of Pure Research, National Research Council of Canada, who kindly made available neutron monitor data from Ottawa. We also express our thanks to Mrs. L. Beach of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, for reduction of the Huancayo data, for computation of *u* values, and for effecting other calculations.

REFERENCES

[1] S.E. FORBUSH, *J. Geophys. Res.*, *63*, 651, 1958.

[2] H.V. NEHER and H.R. ANDERSON, *J. Geophys. Res.*, *67*, 1309, 1962.

[3] J.A. SIMPSON, C.Y. FAN and P. MEYER, *J. Geophys. Res.*, *65*, 2523, 1960.

[4] J. BARTELS, *Terr. Magn.*, *37*, 1, 1932.

[5] S. CHAPMAN and J. BARTELS, *Geomagnetism*. Oxford Press, 1940.

[6] J. BARTELS, *Beitr. Geophysik*, *28*, 1, 1930.

[7] J. BARTELS, *Terr. Magn.*, *40*, 1, 1935.

[8] W. KERTZ, *Ein Neues Mass für die Feldstärke des Erdmagnetischen Äquatorialen Ringstroms. Abhandlungen der Akademie der Wissenschaften in Göttingen, Mathematisch Physikalische Klasse, Beiträge zum Internationalen Geophysikalischen Jahr, Heft* 2, Göttingen Vandenhoeck and Ruprecht, 1958.

[9] A.E. SANDSTRÖM and S.E. FORBUSH, *J. Geophys. Res.*, *63*, 876, 1958.

THE DYNAMICS OF INTERPLANETARY GASES AND FIELDS AND THE RESULTING COSMIC RAY MODULATION

E.N. PARKER

National Center for Atmospheric Research
University of Colorado - Boulder, Colorado

Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago - Chicago, Ill. - U.S.A.

Abstract — The dynamical properties of the solar wind are used to compute the general background configuration of the interplanetary magnetic field. The propagation of energetic charged particles through the interplanetary magnetic field is developed, using the approximate concepts of propagation along the field, drift across the field, and random walk in the small scale irregularities in the field. The energy spectrum of the quasi-steady depression of the galactic cosmic ray intensity by the quiet-day solar wind, and the transient depression by solar blast waves, is computed. The latter spectrum is somewhat flatter than the former. Models discussed by other authors are considered too. It is suggested that blast waves are responsible for the Forbush-type decreases, and the quiet-day wind plus the superposition of decaying blast waves beyond the orbit of Earth are responsible for the 11-year variation of the galactic cosmic ray intensity.

The propagation of energetic particles from the sun is considered, with computations of the delayed arrival and decay following a flare on the sun.

About fifteen years ago FORBUSH [1] showed that the galactic cosmic ray intensity at Earth varies with time. In the course of his studies he showed that the cosmic ray intensity anticorrelates with solar activity over both short and long periods of time: there was shown to be a general depression of the cosmic ray intensity throughout the years of solar activity, called the 11-year cycle; there were shown to be short decreases of cosmic ray intensity following a day or two after large solar flares, usually in association with intense geomagnetic activity. Such decreases, with their frequently abrupt onsets, have come to be called Forbush-type decreases. About eight or ten years ago SIMPSON [2] was able to gather evidence that the variations in the galactic cosmic ray intensity are not the result of terrestrial atmospheric, electric, or magnetic conditions, and so by inference are caused by changing magnetic conditions in interplanetary space. At about the same time BIERMANN [3] pointed out that the analysis of comet tails showed a steady ejection of particles from the sun outward through interplanetary space. These fundamental qualitative points made it clear that interplanetary dynamics is not an empty subject, and, along with the work of CHAPMAN and FERRARO [4] on magnetic storms, made it clear that we are dealing with interplanetary gases and magnetic fields streaming out from the sun.

The first theoretical step was taken by CHAPMAN [5] who showed that the enormous thermal conductivity of the 10^6 °K solar corona leads to extremely high temperatures, at least 10^5 °K, at the orbit of Earth. With all these points in mind it was then a simple matter to write down the hydrodynamic equations and integrate them (Bernoulli's equation) to show that the observed coronal temperatures of 1 or 2×10^6 °K lead to supersonic expansion of the solar corona (1). The velocity of expansion increases outward through the quiet-day corona from less than 1 km/sec at its base to something of the order

(1) It should be noted that the hydrodynamic equations are applicable to the *large-scale* motion of a plasma without collisions if a weak magnetic field is present. A weak magnetic field maintains the thermal motions approximately isotropic through such means as the hose and mirror instabilities. With $p_{ij} \cong \delta_{ij}\, p$ the moments of the collisionless Boltzmann equation reduce to the classical hydrodynamic equation.

of 300-500 km/sec at a distance of several million km out into space (see PARKER [6], [7] and references therein). It was also possible to show (PARKER, [8]) that the transient heating of the corona to 4×10^6 °K or more following a flare leads to blast waves of $1\text{-}2 \times 10^3$ km/sec, arriving at the Earth orbit in one or two days. Such blast waves are to be identified, presumably with the « corpuscular clouds » responsible for the geomagnetic storm and the Forbush-type decrease. The steady expansion of the quiet-day corona of $1\text{-}2 \times 10^6$ °K is to be identified with the quiet-day « solar corpuscular radiation ». This quiet-day solar wind, together with the frequent blast waves during the years of high solar activity, are evidently the cause of the 11-year variation of the galactic cosmic ray intensity with solar activity. This paper presents a brief discussion of some of the more obvious and unavoidable cosmic ray effects that follow from the dynamics of the solar corona and the solar wind in interplanetary space.

The cosmic ray modulation is brought about by the magnetic fields carried in the solar wind. The wind moves approximately radially outward from the sun, so that with the solar rotation Ω the lines of force near the equatorial plane make the Archimedes spiral $r \cong v\,(\Phi - \Phi_0)/\Omega$ in the equatorial plane of the sun, where v is the solar wind velocity, and Φ_0 is the azimuthal angle, or solar longitude, at which the line leaves the sun. The occasional blast wave propagates outward into this quiet-day field, compressing it in the radial direction so that the field is sharply kinked in the blast wave itself and nearly radial in toward the sun behind (see figures in ref. [8]). It is to be expected theoretically that both magnetic configurations, the quiet-day spiral fields and the blast wave kinks will be complicated by small-scale ($\sim 10^5\text{-}10^7$ km) irregularities produced by the mirror and hose instabilities, perhaps by turbulence, by small shocks, etc. Observation is required to determine the degree of this disordering.

Now consider the propagation of cosmic ray particles in these interplanetary magnetic fields. A charged particle in a large-scale magnetic field moves more or less freely along the lines of force of the field (subject to such restrictions as constant magnetic moment, etc.) so that to a first approximation it is possible to say that the rate of propagation of cosmic rays along a field is essentially given by the particle velocity w. A particle may drift across a large-scale magnetic field B as a result of a gradient in B which is perpendicular to **B** and as a result of the curvature of the lines of force. The drift velocity is proportional to wR, where R is the radius of gyration of the particle in B and is a direct measure of the magnetic rigidity of the particle. In the presence of small-scale variations in the magnetic field the charged particle will be deflected and scattered. To a first rough approximation we will suppose that under such circumstances a random walk is added to the systematic motions in the large-scale field. If the small-scale fluctuations in the field lead to large deflections, then the effective mean free path λ for the random walk may be written $\lambda = 1/Nl^2$ where N is the number of fluctuations per unit volume and l^2 is the effective cross-section of each fluctuation. If the small-scale fluctuations in the field lead to small deflections, then the small deflections R/l will accumulate, presumably in a random way, leading to an effective mean free path $\lambda \cong R^2/Nl^4$. If the principal effect is the random deflection of particles, then the particle density $\mu(k, t, \boldsymbol{r})$ at position $\boldsymbol{r}$, time t, and energy k (in units of the rest energy mc^2) may be computed from a diffusion equation.

$$(1) \qquad \frac{\partial \mu}{\partial t} = \frac{1}{3} w \lambda \nabla^2 \mu - \nabla \cdot (\boldsymbol{v} \mu)$$

if we assume that the scattering is isotropic. The term $\nabla \cdot) \boldsymbol{v} \mu)$ takes account of the fact that there is a general transport of the fields, and therefore transport of the particles, with the velocity $\boldsymbol{v}$ of the solar wind.

It will not be attempted to combine diffusion with the blast wave after a flare, though it may be that observation will some day soon require that we do so. Instead we take the simple course of supposing that the blast wave at a radial distance $r(t)$ has a transmission coefficient Ψ for cosmic ray particles (Ψ is approximately the ratio of the field ahead and the field inside the blast wave). Then conservation of particles requires that the cosmic ray density (at some velocity w and energy k) ahead μ_o and behind μ_i the blast wave are related by

$$\text{(2)} \qquad \frac{d\,(r^3\,\mu_i/3)}{dt} = r^2\,\Psi\left[\frac{1}{4}\,w\,(\mu_o - \mu_i) + \mu_o\,\frac{dr}{dt}\right] + S$$

where S is a source term allowing for leakage from the sides into the region behind the wave. If $\Delta\mu \equiv \mu_o - \mu_i$, then put $S = \frac{1}{2}\,\xi r^2 u \Delta\mu$, where ξ is a constant of the order of unity and u is the effective drift velocity perpendicular to B; $u = \frac{1}{2} w_\perp\ R/l$ where $1/l \equiv (\nabla B)_\perp /B$. For an approximately radial field $B \propto 1/r^2$, $l \propto r$; we have $u \propto r$. We expect that this approximate aquation (eq. 2)) should be valid up to those energies (of the order of 10^2 GeV) at which the particles begin to penetrate all the way through the blast wave.

In addition to the actual reduction $\Delta\mu$ in the cosmic ray density, there is an apparent reduction, which we shall denote by ΔM, brought about by the adiabatic cooling or deceleration in the expanding fields carried in the solar wind. Roughly speaking, ΔM is proportional to the rate of expansion of the fields and to the length of time the particle spends in the solar wind. The expansion at a distance r from the sun has a characteristic time r/v for a wind velocity v. Noting that $\Delta\mu$ also is proportional to the amount of expansion occurring during the time that the particle is in the solar wind, it is readily seen that ΔM and $\Delta\mu$ depend upon the same things, and can be shown to be comparable for the observed cosmic ray spectrum

$E^{-2.6}$ (a steeper spectrum leads to $\Delta M > \Delta\mu$, and a flatter spectrum to $\Delta M < \Delta\mu$). It will be sufficient for the present, therefore, to compute $\Delta\mu$ from (1) and (2), and then multiply by two, to obtain an order of magnitude expression for the reduction of the cosmic ray intensity brought about by the solar wind.

Now consider the modulation of the cosmic ray intensity which follows under various circumstances in the quiet-day solar wind and in the blast wave from a flare. First of all, suppose that the simple Archimedes spiral in a uniform quiet-day solar wind were present without small-scale perturbations etc. If the angle between the spiral lines of force and the radial direction is denoted by ϑ, then the net inward flux of particles of velocity w is $\Delta\mu\, w \cos\vartheta/4$ and the outward convective flux is $v\mu$. The resulting stationary reduction of cosmic ray intensity in the inner solar system is accordingly

$$\Delta\mu/\mu \cong 4\ v/w\ \cos\vartheta = 4\ (v/w)(1 + r^2\Omega^2/v^2)^{1/2} \cong 4\ r\Omega/w$$

Then with $w \cong c$, and $\Omega = 3 \times 10^{-6}$ sec, we have $\Delta\mu/\mu = 0.1$ if, for instance, it is assumed that the spiral extends to $r = 15$ AU.

As a matter of fact, there is good evidence, from the observed trapping of energetic solar particles following a flare, that the quiet-day interplanetary field is seriously disordered beyond the orbit of Earth. Thus we do not take seriously the idea that the quiet-day spiral field extends very far into space. Instead it seems more reasonable to suppose that the diffusion equation (1) is appropriate for treating the quiet-day modulation of the cosmic ray intensity. The diffusion coefficient is not expected to be truly isotropic as implied by the simple form of (1) but assuming spherical symmetry about the sun eliminates the effects of any anisotropy by reducing the problem to one dimension. We are interested in the radial component of the diffusion coefficient $w\lambda/3$. Suppose that the perturbed interplanetary field extends from r_1 to r_2 and that there are effectively n scattering centers of scale l in the line of sight from r_1 to r_2. If $R < l$, then the stationary solution of (1) is readily shown to be

$$\mu(r_1, k) = \mu(r_2, k) \exp\left[-\frac{3vn}{c}\frac{k+1}{[k(k+1)]^{1/2}}\right] \tag{3}$$

This equation applies to sufficiently low particle energies that $R<l$. At higher energies for which $R>l$, the effective number of scatterings by the n centers in the line of sight is reduced to $n \cdot l^2/R^2$, and if R_0 is the radius of gryration of a particle with energy $k=2^{1/2}-1$, then it is readily shown that

$$\mu(r_1, k) = \mu(r_2, k) \exp\left[-\frac{3vn}{c}\frac{l^2}{R_0^2}\frac{k+1}{[k(k+2)]^{3/2}}\right] \tag{4}$$

It is evident that (3) gives a flatter energy dependence than (4). For $k \gg 1$ (4) approaches $\Delta\mu \propto k^{-2}$. Observations of the amount of reduction of the galactic cosmic ray intensity at Earth during the years of solar activity suggest that $3vn/c$ is of the order of 2. With $v = 500$ km/sec, this suggests that $n \cong 400$. Thus, $r_2 - r_1 = 4$ AU leads to $\lambda = 1.5 \times 10^{11}$ cm, and $r_2 - r_1 = 40$ AU yields $\lambda = 5 \times 10^{12}$ cm. The radius of gyration R of a typical cosmic ray proton of 2 GeV ($k \cong 2$) is 8×10^{11} cm in a field of 10^{-5} gauss, and 0.8×10^{11} cm in 10^{-4} gauss, so that neither of these two values of λ is unreasonable in the observed interplanetary field. The precise value of R determines the energy at which the modulation changes from (3) to (4). The energy dependence of $\Delta\mu$ given by (3) at low energies and (4) at higher energies is similar to what is observed in the 11-year variation. The one real test that can be applied at the present time is to see whether the values of n and λ deduced here are consistent with the values of λ which follow a little later from the diffusion of energetic solar particles.

Consider the transient depression of the cosmic ray intensity resulting from a blast wave after a solar flare. With $S=0$ and

$\Delta\mu \ll \mu$ ($\Psi wt \gg r$) the formal solution to (2) may be approximated by

$$\Delta\mu/\mu_o \sim \frac{4(1-\Psi)}{\lambda\Psi}\frac{r}{wt}$$

where λ is the parametr such that the blast wave radius r is proportional to $t^{1/\lambda}$ (see PARKER [8] for detailed discussion). The value $\lambda = 3/2$ corresponds to a wave coasting outward from the sun ($\Psi \geq 0.25$, and $\lambda = 1$ corresponds to a wave driven firmly by the enhanced corona, in which case Ψ may be as small as 0.1. The depression $\Delta\mu$ is then inversely proportional to the particle velocity and recovers like $t^{1/\lambda - 1}$. Including the source term S the formal solution of (2) approximates to

$$\frac{\Delta\mu}{\mu_o} \cong \frac{4(1-\Psi)r}{\lambda\Psi wt}\left\{1 - \frac{4r}{3\lambda\Psi wt}\left[4-\lambda+3\xi\lambda u_o t/2a\right]+\ldots\right\}$$

were u_0 is the drift velocity at $r = a$ for the particle energy k in question. The approximation is an expansion based on the assumption that $2(\lambda-1)\xi u_0 r/\lambda\Psi wa < 1$. The resulting $\Delta\mu(k, t)$ is shown in Fig. 1. The interesting feature is that the energy spectrum is very flat in the beginning but the high energy particles recover much more quickly than the low energy particles so that the spectrum is soon steep. The recovery is the result of both decreasing r/t (since probably $\lambda > 1$) and drift of particles in at the increasing area of the sides of the blast wave.

It is interesting to apply (2) to the magnetic tongue, proposed by MORRISON, GOLD, COCCONI and others [9]. The lines of force of the magnetic tongue form a closed configuration, so far as the entrance of galactic cosmic rays is concerned, so put $\Psi = 0$. The solution of (2) is then reducible to the approximate expression

$$\frac{\Delta\mu}{\mu_o} \sim \frac{2a}{\xi u_o t}$$

[6] *Parker* - pag. 8

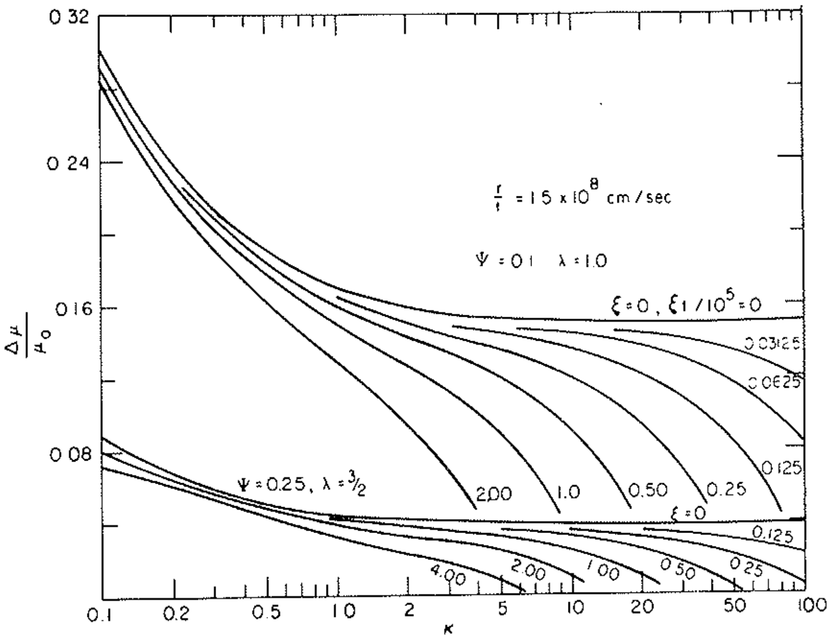


FIG. 1 — Plot of the fractional cosmic ray intensity reduction $\Delta\,\mu/\mu_0$ behind the blast wave with position $r \propto t^{1/\lambda}$ as a function of proton energy k, for various values of time and for various drift rates ξ, putting $u_0 = 0.9 \times 10^6 \ k(k+2)/(k+1)$ cm/sec.

Such a spectrum decreases like $1/k$ at high energies, in disagreement with observation, which suggests a much flatter spectrum (see paper by AMALDI [10] and by ELLIOT [11]). $\Delta\mu$ is plotted in Fig. 2 as a function of time.

Another model of interest to the Forbush decrease is the cloud of disordered field proposed first by MORRISON [12] a number of years ago. Using the diffusion equation (1) we show in Fig. 3 the time dependence of the particle intensity at the center of a disordered magnetic cloud which suddenly increases its radius by the factor $(4/3)^{1/3}$. In Fig. 4 we show the particle intensity at a fixed point in the path of a steadily expanding

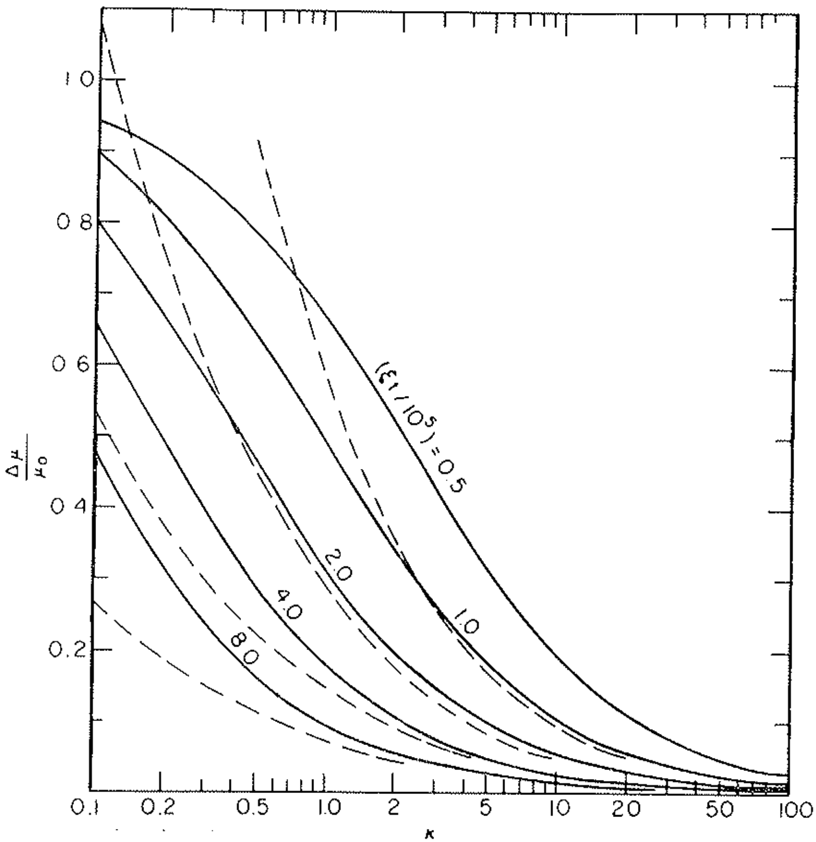


FIG. 2 — Plot of the fractional cosmic ray intensity reduction $\triangle \mu/\mu_0$ in a hypothetical magnetic tongue with radial length $r \propto t$ as a function of proton energy k, for various values of time and for various drift rates ξ, putting $u_0 = 0.9 \times 10^6 \ k(k+2)/(k+1)$ cm/sec.

spherical cloud with radius $r = z_1 t$, and diffusion coefficient $w\lambda/3 = q\ t$, where z_1 and q are constants. In order to fit a disordered cloud model to the observed Forbush decreases, with their flat energy spectrum and abrupt onset, it is necessary to assume in many cases that the interplanetary field is of the

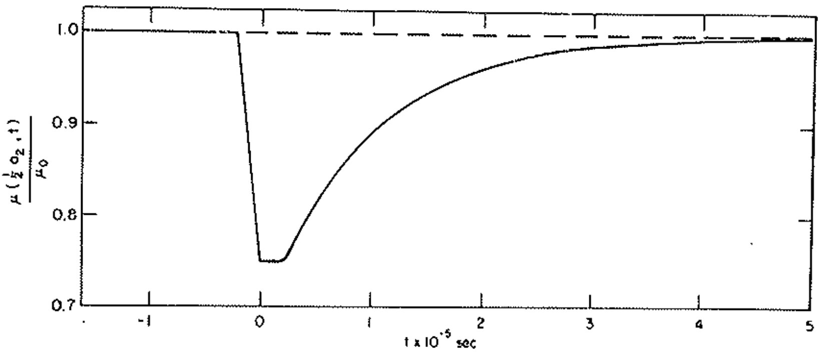


FIG. 3 — Cosmic ray intensity at the center of a disordered magnetic cloud following the sudden increase of the cloud radius by the factor $(4/3)^{1/3}$. The time scale is in units of 10^5 sec. for the case that $\omega\lambda/3 = 2.5 \times 10^{20}$ cm²/sec.

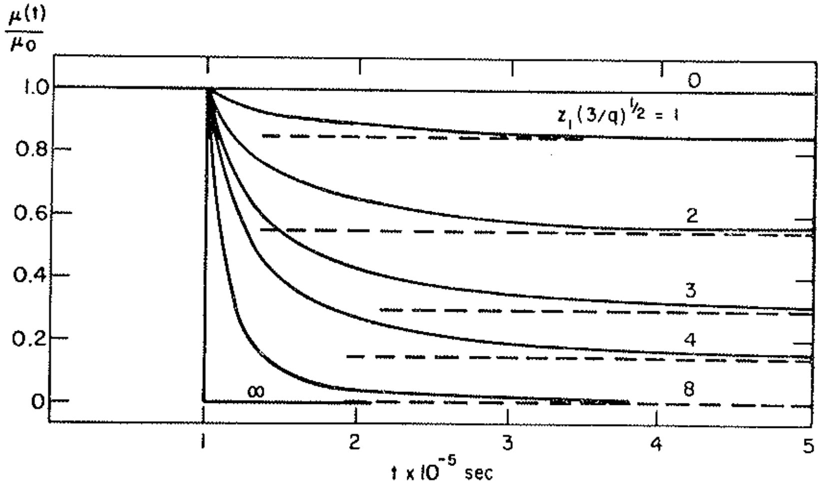


FIG. 4 — Cosmic ray intensity at Earth as a function of time in a spherical cloud centered at the sun and expanding at a uniform rate of 1500 km/sec.

order of 2×10^{-3} gauss, as was first pointed out by MORRISON. This is easily demonstrated by the requirements of a flat spectrum to at least 50 GeV (implying that $R < \lambda$) and a decrease of 30 per cent or more ($\lambda < 10^{11}$ cm). There is no observational evidence to support the assumption of such enormously strong fields in space, and in fact the hydrodynamical considerations of the solar wind suggest that the field cannot be so strong, except perhaps under the most extraordinary circumstances.

To summarize these remarks on the modulation of the galactic cosmic ray density in interplanetary space, we point out that the simple dynamical picture of a quiet-day solar wind, with occasional blast waves following a flare, seem to account for both the 11-year variation and the Forbush-type decrease. Other models, such as the magnetic tongue and the disordered cloud, which are not based on calculations from the hydrodynamic equations, have some difficulty in duplicating the flat spectrum of the early period in a Forbush decrease.

Consider now the related problem of the propagation of energetic solar particles out from the sun into interplanetary space. The two noteworthy features are the delayed arrival, sometimes by many hours, and the subsequent partial storage in the inner solar system, usually for many hours or days. On the basis of the model discussed above in connection with the 11-year cycle, it would be supposed that the storage of the particles in the inner solar system is the result of the disordered magnetic fields near and beyond the orbit of the Earth. The delayed arrival can also be accounted for by supposing that the energetic particles propagate immediately from the flare outward along the spiral quiet-day lines of force into the disordered field beyond the orbit of Earth. Unless Earth happens to be situated directly on the lines of force carrying the particles, it will see no particles at the time. However, upon reaching the disordered field the particles begin to diffuse, spreading laterally around the sun and eventually arriving at the earth with an isotropic distribution. The delayed arrivals by this means from a flare at an angular distance $\pi/2$ and π around the sun are shown in Fig. 5, showing the rapid attenuation as the particles diffuse through large angles at a radial distance around the sun. The broken lines indicate the intensity

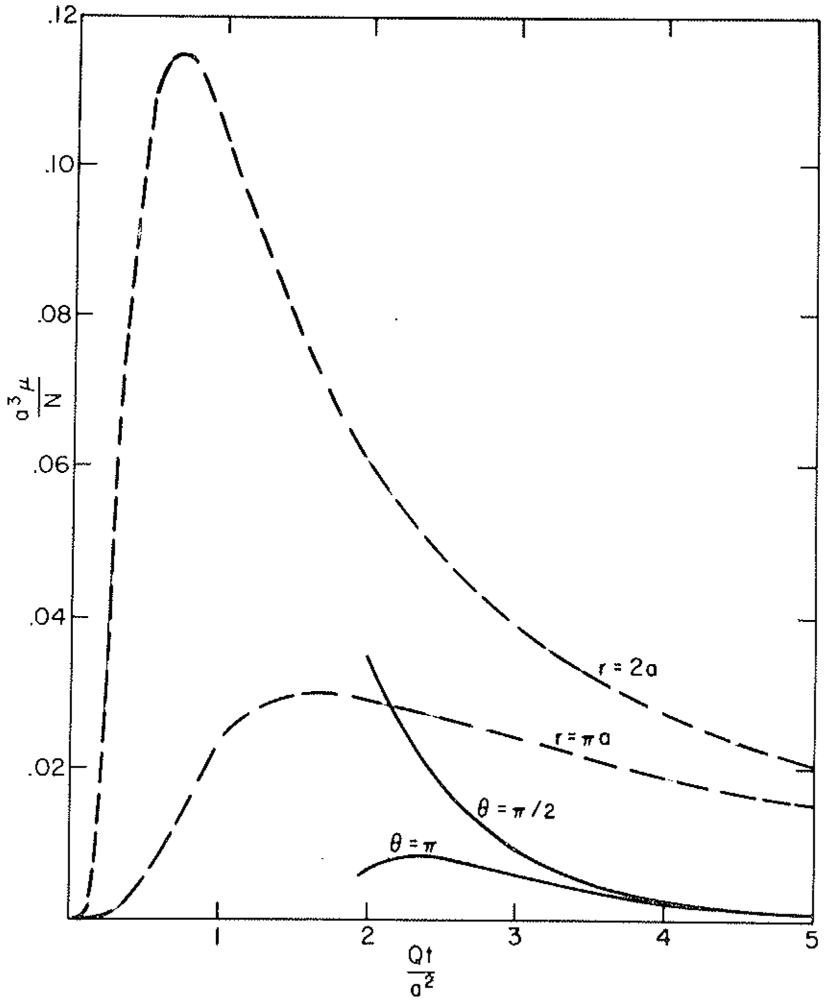


FIG. 5 — Energetic solar particle intensity at angular distance of $\pi/2$ and π around the sun from the point of particle release, based on the assumption that diffusion occurs only outside a radial distance $r = a$ ($\backsim 1$ AU). The two broken lines show diffusion to distances of 2a and πa in a homogeneous diffusing medium for purposes of comparison.

at distance of $2a$ and πa in an infinite homogeneous diffusing medium. Investigation of the numerical values for the diffusion coefficient $w\lambda/3$ yielding the 11-year variation, the delayed arrival of solar particles, and the storage of solar particles following their arrival suggests that 10^{21} cm^2/sec ($\lambda \cong 10^{11}$ cm) for diffusion perpendicular to the quiet-day magnetic field and 10^{22} cm^2/sec ($\lambda \cong 10^{12}$ cm) for diffusion parallel to the quiet-day magnetic field will fit most events very nicely. These are only very rough estimates, of course, but they serve to show the consistency of the present model for the two unrelated phenomena of energetic solar particle propagation and the 11-year modulation of the galactic cosmic ray intensity.

It is to be expected that studies of the galactic cosmic ray intensity from the existing world-wide network of detecting stations, as well as continued monitoring of energetic solar particles, will help to clear up many vague points in the picture of interplanetary cosmic ray modulation. Present and forthcoming observations of the particle intensities in space, as a function of particle energy, time, and position, together with field and plasma measurements, provide a new means of attack on the problem which may afford decisive settlement of most of the main questions existing at the present time. We expect that the modulation model presented here, based on the dynamics of coronal expansion, will need numerous additions and readjustments as observational knowledge improves. One might attempt to anticipate some of the adjustments by compiling an exhaustive list of possibilities. But we feel that the inefficiency of such *a priori* guessing makes it an effort of doubtful value to scientific progress. The reader who is interested in some of the currently held models which are distinct from the dynamical model presented here is referred to the papers presented by GOLD [13] and ELLIOT [11].

REFERENCES

[1] S.E. Forbush, *J. Geophys. Res.*, *59*, 525, 1954.

[2] J.A. Simpson, *Ann. Geophys.*, *11*, 305, 1955.

[3] L. Biermann, *Z. Astrophys.*, *29*, 274, 1951, *Z. Naturf.* *7a*, 125, 1952.

[4] S. Chapman and V.C.A. Ferraro, *Nature*, *126*, 129, 1930; *Terr. Magn.*, *36*, 77, 171, 1931; ibid., *37*, 147, 1932; ibid., *38*, 79, 1933; ibid., *45*, 245, 1940.

[5] S. Chapman, *Space Astrophys.*, Mc Graw Hill, 1961, p. 133.

[6] E.N. Parker, *Ap. J.*, *128*, 664, 1958.

[7] — *Ap. J.*, *132*, 821, 1960.

[8] — *Ap. J.*, *133*, 1014, 1961.

[9] G. Cocconi, K. Greisen, P. Morrison, T. Gold and S. Hayakawa, *Suppl. Nuovo Cim.*, *8*, 161, 1958.

[10] E. Amaldi, F. Bachelet, P. Balata and N. Iucci, contribution to this meeting, p. 299.

[11] H. Elliot, contribution to this meeting, p. 459.

[12] P. Morrison, *Phys. Rev.*, *101*, 1397, 1956.

[13] T. Gold, contribution to this meeting p. 431.

DISCUSSION

Chairman: E. AMALDI

GOLD

I would like to make a few points. First, about the structure of the magnetic field in the expanding corona. The shapes that one sees nearer the sun within one radius or two radii of the solar surface, which we can see during an eclipse, do suggest usually a much more complex shape than just a combed out radial field, and one wonders how a uniform expansion of the corona can fit into that kind of a structure which quite clearly seems to be a magnetically enforced one. I suppose that the situation is this, that in the combing out process of a field, in the stretching out that an expansion would make, one would commonly position side by side opposing lines of force. In the picture that Dr. PARKER drew on the board for example, it is clear that there are going to be many interfaces where one line has one sense and the neighbouring line must have the opposite sense, and all such interfaces are nowadays recognized to be very unstable and to lead to quite quick dissipation. Dissipation where opposing lines of force are concerned would of course mean that the lines of force would be relinked and make a loop closing on themselves closer to the sun and make a corresponding closure for a part which is flying away, so that such a corona would not remain combed out but it would constantly reform loops of fields and would make blobs of field with closed lines of force in them fly away. In that way I suppose one can reconcile an expanding corona with the picture that one sees in the inner corona which does contain all the time such loops. In fact it contains more than such loops; it even contains the shapes that very strongly suggest such a process, namely shapes where you see loops up to a certain distance and then tailing over into a spike. Now then in turn one has to discuss, it seems to me, the pressure gradients which this magnetic field would impose and I would think that would make a great variability over the surface of the sun, in the amount of expansion that would in fact result. A place which has got lines of force going far away will allow the material to stream away under its thermal-driving pressure, as Dr. PARKER explains, quite freely; but on the other hand a region which has looped lines of force will make a substantial pressure gradient and we can in fact see that this is so because we see great variations in the density in the corona. So I suppose that bringing in the magnetic field rather than merely thinking of it as out of the way by smoothly combing it straight, will complicate the picture somewhat and may alter the rates of outstreaming that result from a given temperature distribution near the sun.

The other two points I would like to make concern the particles — the particle fluxes. The greatest problem of the back-to-front radiation is not just that we see no flares from right around the back but that we don't even see flares from a little way round, apparently; and yet we have the impression that the best region for seeing particles from flares is way over to the west of the sun. We have the impression from the time-delay investigation that the lines of force go by some spiral shape so as to favour a place some 60° W of the central meridian of the sun. But on the other hand we have seen flares send particles to the earth — usually with a greater time delay but leading to quite substantial increases — from the east side. If 60° W is the best place, and if particles could diffuse equally well in either sense, then we ought to be seeing them when emitted up to 120° behind the west limb. That is a substantial angle behind the sun in which lots of flares should have occurred and the present statistics don't allow us to think we see their particle fluxes except the one that was just round the corner.

This is rather embarrassing, and it seems to me that one has to search for an explanation for particles to drift in the field more easily in the one sense than in the other. That seems to me the weight of evidence that we have at the moment.

The other point is the question whether the diffusion of the flux happens far out from the sun, so that when particles are emitted somewhere else on the sun they can first get far out and then be diffused to the line of force on which the earth is situated. Well, some of that may of course be taking place, but we have contrary evidence at least on some occasions; namely that even if the time delay between the flare and the arrival of fast particles has been quite substantial, nevertheless the fast particles have arrived, to start with, with a preferential direction. That seems to indicate that the particles were placed on the lines of force closer to the sun, so that they were travelling down an expanding field which will always guide them into the direction of the field. This is the only explanation that we have for a substantial anisotropy in the flux, and we could not use that if we only had the diffusion far from the sun. So I think there is strong evidence from the direction of particles that a diffusion happens close to the sun; and that then goes back to the picture that close to the sun there must be lots of loops of lines of force on which particles can be stored for substantial periods of time, in which they can be hung up and delayed before reaching the lines of force which reach the earth. Only then can there be a time delay and nevertheless an arrival at the earth with a collimated direction.

PARKER

I quite agree with Prof. GOLD on all these things. I can think of several more difficulties myself but time does not permit going into them.

BIERMANN

I would like to make a remark concerning also what Prof. GOLD and myself said in the discussion yesterday. Among the types of instabilities which may have to do with the disconnection of magnetic lines of force there is one which is due to the finite resistivity. As you know from the history of the subject, there has been a general inclination for a long time to use the conception of magnetic lines of force the flux of which is assumed to be effectively constant. This means that the resistivity is taken equal to zero. Now it has been realized quite recently that although the resistivity may be low, its influence on instabilities should by no means be neglected: that is one of the reasons why in experiments we see quite often situations in which the plasma does not behave as an ideal magneto-hydrodynamic fluid. I think that is generally speeking also in line with what we see on the sun.

Another point which I would like to ask is this: if we have continuous radial outflow from the sun and spiralling magnetic lines of force, then we have an induced electric field ($//\mathbf{v}\times\mathbf{B}$) which may be a potential field. In reality I think the velocity field and the magnetic field are much more disordered: I just wonder if that would affect the main point of your picture or whether it only means that everything is more irregular and gives just that type of disorder which is another essential feature of the picture.

PARKER

I don't think one could give a hard and fast answer to the question. I am sure things are chaotic, with all sorts of irregularities imposed on the basic spiral and blast wave picture discussed here. The discussion of the cosmic ray effects was based on the simplest possible model that is adequate to satisfy the observations available at the moment. I am sure there are many disorderings: the ones you mentioned, perhaps the one that Prof. GOLD mentioned. However with regard to the potential field that exists, it is true that in the fixed frame of reference there is this large potential difference due to the electric field minus $-\mathbf{v}\times\mathbf{B}/c$. However, I would point out that field is only present because the electric field in the frame of that this field is only present because the electric field in the frame of reference moving with the gas is zero. So I really don't know what to expect from it.

SINGER

I have just a basic theoretical point I want to ask about. It has actually no bearing to the *real* sun. My tendency has been to look at a quiet solar corona in terms of an evaporating exosphere. I was therefore interested in your remark that you use the hydrodynamic equations even in the absence of collisions, but that you then used instabilities to establish an isotropic « thermal » distribution, presumably an isotropic Maxwellian distribution. My question really is: how do you reconcile an escape by evaporation with a completely isotropic distribution of gas?

PARKER

I don't understand the question. You say, how do you reconcile evaporation with an isotropic thermal distribution?

SINGER

That is right.

PARKER

Well, in the first place, I don't think there can be any evaporation because there are weak magnetic fields which contain the particles to within their radius of gyration. Or, if there were evaporation I think it is completely overwhelmed by the hydrodynamic expansion. You can get the hydrodynamic solution equivalent to evaporation from the hydrodynamic equations if you like. It is the one that CHAMBERLAIN worked out. The velocity of the evaporating gas at the orbit of the earth, as I remember, would be of the general order of 30 kilometers per second. Whereas the hydrodynamic expansion, which is equivalent to expansion through a Laval nozzle into a vacuum, is hundreds of kilometers per second. It just is not clear to me how evaporation could fit into the picture.

ELLIOT

Prof. GOLD has already mentioned the question of coronal shapes, and I wish to ask particularly about the shapes one sees in the polar regions, the polar plumes; these we know are not radial, that is quite certain. It seems clear that the extension of the corona is not spherically symmetrical. I wonder, in this connection, if there is for instance any evidence at all about the streaming of comet tails at high inclinations to the ecliptic?

PARKER

No, clearly it is not spherically symmetric. I know there is evidence from higher altitudes and I will let Prof. BIERMANN describe what it is.

BIERMANN

Well, there is definite evidence insofar as there have been comets which moved over the polar regions of the sun and did not behave at all differently from others. But the relative number of such comets is somewhat smaller than those moving in the vicinity of the ecliptic plane. If you will permit me I will go into this in more detail in my talk later during this study week. I think that the evidence for this fits quite well with PARKER's theory, which, if I remember correctly, was preceded by some discussion about the behaviour of the comet tails which we had at that step.

ELLIOT

But does not fit with the coronal plume shapes then?

PARKER

The coronal plume shapes, which as you point out are not precisely radial, nonetheless are *principally* radial. If you write down the hydrodynamic equation, the asymptotic velocity at infinity is relatively independent of whether the lines open exactly radially or only approximately so. And Prof. BIERMANN is right in pointing out that in fact we are presenting the whole argument backwards here — it went the other way round. *First* I had full assurance from him and his observations that gas did flow in all directions from the sun, and *then* I wrote down the spherical symmetric model — not vice versa.

ELLIOT

If you accept that the barrier is not symmetrical, the question of diffusion from the side comes in, and in this connection I see that you have put in this source function S. But I would like to inquire about the scale size of the field which in this case is presumably determined by the scale size in the photosphere increased linearly with distance from the sun and has nothing at all to do with the turbulence of the medium. I wondered what sort of scale size you put in to determine S.

PARKER

What I did was to assume that the scale was equal to the distance from the sun. In other words, I am saying: let me assume that field does not reverse on a small scale in this region. Now I am fully aware that this may be totally wrong, but I found that I obtain the right kind of numbers by making the simple assumption. I just do not want to go into more complicated models until required to do so by the observations.

ELLIOT

Well, perhaps the scale size should be something like the size of granules on the sun.

PARKER

If that is the case, then my calculations should be replaced by the diffusion equation: and, as I say, one simply needs to look at the cosmic ray evidence. If these crude models are wrong, I won't be surprised and they are readily extended to other cases.

HAYAKAWA

I would like to ask you about the 11-year variation. The modulation factor you wrote down depends on energy and consequently on velocity but the modulation factor observed by MACDONALD and WEBBER seems to depend on the rigidity alone. What is your opinion on this?

PARKER

Well, the point I would make is this: the modulation that I wrote down depended upon a product of velocity and rigidity; for a relativistic particle the velocity may be regarded as constant and so I am left with a rigidity dependence, which for relativistic particles is the same as energy, unless you distinguish between particles of various charge to mass ratios.

HAYAKAWA

As far as I understand MACDONALD and WEBBER made observations of protons, α-particles and heavy particles. And all have the same rigidity spectra.

PARKER

That is not inconsistent with these equations.

ELLIOT

If I may I will have something more to say about this tomorrow. I am not so sure that it isn't inconsistent.

PARKER

That remains to be seen.

VALLARTA

For some time now we have been playing with the idea that the modulation mechanism is a change of the threshold of the cosmic radiation. In order to be able to carry through this idea one must integrate equations of motion, that is trajectories of particles coming from the sun and from external space in the external magnetic field and also of course in the internal magnetic field of the earth, and the difficulty about carrying through this programme is that we do not know enough at this time about the external field. Now by assuming a simple model such as Prof. PARKER drew on the blackboard a moment ago, one can carry through some preliminary computations that are quite encouraging. Now the question I would like to ask is this: this concentration of the field that Prof. PARKER drew on the blackboard behind the blast wave, how good is the evidence for the existence of this concentration field back of or behind the blast wave? That would play a very important role in the calculation I am describing now.

PARKER

I think one could say there is no observational confirmation of any of the pictures that have been drawn. There is just enough information from Pioner V for TOMMY GOLD and I to sit down and argue at great length and come to no precise conclusions in the end. One thing we can say is that whatever the fields are, they are compressed in the blast wave, as is unavoidable. The field densities there were up to 4×10^{-4} gauss, if I remember correctly. I would not take any of these simple models of magnetic field too seriously. I am sure that there will be many revisions that are necessary. I feel that at the moment we are groping with the simplest possible models, and as observations continue to come in, we'll get a clearer and clearer idea of what is going on. Most of the theoretical progress is going to be *ad hoc*.

VALLARTA

May I just add one more word to this, and this applies to those people who have something to say about what kind of instruments are put aboard the space vehicles and satellites. It is fundamental importance from our point of view that the external magnetic field be explored. Now I hope that those of you who have something to say about this can persuade people to put a magnetometer aboard every space vehicle and every satellite so that we may be able to know something about the external field, otherwise any such programme as this cannot be carried through.

PARKER

Well I assure you that every time anything goes into space there is a strong move to put a plasma detector and a magnetometer aboard and if they don't get aboard it is over some dead bodies that they fail to. I think TOMMY GOLD will confirm that.

SIMPSON

I might comment further on the question Prof. VALLARTA raised earlier about whether there is evidence for a magnetic field behind an interplanetary shock front. From the space probe Pioneer V data there may be open questions about the observed orientation of the magnetic fields during quiet periods. However there is no doubt that the magnetic field strength suddenly built up by more than an order of magnitude in intensity behind what we understand to be the shock front. The magnetic field intensity increase was 40-50 γ. This is the first experimental evidence that there is a high intensity magnetic field region behind shocks. The fluctuations of this high intensity field provide evidence of disorder in the field lines behind the front of the region arriving at the earth on March 31, 1960.

SOLAR PARTICLES

E.P. NEY (*)

School of Physics University of Minnesota - Minneapolis, Minn. - U.S.A.

Abstract — Energy spectra of solar protons and α-particles were measured in the event following the November 12, 1960 flare. The ratio of the abundance of protons to the abundance of α-particles above the same rigidity was found to be 2. Spectra of protons, α-particles, and medium nuclei were measured after the November 15, 1960 flare. The proton spectrum showed that the magnetic cutoff existing at Minneapolis until approximately 10 hours after the flare had a value of about 0.7 GV but was not sharp. The ratio of the abundance of the various nucleonic components above the same rigidity was found to be $p:\alpha:\text{CNO} = 100 : 100 : 1$. The abundance of electrons of rigidity greater than 0.7 GV was found to be less than 2% of the abundance of protons. A model is suggested by which it would be expected that the ratios of protons to α-particles and protons to medium nuclei would change considerably between solar events, but the ratio of α-particles to medium nuclei would remain constant.

The relationship between our measurements on solar protons and heavy nuclei with the solar emission of radio waves, white light and X-rays at the beginning of the flare is reported. It is shown that the spectrum of the electromagnetic waves emitted by the sun is consistent with the assumption that these electromagnetic waves arise from synchrotron radiation is shown to be compatible with the rigidity spectrum of the solar cosmic rays, protons, and heavy nuclei as measured at the earth. The total number of electrons required to account for the synchrotron radiation from the sun is also shown

---

(*) Present address: School of Physics - University of Sydnev - Sydney Australia.

to be the same order of magnitude as the total number of protons and heavy nuclei accelerated by the flare. It therefore seems consistent on the basis of these calculations to believe that the electrons show their presence by the emission of electromagnetic waves, whereas the heavier particles because of their greater mass are unable to radiate synchrotron radiation and therefore arrive at the vicinity of the earth.

It was shown in 1942 by FORBUSH [1] and EHMERT [2] that increases in sea level ionization could be produced by large solar flares. That the magnitude of the solar injected fluxes of particles was quite large in a solar flare event was demonstrated in the February 23, 1956 event. This event was analyzed in detail by SIMPSON and his coworkers [3] on the basis of data acquired in the rather extensive neutron monitor network which had been established by SIMPSON prior to the International Geophysical Year.

In 1958 KINSEY ANDERSON [4] showed that solar protons could be detected at balloon altitudes from a flare which produced no sea level increase. At this time it was suggested by REID and LEINBACH [5] and by DANA BAILEY [6] that a good indication of the arrival of medium energy (approximately 50 MeV) protons at the earth was the enhanced absorption of cosmic noise as measured by riometers and forward scatter communication links at high latitude. The riometer absorption was used as a warning system so that balloon flights could be made at times when solar particles were arriving. In this way about thirty events have been rather completely observed.

Since 1958 it has become evident that many if not all large solar flares on the *visible* disk of the sun produce solar cosmic rays.

The first very intense high altitude event in which solar particles were observed in nuclear emulsions occurred on May 12, 1959. Fig. 1 shows a photomicrograph of an emulsion exposed for four hours during this event. A normal exposure to cosmic rays would have shown on the average less than

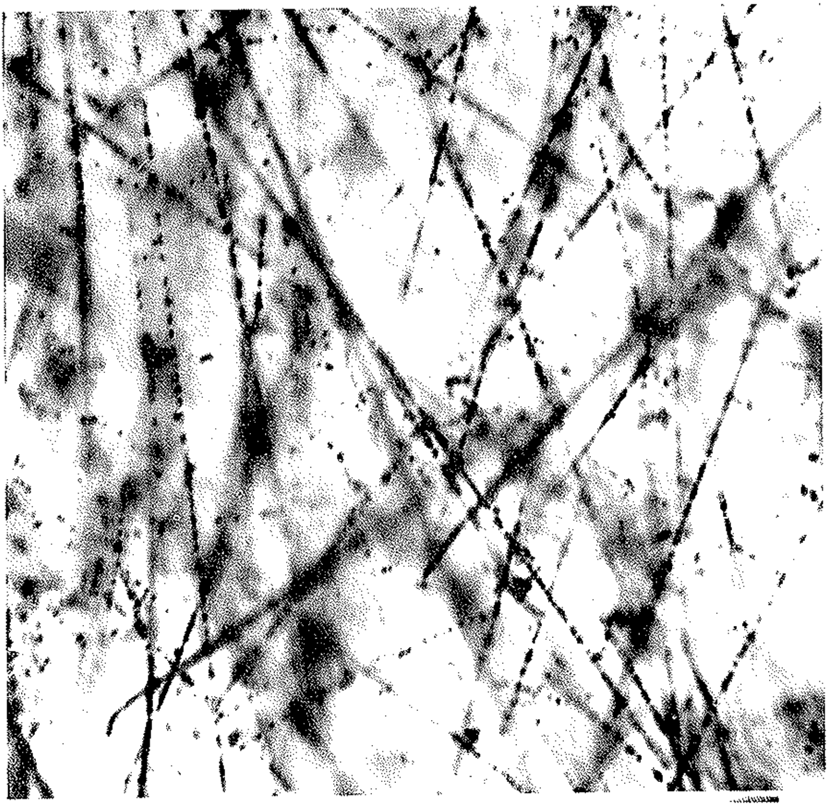


FIG. 1 — Photomicrograph of emulsion exposed to solar protons on May 12, 1959. A normal exposure to cosmic rays would have produced less than one track in the area shown here. The particles observed are largely low energy protons.

one track in the area of this photograph. Solar cosmic rays have now been detected with nuclear emulsions and counters flown on balloons and rockets and satellites and with balloon borne cloud chambers.

The principle characteristics of solar accelerated particles are the following:

1. The energy spectra are much steeper than galactic cosmic rays. If the spectrum is expressed as an integral energy spectrum then

$$N\ (>E) = \text{const. } E^{-n}$$

with n having values between 3 and 6.

2. The beams contain H, He, C, N and O and heavier elements and when we compare the spectra of the various components we find that the rigidity spectra are the same. A frequent representation of these spectra is given as a power law in rigidity. However, when the power law representation is used the exponent changes with the rigidity. FREIER and WEBBER (1) have suggested that the data are all well represented by an exponential rigidity spectrum of the form $dN/dR = C \exp(-R/R_0)$. The value of R_0 may vary from event to event but a characteristic value of the « e-folding » rigidity is 200 MV.

3. The relative abundance of He/CNO is essentially constant but the ratio of H/He varies widely from event to event.

4. The observed abundance of electrons is small. In the November 12 and November 15 events the electrons were less than 2% of the positive particles, and in the September 3 event they constituted less than 0.3% of the particles.

5. Geomagnetic cut offs sometimes exist for solar particles but they are frequently lowered by the presence of coexisting plasma streams. The lowering of the cut offs usually occurs during the main phase of a magnetic storm. At the time

(1) This result which will be published soon is based on a study of data obtained from balloons, satellites, riometers, neutron monitors etc.

when cut offs are lowered by the magnetic storm, the Van Allen radiation belt at the same location seems to be essentially unaffected.

6. The cut offs, whether they are the normal geomagnetic cut off or lowered one, are not sharp as would be expected from basic geomagnetic theory and Liouville's theorem.

Two of the best documented events are the September 3, 4, 1960 and the November 12, 15, 1960 events. We shall use these events to discuss the characteristics of solar cosmic ray beams. Fig. 2 shows the pertinent data on the November 12, 15 events. In this figure we plot the various measured quantities *vs.* time for the period November 12 to November 16. Reading from top to bottom are magnetic activity, the Minneapolis neutron monitor, the sequence of flares and the associated sudden commencements and Forbush decreases, the times of polar cap absorption (marked PCA), the times and duration of balloon flights; and in the lower half of the figure are the measured fluxes of solar particles. In this figure N_v is the flux of particles in units of cm^{-2} sec^{-1} $ster^{-1}$, Rh^{-1} represents roentgens per hour, n the exponent in the energy spectrum, and N_v/ε the ratio of vertical flux to the density of ending particles in units of cm emulsion per sterdian.

The gross characteristics of the events were the following. During approximately 20 hours starting late on November 12, when our first flight was made, the intensity of particles at the balloon altitude of 6 gm/cm^2 remained high and approximately constant. The vertical flux above an energy of 80 MeV was about 200 p cm^{-2} sec^{-1} $ster^{-1}$. (Normal cosmic ray flux is 0.1 p cm^{-2} sec^{-1} $ster^{-1}$). During this entire time particles arrived down to the lowest energy allowed by the range through the air mass overhead. The energy determined by this range is 80 MeV and the corresponding rigidity is 400 MV. The normal geomagnetic cut off at Minneapolis is 700 MV which corresponds to an energy of 220 MeV for protons. The lower-

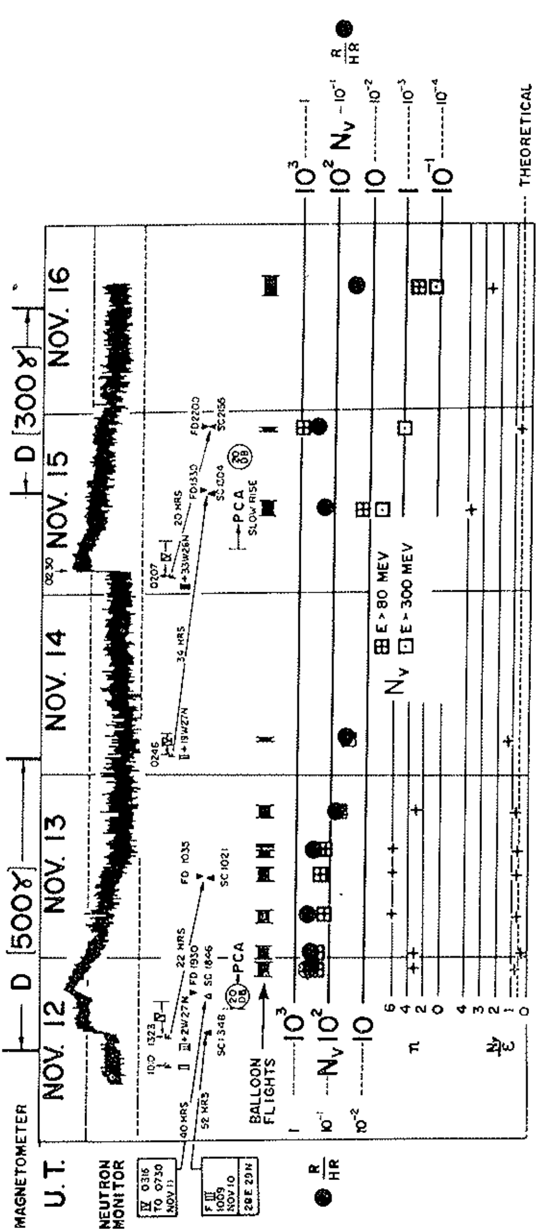


FIG. 2 — The sequence of events from Nov. 12 to Nov. 16, 1960. The plotted data are described in detail in the text.

ing of the cut offs in the November 12 event is believed to be due to one or more of the two magnetic storms which occurred on November 12. Finally at about 1400 UT on November 13 the intensity of the solar cosmic rays began to decrease rapidly, dropping by a factor of 10 in a few hours. We believe that the long period of constant intensity was produced by a relatively stable magnetic trapping condition existing in interplanetary space. The rapid decrease in intensity was probably caused by the destruction of this stable magnetic trap at about the time of arrival at earth's orbit of the plasma cloud injected by the same solar flare that accelerated the solar cosmic rays.

During the November 12 event the exponent in the integral energy spectrum changed from 3 to 6 and back to 3 again. The change from 3 to 6 can be interpreted in terms of high energy particles leaking out of the magnetic trap faster than lower energy ones. The low value of N_v/ε during the November 12 event is a sensitive indicator which shows that geomagnetic cut offs are destroyed. When no cut offs exist the value of N_v/ε can be shown to be ~ 0.6, the value during the November 12 event. However when cut offs are present the value of N_v/ε rises to a high value because the ending particles (those of low energy) are absent.

Fig. 3 shows a very diagramatic view of the solar system during November 12 and November 13. The sequence of events can be explained in detail by the model proposed by GOLD [7] in which magnetic loops coupled to the sun can guide and trap solar injected cosmic rays. Presumably the earth was well connected with the sun in this event because all of the flares which ejected magnetic fields occurred in the same region of the sun as the cosmic ray injecting flare at 1323 UT on November 12.

Fig. 4 shows the neutron monitor profile for the November 15 event. Two flares occurred one on November 14 and one on November 15. The flare on November 15 produced solar

[7] *Ney* - pag. 7

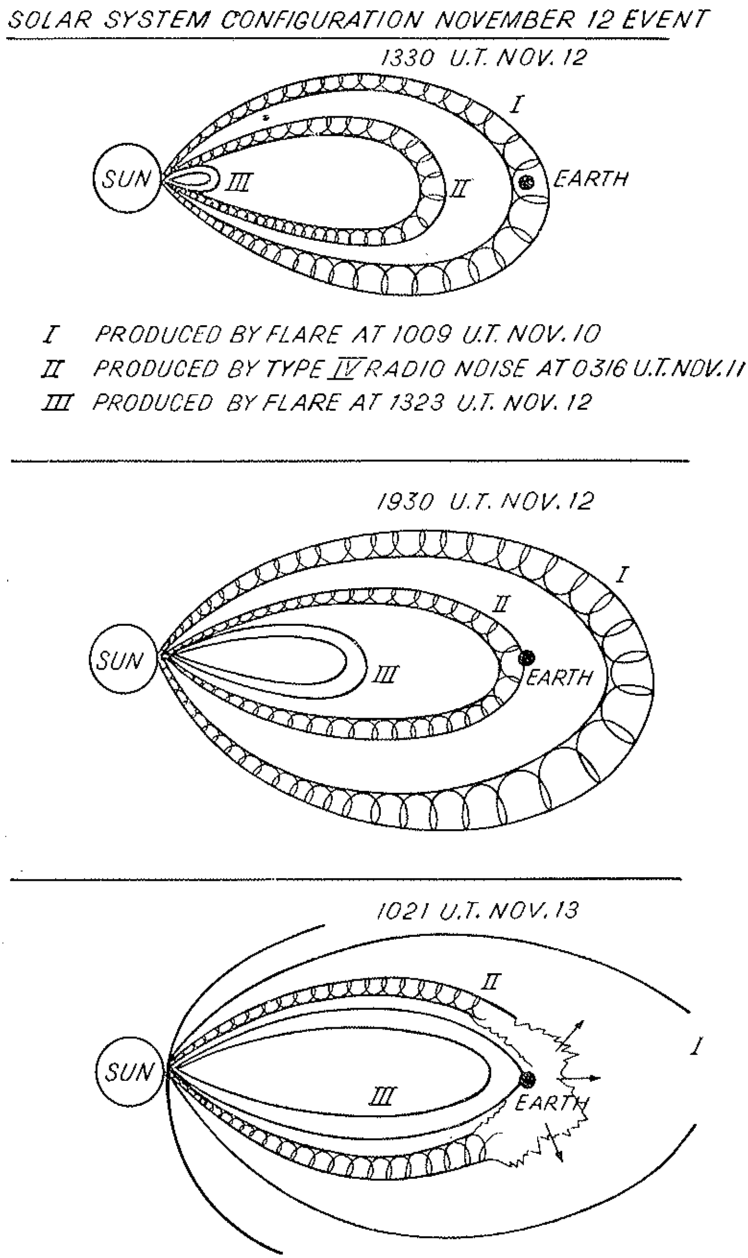


Fig. 3 — The solar system configuration suggested to account for the observations on the Nov. 12, 1960 event.

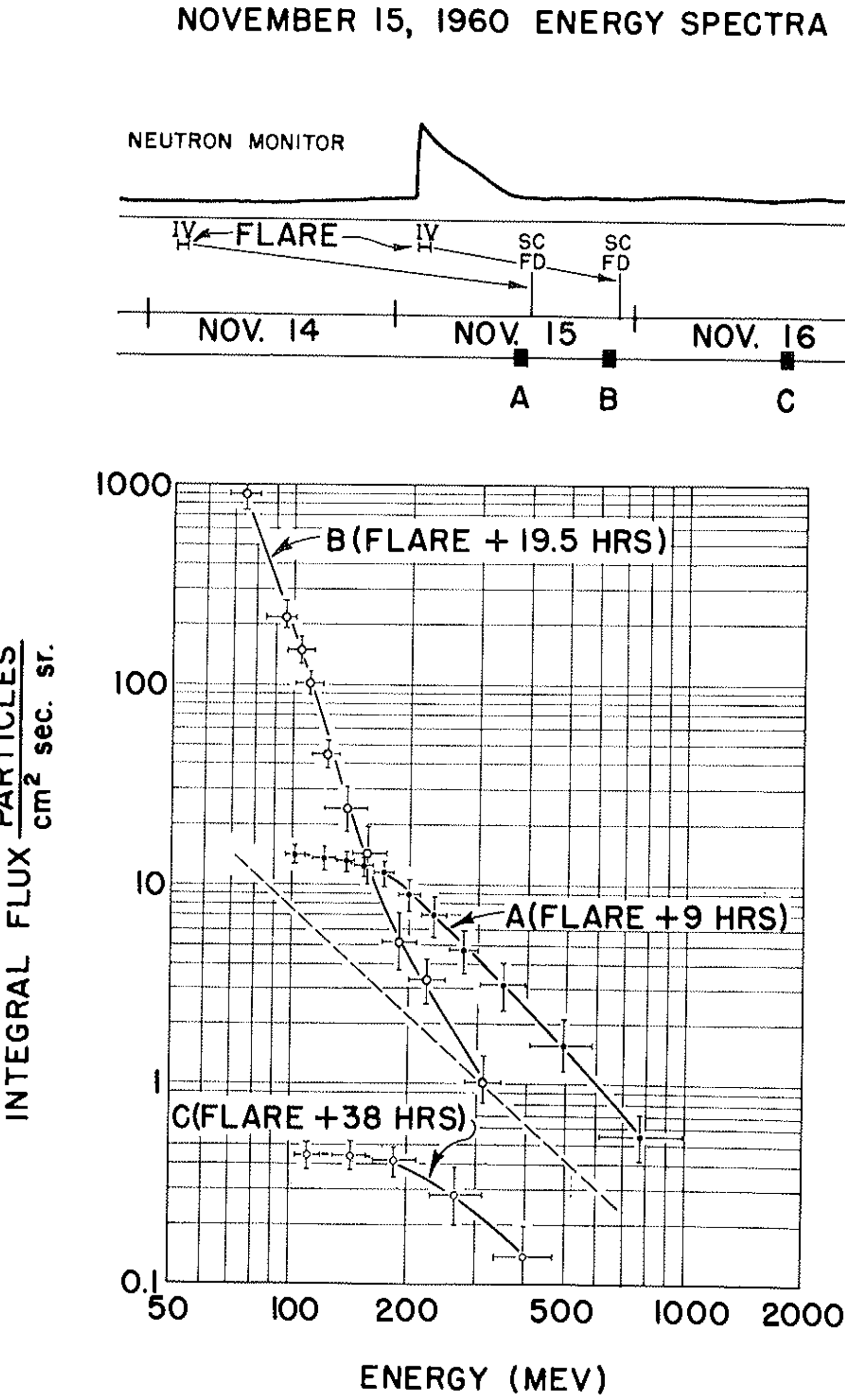


FIG. 4 — The energy spectra of the protons durin gthe Nov. 15 event.

cosmic rays and the flare on November 14 produced a plasma cloud which could guide and trap solar particles.

Three balloon flights were made. Flight A was flown after the cosmic ray flare but before the arrival of any plasma clouds, Flight B after the arrival of the plasma cloud from the first flare and Flight C late in the event. Also shown in Fig. 4 are the integral fluxes as a function of energy measured in Flights A, B and C. Flights A and C both made at magnetically quiet times show the presence of cut offs at about 200 MeV 0.65 GV rigidity). In Flight A (Flare + 9 hours) the integral flux is approximately 150 times cosmic rays and in Flight C (Flare + 38 hours) the flux is about 4 times cosmic rays. At the time of Flight B, the cut offs have been destroyed by the plasma cloud from the November 14 flare and this cloud has produced an excess flux of low energy particles which we believe are trapped in the interplanetary guiding fields associated with the plasma cloud. Note that when the cut offs are removed, the flux rises to about 10,000 times cosmic rays, but the excess particles are all of low energy. The flux of particles of energy greater than 300 MeV can be seen to decrease steadily with time from Flight A to Flight B to Flight C. This time decay at high energy is well fit by a power law of the form N ($>$300 MeV) = const. t^{-2} where t is the time after the cosmic ray flare on November 15.

Fig. 5 shows the solar system configuration for the November 15 series according to the model of Gold.

Flight A of Fig. 4 was at a time of high solar particle flux and the normal geomagnetic cut off was present. Because of these unique conditions, this flight is the only balloon flight in which solar particles heavier than α-particles could be measured. The intensity of solar particles was high enough to give a measurable flux of CNO nuclei and the presence of the cut off removed the large numbers of low energy protons ordinarily present. The combination of circumstances is much

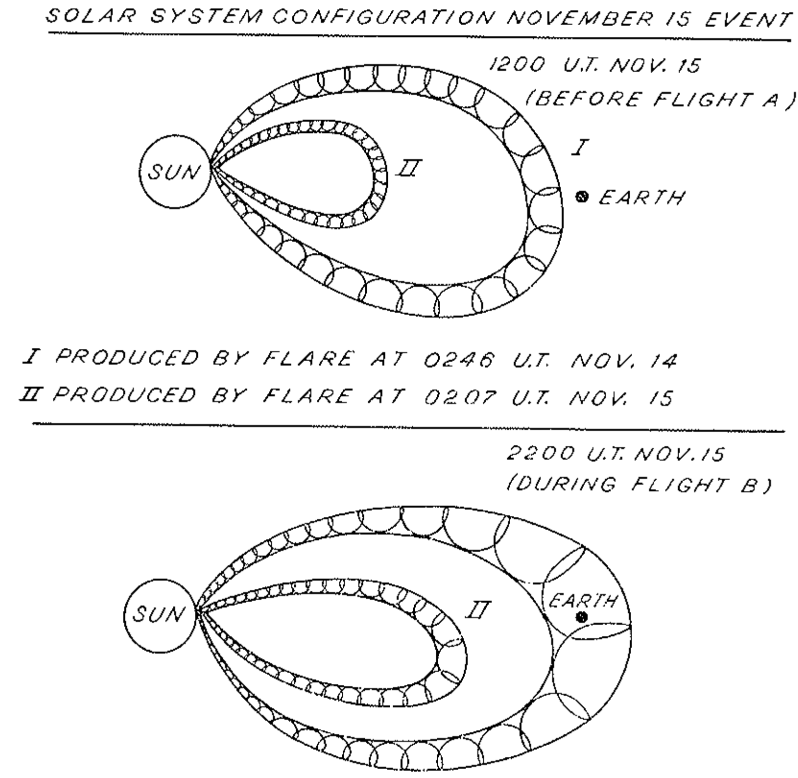


Fig. 5 — Solar system configuration which could account for the events of Nov. 15, 1960.

like the use of a magnetic rigidity selection combined with a range requirement frequently used in accelerator physics.

Fig. 6 shows the differential rigidity spectra for Flight A of the November 15 event. The figure shows the fluxes of protons, alphas, and CNO nuclei. Because of the range condition imposed by the air above, the various components can not be studied in the same rigidity range. However the indication is strong that the rigidity spectra of the several components

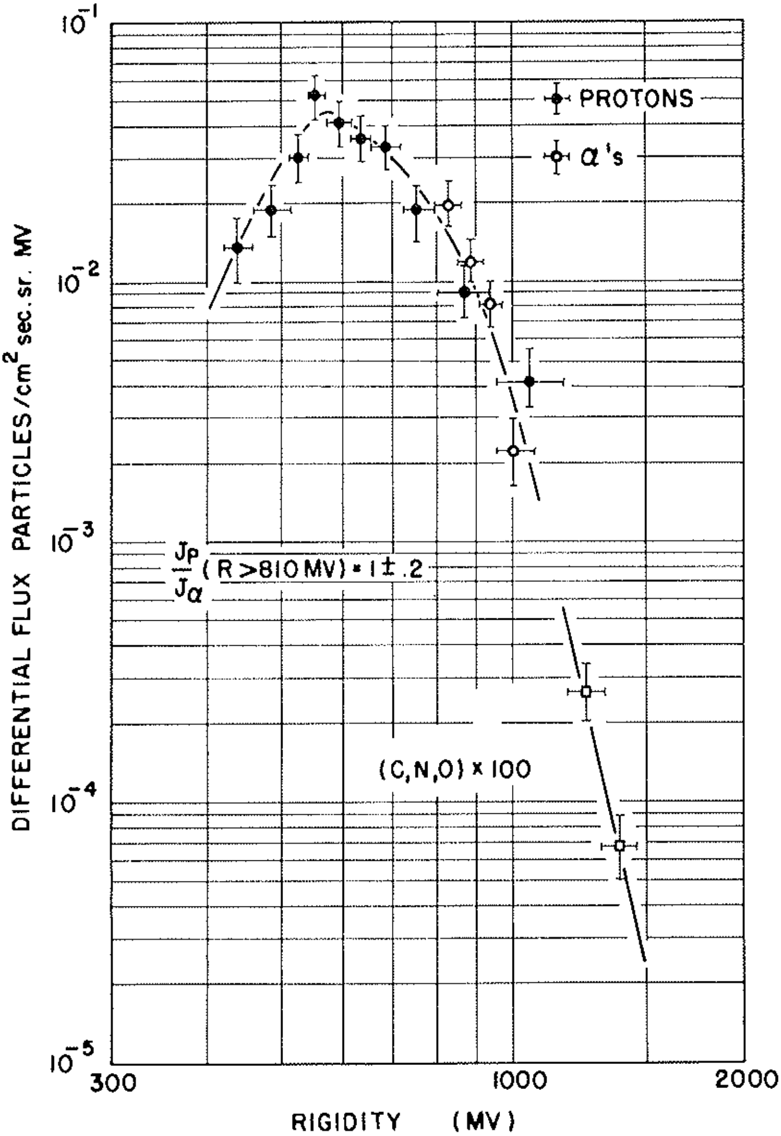


FIG. 6 — The differential rigidity spectra of protons, alphas and CNO in the Nov. 15, 1960 solar cosmic ray event.

are the same. It is important to note that the fluxes of protons and α-particles at the same rigidity are *equal* in this event, but that the CNO flux is 100 times less. The maximum in the differential rigidity spectrum of the protons is due to the presence of a geomagnetic cut off at 600 to 700 MV and the data clearly show that this cut off is *not sharp* as would be expected from simple geomagnetic theory.

Further evidence on the lack of sharpness of the cut off, has been obtained by J. EARL [8] in the September events. Fig. 7 shows cloud chamber pictures obtained at various times on Sept. 4, 1960. The two top pictures were taken before the decrease of the cut off energy. Note the scattered tracks of moderate energy solar protons. The two pictures at the bottom, which were taken after the change in cut offs, show many low-energy solar protons stopping in the plates.

Fig. 8 shows the measurements of EARL on the energy spectrum as a function of time and it can be seen that the maximum in the differential energy spectrum shifts to lower and lower energies as time goes on, but that the cut off is not sharp. Fig. 9 shows a plot of the Minneapolis flux divided by the free space flux as a function of rigidity. Although the cut off is not sharp, the attenuation of particles at low rigidities is very great. The attenuation of particles below the cut off is approximately a factor of 100 for a factor of 2 in rigidity. The intensity changes by 20 db for one octave of rigidity. Therefore if one considers the cut off as a kind of filter, it is a very effective filter. (In an electrical circuit an R-C filter attenuates 6 db per octave).

The ratios of abundances of the components of the solar beam are of some interest. The observations of all components have been made in two events, the November and September series to which we have previously referred. Table I gives a

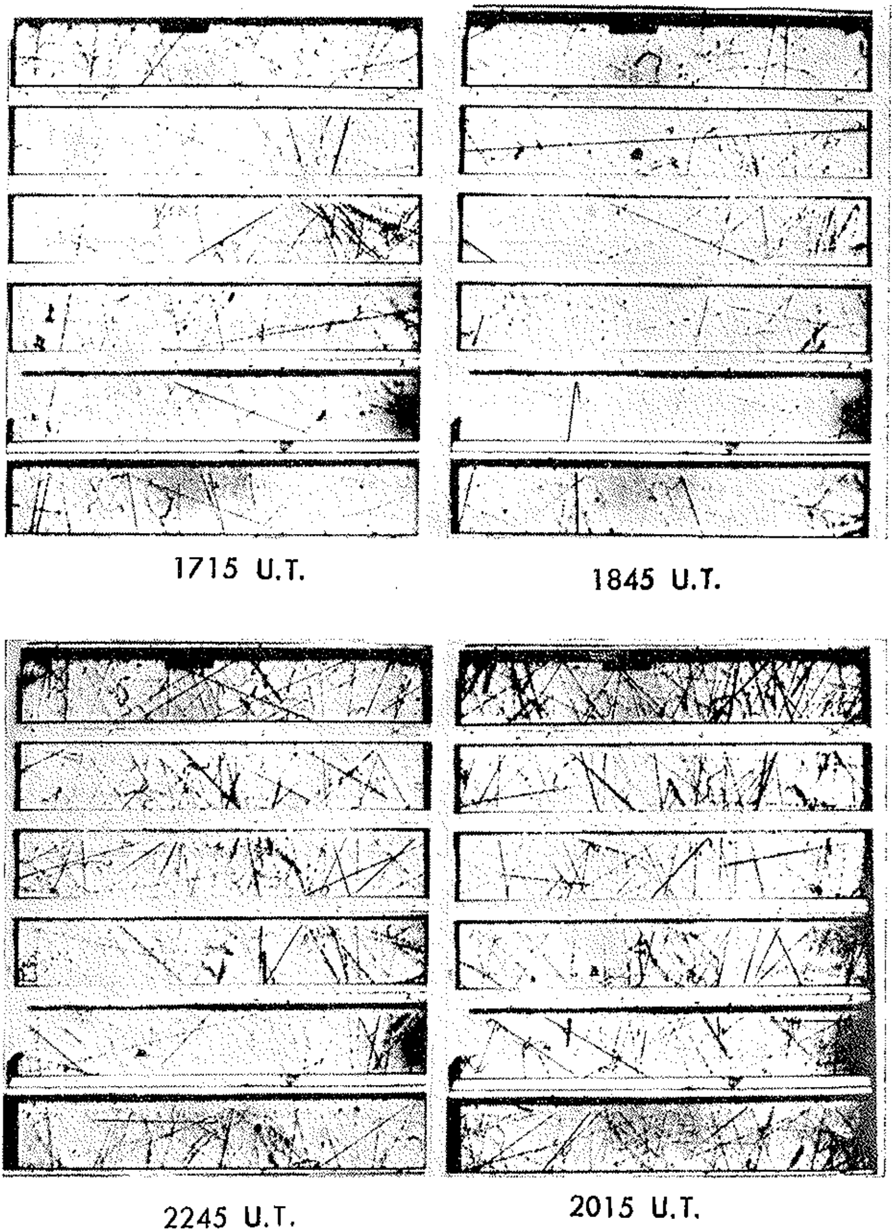


FIG. 7 — Cloud chamber pictures taken during the Sept. 3, 4 event by the balloon borne cloud chamber of J. EARL.

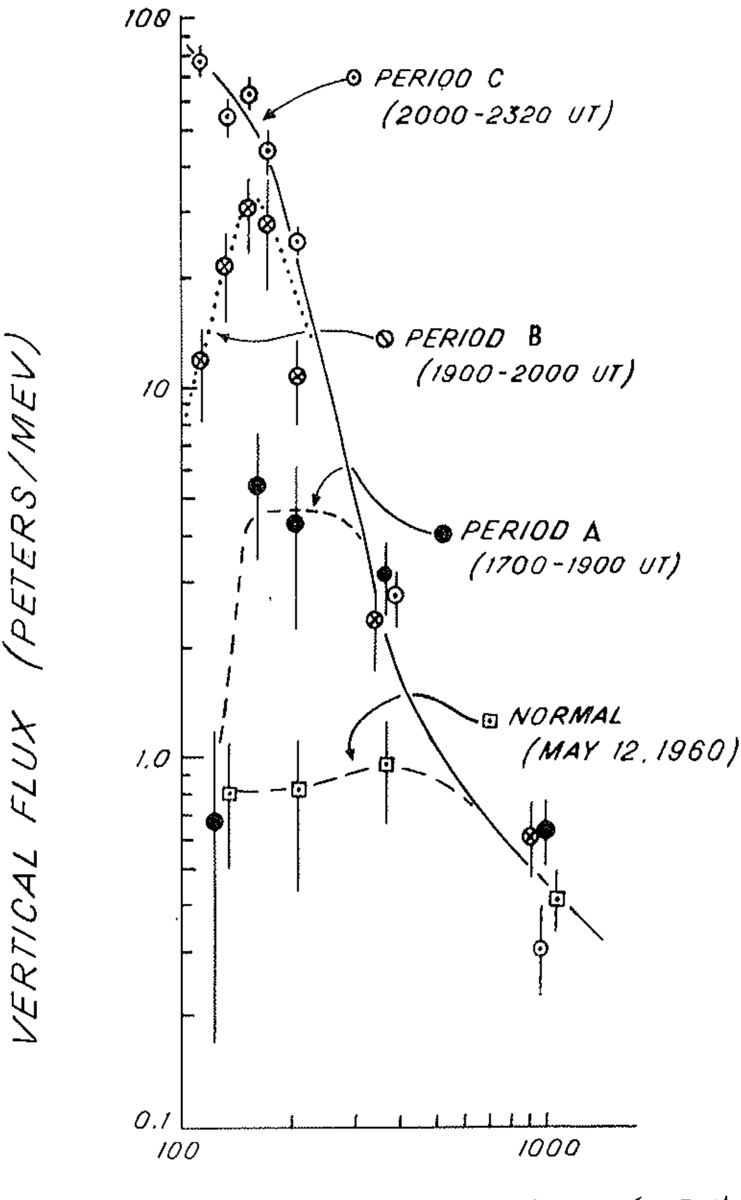


FIG. 8 — Differential energy spectra for the Sept. 3-4, 1960 event as obtained by EARL.

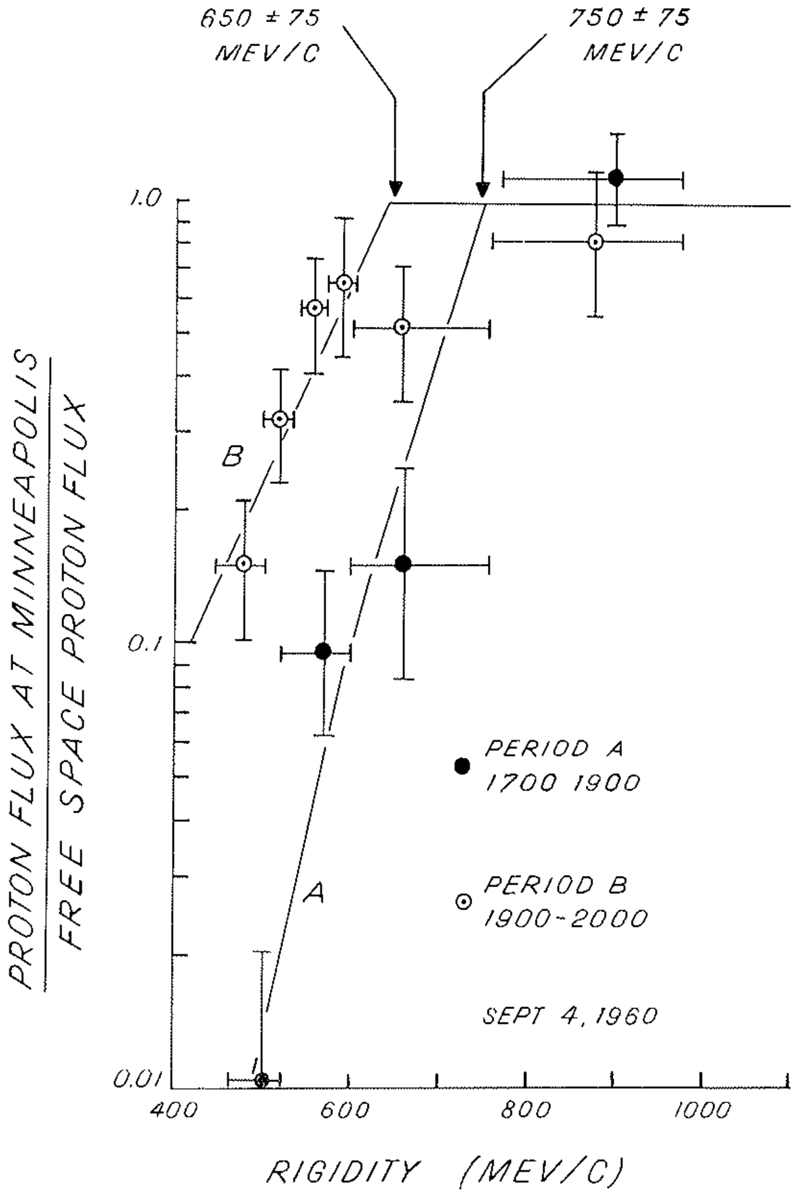


Fig. 9 — Earl's analysis of the attenuation of cosmic rays below the cut off energy. Considered as a filter, the geomagnetic cut-off produces an attenuation of approximately 20 db per octave of rigidity.

TABLE I

EVENT	RIGIDITY INTERVAL (GV)	$J_P / J_\alpha (> R)$	$J_P / J_M (> R)$	$J_\alpha / J_M (> R)$
SEPTEMBER 3, 1960 FICHTEL, GUSS	> .57	—	1250	42
SEPTEMBER 3, 1960 BISWAS, FREIER, STEIN	.87 — 1.32	30	—	
NOVEMBER 12, 1960 BISWAS, FICHTEL, GUSS	.57 — .87	5.5 0.8	330 60	60 75
NOVEMBER 15, 1960 9 HOURS AFTER FLARE NEY, STEIN	.81 – 1.08 PROTONS AND α-PARTICLES 1.18–1.45 (CNO)	1	100	100
NOVEMBER 15, 1960 42 HOURS AFTER FLARE FICHTEL, GUSS	.80	—	120	75
NOVEMBER 15, 1960 38 HOURS AFTER FLARE NEY, STEIN	.80	1.6	—	

summary of the measurements on the nucleonic component. The following facts seem well established:

1. Electrons constitute a very small fraction (less than 2%) of a solar beam as observed at the earth, when the comparison is made for particles of the same magnetic rigidity.
2. The rigidity spectra of the H, He and CNO nuclei are similar.
3. The relative abundance of He/CNO is 70±30 and seems to have the same value in both events (Sept. and Nov.).
4. The ratio of protons to α-particles differs widely from event to event. In the November series H/He = 1±0.2 and in the September events H/He = 30±5.

Several important conclusions may be drawn from these observations. Since the ratio of He/CNO is approximately constant from event to event, the conclusion is that all heavy nuclei (at least up to charge 8) are treated the same in the acceleration and propagation through space. There do not therefore seem to be important differential effects in the acceleration which depend on the ionization potential of the elements involved. Completely stripped He and CNO nuclei have the same mass to charge ratio and will therefore have equal velocities at the same rigidity. They seem to be accelerated and propagated in the same way and the ratio of He/CNO = 70 is believed to be characteristic of the abundances of the source region.

When we compare heavy nuclei with protons, however, we realize that at the same rigidity as the stripped heavy nucleus a proton will have twice the velocity. In a static magnetic configuration the heavy nucleus and proton of the same rigidity will travel the same trajectories, but the proton will travel its trajectory twice as fast. In any situation involving time varying magnetic fields or leakage of particles out of a magnetic trap one would expect that the protons would be propagated differently than the heavy nuclei. When we look at the two series of events previously described we find that the magnetic coupling to the sun was good in November when the H/He ratio was 30. We suggest that the richness of the November beam in helium is due to the differential escape of hydrogen leaving the region rich in alphas. In September it is likely that the particles observed are those which have escaped and for this reason the beam is rich in protons. The abundance of H/He at the sun is supposed therefore to be $1 < H/He < 30$. This means that there is considerable uncertainty about the ratio of H/He at the sun, but that the solar cosmic-ray measurements furnish a good value for the He/CNO ratio which is 70 ± 30. The value of the He/CNO ratio shows that the solar cosmic rays cannot be the source of the bulk as ALFVÉN [9] has suggested because in galactic cosmic rays the heavy nuclei are much more abundant with He/CNO = 15. The difference in the energy spectra of solar and galactic cosmic rays is also an argument (but not such a convincing one) that the sun does not produce the galactic cosmic rays. In order for stars like the sun to be the source of galactic cosmic rays one would have to have a further acceleration in space which flattened the energy spectrum *i.e.* produced more high energy particles) and also a mechanism which could accelerate high elements proportionately more (in order to increase the abundances of heavy nuclei over α-particles in the galactic beam).

The following tabulation gives the principal properties of the November 12 and 15 flares:

Maximum observed particle flux above 80 MeV . . .	= 600 particles/ cm^2 sec ster
Total integrated flux above 80 MeV at orbit of earth . .	= 10^8 particles/cm^2

Total energy in particles passing the earth if the particles are distributed over 2π steradians	$= 3 \times 10^4$ ergs/cm^2
Total energy in particles above 80 MeV emitted at sun, assuming isotropy at the sun .	$= 4 \times 10^{31}$ ergs
Total energy emittet at the sun, assuming emission into 0.1 steradians	$= 4 \times 10^{31}$ ergs
Total radiation does in space due to particles of energy greater than 80 MeV . . .	$=$ 60 roentgens
Average energy density in particles observed at the earth	$=$ 20eV/ cm^3
Magnetic field necessary for magnetic energy density to be equal to particle energy density	$= 3 \times 10^{-5}$ gauss.
Total number of protons accelerated at sun	$= 10^{33}$

* * *

One final point must be discussed in connection with abundances and this is the observed very low abundance of electrons of the same rigidity as of positively charged nucleons. Mr. WAYNE STEIN has approached this problem in a very interesting way. He has investigated the possibility that the electrons are indeed accelerated in such a way that they acquire the same rigidity spectrum as the protons and are in approximately equal numbers, but that the electrons lose their energy by synchrotron radiation in solar magnetic fields. The task is to see whether the observed electromagnetic radiation from flares is consistent with the above assumptions. To anticipate the result, it seems that the electromagnetic radiation both in the radio range and in the *visible* portion of the spectrum may be accounted for. Mr. STEIN and I take as an important feature of the cosmic ray flare, the emission of visible light. Although the sun is *not* monitored in white light, visible light has been frequently seen by chance during large flares which accelerate cosmic rays. Examples of white light flares are Sept. 1, 1959, Aug. 30, 1957, Sept. 3, 1960 and Nov. 15, 1960. STEIN and I have investigated the possibility that the white light is due to one or more of the following causes:

1. Scattering by free electrons.
2. Free-bound transitions and capture of H-ions.
3. Čerenkov radiation.
4. Bremstrahlung or free-free transitions.
5. Synchrotron radiation.
6. Black-body radiation.

We have shown that mechanisms 1, 2, 3, 4 and 6 fail by orders of magnitude to account for the white light. Consequently we have looked for the conditions under which 5 could be responsible for both the radio emission and the white light from the flare. We consider that the acceleration of particles takes place during the flash phase of the flare and have taken flux values for the time appropriate to this. It is true that radio emission is observed long after the flash phase but the frequency spectrum of this late radio emission seems characteristic of low energy electrons.

Fig. 10 shows the order of magnitude of the fluxes required as a function of frequency. Note that when one includes the white light point at 10^{15} c/sec the spectrum is one in which the intensily increases with increasing frequency from 10^9 to 10^{15} c/sec. It can be shown that any *power law* spectrum of electrons *i.e.* $N(>E) \approx E^{-n}$ with $n > 1$ will give a synchrotron spectrum with the opposite slope *i.e.* one in which the intensity decreases with increasing frequency). The physical reason for this is that power law spectra have too many low energy electrons and therefore produce excess intensity in the radio range of the frequency spectrum.

Fig. 10, however, does have a certain qualitative resemblance to the universal synchrotron spectrum for *monoenergetic* electrons of OORT and WALRAVEN [10] which is reproduced in Fig. 11. In Fig. 11 we plot OORT's $F(\alpha)$ which is related to the power/c/sec by the equation $P = 2.3 \times 10^{-29} BN_e F(\alpha)$ where B is the magnetic field in gauss and N_e the number of radiating electrons. It appears that the general form of the electromagnetic spectrum could be fit by the radiation of monoenergetic electrons. Although various combinations of electron energy, magnetic field, numbers of electrons and half life against radiation are possible, the following set of values represents a reasonable situation:

Electron energy	=	500 MeV
Number of electrons	=	10^{33}
Magnetic field	=	300 gauss
Half life of electrons	=	6 seconds

It can be seen that rather high energy electrons are required, but that the total number of these electrons is equal to the inferred number of accelerated protons. Also the magnetic field required is not excessive, and the time constant is com-

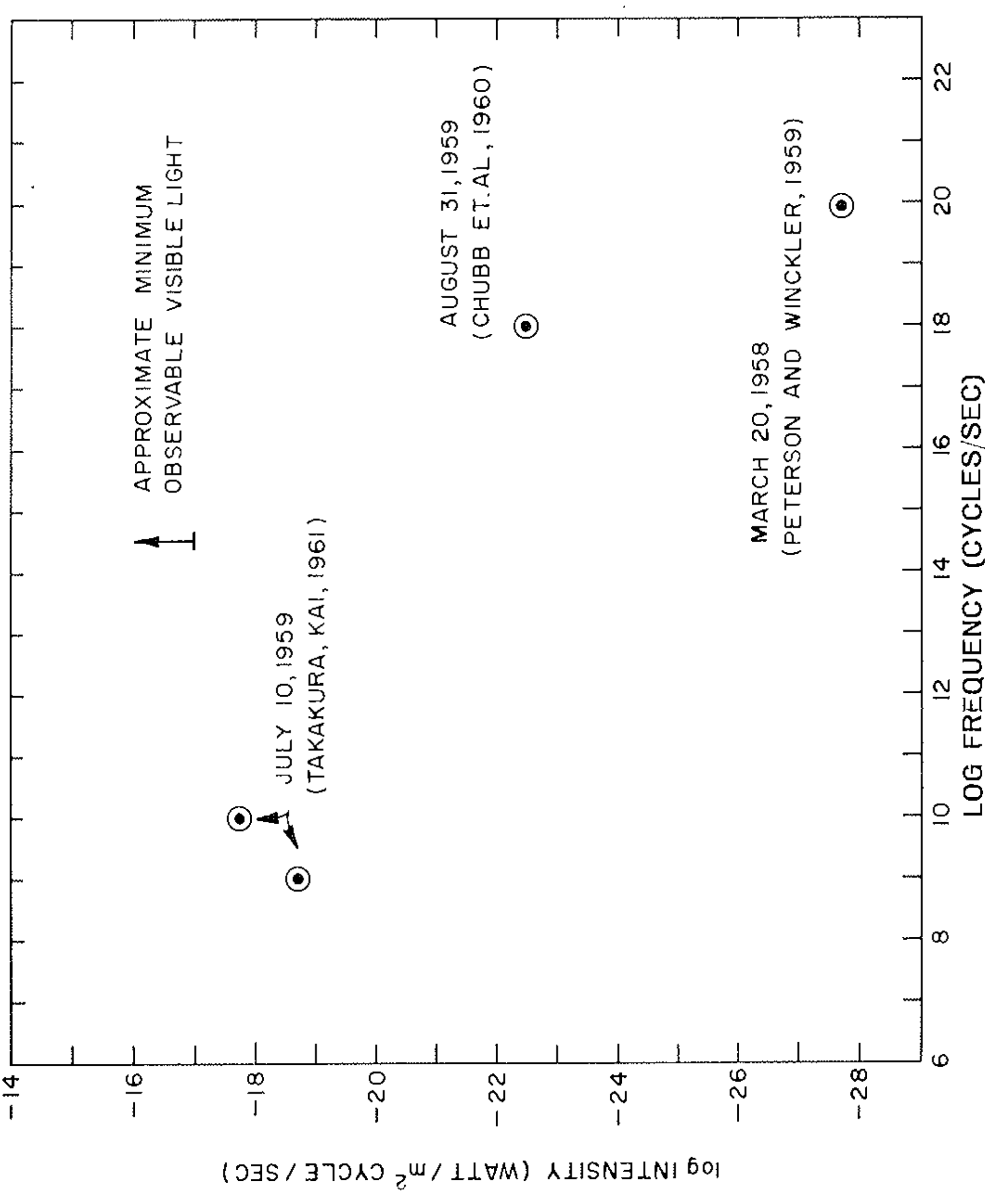


FIG. 10 — Typical values of flux as a function of frequency for solar cosmic ray flares.

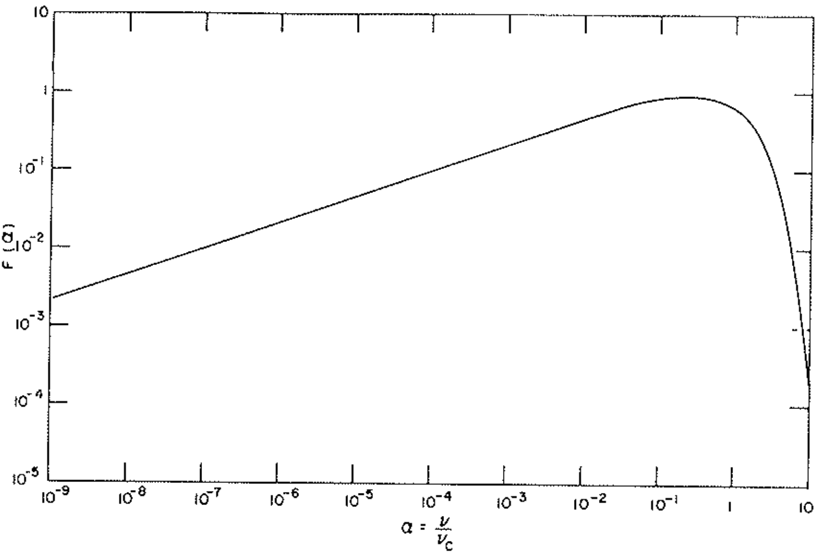


FIG. 11 — The universal synchrotron radiation curve of OORT and WOLRAVEN.

patible with the idea that the electrons lose their energy before they can escape the high fields near the sun.

However, it seems that the assumption of monoenergetic electrons is somewhat artificial and Mr. STEIN looked into the possibility that an *exponential* rigidity spectrum of the kind the protons are known to have, could also fit the observed electromagnetic spectrum.

Fig. 12 shows STEIN's result. He has numerically integrated the synchrotron radiation eqnation for an exponential rigidity spectrum and he does in fact find the same general form of the power *versus* frequency curve that the monoenergetic spectrum gave. His curves are calculated for various values of R_o, the « e-folding » rigidity in the spectrum. An $R_o = 200$ MV corresponds to the kind of proton spectrum observed in the November 1960 events. The exponential rigidity spectrum of electrons with an « e-folding » rigidity of ≈ 200 MV and with

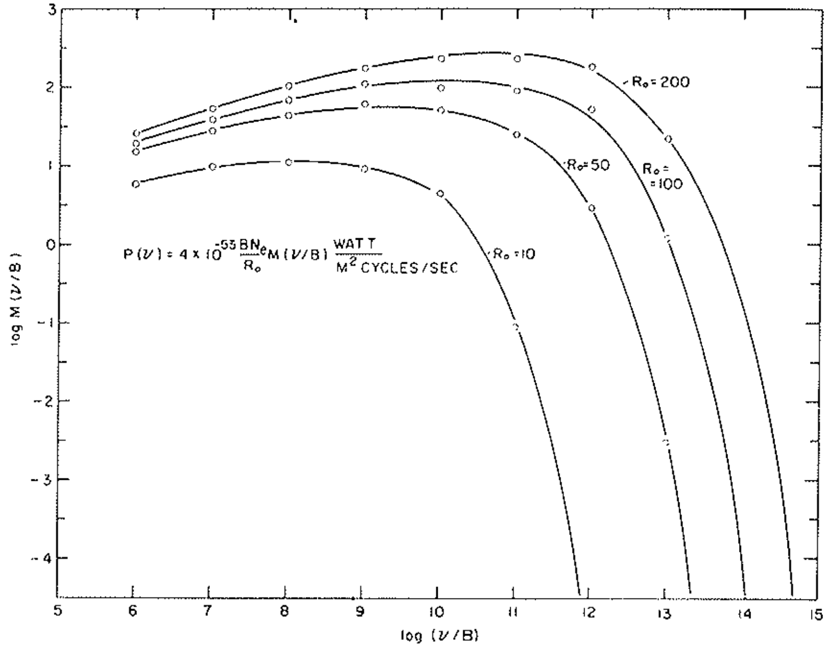


FIG. 12 — The synchrotron radiation curves for an exponential rigidity spectrum of electrons.

about 10^{32} to 10^{33} electrons will account for the radio and visible light from the flare provided the magnetic field is of the order of 500 gauss. When we turn to the X-rays however it seems that the synchrotron model gives too small X-ray fluxes in general and it is probable that some other process such as bremstrahlung must be responsible for them as has previously been suggested by WINCKLER.

[7] *Ney* - pag. 25

REFERENCES

[1] I. Lange and S.E. Forbush, *Terr. Magn.*, *47*, 331, 1942.

[2] A. Ehmert, *Z. Naturforsch*, 3a, 264, 1948.

[3] P. Meyer, E.N. Parker and J.A. Simpson, *Phys. Rev.*, *104*, 768, 1956.

[4] K.A. Anderson, *Phys. Rev. Lett.*, *1*, 335, 1958.

[5] G.C. Reid and H. Leinbach, *J. Geophys. Res.*, *64*, 1801, 1959.

[6] D.K. Bailey, *Proc. Inst. Radio Engrs.*, *47*, 255, 1959.

[7] T. Gold, *J. Geophys. Res.*, *64*, 1665, 1959.

[8] J.A. Earl, *J. Geophys. Res.*, *67*, 2107, 1962.

[9] H. Alfvén, *Tellus*, 3, 232, 1954.

[10] J.H. Oort and Th. Walraven, *Bull. Astron. Instr. Nether.*, *12*, 285. 1956.

DISCUSSION

Chairman: E. AMALDI

HAYAKAWA

As far as I understand, you correlate the radio spectra with the electrons near the solar surface. I wonder whether these electrons can get out of the magnetic barrier? If you correlate the energy spectra for the type IV outburst, emitted far from the solar surface, these electrons can certainly reach the earth, but other electrons would not.

NEY

Let me show another slide (Fig. 13). The slide is constructed for a magnetic field of 500 gauss. It shows the way the energy spectrum will be expected to change with time. At $t=0$ it is assumed to be an exponential spectrum, at later times it becomes steeper, and by the time 100 seconds have elapsed the energy spectrum has gone so steep that probably it would be undetectable at the earth. What we believe is that this is the reason why the electrons do not escape to be detected at the earth. Was that the question or did you have another point in mind?

HAYAKAWA

I was just wondering whether your model was concerned with radio emissions near the solar surface where the magnetic field is very strong.

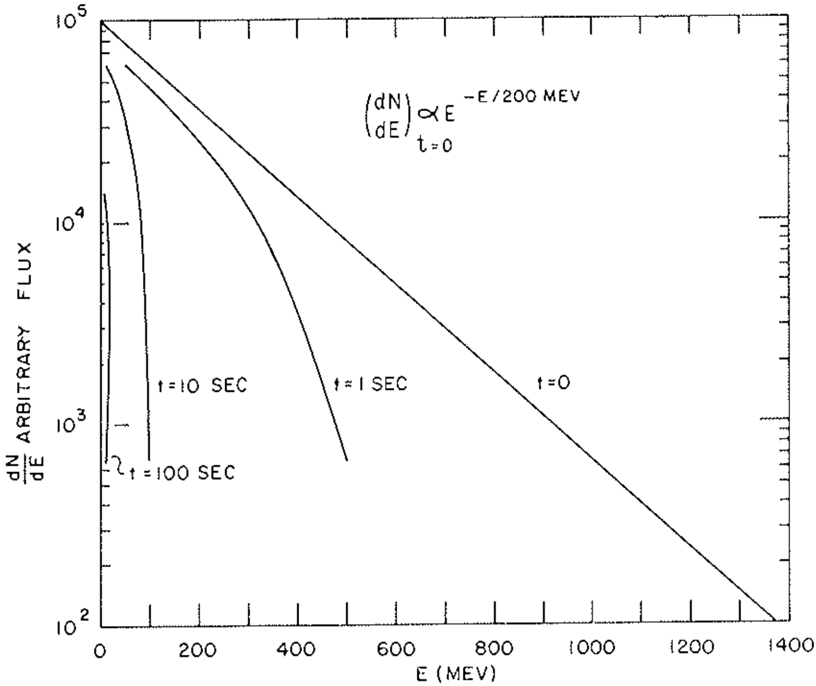


FIG. 13 — The energy spectrum as a function of time for solar electrons, initially having an exponential rigidity spectrum in a magnetic field of 500 gauss.

NEY

Yes, in the chromosphere.

HAYAKAWA

But if we pay attention to radio waves emitted far from the solar surface, say at one solar radius, the elapse then would be much longer, so that energy spectrum cannot appreciably change.

NEY

Yes, because the magnetic field would be lower. I would not want to go too high up in the chromosphere, but be where the electron density is low enough so that collisions do not dominate but where the field is still adequate for synchrotron radiation.

BIERMANN

This question of whether or not the continuous light can also be regarded as a non-thermal emission is a very interesting one. For some years REIMAR LÜST and I have endeavoured to see in which various ways the non-thermal energy is both gained and spend. Up to now our impression was that if you take the total energy which is spent in a flare, the largest amounts are possibly given out in the form of corpuscular radiation, which in Prof. PARKER's picture becomes the blast wave, and of white light, whereas the amount going into nearly or fully relativistic particles such as protons and electrons is something like 10^{-2} of this (see for instance the work of the Chicago group on the February 1956 flare, which appears to be consistent with the evidence from other flares). If we have really a white light emission, then the emission is comparable to the ordinary flux of thermal energy on the surface. I have some difficulty in accepting that this is due to synchrotron radiation which would make it necessary to assume that we get a much larger proportion in the form of energy of relativistic particles than we have assumed so far.

NEY

I can say that what we consider as possible alternatives are: 1) scattering by free electrons, 2) free-bound transitions and electron capture to produce H^-, 3) Čerenkov radiation, 4) brehmsstrahlung or free-free transition, and 5) synchrotron radiation. The first four fail by orders of magnitude in accounting for the intensity of the white light, but the synchrotron radiation with essentially monoenergetic electrons or with an exponential rigidity spectrum does in fact work out quantitatively.

BIERMANN

As far as I know it is not at all impossible, as for instance has been discussed by UNSÖLD, to give a picture of a chromospheric flare, in which one accounts for the continuous radiation by assuming a temporarily higher temperature of certain levels of the upper photosphere. That, I think, is the most conventional way of looking at the phenomenon. Did you consider this?

NEY

We considered black-body radiation and we concluded that it required excessive particle densities.

SIMPSON

The point that Dr. NEY has emphasized regarding the absence of high energy electrons beyond the solar corona is a very important one. There is one case, however, that we know of where electrons are present following a flare. The spectrum has been published by MEYER and VOGT for the flare of July 14, 1961. An electron spectrum for energies > 100 MeV was observed at a higher level than the background electron flux. This is an area of research which needs a great deal of exploration before the time of solar minimum activity to understand solar particle acceleration and propagation through the corona.

NEY

I think if it can be verified that the observation of MEYER and VOGT really represented electrons from the sun, then what I said about electrons is probably nonsense. However, I think there are some real questions about the observation. It is a very small event and very late after the flare. Also MEYER and VOGT get a spectrum which is not as steep as the spectrum of the protons themselves, and it is hard to see how electrons can have a less steep spectrum when they are subjected to synchrotron radiation losses. If it is right, then one has to have a completely different picture from the one I have outlined.

PETERS

I did not quite understand whether you suggested that the fractionation mechanism which changes the proton to α-particle ratio occurs during acceleration or during storage.

NEY

My own belief is that it happens during propagation because of this auxiliary information that the well connected event was the one that was rich in α-particles and the poorly connected event was rich in protons. That is the only argument that I can make for it, but I believe that is an argument for fractionation occurring during the propagation rather than during the acceleration.

PETERS

Does this imply a non-magnetic effect acting on the particles after they leave? I do not understand how you can get different propagation for particles with the same rigidity.

GOLD

The particles are stored to a considerable extent in fields in the vicinity of the sun. What the fractionation seems to imply is that between the source and the arrival at the earth particles are diffused not only in a static field, which would not achieve this effect at all, but that they are diffused in a field in which time variation plays an important part. Now, that is just what one would expect to occur near the sun where the feet of all those loops are anchored in the turbulent photosphere and where therefore the process of getting particles from one region to another will be more of shunting them around in an arbitrary and random fashion. The particular magnetic regions accessible to a particular particle will rapidly change from one time to another. Therefore particles that have a different transit time will go through this maze in quite a different fashion, so one could expect a large difference in the proton to α ratio at the earth. But if, on the other hand, we only had a diffusion by a nearly static, or at any rate a very slowly varying system out in space, then it would only be the rigidity that should count, although of course the time of arrival might still be very different. But over the whole of an event we should not have a very different ratio of proton to α.

VALLARTA

A comment about the disappearance of the geomagnetic threshold that you spoke about. According to standard theory the threshold that we expect at the latitude of Minneapolis and beyond would be essentially determined by the shadow cone, so if you find a disappearance of the geomagnetic threshold it means essentially that the shadow cone has disappeared. That is quite in agreement with the theory, it takes a very small perturbation for the shadow cone to disappear. And we must expect that there is an external magnetic field quite different from the ordinary external field when you have the appearance of a solar flare.

Now, I should like to raise one question at this point: how do you known that these protons you are talking about are really solar?

NEY

At the time when these things happen, the fluxes can be as high as a thousand times cosmic rays and it is hard to imagine that the particles would be coming from anywhere else.

LES ERUPTIONS ET L'EMISSION DES RAYONS COSMIQUES SOLAIRES

J.F. DENISSE

Section d'Astrophysique - Observatoire de Paris - Meudon - France

Sommaire — Les éruptions solaires chromosphériques qui sont associées à une émission de rayons cosmiques possèdent plusieurs propriétés caractéristiques. Optiquement elles se caractérisent par une structure en forme de filaments allongés, généralement double, qui se situe au dessus des ombres des taches elles-mêmes, c'est-à-dire au-dessus des régions de forts champs magnétiques. Ces éruptions sont souvent accompagnées d'un phénomène explosif caractéristique (effet Moreton) et d'un assombrissement du spectre continu (nimbus d'Ellison).

Dans le spectre Hertzien, elles émettent un rayonnement très caractéristique: le sursaut du type IV, interprété comme le rayonnement de particules relativistes. La longue durée des émissions radioélectriques associées à ces éruptions suggère qu'il existe un mécanisme capable de piéger une partie au moins des rayons cosmiques au voisinage du soleil.

La découverte des rayons cosmiques produits par le Soleil et l'interprétation des émissions radioélectriques et des rayons X solaires laissent à penser que le phénomène essentiel qui se produit au cours d'une éruption est la production de particules,

---

Abstract — Solar flares associated with cosmic ray emission show several characteristic properties. Optically they are characterised by an elongated filament structure, double in general, which is situated above sun spots *i.e.* above regions of high magnetic fields. These flares

ions et électrons, d'énergies élevées. Si les cas où les énergies atteignent quelques GeV sont exceptionnels, il est probable que des énergies de l'ordre du MeV sont produites même lors d'éruptions relativement banales.

Jusqu'à ces dernières années, l'extrême diversité de l'aspect optique et de l'évolution des éruptions chromosphériques n'avait pas permis d'en donner autre chose qu'une classification rudimentaire par ordre d'importance, selon des critères d'ailleurs assez variables suivant les observateurs et surtout les moyens d'observation qui s'appuient suivant les cas sur l'étendue, sur la brillance, ou sur la largeur de la raie Hα, etc. de l'éruption.

La découverte, au cours de ces dernières années, de nombreuses émissions de rayons cosmiques liés aux éruptions [1] [2] et d'un rayonnement hertzien caractéristique: le sursaut de type IV [3], apparemment dû à l'émission synchrotron des électrons relativistes produits [4], a permis d'isoler dans la masse des éruptions une catégorie particulière d'événements singulièrement efficaces quant à leurs possibilités d'accélération.

Il n'est pas douteux qu'une étude approfondie de ces éruptions particulières à l'aide des différents moyens dont on dispose actuellement dans les domaines optiques, X, γ, hertzien, corpusculaires, permettra de dégager des caractères communs à cette catégorie particulière d'éruptions qui représentent *grosso-modo* 25% des éruptions 3, 4% des éruptions 2 et 0,4% des éruptions 1 [5].

On peut espérer que ces caractères communs aboutiront, entre autres choses, à une connaissance plus précise des énergies mises en jeu, des configurations des régions intéressées, de

---

are often accompanied by an explosive phenomenon (Moreton effect) and by a darkening of the continuum spectrum (Ellison nimbus).

In radio wave spectrum these flares are emitting a very peculiar radiation, the type IV burst, which is interpreted as magnetic bremsstrahlung by relativistic particles. The long duration of the radio emission associated with such flares suggests the existence of a mechanism suitable for trapping at least a part of cosmic rays near the sun.

l'échelle de temps des phénomènes essentiels, du nombre et de la nature des particules accélérées, etc. et permettront de mieux connaître le mécanisme d'accélération des particules.

Nous nous bornerons, dans cet exposé, à décrire les caractères communs qui apparaissent à l'heure actuelle significatifs de cette catégorie d'éruptions. Dans ce domaine, les observations radioastronomiques, bien qu'encore rudimentaires, ont apporté beaucoup d'éléments nouveaux et bien caractérisés. Ceci tient au fait que les particules de haute énergie ne se manifestent qu'indirectement dans les domaines optiques ou X par l'excitation du milieu environnant quand celui-ci est suffisamment dense, alors qu'elles peuvent être détectées dans le domaine radio directement par le rayonnement synchrotron, pour les électrons, et indirectement, pour les particules des deux signes, par l'excitation Čerenkov du plasma très peu dense de la couronne.

On peut schématiquement décomposer l'évolution d'une éruption typique en plusieurs phases distinctes. Ces phases sont bien connues, et, comme nous venons de le dire, nous en décrirons seulement les quelques caractères qui nous paraissent plus significatifs que les autres.

1. La structure du centre éruptif et la phase préliminaire

Les éruptions qui nous intéressent ont tendance à se produire à l'intérieur de plages faculaires qui enserrent un groupe de taches multipolaires complexes à champ magnétique fort.

Observé sur le disque, le centre est le siège de structures allongées le long desquelles se produit généralement l'éruption. Parfois, cette structure est matérialisée par un petit filament sombre caractéristique dit *filament de plage* [6], généralement actif, d'intensité variable et de courte durée de vie. Parfois, la structure allongée se présente au contraire comme une région plus brillante que le reste de la plage faculaire.

A priori, ces structures ne paraissent pas occuper de position très définie par rapport aux taches visibles (Fig. 1); pourtant elles se retrouvent nettement dans la forme de l'éruption, elles restent fixes en dépit de leur variation d'éclat et figurent certainement un domaine d'importance essentielle pour la suite des évènements.

Quand on l'observe au voisinage du limbe, le centre actif apparait surmonté d'arches brillantes d'éclat variable.

Dans le domaine radioélectrique, le centre d'activité est le siège d'une source d'émission de faible étendue et de brillance exceptionnelle sur ondes centimétriques [7]: ces condensations étroites, dont le rayonnement est polarisé circulairement, indiquent que la haute chromosphère, au lieu où se produira l'éruption, présente une densité et une température qui sont anormalement élevées.

Quelques dix minutes avant que ne se produise l'éruption proprement dite, se manifestent les signes avant-coureurs du phénomène explosif. Ils se traduisent par une activation d'abord progressive du centre, de petits points brillants apparaissent souvent le long du filament de plage, celui-ci parfois s'évanouit en partie ou complètement au cours de cette phase qui voit également augmenter progressivement l'émission radioélectrique de la condensation alors que les arches visibles au bord du disque intensifient leur éclat [8].

2. La phase explosive

Brusquement, en l'espace d'une demi-minute environ, se produit la phase explosive de l'éruption [9]; généralement l'éruption s'étend le long des structures allongées et souvent se forme en deux filets brillants qui l'encadrent [6] (Fig. 2). Dans presque tous les cas, l'emplacement du filament est déterminant même lorsque l'on assiste en même temps à sa disparition partielle ou totale. Ellison [10] a montré que dans le

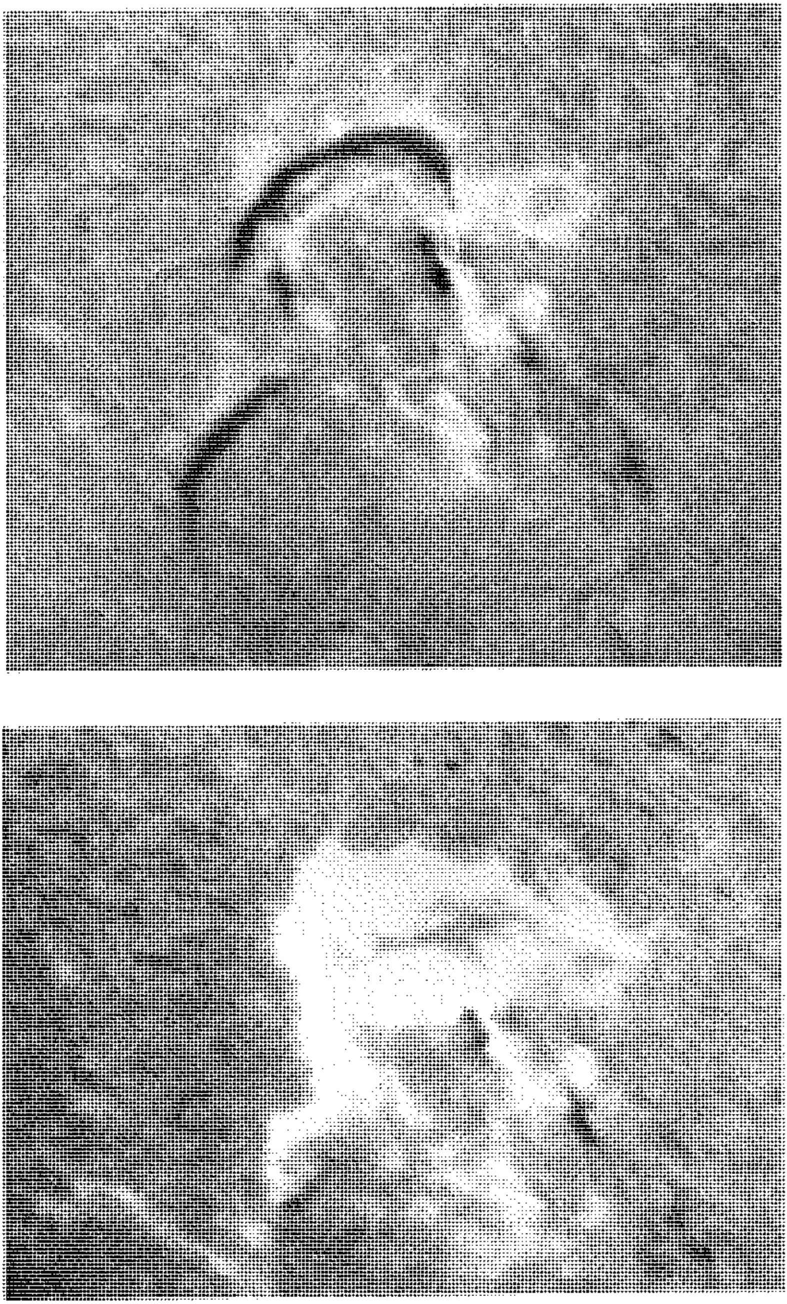


FIG. 1 — Deux aspects du centre d'activité avant et pendant l'éruption du 3 Juillet 1957 (MEUDON).

FIG. 2 — Trois phases de l'éruption du 21 Avril 1939, photographiée à Meudon à 16h 45m, 17h 05m et 17h 33m.

cas particulier des plus fortes éruptions qui ont produit des rayons cosmiques observables au voisinage du sol, cette structure des éruptions en forme d'un double filet est tout à fait caractéristique. La phase explosive de l'éruption est particulièrement nette dans le domaine radio où elle se traduit non seulement par un accroissement très brutal de la brillance du centre éruptif en ondes centimètriques, mais aussi par l'éjection d'une perturbation qui traverse la haute couronne avec une vitesse ascentionnelle égale à une fraction de la vitesse de la lumière (60.000 à 270.000 km/s): c'est le sursaut de type III [11]. La durée de ce « flash » n'excède guère quelques secondes et occasionellement peut d'ailleurs se reproduire plusieurs fois en l'espace de quelques minutes. Bien que le mécanisme exact du rayonnement de ce sursaut ne soit pas complètement élucidé, on peut penser qu'il est dû à l'excitation d'oscillations du plasma coronal par des électrons rapides. Ainsi ce phénomène montre qu'aux premiers instants de l'éruption, pendant la phase explosive, des particules de haute énergie sont déjà produites.

Moins d'une minute après le type III apparaît parfois un continuum fugitif (sursaut de type V) probablement dû au rayonnement synchrotron de ces mêmes particules [12].

Quelquefois, au cours de cette phase de l'éruption, on observe des émissions de rayons X [13] qui doivent sans doute leur origine au rayonnement de freinage des électrons rapides et dont l'intensité doit dépendre beaucoup de l'altitude à laquelle se produit l'éruption.

3. La phase d'expansion

Au cours de cette troisième phase, la luminosité de l'éruption continue à s'étendre progressivement le long des configurations stables décrites plus haut (Fig. 2 et 3); les deux filets brillants ont tendance à s'écarter l'un de l'autre [6] et dans le cas des plus importantes éruptions à rayons cosmiques [10],

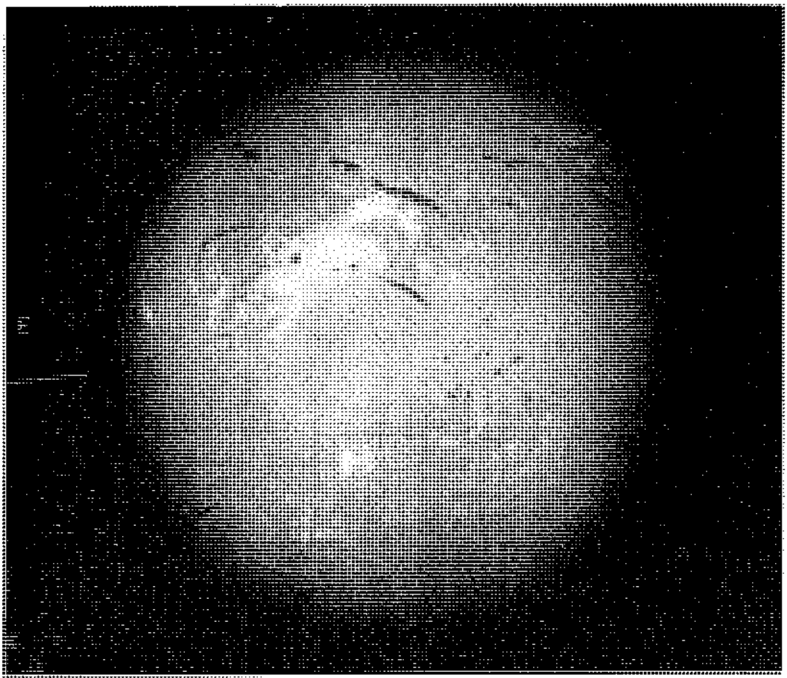


FIG. 3 — Eruption du 25 Juillet 1946 (MEUDON).

[14] ces deux filets se situent au-dessus des taches optiques elles-mêmes [14] et apparemment recouvrent chacun des taches de polarité différente. En même temps, la luminosité diffuse lentement pour s'étendre aussi à d'autres régions du champ. Immédiatement après la phase explosive, des masses de matières absorbantes voisines de la zone éruptive sont projetées dans l'espace avec des vitesses généralement de l'ordre de quelques centaines de km/s (Fig. 4).

Cette phase d'expansion est caractérisée au point de vue radio par deux perturbations distinctes.

L'une d'elles, bien localisée dans l'espace, le sursaut de type II [12], s'élève dans la couronne avec une vitesse de

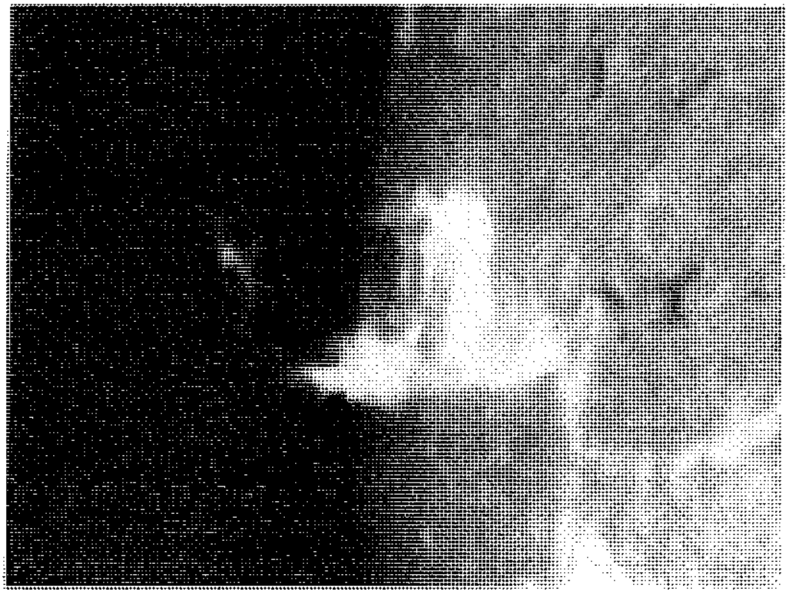


Fig. 4 — Eruption du 4 Décembre 1957 (Meudon).

l'ordre de 1000 km/s et s'interprète comme l'excitation du plasma coronal par l'onde de choc produite par l'explosion initiale.

La seconde apparaît immédiatement après et se présente comme un nuage dont les dimensions atteignent une dizaine de minutes d'arc et qui s'éléve aussi dans la couronne avec une vitesse comparable à celle du type II. Le rayonnement de cette source, le sursaut de type IV [3] se présente comme un continuum très stable et a été interprété comme le rayonnement synchrotron d'électrons relativistes peut-être piégés dans le milieu aval de l'onde de choc [4].

Pour le moment, il n'existe que de très rares mesures simultanées des positions des sources de type II et IV et la liaison physique qui existe sans doute entre ces deux phénomènes n'a pas été précisée. Certains types IV ont pu être suivis dans leur ascension jusqu'à des distances de 6 à 8 rayons solaires. L'émission observée sur une seule fréquence parait ensuite s'éteindre sur place au bout d'une heure environ, mais il n'est pas sûr que la perturbation ne poursuive pas sa progression en rayonnant sur des fréquences de plus en plus basses.

C'est ce sursaut de type IV qui paraît le plus étroitement lié à l'émission des rayons cosmiques solaires [5], comme d'ailleurs aux orages géomagnétiques [15] et aux décroissances de Forbush [16].

Deux phénomènes optiques récemment découverts, mais qui n'ont pas encore reçu d'interprétation satisfaisante sont probablement la contrepartie dans le domaine visible de ces sursauts radio.

L'un d'eux a été décrit par MORETON [17]: il s'agit d'une modification progressive de la visibilité des matières filamenteuses obscures situées dans la chromosphère alentour du centre éruptif; les films de la chromosphère pris avec des filtres monochromatiques montrent que ces changements d'aspect s'étendent progressivement jusqu'à des distances de l'éruption de plusieurs centaines de milliers de km avec des vitesses d'expansion comparables à celles dn type II.

L'autre phénomène est le « nimbus » d'ELLISON [18] qui se traduit par un obscurcissement diffus de quelques pourcents de la plage qui entoure le centre éruptif et qui n'apparaît que lors des éruptions les plus importantes.

4. Les suites de l'éruption

A la suite de la phase d'expansion, s'établissent progressivement dans la couronne des régions stables qui continuent à émettre un intense rayonnement radio, principalement sur ondes longues, pendant des heures et même des jonrs après le début de l'éruption, c'est-à-dire bien longtemps après qu'aient cessé complètement toutes les manifestations optiques de l'activité éruptive. Ces régions sont probablement associées aux jets coronaux et leur rayonnement, polarisé circulairement, constitue la famille des orages radioélectriques [5].

On ne voit guère que les particules énergiques accélérées au cours de l'éruption qui soient capables d'entretenir aussi longtemps l'activité de l'orage et il faut alors imaginer que celles-ci restent piégées au voisinage du soleil dans des configurations magnétiques convenables. Une difficulté de cette interprétation réside dans le fait que ces sources d'émission sont « unipolaires » dans le sens que leur sens de polarisation est rattaché à la polarité de la plus grosse tache du groupe associé, généralement la tache de tête [19], alors que les configurations les plus simples que l'on puisse imaginer pour piéger les particules devraient être bipolaires. Si toutefois l'émission de ces sources est dûe, comme il semble, au rayonnement Čerenkov des particules dans le plasma, seuls des gradients élevés de la densité coronale peuvent permettre à ce rayonnement de sortir de la couronne sans absorption excessive et il est possible que ces conditions particulières créées par l'éruption elle-même ne soient réalisées qu'au voisinage d'une polarité privilégiée.

REFERENCES

[1] S.E. FORBUSH: *Phys. Rev.*, *70*, 771, 1946.

[2] J.R. WINCKLER, *J. of Phys. Soc. of Japan*, *17*, Supp. A II, 353, 1962.

[3] A. BOISCHOT, *Comptes-Rendus*, *244*, 1326, 1957.

[4] A. BOISCHOT et J.D. DENISSE, *Comptes-Rendus*, *245*, 2194, 1957.

[5] M. PICK-GUTMANN, *Ann. Astr.*, *24*, 183, 1961.

[6] M.J. MARTRES-TROPÉ et M. PICK-GUTMANN, *Comptes-Rendus*, *254*, 3975, 1962.

[7] M.R. KUNDU, *Ann. Astr.*, *22*, 1, 1959.

[8] G. NEWKIRK, *Astrophys. J.*, *133*, 983, 1961.

[9] R.G. GIOVANELLI, *Aust. Journ. Phys.*, *11*, 191 et 350, 1958.

[10] M.A. ELLISON, *Dunsink Observatory Publications*, *1*, 53, 1961.

[11] J.P. WILD, *J. of Phys. Soc. of Japan*, *17*, Supp. A II, 249, 1962.

[12] J.P. WILD, K.V. SHERIDAN and A.A. NEYLAN, *Aust. J. Phys.*, *12*, 369, 1959.

[13] M.R. KUNDU, *J. of Phys. Soc. of Japan*, *17*, Supp. A II, 259, 1962.

[14] H.W. DODSON-PRINCE et E.R. HEDEMAN, *Astron. J.* 5, *65*, 51, 1960.

[15] P. SIMON, *Ann. Astr.*, *23*, 102, 1960.

[16] Y. KAMIYA, *J. of Phys. Soc. of Japan*, *17*, Supp. A II, 391, 1962.

[17] R.G. ATHAY et G.E. MORETON, *Astrophys. J.*, *133*, 935, 1961.

[18] M.A. ELLISON, S.M.P. MCKENNA et J.H. REID, *M.N.R.A.S.*, *122*, 491, 1961.

[19] A.M. MALINGE, *C.R.*, *250*, 1186, 1960.

DISCUSSION

Chairman: E. AMALDI

BIERMANN

I think that the asymmetry you are talking about could be connected with the following structure of the magnetic field. Supposing the flux which comes out of the spot region is going back over a much larger area, which is often the case according to the magnetic field measurements. The field configuration should be such that at some lateral distance the particles are reflected mostly in a region where the field is weaker. In this way these might result in a pronounced asymmetry of the radio emission. Is that a picture with which you would agree?

DENISSE

I can agree with this scheme, if we can actually have a reflection on the regions of opposite polarity at high enough altitude for those particles not being absorbed in the chromosphere. We have to consider that those storm sources may last for a week or more, and in spite of the fact that they seem to be replenished by other flares, it is probable that the particles have to spend most of their life at high altitude to be able to survive. If those conditions are satisfied, I do not think the observations are contradictory to your proposal, but if such is the case it is rather surprising that we do not observe more often some storms with polarisation of both senses.

ROSSI

Pourrais-je vous demander un renseignement sur la hauteur à laquelle ces émissions se produisent?

DENISSE

Cela dépend de la longueur d'ondes d'observation; par exemple, ces émissions sont observées à un demi rayon solaire d'altitude, sur 2 m de longueur d'onde. On a pu en observer jusqu'à des altitudes supérieures à un ou deux rayons solaires.

ROSSI

Vous avez dit que l'émission dure pendant des journées entières?

DENISSE

Ces emissions peuvent se prolonger avec de très grandes fluctuations d'intensité, 5 à 6 jours après l'éruption solaire.

VALLARTA

Quel est le spectre du rayonnement électro-magnetique émis par le soleil pendant un orage?

DENISSE

Pendant ce type d'orage le spectre émis est assez étroit; il est lié visiblement à la fréquence critique du milieu coronal; on observe de nombreux effets d'occultation et de réfraction qui montrent que l'indice est certainement voisin de zéro dans cette région; c'est pour cette raison, que l'on peut l'interpréter comme un rayonnement Čerenkov.

GHERZI

Les différentes fréquences que l'on enregistre en radioastronomie sont-elles émises par des sources distinctes, ou est-ce qu'une très haute fréquence initiale devient graduellement plus basse? On enregistre sur un mètre, etc... est-ce qu'il y a des formations successives de ces radiations électro-magnétiques?

DENISSE

Dans le cas des orages et surtout des sursauts de type II et III, les fréquences émises diminuent quand augmente l'altitude d'observation. Ce n'est pas entièrement vrai pour le type IV dont toutes les fréquences sont approximativement émises au même endroit.

GOLD

Is the polarization asymmetry equally strong at the highest frequencies that you can see in these outbursts as at the lower frequencies? The reason I am asking this is because the mirror points of the particles would of course be expected to be at the same field strength in the loop, no matter whether this field is dense on one side and loose on the other, so the emission should be similar from the two sides. On the other hand, if the critical plasma layer intervened, then it would obscure perhaps one side from your sight, and allow the other side to be seen.

DENISSE

If, as you say, the mirror point was lower on the opposite polarity we should observe the other polarisation, say, on decimeter wave, and this is not observed: this emission is mostly ordinary. In the frequency spectrum, there is actually a shift from extraordinary to ordinary, which occurs in the decimetric region as was shown by Japanese observers. But this decimetric emission only lasts half an hour or so just after the flare, and disappears during the noise storm.

A STUDY OF THE CHANGES IN THE PRIMARY COSMIC RADIATION DURING A SOLAR CYCLE

H.V. NEHER
California Institute of Technology - Pasadena, Cal. - U.S.A.

Abstract — Some features of the variation of the primary cosmic radiation during the solar activity cycle are presented with particular reference to the upper atmosphere measurements near the North geomagnetic pole in the period 1937-1961.

Several questions are discussed which arise in trying to fit this information into a consistent picture of the conditions in interplanetary space.

One of the important characteristics of cosmic rays is the fact that they change by a large factor during the period of a solar cycle. So far, our knowledge of this change is rather meager, but it is to be hoped that with space probes now available, more information will be forthcoming.

The reasons for our lack of knowledge of the nature of the 11-year variation in cosmic rays (which is also the period of a solar cycle) arise from several causes. First, we might mention the obvious reason of the necessary length of time involved. It has only been realized within the last 10 years that such a phenomenon exists. It is then not surprising that our information is not complete since we have not yet witnessed, since the discovery, a full solar cycle of change. We recall that the time from a minimum solar activity to a maximum is, on the average, 11 years, but it is also known that the real solar cycle is 22 years. There are some things in nature we cannot hasten — man cannot as yet control the activity of the sun!

Another reason why our information is incomplete about the 11-year cycle variation in cosmic rays, is that to study the effect as such, one needs to make experiments in the polar regions near the top of the atmosphere, if the effect is to be studied from the earth. The reason for this is that the largest effect on cosmic ray particles during this secular change, is among those particles with low energy, and it is only at the higher latitudes that such low energy particles are admitted. This is because the magnetic field of the earth turns away the slower particles at lower latitudes. Hence, there is a question of accessibility. Also, since the particles have low energy they are easily absorbed in the atmosphere, and hence high altitude balloons are required. These two requirements, of high altitude and high latitude, thus present experimental difficulties.

We do, however, have considerable information about this 11-year solar-cycle-connected change in cosmic rays.

a) The most important property is that there is an inverse correlation between solar activity and cosmic-ray intensity. Thus, when the sun is most active the cosmic-ray intensity is a minimum and when the sun is least active, the cosmic-ray intensity is a maximum. This inverse relationship was pointed out by Forbush in 1953.

b) The two above phenomena are not exactly anti-correlated. There appears to be a 9-12 month lag of cosmic ray effect from being inversely correlated with solar activity. This was also first pointed out by Forbush.

c) The change in the numbers of cosmic-ray particles during an 11-year period is quite large, amounting to a factor of 3 to 5 from solar maximum to solar minimum. The major part of this change is in those particles that can penetrate the earth's magnetic field only above geomagnetic latitude 50°. For protons this corresponds to an energy of about 1.6 GeV.

d) During a time of medium to high solar activity, there appears to be a definite cut-off of particles with energies below those that could arrive at the earth above 53° to 55° geomagnetic latitude. This is evidenced by the fact that at very high altitudes, there is a latitude at which an abrupt change in the spectrum of the primary particles occurs as one proceeds toward the poles. Most of the time during the solar cycle, this cut-off exists even though the number of primary particles may vary by a factor of 2 or more. The latitude at which this so-called « knee » occurs shifts slightly during such a change of the primaries, but the shift is only a degree or two. However, during the last solar minimum, there were two years, namely in 1954 and 1955 when this knee did not exist and primary particles down to 100 MeV for protons were present in the primaries. Normally when the knee exists the cut-off is about 800 MeV for protons.

e) The particles that change have the same atomic numbers as those always present in cosmic rays. Thus, the major change is in the protons, but there are also changes in the α-particles, and in the light, medium and heavy nuclei.

f) These changes are of such a nature tbat it appears that magnetic fields are responsible for the change.

A remark or word of caution should be injected here in regard to what one might anticipate in future years. The solar minimum of 1954 was lower than had ever been recorded. Further, the solar maximum of 1958 was higher than any solar maximum that has been recorded. Consequently, in view of the chance of a recurrence of such behavior of the sun, we might not find cosmic rays increasing to as high a maximum as they exhibited in 1954, during this next solar minimum of 1964-65. Likewise, cosmic rays may not reach the very low value at the next solar maximum of 1969-70, that they had in 1958-59.

An illustration of what may occur is illustrated in comparing the years 1937 and 1958. Balloon flights were made at high latitudes during each of these years. Also, the sun was at a maximum of activity during these two years. However, the intensity of cosmic rays was about 60% higher in 1937, at high altitudes and latitudes, than in 1958. This is in keeping with what would be expected since the solar maximum of 1958 was much more pronounced than it was in 1937.

In Fig. 1 are shown the changes in the intensity of cosmic rays near the north geomagnetic pole that have taken place over the years. The change in the number of particles involved is even more than the change in the areas under these curves. In Fig. 2, the data in Fig. 1 have been replotted and other years have also been included, showing the changes that have taken place during the period 1951-1961, at given atmospheric depths. At the top of this figure are also given the changes in the sun spot numbers and the magnetic character figures that have taken place during the same period.

In Fig. 3 are the results of baloon flights made in the southern hemisphere during 1958 [3]. These curves show the way in which the cosmic ray intensity suddenly ceases to increase as one proceeds to higher latitudes. In Fig. 4 the change of the geomagnetic latitude is shown at which the knee occurs for different amounts of air overhead. The indication is that even with no air overhead, the latitude at which the knee occurs would not move much further toward the pole. The evidence points to an absence of primary particles below a certain magnetic rigidity.

In trying to fit the above information into a consistent picture of the conditions in interplanetary space, one is faced with a number of questions. Some of these may be stated as follows:

1. During a solar minimum is the vicinity of the earth expe-

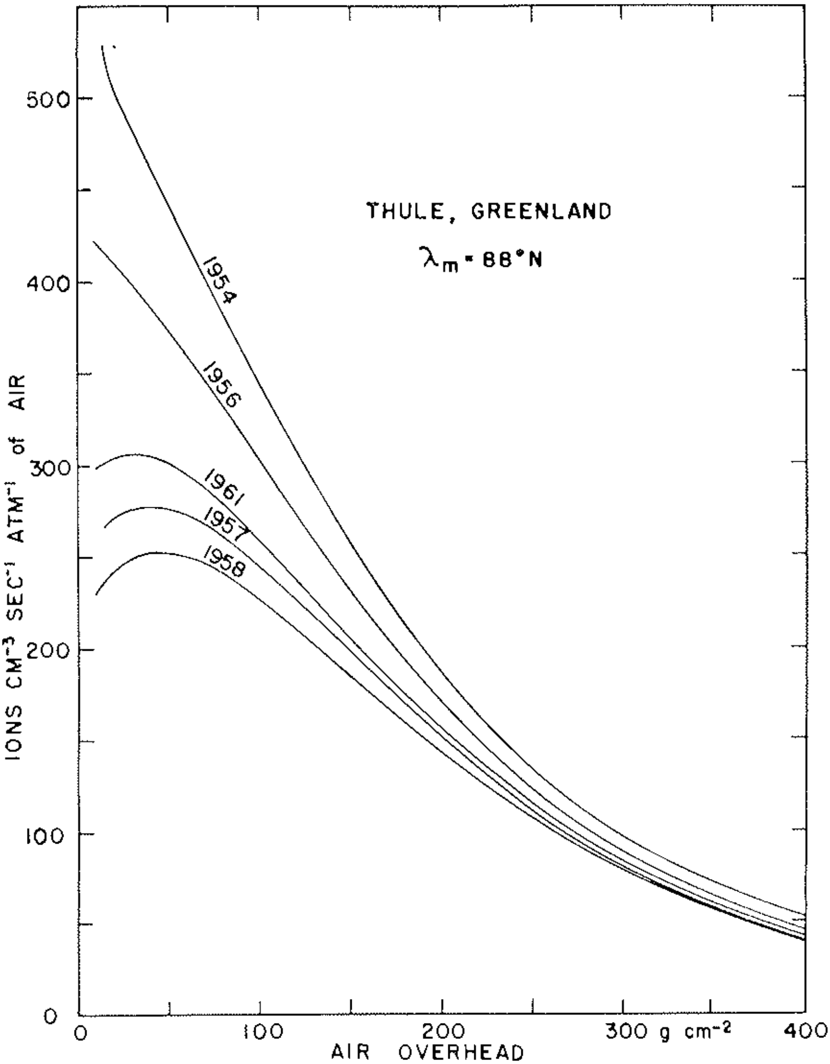


FIG. 1 — The ionization produced in the atmosphere by cosmic rays is here plotted against depth in the atmosphere for several years. These data were taken with balloon borne instruments sent up near the north geomagnetic pole. Analysis shows that the number of primary cosmic ray particles changes by a factor of at least 4 during a solar cycle.

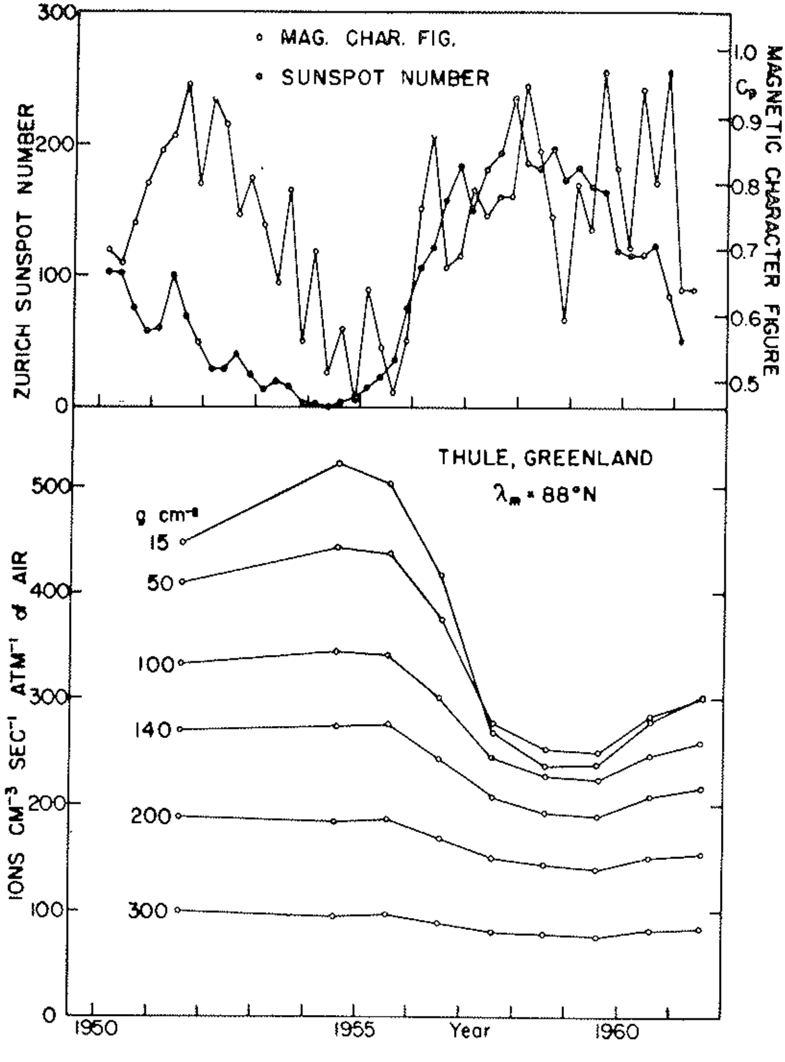


Fig. 2 — The lower part of this figure shows the ionization produced by cosmic rays at given depths in the atmosphere over a 10-year period. The top part of the figure shows the corresponding sun spot numbers and magnetic character figure for the same period.

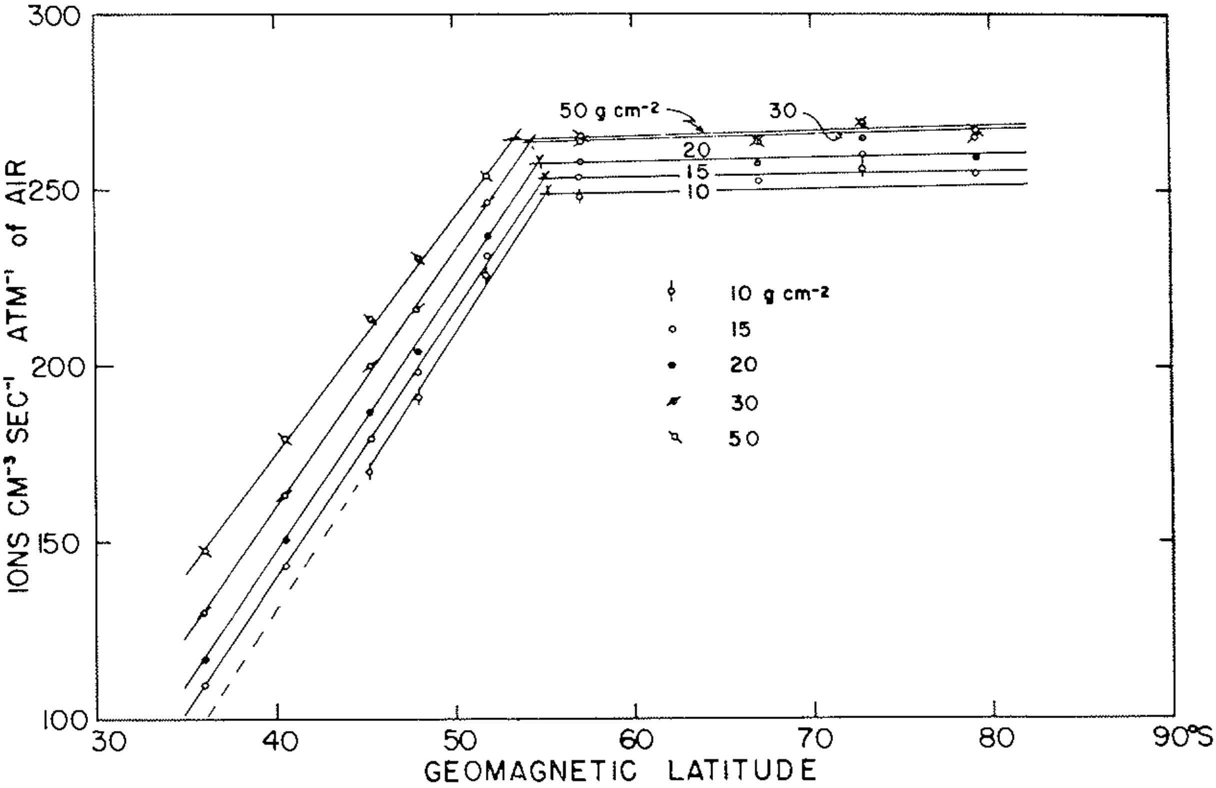


FIG. 3 — During 1958 a survey was made from the Arctic to the Antartic. Here we have plotted the ionization due to cosmic rays at various given depths in the atmosphere *vs* geomagnetic latitude. It is seen that above a certain geomagnetic latitude, called the « knee », the change with latitude is very small.

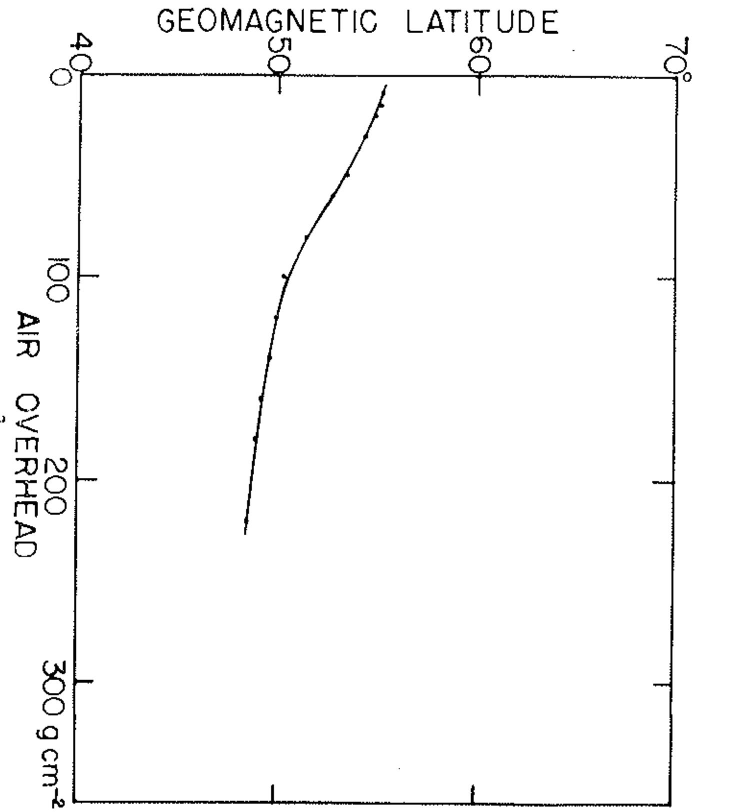


FIG. 4 — Here the location of the knee is plotted as a function of the amount of absorbing air above the instrument.

riencing the full galactic intensity of cosmic rays? Is there any evidence that it is not?

2. Indeed, is the major part of the cosmic-ray particles that we normally measure not of galactic origin at all, but, as Prof. ALFVÉN [4] insists, of solar origin?

3. Assuming that cosmic rays are of galactic origin, over what

region of the planetary system is the 11-year modulation mechanism effective?

4. There appears to be a time lag of 9 to 12 months of cosmic ray changes from being anti-correlated with solar activity. Are we to interpret this as being the time for the solar plasmas, with their associated magnetic fields to travel out into, or to collapse from the planetary system?

5. Is the 11-year cycle of change in cosmic rays of the same nature as the Forbush type of change? Thus, are solar plasmas responsible for both kinds of change, with the chief difference being in the extent of the region over which the mechanism is operative?

6. It appears from BABCOCK's work [5] that the sun is a magnetically variable star with a period of 22 years. Evidence is that it reverses polarity at a time of a maximum solar activity. How is this to be taken into account in our picture of the influence of the sun on charged particles in the planetary system? Also, how does this affect some of the mechanisms that have been proposed for magnetic effects on solar produced high energy particles?

7. What is the mechanism responsible for the cut-off of low energy particles in cosmic rays when the sun is active?

8. How sharp is the cut-off and is this consistent with what is to be expected from the action of plasmas with their magnetic fields, or, is some other mechanism involved?

A few remarks might be made in, at least, partial reply to the above questions. In regard to the first question, in 1940 a series of balloon flights was made from Bismarck, N.D. ($\lambda_m = 56°$N) to San Antonio, Texas ($\lambda_m = 38°$N). At the higher latitude station, namely Bismarck the cosmic ray intensity was some 10% higher at high altitude than it was at the same station in 1954. In 1954 the sun was at a minimum of activity and one might expect that the full galactic intensity of cosmic rays would be arriving at the earth. There is every reason to think that the data of 1940 can be compared with those of 1954 since the same instruments were used for standardization in the two years. The high values of 1940 were persistent for at least a few days and were present during the three flights made at Bismarck. The data taken by the ionization chamber at Huancayo also shows a larger value than normal for these few days. The interpretation is then, that cosmic rays were more intense at this time than during the very inactive period of the sun which occurred in 1954. The two interpretations seem to be, 1) that during 1954 there was still some modulation of cosmic rays occurring or 2) that the galactic intensity of cosmic rays can change in relatively short periods of time.

In regard to the second question there seem to be several strong arguments against a general solar origin of cosmic ray particles. While the sun is known to give rise to high energy particles at frequent intervals, Alfvén has argued that the sun could be a source of all cosmic ray particles with energies less than say 10^{12} to 10^{14} eV. If the region in the vicinity of the sun were effective in accelerating particles to high energies one would reasonably expect such a mechanism to be most effective during an active period of the sun. To account for the inverse relationship between solar activity and cosmic ray intensity it would be necessary to have a storage mechanism which would give a delay of 5 or 6 years. Thus one would expect a maximum of solar activity to be followed by a maximum of cosmic ray activity some 5 or 6 years later. Experimental evidence points to a close anticorrelation but with cosmic rays lagging about 6 to 9 months behind.

A second objection to the sun being a major source of cosmic rays is that one would not expect the chemical composition in that case as is actually found in cosmic rays. Thus the sun has a very low relative abundance of Li, Be and B compared with C, N and O. It is difficult to see how these nuclei could be produced in sufficient quantity by spallation effects if they are acceleration in the possible Van Allen bands of the sun or in its corona.

There are certainly further objections to the idea that any large proportion of cosmic rays are produced by the sun. I give this to you for further comments.

In conclusion I want to give some of the preliminary results HUGH ANDERSON and I have already obtained from the Venus space vehicle, Mariner-R2. This space probe is behaving very well, having transmitted back to earth about 5 weeks of data so far. The ionization chamber on board was carefully calibrated against our standards. Also the Geiger counters were calibrated in terms of particles cm^{-2} sec^{-1} for the whole solid angle. We have flown with the same balloon one of these space vehicle ion chambers, which has a thin wall (10 MeV for protons) along with one of our usual balloon chambers which has a wall twice as thick. The space instrument also is smaller, being only 5 inches in diameter compared with 10 inches for the balloon instrument.

These instruments were carefully compared with our standards before making a flight. The data from the space craft instrument was 3% lower than that from the other instrument.

Data from the space craft show an ionization of about 610 ions cm^{-3} sec^{-1} atm^{-1} of air. Instruments flown at Thule, Greenland some three weeks before showed an ionization near the top of the atmosphere of 370 ions cm^{-3} sec^{-1} atm^{-1} of air. One would expect a factor of 2 when comparing these data, since the earth shields out one - half the solid angle at Thule. Thus one would expect 740 ion cm^{-3} sec^{-1} atm^{-1} of air in space from the results at Thule. Allowing for 3% mentioned above, one is left with a difference of 12%. Tentatively we think this is due to the albedo effect which exists at Thule, which is not present out in space.

A further result is as follows: The quantity that connects the number of particles passing through a given volume of gas and the ionization they produce, is the average specific ionization. Thus $I = \bar{\sigma} J$. Now the Geiger counter on board, that has the same wall thickness as the ion chamber, has been counting 3.0 particles cm^{-2} sec^{-1}. Thus the average specific ionization is

$$\bar{\sigma} = \frac{I}{J} = \frac{610}{3.0} = 203 \text{ ions cm}^{-1}.$$

This number is close to that estimate for the average specific ionization of cosmic ray particles in space.

REFERENCES

[1] S.E. Forbush, *J. Geophys. Res.*, *59*, 525, 1954.

[2] — *J. Geophys. Res.*, *63*, 651, 1958.

[3] H.V. Neher, *J. Geophys. Res.*, *66*, 4007, 1961.

[4] H. Alfvén, *Tellus*, *3*, 232, 1954.

[5] H.D. Babcock, *Astrophys. J.*, *130*, 364, 1959.

DISCUSSION

Chairman: S. HAYAKAWA

SIMPSON

In view of your possible 12% albedo effect, could you guess what the revisions would be on the rest of the latitude curve, taking into account albedo at lower latitudes?

NEHER

No, I am afraid I cannot do that. Other people have tried to make estimates of this, but I would rather not try and make guesses at this time. We hope to do this experimentally in 1964 if we get on the satellite POGO.

BIERMANN

Reference was made to Prof. ALFVÉN's proposal of a solar theory of the origin of cosmic rays. Now of course this theory is quite old, but as you say it has been more or less forgotten about for quite a long time. What is in this scheme the explanation of the very large differences in the energy spectrum, that is to say between the values of ≈ 2 and ≈ 6 of the exponent of the power law? Another comment would be that the magnetic fields, which are necessary to store energetic particles of solar origin, would have to be assumed for this purpose. I do not know of independent reasons for assuming such fields of suitable structure to be present. Coming back to the energy spectrum is there any answer to the question, what causes the solar particles, which are produced whith a very steep energy spectrum, to be transformed into particles which have a much flatter spectrum?

NEHER

I think that this is a serious difficulty. One would have to have some selecting mechanism by which you lost a large fraction of the low energy particles.

ELLIOT

There is a small point, concerning your 12% discrepancy. Presumably there is some reduction due to the shielding of the space craft. Is it possible accurately to account for this?

NEHER

The space craft subtends a small solid angle at the instrument, and it is not clear actually whether the body of the space craft would increase the number of particles or decrease them. In any case, the contribution one way or another should be very small.

NEY

I just want to agree completely with Prof. BIERMANN that all one knows about solar cosmic rays makes it less likely that the sun is the source of all cosmic rays. Solar events give you a chance to see just how effective the trapping is. What one observes is that one gets a thousand times as many particles as galactic cosmic rays, and then they all go away, and you are right back to the original value. I would, however, like to make a direct comment on your paper. Do you believe that in 1940 the cosmic ray intensity was the highest recorded and do you think that it is not associated with a solar proton event?

NEHER

It lasted over a period of at least a few days and I do not think that it is due to any single solar event as we think of them.

GOLD

I quite agree with what Dr. BIERMANN and Dr. NEY think. ALFVÉN's suggestion would require a very long storage, because of the great variability of solar high energy bursts which would need to be smoothed over several solar cycles to lead to the observed constancy of the cosmic rays over several solar minima.

In the vicinity of a star like the sun the galactic field suffers a bulge which is always held out by the pressure from the star, by the gas pressure and the radiation pressure, and this forms a mirror machine so constructed that it would hold the particles in. But the quality of that mirror machine is just outrageously high if it is to store particles over periods like several solar cycles, and we know that galactic motions are erratic and irregular. One cannot envisage a machine that is constructed so precisely as all that.

OORT

One might remark that there is some direct evidence at any rate of cosmic rays in the galactic system. From the radio frequency radiation we know that there are at least electrons with cosmic ray energies and it is very likely that they are accompanied by very much larger quantities of cosmic ray protons.

PETERS

The galactic radiation differs from solar flare particles not only in its energy spectrum but also in its composition. This makes it still more unlikely that what we call galactic particles are actually particles from the sun which have been stored for long periods.

EXPERIMENTAL DATA ON SPECTRAL VARIATIONS DURING FORBUSH DECREASES

E. AMALDI, F. BACHELET, P. BALATA, N. IUCCI

Istituto di Fisica della Università di Roma
Istituto Nazionale di Fisica Nucleare, Sezione di Roma.
Roma - Italia

Abstract — The rigidity dependence of the cosmic ray variation during Forbush decreases has been studied for many years, in connection with theories of modulation of galactic cosmic rays through interplanetary space by solar perturbations. Only in recent years, however, the large network of C.R. neutron stations set up for the IGY and the high rate of recorded events during last solar maximum have allowed several investigators to carry out systematic studies on the variation of the primary rigidity spectrum on the occasion of such perturbations. A critical review is given of experimental analyses on the subject made by Dorman (1957), Lockwood (1960), Sarabhai et al. (1962), Kondo (1962), Filippov and Shafer (1962), Kuzmin and Krimsky (1962), Mathews (1962), Bachelet et al. (1963) and Kane (1963). The conclusion is reached that in the low rigidity region ($1 \leq R \leq 15$ GV) the spectral variation of the F.D. can be fairly well represented by an inverse power law with an exponent smaller than one. The results of various authors in the high rigidity region do not agree, so that not even a first quantitative conclusion can be reached.

1. Introduction

The variations of the primary spectrum of cosmic rays (C.R.) during Forbush decreases (F.D.) is one of the many effects on which is based any attempt aiming to determine a model of the modulation mechanism of these events. Other effects that can be used for the same purpose are:

a) the transit time of the perturbation from the sun to the earth;

b) the time length of the perturbation;

c) the shape of the decreasing and recovering phases;

d) the enhanced diurnal variations;

e) the propagation of solar C.R. at the time of a F.D.;

f) the correlation with geomagnetic storms and solar events;

g) the depression of C.R. in space far from the Earth;

h) the plasma and magnetic field determination in interplanetary space;

and finally

i) the astrophysical information on the sun, solar flare radiobursts, extended corona, etc.

In the present contribution we review and discuss the analyses of the experimental data on C.R. observed at ground and underground stations during F.D. which aim to get information on the variation of the primary spectrum just after the decreasing phase.

Systematic investigations on this subject have been made only during and after the I.G.Y.; the number of stations, in particular of those with neutron monitors, has been considerably increased and the observations have been made with more continuity; the maximum of the solar activity supplied a large number of Forbush events; and finally the study of the influence of the geomagnetic field on C.R. has been considerably improved.

The data at ground and underground are in practice the only ones suitable for a systematic analysis; upper atmosphere balloon data have been obtained only occasionally. Direct measurements of the primary spectrum at high altitude during

F.D. are still very scanty. Besides a balloon measurement made by McDonald in the rigidity region 0.5-3.0 GV [1], we only know of a recent satellite experiment made by Yagoda with emulsions exposed during the event of December 7, 1960, the analysis of which is still in progress [2].

2. General principles of the analysis

The first information on the unperturbed primary spectrum has been deduced by combining the absorption in the atmosphere with the latitude effect of secondary components. A similar procedure can be followed for the variation of the primary spectrum occurring during F.D.

The connection between the intensity of the various secondary components with the differential primary spectrum D(R), expressed as a function of the magnetic rigidity

$$\text{(1)} \qquad R = \frac{pc}{Ze} = H\rho \, ,$$

involves the so called *multiplicity function* or *yield function* m_{cx} (R):

$$\text{(2)} \qquad I_{cx}(R) = \int_R^\infty m_{cx}(R')\, D(R')\, dR' = \int_R^\infty W_{cx}(R')\, dR' \quad ,$$

where I_{cx} (R) is the intensity given by a monitor of component c, placed at depth x in the atmosphere, at geographical position where the vertical geomagnetic cut-off rigidity is R, and

$$\text{(3)} \qquad W_{cx}(R) = m_{cx}(R) \;\; D(R)$$

is the so-called *coupling coefficient* or *differential response*.

If the primary spectrum undergoes the variation δ D(R), the corresponding relative variation of the secondary intensity, corrected for atmospheric effects, is given by the relationship

$$\frac{\delta I_{cx}}{I_{cx}} = \frac{\int_R^\infty m_{cx}\, \delta D\, dR'}{\int_R^\infty m_{cx}\, D\, dR'} = \frac{\int_R^\infty W_{cx} \frac{\delta D}{D} dR'}{\int_R^\infty W_{cx}\, dR'} \tag{4}$$

the validity of which is subject to the assumption that the rigidity cut-off R remains constant during the perturbation.

This assumption, usually not sufficiently emphasized, is not *a priori* fulfilled because of the strong correlation existing between the F.D. and the geomagnetic storms; the importance of the superposition of the effect of a change of the cut-off R to the modulation of the primary spectrum has been pointed out by Kondo [3]. Therefore one should be careful in using Eq.(4) only when the F.D. is not accompanied by a strong geomagnetic storm.

Another assumption implied by Eq.(4) is that the variation $\delta D/D$ of the primary spectrum is isotropic; that this is not true, at least in the equatorial plane, is proved by the presence of diurnal variations which are enhanced during the F.D. The use of Eq.(4) seems, however, to be justified when it is applied to the interpretation of the mean value of δI_{cx} taken over at least one full solar day. Then, obviously, $\delta D/D$ represents the relative variation of the primary spectrum averaged over the components of the anisotropy lying in the equatorial plane.

No experimental evidence is available about any anisotropy of $\delta D/D$ in the meridian plane. The possible existence of such an anisotropy could be detected if the asymptotic directions of the primaries, whose secondaries are measured by monitors at different stations, were known, and furthermore, if they turned out to cut in the celestial sphere well defined regions. This is the actual situation met in the case of the solar C.R. whose spectrum extends only to 4 GV rigidity for stations at high geomagnetic latitude, according to McCracken calculation [4] [5]. Similar computations are not yet available for the galactic C.R., except for the simple dipole model of the geomagnetic field which is certainly inadeguate for such a discussion.

Therefore the existence of an anisotropy in the meridian plane is difficult to prove [6]; such a possibility has been neglected in most of the investigations discussed below.

The relationship between the measured quantity $\delta I_{cx}/I_{cx}$ and the unknown δ D/D given in integral form by Eq.(4), can be expressed in differential form in that interval of rigidity in which the secondary intensity I_{cx} is sensitive to the geomagnetic field (1):

$$(5) \qquad \frac{\delta D}{D}(R) = \frac{m_{cx}\,\delta D\, dR}{m_{cx}\, D\, dR} = \frac{d\,\delta I_{cx}}{d\, I_{cx}} = \frac{d\left[g_{cx}\,\frac{\delta I_{cx}}{I_{cx}}\right]}{d\, g_{cx}}$$

where

$$(6) \qquad g_{cx}(R) = \frac{I_{cx}(R)}{I_{cx}(R_o)}$$

is the so-called *latitude effect*, which is connected to the coupling coefficient W_{cx} (R) defined by Eq.(3), by the relation

$$(7) \qquad W_{cx}(R) = I_{cx}(R_o)\,\frac{dg_{cx}(R)}{d\,R}\ .$$

(1) This can be understood from Eq. (5) which can be used for a given component only for those values of R for which dI_{cx}/dR is different from zero.

In Eq. (6) and (7) R_o is an arbitrary value of the rigidity; the factor $I_{cx}(R_o)$ is useful for normalization purposes.

The various authors have adopted two different approaches to the problem, which will be indicated in the following for the sake of brevity, as *integral* and *differential method.*

The *integral method* is based on the use of Eq. (4) in which one introduces for $\delta D/D$ a particular law containing at least one free parameter. The calculated values of $\delta I/I$ are then compared with the experimental values to find either the values of the parameters or the form of the law as well as the values of the parameters which give the best fit to the experimental results.

The *differential method* is based on the use of Eq. (5) by replacing the differential increments with the experimental finite variations of the intensity of the secondary component (latitude effect) and of the amplitude of the F.D.

3. Remarks on the definition of the experimental amplitudes

In both methods of analysis of the F.D. one is confronted with the difficulty that the relative amplitudes $\delta I_{cx}/I_{cx}$ of the same component c measured at the same depth x and at the same geomagnetic cut-off R turn out to be spread more than expected according to the statistical error. The causes of such a wide spread can be:

1) *inadequate correction for atmospheric effects.* These corrections are usually made by each station on its own data and one can not foresee a considerable improvement in the near future, since it would be necessary to dispose of more accurate studies, such as those recommended by SCRIV for the next period of solar activity minimum [6]. It should be remembered that these corrections are more uncertain for the muon component than for the nucleonic component;

2) *changes in the efficiency* of the recorders occurring during the events;

3) *uncertainty in the adopted value of the geomagnetic cut-off.* Since the purely dipole model has been recognized inadequate, various improvements have been achieved by ROTHWELL [8], QUENBY and WEBBER [9] and QUENBY and WENK [10]. The results of the last group appear to be superior to the previous ones since they produce a remarkable reduction in the spread of points about the curve of the latitude effect of the nucleonic component measured at airplane altitude ($x = 680$ g/cm^2) by POMERANTZ [11]. We have some indication that, using these cut-offs, the spread of the relative amplitude $\delta I/I$ of the F.D. also is reduced;

4) *uncertainty in the definition of the relative amplitude* $\delta I/I$ *of a F.D.* In this connection the following points should be born in mind:

   a) only the inspection of the bi-hourly data at all the stations allows the choice of an interval of time unique for all the stations to sample both the unperturbed and the perturbed phases, so that the transition phase is avoided (2);

   b) by the same inspection one can easily recognize the presence of perturbation other than the diurnal variations (see point *c*) which, overlapping the F.D., do not allow a clear definition of both the pre-storm and full-storm intensity;

   c) as mentioned above, in order to average the anisotropic component in the meridian plane, the interval of time mentioned under *a*) should be chosen equal to at least one or a few solar days;

(2) The expression « transition phase » refers not only to the decreasing phase of the F.D. but also to the possible precursory increase.

d) the adoption of point *b*) and *c*) introduces a very strict selection of the events that can be used for the analysis.

4. Analytical expressions used by various authors for $\delta D/D$ as a function of R

The first expression for $\delta D/D$ used for this kind of analysis $\delta D/D$ AS A FUNCTION OF R

$$\frac{\delta D}{D} = \begin{cases} a & \text{for } R < R^*/4 \\ 0 & \text{for } R > R^*/4 \end{cases} \tag{8}$$

where

$$R^* \propto l_o H_o \tag{9}$$

with l_o representing the linear dimensions of the solar plasma beam inside which the frozen magnetic field has the average value H_o. The constant a is determined by the direction of the incoming particles with respect to the direction of the magnetic field in the beam.

Eq. (8) is a simplification of the theoretical expression

$$\frac{\delta D}{D} = \begin{cases} a & \text{for } R < R^*/4 \\ \frac{2}{\pi} a \text{ arc sin} \left(\frac{R^*}{2R} - 1 \right) & \text{for } R^*/4 < R < R^*/2 \\ o & \text{for } R > R^*/2 \end{cases} \tag{10}$$

Lockwood [13] uses the expression

$$\frac{\delta D}{D} = \frac{A}{R} + a_F \tag{11}$$

with A and a_F constants. This equation contains the first term, proportional to R^{-1}, of the theoretical expression suggested by Singer et al. [14]:

[10] *Amaldi* - pag. 8

$$\frac{\delta D}{D} = \frac{k_1}{R} - O\left[\left(\frac{k_1}{R}\right)^2\right] + \ldots\ldots , \tag{12}$$

plus a constant term introduced by LOCKWOOD in order to fit the experimental data.

Finally various authors have used the expression

$$\frac{\delta D}{D} = B R^{-k} \tag{13}$$

where B and k are both adjustable parameters. This expression appears to be convenient for fitting — by means of the differential method — the experimental data obtained with neutron monitors.

In spite of the fact that B and k have no direct connection with the parameters of any theoretical model, Eq. (13) is suitable for a comparison between the experimental results and the various theories.

5. GENERAL REMARKS ON THE DIFFERENTIAL METHOD

In order to appreciate the advantages as well as the limitations of the two methods outlined above, let us first examine in detail the coupling coefficient defined by Eq. (3) for the various components of C.R. These are shown in Fig. 1 which has been obtained by taking from WEBBER and QUENBY [15] the curves referring to neutrons at mountain altitudes ($x = 680$ g/cm^2) and neutrons and muons at sea level ($x = 1033$ g/cm^2) and from MATHEWS [16] the curves relative to underground muons (40 and 60 m w.e.). The primary spectrum [15] given in the same figure serves only as a term of reference.

From Fig. 1 we see that neutrons both at mountain altitude and at sea level, constitute the components most convenient

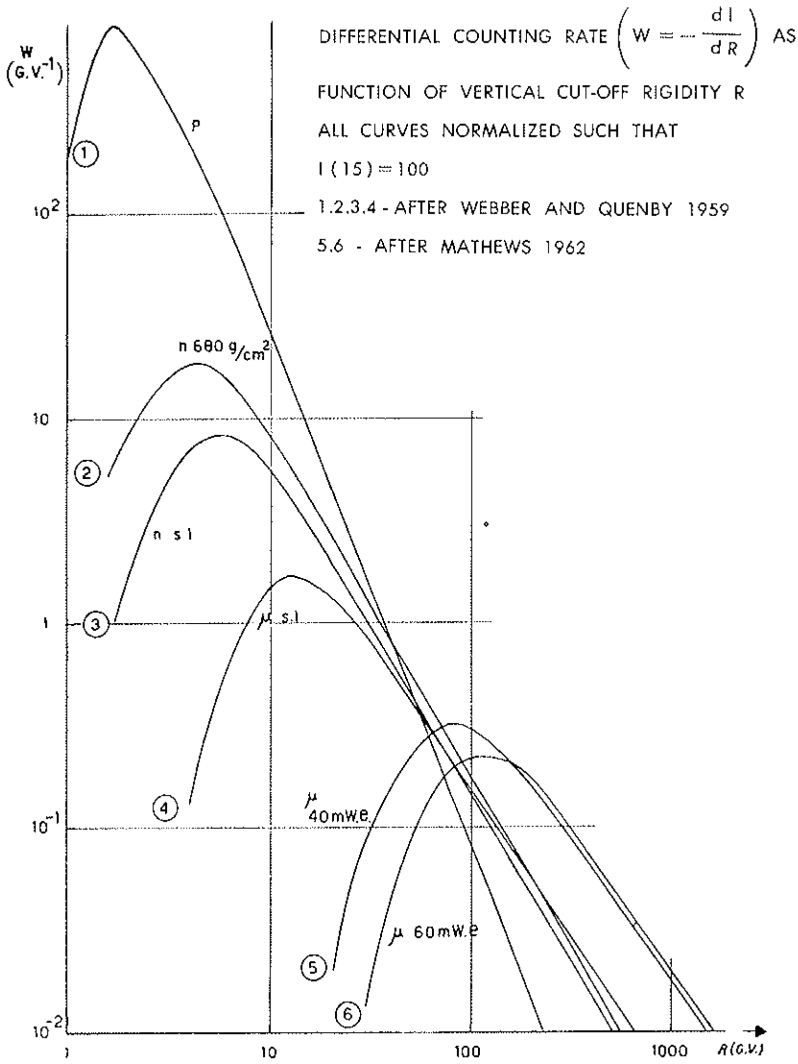


Fig. 1 — Differential response for different secondary components at different depths. Primary spectrum given for reference.

for the differential method because of the two following reasons:

a) at the same cut-off rigidity the quantities

$$\frac{1}{I_{cx}} \frac{d\, I_{cx}}{d\, R} \quad \text{and} \quad \frac{1}{I_{cx}} \frac{d\, \delta\, I_{cx}}{d\, R} \tag{14}$$

are both larger than for any other component;

b) the interval of values of R for which the quantities (14) are different from zero is larger than for the other components (see footnote on p. 5).

For muons at ground, on the contrary, the quantities (14) are so small and the experimental errors so large that the differential method in practice fails completely. The muons underground are due to primaries belonging to a rigidity region completely above the geomagnetic cut-off interval and therefore they cannot be used for the differential method.

For what concerns the quantity $\frac{\delta\, D}{D}(R)$ derived from Eq. (5), it is obvious that the differential method provides information only for rigidities below the geomagnetic equatorial cut-off.

Finally one should keep in mind that any perturbation of the geomagnetic field, if not corrected for, affects the results of the differential method more than those of the integral method.

6. Discussion of neutron measurements

Let us now consider the analyses made by Lockwood [13], Filippov and Shafer [17] and Bachelet et al. [18] all based on neutron measurements. The results of these authors, when expressed in the form (13), give a value of the exponent k appreciably different from zero, say between 0.4 and 1.

The main features of the analysis of the Rome group [18] are: the use of the differential method applied to neutrons at ground, the definition of the relative amplitude of the F.D. according to the criteria listed in Sect. 3, the use of the more recent geomagnetic cut-offs by QUENBY and WENK [10], the separation of the F.D. in two classes, the first including events in which the main phase of the associated magnetic storm is negligible, the second including events accompanied by a storm with a large main phase. All the analysed events took place between 1957 and 1959.

The strict selection of the events brings the disavantage of reducing their number to four, for the first class, and to three, for the second class, but guarantees that the results of the analysis refer to typical large and « clean » events.

By applying Eq. (5) to all these events, these authors find that the power law (13) fits very well the experimental points of $\delta I_{cx}/I_{cx}$ with an exponent k between 0.3 and 0.4 for the events of the first class, and with k between 0.8 and 1.3 for the second class.

The difference of behaviour of the two classes can be attributed to the variation of the geomagnetic cut-off, which is expected to take place in the second case. An indirect check of this interpretation is obtained by assuming that the power law (13) with the exponent k as unique parameter to be determined, holds not only for $R \leqslant R_{\text{equatorial}}$ but also for rigidities extending to infinity. Then the integral method is applied for predicting the ratio of the relative amplitudes of the muon and the neutron components measured at stations above the corresponding latitude knees where the actual cut-off is determined by the atmospheric absorption. The amplitude of the F.D. observed at these stations clearly are not affected by the possible changes of the geomagnetic cut-off.

By choosing the value of k which gives the best fit to the experimental value of the ratio

$$\frac{\delta\, I_{n\,\text{sea level}}}{I_{n\,\text{sea level}}} \Bigg/ \frac{\delta\, I_{\mu}}{I_{\mu}} \qquad (R_{\text{geomag.}} < R_{\text{absorpt.}})$$

the BACHELET group finds values of k between 0.4 and 0.5 for all the events of the two classes defined above.

The same results is obtained by applying again the integral method as explained above to the ratio

$$\frac{\delta\, I_{n\,\text{mountain}}}{I_{n\,\text{mountain}}} \Bigg/ \frac{\delta\, I_{n\,\text{sea level}}}{I_{n\,\text{sea level}}} \qquad (R_{\text{geomag.}} < R_{\text{absorpt.}})$$

relative to the neutron stations at mountain altitude and at sea level.

In these results they find a strong indication that the exponent k of the law (13) is for all the typical events appreciably smaller than 1, provided the effect of the perturbation of the geomagnetic field is eliminated in some way.

At an earlier time, FILIPPOV and SHAFER [17] had analysed by the differential method the average spectral variation of 15 F.D. occurred during the I.G.Y. They found that the power law (13) with the exponent $k = 0.8 \pm 0.2$ fits their data well These had been obtained:

a) by using the geomagnetic cut-offs of QUENBY and WEBBER [9], the most refined available at that time;

b) by taking the pre-storm level averaged over 20-30 hours before the decrease and excluding any possible precursory sharp peak, and the intensity in the full storm averaged over 4-8 hours.

In spite of these minor differences of procedure, the results of FILIPPOV and SHAFER do not appear to be in disagreement with the results of the Rome group especially if one considers that the higher value of k can be explained as due to the inclusion of events of the second class.

The even previous analysis by LOCKWOOD [13] is discussed here because it refers only to neutron data. However, it is based on the integral methods assuming *a priori* the law (11) taken to be valid for

$$R \leqslant 100 \text{ GV} .$$

He had individually analysed 18 events — which occurred in 1957-1959 — with the geomagnetic cut-off of QUENBY and WEBBER [9]. The amplitude of each event was defined by this author taking the pre-storm level by averaging at least 12 hours prior to the onset of the decrease (3) and for full-storm level the lowest bi-hourly value.

The spread of the points in the plane $\delta I_n/I_n$ versus R is rather large, probably because of the amplitude definition which appears to be very sensitive to any spurious perturbation.

In spite of the uncertainty involved in fitting a curve to widely spread points, LOCKWOOD represents his events with the law (11), some with $a_F > 0$, other with $a_F = 0$. These two groups of events, when represented in terms of Eq. (13), correspond respectively to $k < 1$ and $k = 1$.

One can conclude that the LOCKWOOD results also do not disagree with those of the other authors mentioned above.

7. GENERAL REMARKS ON THE INTEGRAL METHOD

As already stated above, the μ-meson data at ground and underground can be used, along with neutron data, only for the application of the integral method.

On the other hand for the muon component the errors in the amplitude of the F.D., due to incomplete atmospheric cor-

(3) The onset time is defined by LOCKWOOD as the last hour before the main phase commences as indicated by the decrease in the counting rate of at least 2 standard deviations.

rection and to variations of the counter efficiency, are considerable. Moreover the knowledge of the coupling coefficients is more uncertain.

Therefore, if the best fit of a given law to the experimental points were applied only to the muon-component data, the determination of the adjustable parameters would be very uncertain. The uncertainty, however, is strongly reduced by the fact that the best fit can be extended to include all the components.

The method is complementary to the differential method because it involves information on the variation of the primary spectrum at rigidities greater than the equatorial geomagnetic cut-off.

On the other hand, the problem of the statistical analysis is rather difficult, especially when the number of free parameters is large. For these reasons the results of this method should be taken with caution.

8. Discussion of muon measurements

Research including the analysis of the muon components has been made by Dorman [12], Sarabhai et al. [6], Kuzmin and Krimsky [19], Mathews [16] and Kane [20].

The paper by Kane is illuminating on the difficulties met in the application of the integral method: if the fitting of the experimental data is made with a single law with too few free parameters, the result turns out to be rather arbitrary; while, if the fitting is attempted with various laws and/or many parameters, the sensitivity of the method is so low that no definite discrimination can be obtained.

The analysis made by Kane refers to a large number of events during the I.G.Y. out of which 11 are large or medium F.D. For each of these he utilized the neutron and muon data at ground (from about 70 stations) with the geomagnetic cut-offs of QUENBY and WENK [10]. The amplitude of the perturbations are estimated on daily averages irrespective of the onset time.

He tries first to fit the experimental data with the law (13) for $R<R^2$ and $\delta D/D=0$ for $R>R_2$. Thus, for each event, he has to determine three free parameters: B, k and R_2, of which only the two latter are of interest for our discussion. For the F.D. the k-values turn out to be all in the interval 0.3-0.6 and the R_2 values between 60 GV and ∞.

Each event can be fitted equally well by several pairs of values of k and R_2; the correlation is always in the sense that a higher value of k is associated to a higher value of R_2. From this remark, KANE concludes that it should be possible to fit the same data even by an exponent $k=0$ provided the high energy limit R_2 is adequately reduced. This is equivalent to try the expression (8). He prefers to try the expression (10) from which he derives values of R^* of the order of 100 GV. Thus, KANE arrives at the clear conclusion that the exponent k should be smaller than one; but he recognizes the impossibility of a discrimination between the expression (13) with $k\leqslant 6$ and the expression (10).

In contrast with this unbiassed attitude of KANE, both DORMAN [12] and SARABHAI et al. [6] interpret their data as definitely in favour of the expression (8) with $R^*/4 \simeq 40$ GV. Besides the general remarks given above, one can add the following points. The analysis by DORMAN refers to data collected before the I.G.Y. which do not include neutron measurements and is based on the use of the geomagnetic cut-offs derived from the pure dipole model. SARABHAI et al. [6] use only a few stations chosen in view of a study of a possible anisotropy in the meridian plane. Therefore it appears to us that the results of both these two groups of authors, although interesting from other points of view, do not bring a definite contribution to the determination of the shape of the variation of the primary spectrum.

KUZMIN and KRIMSKY [19] analyse the muon data collected at sea level as well as at various depths underground (from 7 to 60 m w.e.; Yakutsk station) during 26 F.D. occurred during the I.G.Y. They try only the power law (13) extending to ∞, since this expression had been suggested by the analysis of the neutron data made by FILIPPOV and SHAFER. They find an exponent k of the order of 0.8.

In the light of the discussion of the neutron data given in Sect. 6, as well as the discussion given by KANE, this result appears to be compatible with a lower value of k (say 0.5) in the low rigidity region, combined with a cut to zero at high rigidity.

Finally MATHEWS [16] considers the data referring to neutrons at ground as well as to muous at ground and at 40 and 60 mw.e. underground, for 2 events occurred in 1960-1961. He compares the experimental data with three different theoretical laws given by SINGER [first term of Eq. (12)], PARKER [21] and ELLIOT [22]. The comparison is made, for each law, for a selected set of values of the parameters; no agreement is found in any case.

The inspection of the deviation of the SINGER law from the experimental data of MATHEWS suggests again that a better fit could be obtained by using Eq. (13) with a k value smaller than 1.

9. CONCLUSIONS

In this situation it does not appear easy to derive definite conclusions. The only points which seem to emerge are that in the low rigidity region ($1 \leqslant R \leqslant 15$ GV) the spectral variation of the F.D. can be fairly well represented by Eq. (13) with

$k > 0$. Furthermore, if the discussion — given in Sect. 6 — of the effect of geomagnetic perturbations superimposed on interplanetary modulation is correct, than we believe that one could conclude that k should be smaller than 1 in the low rigidity region. For the high rigidity region all the analyses made to date do not appear to be adequate even for a first quantitative conclusion.

REFERENCES

[1] F.B. McDONALD, *J. Geophys. Res.*, *65*, 767, 1960.

[2] Whe thank Dr. H. YAGODA for this information.

[3] I. KONDO, *Proc. Kyoto C.R. Conf. J. Phys. Soc. Jap.*, *17*, Suppl. AII, 402, 1962.

[4] K.G. McCRACKEN, *J. Geophys. Res.*, *67*, 423, 1962.

[5] H. CARMICHAEL, *Space Science Rev.*, *1*, 28, 1962.

[6] V.A. SARABHAI, G.L. PAI and U.R. RAO, *J. Phys. Soc. Japan*, *17*, Suppl. A II, 379, 1962.

[7] SCRIV Recomandation at Kyoto meeting, Sept. 1961.

[8] P. ROTHWELL, *J. Geophys. Res.*, *64*, 2026, 1959.

[9] J.J. QUENBY and W.R. WEBBER, *Phil. Mag.*, *4*, 90, 1959.

[10] J.J. QUENBY and G.J. WENK, *Phil. Mag.*, *7*, 1457, 1962.

[11] M.A. POMERANTZ and S.P. AGARWAL, *Phil. Mag.*, *7*, 1503, 1962.

[12] L.I. DORMAN, *Cosmic Ray Variation* English translation 1957.

[13] J.A. LOCKWOOD, *J. Geophys Res.*, *65*, 3859, 1960.

[14] S.F. SINGER, H. LASTER and A.M. LENCHEK, *J. Phys. Soc. Japan*, *17*, Suppl. A II, 383, 1962.

[15] W.R. WEBBER and J.J. QUENBY, *Phil. Mag.*, *4*, 90, 1959.

[16] T. MATHEWS, Preprint 1962.

[17] FILIPPOV and SHAFER, Preprint 1962.

[18] F. BACHELET, P. BALATA and N. IUCCI, *Nuovo Cim.*, *27*, 425, 1963.

[19] A.I. KUZMIN and G.F. KRIMSKY, Preprint 1962.

[20] R.P. KANE, *Nuovo Cim.*, *27*, 441, 1963.

[21] E.N. PARKER, *Ap. J.*, *133*, 1014, 1961.

[22] H. ELLIOT, *Phil. Mag.*, *5*, 601, 1960.

DISCUSSION

Chairman: S. HAYAKAWA

ELLIOT

Perhaps I can try to add something to Prof. AMALDI's remarks about MATHEWS' work and I can say a little more about it on Thursday. I think perhaps one might convey slightly the wrong impression by saying that MATHEWS found no agreement. He didn't find perfect agreement, and being a young man perhaps he hoped to. There are quite serious difficulties in interpreting the underground data which I think one should not fail to mention. First of all the yield functions are really a bit uncertain and the second thing is that at a depth of 60 m.w.e. quite a large part of the Forbush decrease is certainly not isotropic — this one can see. I think that this makes for some difficulty because even if one takes averages over 24 hours this still does not solve the problem since the daily variation may not be a modulation up and down equally about a true mean. Instead it is more likely that additional particles are missing at some parts of the day and consequently, taking a daily average does not eliminate the effect of this anisotropy. I think that in view of these things the discrepancies that MATHEWS gives are not to be considered as overwhelmingly against any of the models that he discusses.

One other remark concerns the interpretation of the Forbush decrease — the energy dependence of the Forbush decrease rather — in terms of power laws. I think that this can perhaps be a little misleading because there is no reason to suppose that K should be constant over the whole of the energy range; and to fit a constant K to it may be to throw away some information that one should have.

AMALDI

First I would like to comment on the agreement or disagreement between MATHEWS' results and the various theories mentioned above. Of course, you know MATHEWS' paper and what is behind it more than we do. Reading the paper we had the impression that there was no agreement, also because MATHEWS expressed this opinion; but even if the disagreement is not too bad, it seems to me that our conclusions remain valid, that very little can be said today about the shape of the spectrum in the high energy region ($R > 15$ GV). In particular I agree with Prof. ELLIOT on the fact that for the muon component the coupling coefficients are very uncertain; I actually tried to stress this point in my report.

My second comment refers to the low rigidity region. It is quite clear, as already emphasised, that any one of the used laws is an oversimplification of the reality; particularly it is clear that there is no reason to believe in a simple inverse power law. But if one introduces more complicated laws, with more parameters, then their determination from the experimental data becomes illusory, because of the various errors and uncertainties that I mentioned in my report.

SIMPSON

I have two comments on Prof. AMALDI's interesting paper. My first remark follows from Prof. ELLIOT, namely the K value is undoubtedly not a constant for most events. We see this most clearly from the neutron intensity over a wide range of geomagnetic latitudes obtained in aircraft during and after a FORBUSH decrease. From the value of $\delta D/D$ over a wide range of latitude we find that K is constant up to 6 GV, but at higher rigidities the value begins to change.

[10] *Amaldi* - pag. 22

My second comment is that we confirm your conclusions that there exist two groups of rigidity dependencies, one related to a large geomagnetic field effect and the other which is not. We have isolated them by deducing the location of the maximum of the primary differential spectrum; *i.e.* looking for a « knee » shift in the neutron intensity latitude curve. Most Forbush decreases show no « knee » shift $\geqslant 1^\circ$ latitude. However, for events such as February 11, 1958, the Forbush decrease has in association with it a large-scale observed shift in position of the « knee » of the latitude curve during the Forbush decrease.

RECENT INVESTIGATIONS OF THE LOW ENERGY COSMIC AND SOLAR PARTICLE RADIATIONS (*)

J.A. SIMPSON

Enrico Fermi Institute for Nuclear Studies and Department of Physics University of Chicago - Chicago 37, Ill. - U.S.A.

Abstract — The first part of this paper is a preliminary study of changes in intensity and spectrum of the solar modulated cosmic radiation over a solar activity cycle. Neutron intensity monitors responsive to changes in primary particle magnetic rigidity as low as ∽1 GV have been analysed for the period 1952-1962. It appears that the experimental results are to be explained by the growth and decay of a modulating electrodynamical region bounding a large volume of interplanetary space. The non-linear growth and decay are functions of both solar activity and particle magnetic rigidity. The results suggest the build-up and subsequent relaxation of a heliocentric magnetic field modulating region which terminates in an interface with the stellar gas or galactic magnetic field. The second part is a report on recent experiments by Meyer and Vogt to study the origin of 80-350 MeV primary protons shown to be continuously present during years near maximum solar activity. The alternatives for their solar origin are discussed.

(*) This research was supported in part by the Air Force Office of Scientific Research under Contract AF 49 (638)-1008 and Grant AF-AFOSR-62-23, and by the Air Force Geophysical Research Directorate under Contract AF 19 (604)-4554.

Part I

SPECTRUM AND INTENSITY CHANGES OF COSMIC RADIATION ABOVE $\sim$1 GV AND THEIR ASTROPHYSICAL IMPLICATIONS

1. Introduction

Forbush was the first to demonstrate the existence of an anticorrelation between solar activity over the 11-year sun spot cycle and the cosmic ray intensity as measured deep within the atmosphere by ion chambers [1]. The measurements of Meyer and Simpson showed that these 11-year changes were accompanied by a change of exponent $\Delta\gamma \sim 0.7$ in the power law spectrum of the primary flux between solar maximum and solar minimum [2]. Both Neher [3], and Meyer and Simpson [2] found that the so-called low energy cut-off (1) for the primary radiation shifted to higher rigidities at solar maximum. Neher [3] showed that near solar minimum activity there appeared a flux of very low energy primary radiation not detectible at low latitudes and assumed to be from the galaxy. These combined results suggested models wherein the sun controlled and modulated the galactic flux through interplanetary magnetic fields controlled by solar plasmas [4, 5]. Evidence in favor of the magnetic rigidity rather than energy modulation of the protons and α-particles came from the measurements of McDonald and Webber [6]. Direct proof that the modulation mechanism for the 11-year cosmic ray intensity variations is heliocentric within the inner solar system was provided by cosmic ray gradient experiments on the space probe

(1) To be interpreted as the energy at maximum intensity of the differential primary spectrum.

Pioneer V [7]. The existence of, at most, a small intensity gradient in space over 0.1 AU inward from the orbit of Earth suggests that near solar maximum activity the heliocentric modulation must be most effective beyond the orbit of the Earth [8]. FORBUSH [9] and NEHER [10] have shown that there appears to be a time lag of 9 to 12 months between the onset of a new sunspot cycle and the onset of cosmic ray intensity modulation. It was also apparent that this phase lag was smaller for high latitude observations [9, 11].

The present paper is a preliminary analysis of changes in intensity and spectrum of the solar-modulated cosmic radiation over a solar activity cycle. The results provide clues to the origin of the 11-year solar modulation mechanism. The data lead to the tentative conclusion that the time constants of the 11-year cycle are associated with the growth and decay of a modulating electrodynamical system in interplanetary space, and are determined by solar activity and particle magnetic rigidity. The results suggest a heliocentric magnetic field boundary for the modulating region, possibly formed by an interface with a galactic magnetic field.

2. SPECTRAL AND INTENSITY CHANGES AS A FUNCTION OF SLOWLY VARYING SOLAR ACTIVITY

Changes in the primary cosmic ray spectrum were deduced by observing the nucleonic component intensity within neutron monitor piles located over a wide range of geomagnetic latitudes. The techniques and details of the experimental apparatus have been described elsewhere. Since the nucleonic component deep in the atmosphere has been shown to arise from primary cosmic radiation with magnetic rigidities as low as ~ 1 GV (1), it then follows that the neutron intensity monitor

(1) *i.e.* the specific yield function is finite at ≥ 1 GV.

is an effective device for measuring changes in the integral intensity above geomagnetic rigidity cut-offs in the range of 1-14 GV. To construct the primary spectrum from observations deep in the atmosphere requires the use of specific yield functions, or coupling coefficients, for extrapolating the neutron observations to primary fluxes at the top of the atmosphere. However, the slowly varying and large scale changes observed over the 11-year solar cycle are so outstanding that these extrapolations are not required to arrive at some major conclusions regarding the physical changes taking place in the primary cosmic radiation. Hence, in this preliminary study, *relative* changes in the spectrum have been determined from neutron monitor intensity data normalized to unity at the solar minimum in 1954, which lead to the qualitative description of conditions in interplanetary space. The values assigned to the geomagnetic cut-off rigidities are those calculated by QUENBY and WEBBER [12].

The data have been corrected for barometric pressure changes. Fig. 1 displays these intensity measurements as monthly averages over the period 1952-1962. The relative changes of integral intensity with cut-offs at >1.5 GV and >14 GV are shown in Fig. 2. The most outstanding features are as follows:

1. The onset of modulation following solar minimum occurs at first only for the low rigidity particles in the primary spectrum, *i.e.* this onset of modulation produces a strongly rigidity dependent change of spectrum for particles with low magnetic rigidities. For primary particles of magnetic rigidity <2 GV it is possible that a residual modulation existed throughout the period of solar minimum in 1954.

2. Once primary particles >14 GV undergo modulation, the lower energy portion of the spectrum remains relatively unchanged over a large decrease of primary integral intensity, continuing nearly to the time of solar maximum acti-

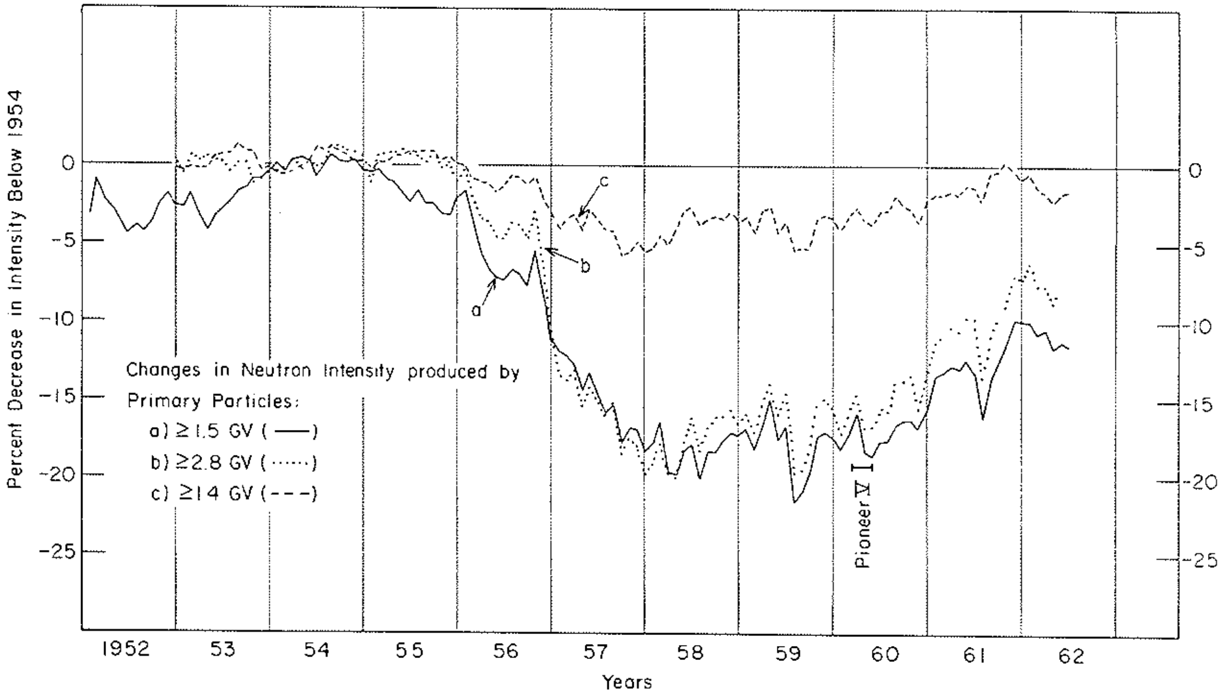


FIG. 1 — These neutron intensity monitor data have been normalized to « 0 » percent in 1954. The pressure correction for the 1954 primary spectrum were used. All monitors are the standard Chicago-type. The time of the *Pioneer V* space probe observation of a negligible cosmic ray intensity gradient is shown [7, 8].

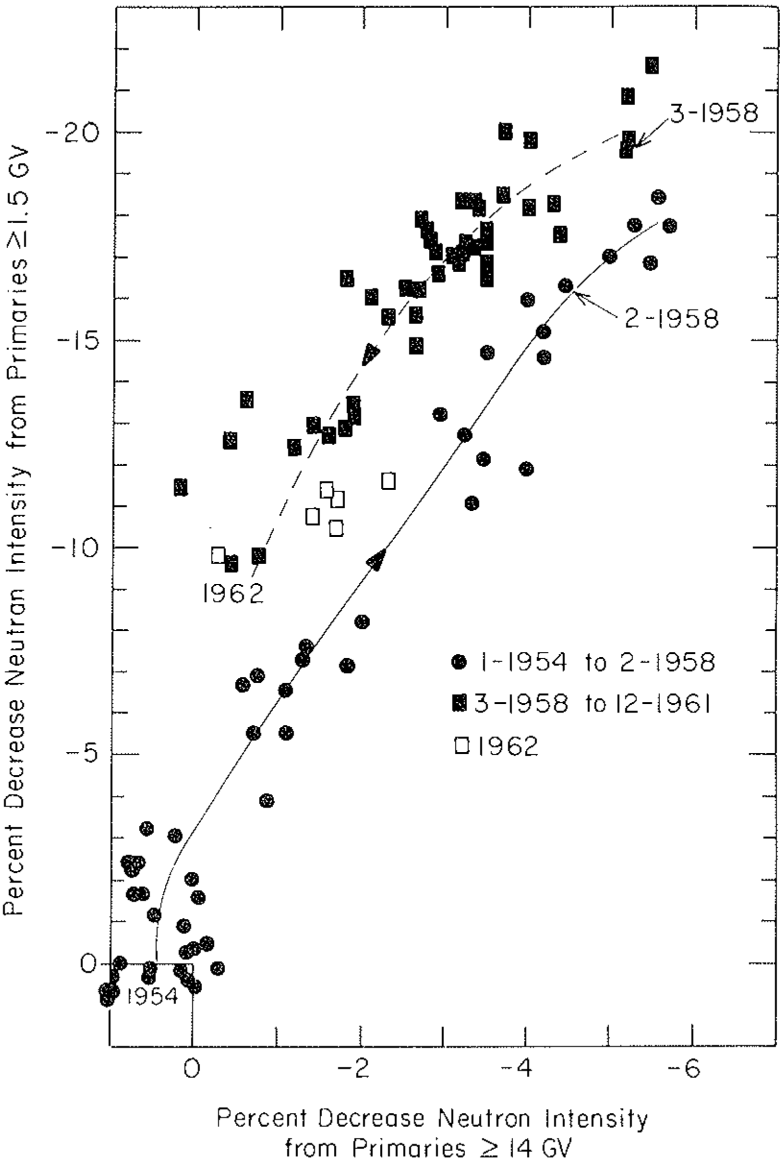


FIG. 2 — A constant slope represents an unchanged spectral distribution of primary particles over the indicated change of integral intensity. Thus, the spectrum from 1958 to 1962 for low magnetic rigidities is flatter than from 1955 to 1958. The arrows indicate the time sequence of the spectral changes.

vity. The ratio of percent change of neutron intensity >1.5 GV/>14 GV in Fig. 2 (lower solid line) is ~ 3 for the period leading to solar maximum activity. These spectral changes are qualitatively reflected in the sketch of primary spectrum changes in Fig. 3.

3. During the period of increasing primary intensity, the rigidity dependence of the spectrum changes again (upper dashed curve, Fig. 2). During the increase of intensity towards the next solar minimum in $\sim$ 1964-1965, the slope for the upper curve in Fig. 2 is increasing, and exceeds 4 in 1962.

4. There is a spectrum change between the lower and upper curves of Fig. 2 which occurs in less than a 3-month interval near solar maximum.

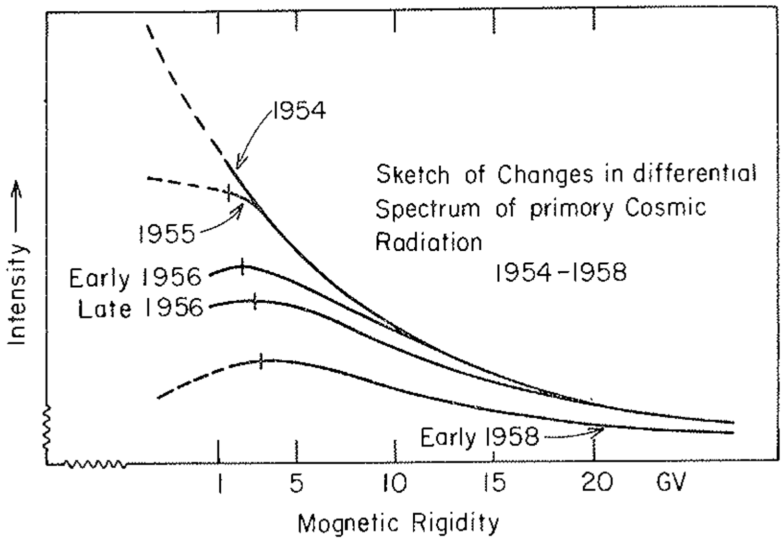


FIG. 3 — This sketch is not to scale. It represents the kind of changes in the low energy primary spectrum predicted by the neutron intensity observations as shown in Figs. 7 and 8.

The phase lag between sun spot number and cosmic ray intensity noted by FORBUSH [9] and NEHER [10] is clearly evident in the above results.

Since at present we believe that interplanetary magnetic fields which produce the modulation of intensity are controlled by solar plasma, it is important to represent the spectral changes as a function of solar activity parameters physically associated with the energy source of the solar wind instead of sunspot number, which is a phenomenological index. Suitable parameters observed over at least one solar cycle are difficult to find, especially since the basic mechanism for heating the corona is not firmly established. However, the slowly varying radio emissions from the chromosphere and deep in the corona likely receive their energy from underlying solar energy sources which also contribute to the heating of the corona. In Fig. 4, the flux of 10.7 cm wave length solar radio emission observed by COVINGTON [13] for more than a solar cycle is compared with the classical sun spot number representation of solar activity. On the basis of this remarkable correlation the representation of slowly varying solar activity by sun spot number appears to be a useful index of solar wind « strength » for correlation with the cosmic ray spectral changes reported here. Consequently, monthly averages of sun spot number will be used as a parameter in the preliminary discussion which follow. (Other parameters reflecting the « strength » of the solar wind include geomagnetic disturbance indices, coronal temperatures, and the slowly changing intensity of the horizontal component of the equatorial geomagnetic field over 11-years.)

The short-term changes of intensity such as Forbush-type decreases which generally have a significantly different rigidity dependence from the 11-year intensity variations, are included in the data [13a]). From the evidence to be presented it will be clear that their presence does not conceal the main features of the 11-year spectral changes. Indeed, some of the 11-year

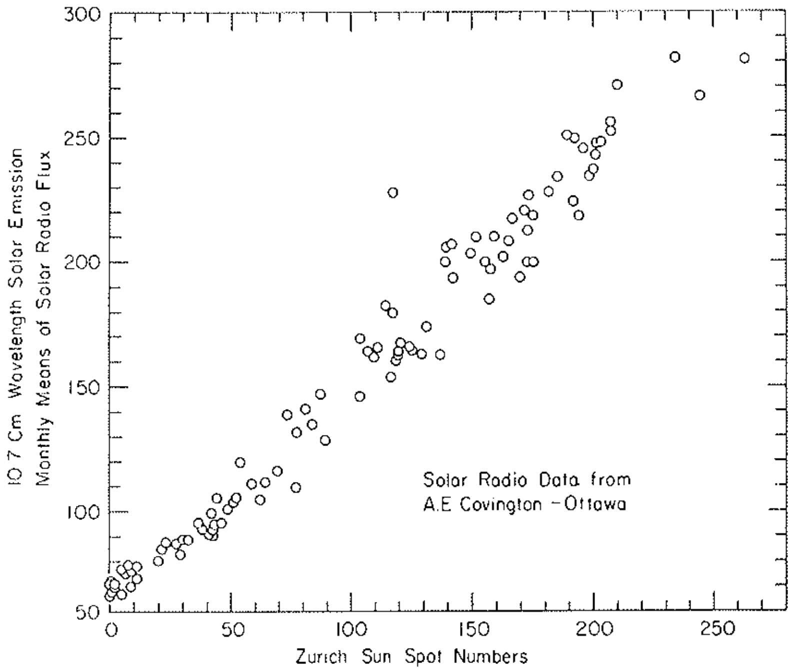


Fig. 4 — Correlation known to exist between sunspot number and background high frequency radio wave emissions from deep in the solar atmosphere. The 10.7 cm. wave-length data are published by A.E. Covington [13]

spectral and intensity changes appear to begin with major short-term events (for example, November 9, 1956).

The changes in integral intensity above 1.5 GV and 14 GV are shown in Figs. 5 and 6, respectively, as a function of solar activity between 1954 and 1962. To good approximation these double-valued functions for the cosmic ray intensity may be represented by the smooth curves shown in Fig. 7. (Compare the data in Fig. 5 with the smoothed loop ≥ 1.5 GV in Fig. 7). Additional integral intensity curves cutting off at ~ 1 GV and

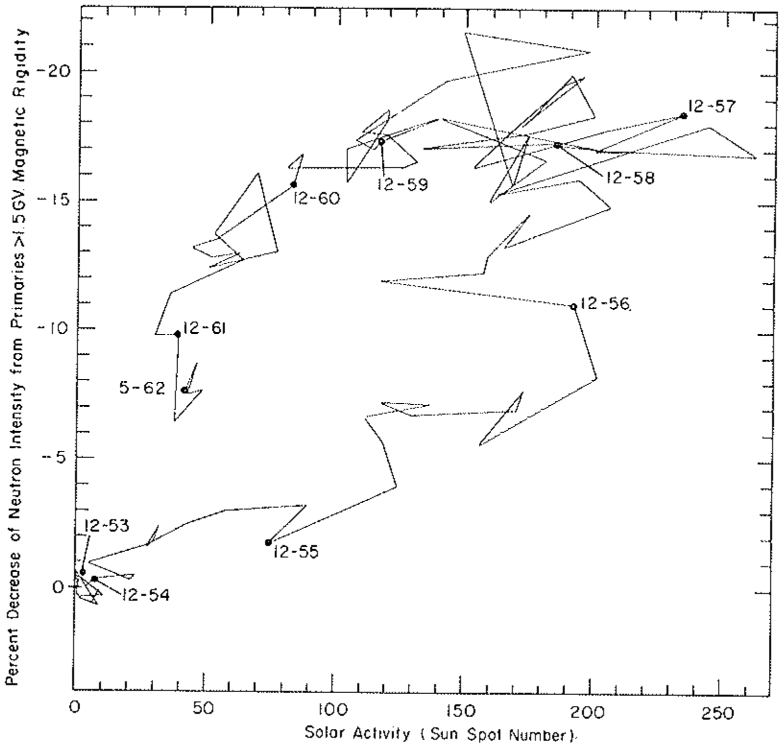


FIG. 5 — The one month averages of neutron monitor intensity at Chicago, Illinois are shown as a function of monthly sun spot number and time.

2.8 GV are also shown. (The data for the >1 GV « loop » are from the Ottawa, Canada neutron intensity monitor.) (¹)

It is clear that:

1. For primary particles of magnetic rigidity <1.5 GV modulation is probably underway for even the lowest measurable levels of solar activity; *i.e.* there may be no time lag

(¹) The author wishes to thank Dr. D.C. ROSE, National Research Council, Canada for permission to use his data.

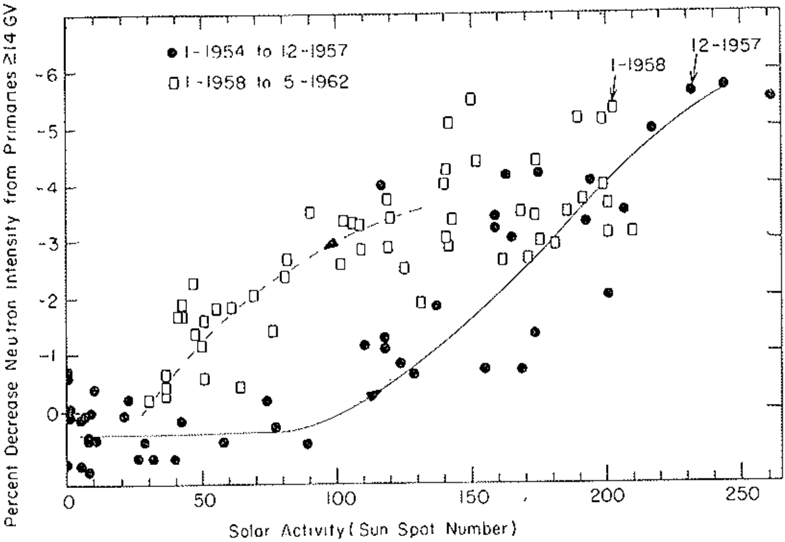


FIG. 6 — The one month averages of neutron monitor intensity at Huancayo, Peru are shown as a function of monthly sun spot number.

between the increase of solar activity after solar minimum and the onset of primary cosmic ray modulation. This conclusion is also suggested by the curve ≥1.5 GV in Fig. 1.

2. As solar activity increases, the onset of modulation takes place at increasing particle rigidity. On the declining portion of the solar cycle the progressive disappearance of modulation from the primary flux takes place at much lower values of solar activity. This is illustrated in Fig. 8.

3. Figs. 2 and 7 show that a major transition in spectral characteristics takes place on the first approach to maximum solar activity, an effect which is not reversed. Whether this is the consequence of the observed reversal of the Sun's polar magnetic field [14] at this time or whether it is initiated by the November 1956 event is an important but open question.

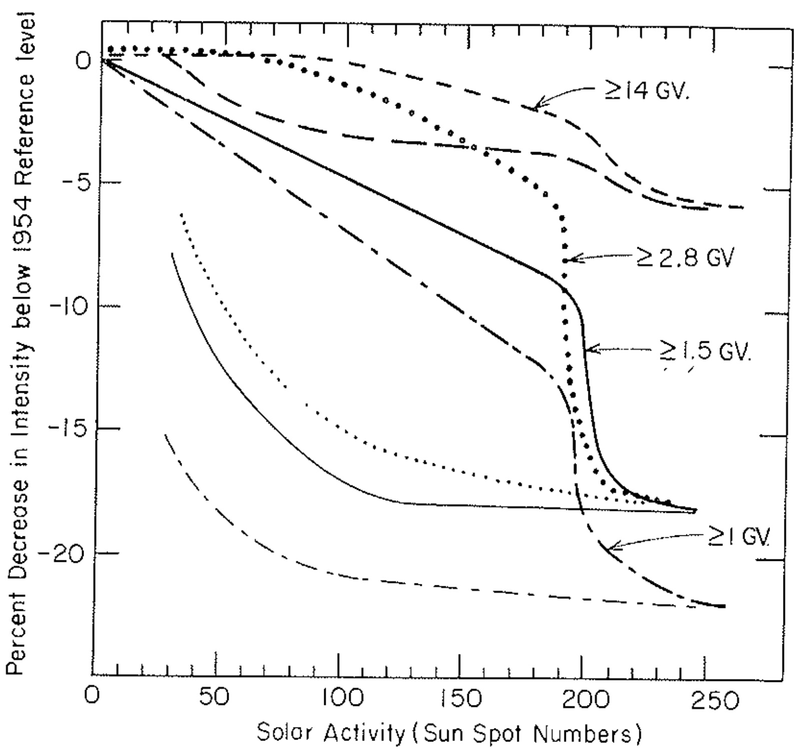


FIG. 7 — Smooth curves have been drawn through the observations shown in Figs. 5 and 6 to emphasize the first order changes taking place in the cosmic radiation intensity. Similar curves were prepared for neutron monitor observations at Climax, Colorado (geomagnetic field cutoff ∼2.8 GV), and at Ottawa, Canada (∼1 GV magnetic rigidity cut-off). The Ottawa data are from Dr. D.C. ROSE, National Research Council.

4. By early 1962, the integral flux >14 GV had returned to approximately the level of 1954.

The above phenomena lead to a rough description of the changing primary spectrum which has been sketched (not to scale) in Fig. 3 under the assumption of a power law spectrum in 1954.

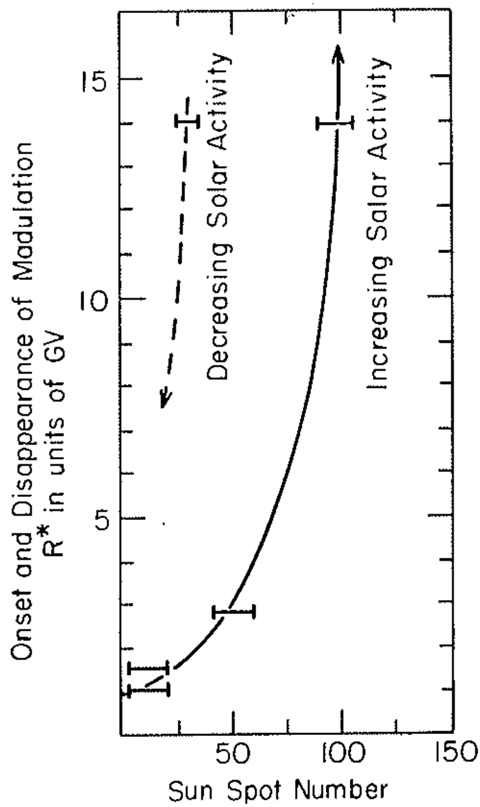


FIG. 8 — At any time during the 11-year solar cycle there is a primary particle magnetic rigidity R* above which *no* solar modulation is observed. These data are derived from Fig. 7.

The residual modulation of galactic radiation at minimum solar activity is at present unknown. As noted above, for particles below ∾1.5 GV magnetic rigidity it is not yet certain whether the full galactic intensity could reach the orbit of the Earth in 1954. It will be important to decide whether the spectra and integral fluxes are the same at each solar activity minimum.

3. Implications for the Interplanetary State and Theories for Solar Modulation

It is interesting to explore how these experimental results may extend our understanding of the physical processes which are believed to modulate the cosmic radiation in the solar system. Clearly, the existence of the 11-year modulation cycle and the heliocentric distribution of the modulation mechanism proves that the phenomenon is based on large-scale magnetic fields in interplanetary space. The solar wind and shock waves are mainly responsible for the changing structure and degree of stability of the interplanetary magnetic fields. The solar energy is carried out into the medium by at least three mechanisms; namely, 1) the quiet solar wind; 2) shock or blast waves, or 3) enhanced solar wind associated with M-regions.

For the present we assume that 1) and 2) above are the major contributors. The question then arises, do the time constants for the build-up and relaxation of the modulation magnetic fields shown to exist in this paper originate, *a*) at the sun through the transfer of solar energy to the escaping wind or shock, or *b*) in the volume of the interplanetary medium out to 1 or 2 AU, or *c*) through the pumping-up and subsequent relaxation of a large magnetic boundary region lying at many AU from the sun and terminating in a boundary with the interstellar gas or galactic magnetic field?

Alternatives *a*) and *b*) are not promising because the characteristic time constants are too short. With respect to *b*), interplanetary conditions within 1-2 AU heliocentric radius — exclusive of any assumed outer boundary — respond in the order of days to the changes in solar activity. With reference to alternative *a*), it is well known that the frequency of recurring geomagnetic storms is not in phase with the solar activity cycle. However, preliminary studies of the cosmic ray modulation as a function of the geomagnetic disturbance index A_p also lead to loop curves not unlike those shown in Fig. 7. Hence, the solar wind strength probably is correlated closely with the average level of solar activity, since geomagnetic indices reflect in some measure the impact of the solar wind upon the geomagnetic field. Furthermore, Fig. 8 suggests that solar modulation is a continuous function of solar activity to the lowest measured values of activity. If subsequent studies show that this is essentially correct, then the time constants are not connected with the transfer of solar energy input to the solar wind.

The experimental results support the third alternative; namely, that the observed build-up and relaxation times for solar modulation require a large scale heliocentric volume of interplanetary magnetic fields, which terminates in a boundary with the interstellar gas and possibly a galactic magnetic field. The solar wind and shock waves « pump up » the size of this interplanetary volume, dissipating energy near and at the boundary through magnetic instabilities, by escape of solar plasma and through work against any external galactic magnetic field. Upon turning off the solar energy source to the solar wind and shock waves, this heliocentric volume would then diminish with a relaxation time whose characteristics depend in a nonlinear way upon the size of the volume, and other parameters. Without going into details in this paper, it is likely that at such a magnetic field interface there may develop an appreciable hold-up of conductive interplanetary material with an attendant build-up of magnetic instabilities and large-scale changes in the boundary. For example, shock fronts will sweep up ambient interplanetary plasma [15]. This will tend to increase temporarily the plasma density near the magnetic field boundary. There must exist a region of space beyond the orbit of earth where the successive dissipating shock waves overtake one another to develop this region of « pile-up ». Tentatively, it appears that a heliocentric region with boundary somewhere between 5 and 30 AU might satisfy the above conditions for « pile-up » and observed relaxation times reported here.

The concept of a solar « plasma bubble » contained within a galactic arm field was proposed by DAVIS, at first with a radius of order 100 AU and more recently in a model of radius 5-20 AU [16]. This model might be extended to account for the dynamical changes over the solar cycle now shown to exist. It may also develop upon further investigation that the existence of a galactic magnetic field is not required to satisfy the observations if, for example, it can be shown that the interplanetary magnetic fields can generate, through instabilities, a heliocentric region to modulate cosmic rays such as the barrier region invoked for the storage of high-energy, solar flare protons [17].

The experimental resnlts in Fig. 8 also suggest that the scale-size of the magnetic irregularities which deflect the galactic cosmic radiation is a function of the solar wind strength. Namely, it appears as though magnetic irregularities of progressively larger scale develop with increasing solar energy input to the solar wind. This is analogous to extending the wave-number spectrum for magnetic instabilities to lower wave numbers with increasing available solar energy transported through the interplanetary medium by solar winds and shocks. On the declining phase of the solar cycle this process is reversed.

Thus, both the time constants for build-up and relaxation of the 11-year modulation of the cosmic radiation and the progressive spectral changes over the solar cycle place special requirements on the mechanism for solar modulation of cosmic radiation. The results also suggest that the storage times of solar flare particles should be slowly changing over the 11-year solar cycle.

It must be emphasized in conclusion that this paper is a preliminary overview of the 11-year modulation of the cosmic radiation, and we have yet to prove whether the tentative conclusions derived from these experiments are correct.

PART II

EVIDENCE FOR A PERSISTENT FLUX OF SOLAR PROTONS IN THE INNER SOLAR SYSTEM

1. THE EXPERIMENTS

It was shown by VOGT [18] during 1960 — not far from maximum solar activity — that there was a persistent flux of protons in the energy range 80-350 MeV with a spectral distribution radically different from predictions based on present ideas regarding the solar modulation of galactic particles.

To decide whether it is necessary to revise present ideas on solar modulation or whether these low energy protons are accelerated in the solar system, MEYER and VOGT [19] have measured the proton flux and energy spectrum in the year 1961.

This report is a brief summary and comment upon their most recent work [19].

The apparatus used in their 1961 measurements was almost identical with the 1960 apparatus. A cross-section of the energy-loss and particle range telescope is shown in Fig. 9.

Five balloon flights at geomagnetic latitude 73° N were undertaken in the interval July 22 through August 8, 1961 with a residual atmosphere of between 4.5 and 5 g/cm^2.

During July low energy protons from solar flares were observed, but in the period August 1-8, 1961 no significant changes of the low energy primary proton spectrum or flux were found. The absence of any decline in intensity over this period demonstrated that the low energy protons probably are not the residue of stored particles from previous large solar flares, but arise from a more continuous source.

The primary proton spectrum for 1961 is shown in Fig. 10 along with the spectrum for the persistent flux in 1960. The 1961 flux of protons below 190 MeV is 65 percent *below* the 1960 value.

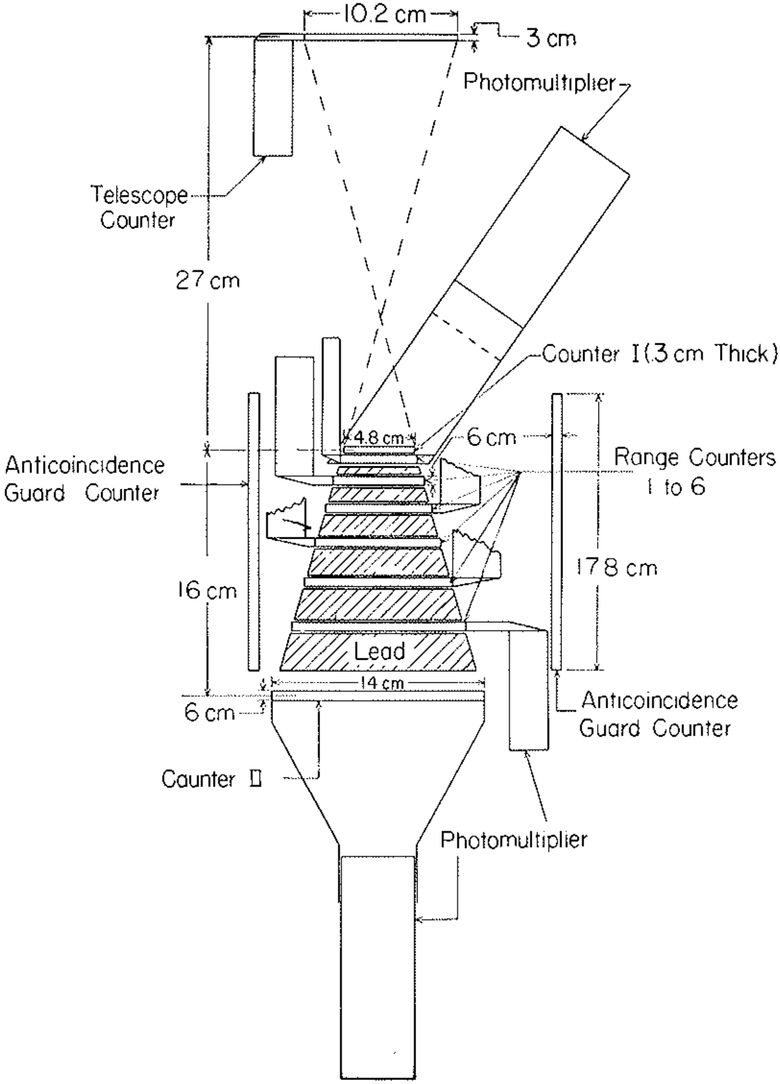


FIG. 9 — Cross-section of the telescope used by MEYER and VOGT [19] to measure the primary flux and spectrum of protons 80-350 MeV at balloon altitudes.

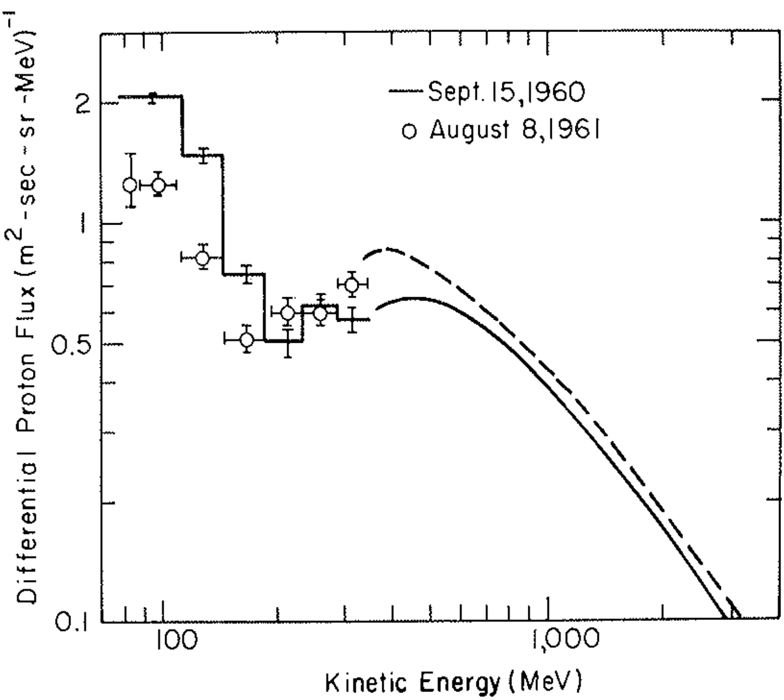


Fig. 10 — The primary spectrum of protons in the range 80-350 MeV is shown along with the change between 1960 and 1961 for cosmic ray spectrum at higher energies predicted by the 11-year change of intensity from Fig. 1 (Part I). The integral cosmic ray flux was also measured by Meyer and Vogt [19). The 1960 data are from Vogt [18].

On the other hand, the intensity of protons above 350 MeV *increased* by 10 percent between 1960 and 1961, in rough agreement with the intensity increase of the cosmic radiation extrapolated from neutron monitor observations (see Part. I, Fig. 1), and expected from the 11-year changes in the cosmic ray spectrum by solar modulation.

From these observations, Meyer and Vogt conclude that two independent mechanisms are responsible for the changes in the primary proton spectrum.

2. The Origin of the Low Energy Primary Protons

Above ∼ 200 MeV the solar modulation of galactic particles is the process which produces the observed changes. Below ∼ 200 MeV the proton intensity is observed to decrease slowly with declining solar activity.

The recent measurements in 1961 on Explorer XII beyond the magnetosphere by Bryant, Cline, Desai and McDonald [20] confirm that not only is their flux and energy spectrum of low energy protons in agreement with the present results but that the flux is continuous over long periods of time.

Meyer and Vogt therefore propose that the low energy protons are either continuously or very frequently emitted by the sun, possibly in association with small solar flares and sub-flares and subsequently stored in the interplanetary medium. The energy required for the solar production of these particles was shown to be very small [18] (∼ 10^{20} ergs/sec) in terms of the total energy output of the sun.

The above conclusions by Meyer and Vogt appear to be the most likely explanation for these low energy protons. However, should there develop difficulties in providing models for the escape of a sufficient flux of protons through the magnetic fields of the chromosphere and corona, it may be worthwhile to consider an alternate process. If both protons and α-particles are accelerated more or less continuously but suffer collisions deep in the solar atmosphere there will be charge exchange processes yielding a solar neutron flux — a process particularly efficient with α-particles. It might then be supposed that some of the solar neutrons escape through the solar magnetic fields to decay in space. The resulting decay-product protons would then be trapped in interplanetary magnetic fields like the solar flare protons already observed. If this process is important, then the proton flux observed by Meyer and Vogt should not be accompanied by a primary α-particle flux.

REFERENCES

PART I

[1] S.E. FORBUSH, *J. Geophys. Res.*, *59*, 525, 1954.
[2] P. MEYER and J.A. SIMPSON, *Phys. Rev.*, *99*, 1517, 1955; ibid, *106*, 568, 1957.
[3] H.V. NEHER, *Phys. Rev.*, *103*, 228, 1956 (and references therein).
[4] P. MORRISON, *Phys. Rev.*, *101*, 1397, 1956.
[5] E.N. PARKER, *Phys. Rev.*, *110*, 1445, 1958.
[6] F.B. MC DONALD and W.R. WEBBER, *Phys. Rev.*, *115*, 194, 1959.
[7] C.Y. FAN, P. MEYER and J.A. SIMPSON, *Phys. Rev. Let.*, *5*, 272, 1960.
[8] J.A. SIMPSON, C.Y. FAN and P. MEYER, *J. Phys. Soc. Japan*, *17*, Supp. A II, 505, 1962.
[9] S.E. FORBUSH, *J. Geophys. Res.*, *63*, 651, 1958.
[10] H.V. NEHER, *J. Phys. Soc. Japan*, *17*, Supp. A II, 492, 1962.
[11] J.A. SIMPSON, *Bul. I.G.Y.*, *15*, 11, 1958.
[12] J.J. QUENBY and W.R. WEBBER, *Phil. Mag.*, *4*, 90, 1959.
[13] A.E. COVINGTON, *J. R. Ast. Soc. Can.*, *55*, 167, 1961.
[13a] A. FENTON, K.B. FENTON and D.C. ROSE, *Can. J. Phys.*, *36*, 824, 1958.
[14] H.D. BABCOCK, *Ap. J.*, *130*, 364, 1959; ibid, *133*, 572, 1961.
[15] E.N. PARKER, *Ap. J.*, *133*, 1014, 1962.
[16] L. DAVIS, *J. Phys. Soc. Japan*, *17*, Supp. A II, 543, 1962 (and references therein).
[17] P. MEYER, E.N. PARKER, and J.A. SIMPSON, *Phys. Rev.*, *104*, 768, 1956.

PART II

[18] R. VOGT, *Phys. Rev.*, *125*, 366, 1958.
[19] P. MEYER and R. VOGT, *Phys. Rev.*, *29*, 2275, 1963.
[20] D.A. BRYANT, T.L. CLINE, V.D. DESAI and F.B. McDONALD, *J. Geophys. Res.*, *67*, 4983, 1962.

Note added in proof: Recently J. KATZMAN and D.C. ROSE (*Can. J. Phys.*, *40*, 1319, 1962) have reported studies of their high latitude neutron and meson intensity monitors for the period 1955-61. Their results display many of the characteristics of the 11-year solar cycle.

DISCUSSION

Chairman: S. HAYAKAWA

NEY

Have MEYER and VOGT carried out the same experiment at low latitude to be sure that the low energy protons are not secondary?

SIMPSON

Yes, they have. They have not analysed their data yet, but the argument that they could not be albedo protons is based on the low geomagnetic cutoff at which they made their measurements. I think that no appreciable albedos in the low energy range they observed are coming in at that latitude.

NEY

My point was that an experiment at low enough latitude to be sure that low energy particles would be excluded as incoming primaries would be convincing. One might tend to be suspicious that the low energy particles are secondaries if the experiment is only done at high latitude.

SIMPSON

They also have measuremeuts for 1962, but their data are not yet analysed. An independent confirmation that the flux is primary comes from Explorer XII measurements beyond the magnetosphere.

BIERMANN

I would like to make two points. The first refers to the question of a good index of solar activity. I would like to ask if one index can really be expected to be representative. We have heard that all efforts in this direction have so far given only the result that each good index was correlated so well with others that one was referred back to the traditional sunspot number. Now following up the theoretical scheme of the solar wind, one might consider first that the solar wind should be mainly governed by the energy input from the turbulence of the hydrogen convection zone. Secondly, solar activity should depend on the solar magnetic fields; their influence might be rather complicated as is made evident by the change of the polarity of the polar regions around the time of maximum solar activity. So one might ask oneself whether in the future one might not try to find a two-dimensional index which is related first to the intensity of the solar wind (or perhaps its velocity and density separately) and second to the magnetic fields carried along with it. This of course will be possible only after the relation between what is seen on the sun's surface and what is measured on or around the earth is understood much more in detail than today.

The other point which I want to make refers to the last observations of MEYER and VOGT. It appears to me that they fall very well in line with the other evidence related to the production of energetic particles on the sun. First, one discovered the production of particles of several GeV — which could be observed at sea level — then next, of those which could be observed at high altitude and not too low geomagnetic latitude. Furthermore, one got evidence from radio data that not only the type IV and V burst, but also the very common type III burst are presumably due to relativistic electrons; that increased the number of events during which at least MeV particles are produced enormously, at times of high solar activity, to something like one event per hour. However, it does not seem unreasonable at all that we have another fairly large number of small events which are just sufficient to produce these protons.

In any case, one should now also look for γ-rays and for primary neutrons which might be connected with the origin of the low energy protons observed by MEYER and VOGT. This might be another extension of the picture which is evolved in recent years.

GOLD

So far as the 11-year variation is concerned and its possible explanations, I think that one could think of two different schemes that can be separated fairly sharply from each other. The first is a modulation that is imposed by a diffusing region that is all the time streaming out from the sun such as Dr. PARKER discussed earlier today, when all the time the flux is trying to come in against an outgoing rush of wind; and in that case it would not be at all clear to me how far out we have to place the region. We know that we can get that amount of modulation in 1 AU, so that if we require a little more smoothing in this effect, possibly 2 or 3 or 4 AU would suffice. But for such a process it would be necessary for the solar wind to be very constant and smoothly dependent on the sunspot cycle. Of course, the larger out one extends the process the more smoothing there would be in it and the less onus would be placed on the sun's outstreaming being constant.

The other point of view is of a cavity in the galactic magnetic field where the sun no doubt will tend to blow up a bulge in the otherwise largely homogeneous local region of field and the size of this bulge will no doubt fluctuate with solar activity. That bulge will hold out galactic cosmic rays which would be streaming spiralling around the field lines, and it will hold them out more when it is being blown up and less when it is contracting. That is all perfectly all right and it seems to me that one could squeeze out of either of these models all the spectral effects that we know so far, by adjusting the fine structure unevenness in that field. I am not clear, however, whether we can be absolutely sure that the size of such a bubble and its growth and diminution are entirely a function of the solar wind. It is unfortunately true that the amount of energy poured out in ionizing radiation from the sun is not negligible compared with the solar wind. On the whole I tend to think that the solar wind will dominate, but this is not completely certain. We may need to know the ionizing radiation and its change in the solar cycle too. That is no doubt another feature which goes together with most of the solar cycle characteristics but it would be a different kind of index which we must rely on in that case.

Then I wanted to say something about your point about the low energy particles. I don't really see why you think that a neutron explanation is necessary, because the way in which low energy particles will differ from their high energy counterparts in their movements would be merely that they would take a longer time to reach any particular region of space, but the attenuation from collisions would still not be very great; so they would be still more smoothed out. All you must expect is that from any one event the low energy pulse will be a very long drawn out affair that would arrive here very slowly and would take a very long time to decay. In that case a superposition of a succession of minor events will make a very smooth arrival here — and isn't that all that we need to account for?

SIMPSON

Yes, this is, in general terms, the main point that MEYER and VOGT make; namely, that there are many solar accelerated events with a « smoothing » taking place either in fields near the sun, or in the storage fields in the interplanetary medium. In this way a general dynamic level is established for the observed proton flux.

NEHER

I just wanted to say that I agree with your analysis here all except 1955, at least in the summer of 1955.

ELLIOT

If this does represent continuous production of low energy protons, I wonder if there is any possibility of seeing this process going on in terms of type IV radio emission as in the case of the other particles which come from flares and which are not really of so much higher energy. There might perhaps be a chance that electrons are produced at the same time and reveal their presence in this way.

SIMPSON

I think that is the nearest thing. I am not aware of what the ambient level of type IV would be; one would presumably look for a large number of relatively small events. Could I ask Prof. DENISSE if he would have an opinion on that?

DENISSE

This number of small events would depend on the importance of flares that are likely to produce 100 MeV protons. As I said this morning, there is a great number of very small flares that give rise to type III events, for instance, where high energy particles are produced. The number of those flares changes, of course, very much with the solar cycle, but I would say that in 1960 or 1961 there might have been on the average as many as one flare a day. The number of type IV flares was at least an order of magnitude lower during the same period.

I like to ask Prof. SIMPSON one question about the cycle of hysteresis he just described. It is noteworthy that the hysteresis is concomitant with recurrent magnetic storm and not with a S.C. magnetic storm, and I wonder if you consider that both effects might be in some way related?

SIMPSON

The preliminary work that we have done has indicated that it does not account for the phase shift. We tried to analyse data in such a way that we could find whether or not we were in phase with geomagnetic disturbances during the years of recurrent geomagnetic storms.

PETERS

I would like to come back for a moment to the possibility that a continuous production of low energy nucleons takes place and that these nucleons have to get out of the corona as neutrons which later decay into protons. Neutrons of 100 MeV will take about 15 minutes to reach us, so that the slow protons which have been observed should be accompanied by a steady stream of 100 MeV neutrons at all latitudes not only at the poles. This would be a measurable effect which may provide some check on the underlying ideas.

SIMPSON

Yes, if one assumes that a large flux of neutrons decay in the vicinity of the earth, in order to maintain the proton flux level, the neutron flux will be at its highest value. A rough estimate shows that no experiments performed so far would have detected such a flux. On the other hand, the principal region for neutron decay leading to protons stored in interplanetary fields will be near the sun. The decay protons would then propagate throughout the magnetic fields of the medium. Under such conditions the neutron flux observed at the earth may be very small compared to the observed proton flux.

VALLARTA

There is one point I would like to emphasize and I think that this comment applies to all three papers that were presented this afternoon, and that is that the geomagnetic cutoff is not a constant but is a function of time. It is affected not only by the secular variation of the internal field of the earth but also mainly by the external field which depends on the solar activity, and therefore plays a major role in this connection. Now I believe so far that this effect appears mainly at low energies and at high latitudes: At intermediate latitudes and high energies then it turns out that the pass in the Störmer allowed regions is inside the cavity that Prof. ROSSI discussed yesterday. And therefore you must expect that at these energies the change in the geomagnetic cutoff is relatively smaller. Now there is every chance that many of the difficulties that are met with at this time are connected very closely with the question of the change of the geomagnetic cutoff; mainly at low and intermediate energies.

SINGER

Possibly I missed this point, but I did not hear you say anything about the diurnal variation of these low energy protons. If neutrons play any sort of a role, they will be coming from a point source, the sun, and be producing a fairly uniform field of decay protons between the sun and the earth. The protons should have therefore a non-isotropic distribution which might show up as a diurnal variation. Is there any such evidence?

SIMPSON

There is no evidence. However, I would expect the neutron decay protons to become distributed isotropically in the interplanetary medium in the same way that low energy protons from solar flares have been observed to fill the nearby medium at late times in the flare event.

GOLD

I would like to make another point about the neutron hypotheses. If neutrons played a part in this story, then would you not expect the neutron flux on the occasion of a flare to be enormous? And yet one has looked and not found it. A big flare produces presumably a vastly greater number in any energy range than in the case that we are discussing here. So that should be a plainly visible effect.

Simpson

In the 1956 flare, for example, you would not have seen the effect of neutrons at the equator unless their intensity was greater than 5% or 10% of the total flux. But this really is not an answer to the question because the ratios of charged particles to neutrons may be sensitive to the energy of the solar event.

INVARIANTS AND LONG-RANGE STABILITY (*)

RENE DE VOGELAERE

Mathematics Department, University of California
Berkeley, Cal. - U.S.A.

Abstract — A comparison will be made of the known so-called invariants and adiabatic invariants for the Störmer problem. This will be used as a starting point for a discussion of long-range motion of the mirror points of trajectories in the magnetic dipole field exploring the role played by special trajectories: the unstable periodic ones and the asymptotic trajectories to these periodic orbits.

(*) The text of this contribution was not received; the discussion on it took place after the contribution by Prof. Bossy, *The motion of particles trapped in a magnetic dipole field as a special case of the Störmer problem* along with the discussion on this last report.

THE MOTION OF PARTICLES TRAPPED IN A MAGNETIC DIPOLE FIELD AS A SPECIAL CASE OF THE STÖRMER PROBLEM

L. BOSSY

Institut Royal Météorologique
Bruxelles - Belgique

Abstract — The motion of particles trapped in the field of a magnetic dipole is considered in the scope of the STÖRMER problem and described in a special system of coordinates. It is shown that in this representation the locus of the mirror points is a fixed one at least to the second approximation and that the drift motion of a set of independent particles differs widely from the drift of the individual particles. Finally, some indications are given, on the basis of the numerical computation of some trajectories, on the actual spreading of the mirror points.

1. INTRODUCTION

There are many fields of physics and especially of geophysics where a more or less accurate knowledge of the movement of charged particles in an electromagnetic field is required. The usual approach to this knowledge follows the way first indicated by ALFVÉN [1] and ending in the well known guiding-center approximation. The precision of the results obtained is not quite determined; according to the authors, the only limitation is that, in the case of a static field, the radius of gyration of the particles shall remain small in respect to the scale of variation of the magnetic field.

This study starts from expressions obtained by the author [2] in the search for the analytical representation of orbits of the Störmer problem in the case where these orbits penetrate deeply in the valleys towards the magnetic dipole and which can be found partly in Lemaître and Bossy [3].

We will show that these expressions lead to the same results as the Alfvén method for the features of the movement that are based on the first approximation of the orbits. This is the case of the perpendicular and the parallel component of the velocity and of the period of oscillation between the mirror latitudes.

On the other hand, the drift movement has a principal part where the phase of the orbit is present, so that only a mean value has a significance. Therefore, in the case where there are no interactions between the particles, we will define a decomposition of a symmetric set of particles in what we will call « elementar pseudo-plasma » and we will show that the evaluation of the quantities connected with the drift of the particles requires a careful analysis.

At the end, we will emphasize the fact, that our developments are not suitable when we consider the movement during a comparatively long period. This fact appears when we consider the trajectories obtained by the numerical integration of the Störmer equations and it is evident at first sight that the latitude of the mirror points is not a constant. The decomposition in elementar pseudo-plasmas will consequently have only a limited duration of validity and this instability of the mirror points must be taken into account in the study of the removal of particles from the Van Allen belts.

2. The movement of the individual particles

The Störmer problem [4] considers the movement of a particle of charge Ze and proper mass m in the field of a magnetic dipole of moment M. The first peculiarity of this problem is that, if we consider a meridian plane attached to the particle, it is permitted to treat separately the relative displacement of the particle in the meridian plane and the rotation of this plane.

Using spherical coordinates, the hamiltonian function of the relative movement is

$$2\,H \equiv p_r^2 + \frac{1}{r^2}\,p_\lambda^2 + V^2\left(\mp\frac{2\gamma}{r\cos\lambda} \pm \frac{Z\,|e|\,M}{mc\,V}\,\frac{\cos\lambda}{r^2}\right)^2 - V^2 = 0 \qquad (1)$$

and the angular velocity of the meridian plane is given by

$$\frac{d\varphi}{dt} = \mp\frac{1}{r^2\cos^2\lambda}\left(2\,\gamma\,V - \frac{Z\,|e|\,M}{mc}\,\frac{\cos^2\lambda}{r}\right) \qquad (2)$$

In these expressions, γ is a constant of the dimension of a length and the upper sign refers to the positive particles, the lower sign to the negative.

It is customary to introduce a characteristic length, the störmer L, defined by

$$L = \sqrt{\frac{Z\,|e|\,M}{mc\,V}}$$

and the dimensionless constant γ_1 by

$$2\,\gamma = 2\,\gamma_1\,L$$

so that (1) and (2) can be written

$$2\,H \equiv p_r^2 + \frac{1}{r^2}\,p_\lambda^2 + V^2\left(\frac{2\,\gamma_1}{(r/L)\cos\lambda} - \frac{\cos\lambda}{(r/L)^2}\right)^2 - V^2 = 0 \qquad (1')$$

and

$$\frac{d\varphi}{dt} = \mp\frac{V\,L}{r^2\cos^2\lambda}\left(2\,\gamma_1 - \frac{\cos^2\lambda}{r/L}\right) \qquad (2')$$

We see that, in all the cases where γ_1 is positive, the sign of $\dfrac{d\varphi}{dt}$ changes each time the particle crosses the curve

$$r = \frac{L}{2\gamma_1}\cos^2\lambda = r_T\cos^2\lambda \quad .$$

This curve is named the thalweg, r_T is its equatorial radius and we obtain a physical definition of γ_1 by

$$2\gamma_1 = \frac{L}{r_T}$$

so that, for non relativistic particles γ_1 is inversely proportional to the square root of V and to r_T.

On the other hand, the relative movement takes place in the regions where

$$1 - \left(\frac{2\gamma_1}{(r/L)\cos\lambda} - \frac{\cos\lambda}{(r/L)}\right)^2 \geqslant 0$$

and, in the cases where $\gamma_1 > 1$, these regions consist of *a*) the part of the plane extending to infinity at the right of a barrier of potential and *b*) a region bounded by two curves on each side of the thalweg. These regions are shown in Fig. 1 and the boundary curves of the inner one crosses the equator at two points I and E where

$$r_I = r_T\left[1 - \left(\frac{r_T}{L}\right)^2 + 2\left(\frac{r_T}{L}\right)^4 - 5\left(\frac{r_T}{L}\right)^6 + \ldots\right]$$

$$r_E = r_T\left[1 + \left(\frac{r_T}{L}\right)^2 + 2\left(\frac{r_T}{L}\right)^4 + 5\left(\frac{r_T}{L}\right)^6 + \ldots\right] \quad .$$

Hence, the thalweg bissects the permitted region within terms in $\left(\dfrac{r_T}{L}\right)^2$ and the equatorial width, which is the maximum width of the region, is equal to

$$D = 2\,\frac{r_T^3}{L^2}\left[1 + 10\left(\frac{r_T}{L}\right)^4 + \ldots\right] \quad . \qquad (3)$$

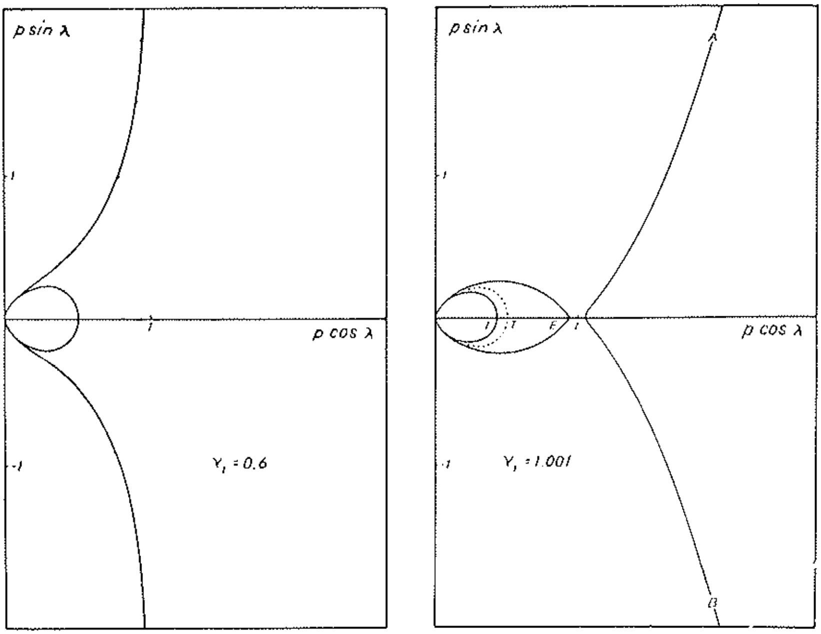


FIG. I — The permitted regions for $\gamma_1 = 0.6$ and $\gamma_1 = 1.001$
(after STÖRMER, 1955)

The principal problem is the representation of the relative movement. In the cases under consideration where $\gamma_1 > 1$, a particle starting in the inner region from a point on the equator oscillates with a variable amplitude from one side of the thalweg to the other while progressing in the direction of the dipole. When the amplitude of the oscillation and the half-width of the valley become eqnal, this progression stops and the mirror latitude is reached.

To establish our approximate representation of the trajectories we will use coordinates which are quite far from the physical ones.

We make first the Goursat conformal transformation

$$x = \log \frac{r}{r_T} \quad , \quad \lambda = \lambda \tag{4}$$

together with the change of independent variable

$$d\sigma = 2\gamma_1 \mathrm{LV} \frac{dt}{r^2} = \frac{\mathrm{L}^2\mathrm{V}}{r_T} \frac{dt}{r^2} \tag{5}$$

so that the new hamiltonian function takes the form intensively used by LEMAITRE and VALLARTA [5]

$$2\,\mathrm{H} \equiv p_x^{\,2} + p_\lambda^{\,2} - \left[(2\,\gamma_1)^{-4} e^{2x} - (e^{-x} \cos\lambda - \sec\lambda)^2 \right] = 0$$

and the permitted inner region has the shape given by Fig. 2.

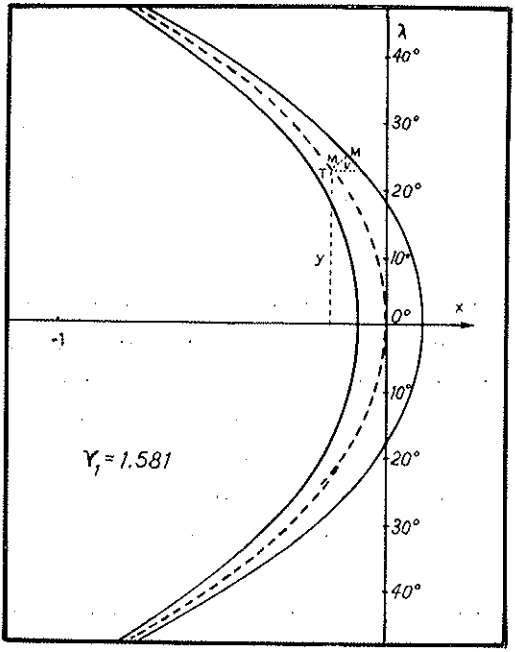


FIG. 2 — The inner permitted region for $\gamma_1 = 1{,}581$ in the plane (x, λ) and the coordinates (u, y).

[13] *Bossy* - pag. 6

In a last transformation, we introduce the coordinates u and y through the relations

$$\begin{aligned} x &= 2 \log \cos y + u \cos v \ , \\ \lambda &= y + u \sin v \end{aligned} \tag{6}$$

where $tg\, v = 2\ tg\, y$. It is easy to see that u is the shortest distance from a point P to the thalweg and y the latitude of the foot of the normal drawn from P to the thalweg.

Our definitive hamiltonian function is then

$$2\,H \equiv p_u{}^2 + \frac{1}{Q(u\,,y)}\, p_y{}^2 - P(u\,,y) = 0$$

where

$$Q(u\,,y) = \frac{1}{\cos^2 v}\left(1 + 2\,\frac{\cos^3 v}{\cos^2 y}\,u\right)^2$$

and

$$\begin{aligned} P(u\,,y) = {} & \varepsilon^4 \cos^4 y\,[1 + 2\,u \cos v + 2\,u^2 \cos^2 v + \ldots] \\ & - \cos^{-2} y\,[u^2 \cos^{-2} v + u^3 \cos v\,(-1 + 4\,\mathrm{tg}^2 y + 8\,\mathrm{tg}^4 y) + \ldots] \ . \end{aligned} \tag{7}$$

In this last expression, we have replaced the parameter $2\gamma_1$ through its inverse ε which is small and will serve to define the different orders of approximation. We have so

$$\varepsilon = \frac{1}{2\,\gamma_1} = \frac{r_T}{L}$$

and we see at once from (3) that u is a small quantity of the order of ε^2.

The equations of the relative movement are respectively the lagrangian equation in u

$$2\frac{d^2 u}{d\sigma^2} - \frac{\partial Q}{\partial u}\left(\frac{dy}{d\sigma}\right)^2 = \frac{\partial P}{\partial u} \tag{8}$$

and the integral of energy

$$\left(\frac{du}{d\sigma}\right)^2 + Q\left(\frac{dy}{d\sigma}\right)^2 = P\ . \tag{9}$$

We remark, from (7) that P (u, y) is of the order 4 so that $\frac{dy}{d\sigma}$ is of the second order. Therefore, we can develop (8) and (9) as

$$\frac{d^2 u}{d\sigma^2} + u\cos^{-2} y \cos^{-2} v = 0$$

$$+ \cos v\left(\varepsilon^4 \cos^4 y + \cos^{-2} y\left[u\left(\frac{3}{2} - 6\,\mathrm{tg}^2 y - 12\,\mathrm{tg}^4 y\right) - 2\left(\frac{dy}{d\sigma}\right)^2\right]\right)$$

$$+ \dots$$

$$\left(\frac{dy}{d\sigma}\right)^2 = \cos^2 v \left(\begin{array}{l} \varepsilon^4 \cos^4 y - u^2 \cos^{-2} y \cos^{-2} v - \left(\frac{du}{d\sigma}\right)^2 \\ + u\cos v\left\{2\varepsilon^4 \cos^4 y + \cos^{-2} y\left[u^2(1 - 4\,\mathrm{tg}^2 y - 8\,\mathrm{tg}^4 y\right\}\right. \\ \left. - 4\left(\frac{dy}{d\sigma}\right)^2\right]\Bigg\} \\ + \dots \end{array}\right).$$

[13] *Bossy* - pag. 8

Through successive substitutions, we find the expressions of u and $\left(\frac{du}{d\sigma}\right)^2$ respectively within terms of the sixth and the eight order, in the form

$$\begin{aligned} u = {} & \varepsilon^2 \sqrt{\mu} \sqrt{\cos y \cos v} \sin \Phi \\ & + \varepsilon^4 \left[\begin{array}{l} 3 \cos^6 y \cos^5 v (1 + 2 \operatorname{tg}^2 y) - \mu \cos y \cos^4 v \left(\frac{5}{4} + 5 \operatorname{tg}^2 y + 6 \operatorname{tg}^4 y \right) \\ + \mu \cos y \cos^4 v \left(\frac{1}{4} - \operatorname{tg}^2 y - 2 \operatorname{tg}^4 y \right) \cos 2\Phi \end{array} \right] \\ & + o(\varepsilon^6) , \end{aligned} \tag{10}$$

$$\begin{aligned} \left(\frac{dy}{d\sigma}\right)^2 = {} & \varepsilon^4 \cos^4 y \cos^2 v (1 - \mu \cos^{-5} y \cos^{-1} v) \\ & + \varepsilon^6 \left[\begin{array}{l} -8 \sqrt{\mu} \sqrt{\cos y \cos v} \cos^2 y \cos^5 v (1 - \mu \cos^{-5} y \cos^{-1} v) \sin \Phi \\ + \frac{1}{2} \mu \cos^3 v (\sin y \cos y + 2 \sin v \cos v) \sqrt{1 - \mu \cos^{-5} y \cos^{-1} v} \sin 2\Phi \end{array} \right] \\ & + o(\varepsilon^8) . \end{aligned} \tag{11}$$

where the argument Φ is connected to y and σ by

$$\frac{d\Phi}{d\sigma} = \pm [\cos^{-1} y \cos^{-1} v + o(\varepsilon^1)] \tag{12}$$

and where $\sqrt{\mu}$ is a constant amplitude factor. When integrated, this last equation gives the first approximation of the argument

$$\Phi - \Phi_0 = \pm \frac{1}{\varepsilon^2} \left[\int_0^y \cos^{-3} y \cos^{-2} v \frac{dy}{\sqrt{1 - \mu \cos^{-5} y \cos^{-1} v}} + o(\varepsilon^2) \right] . \tag{13}$$

The expression (10) of u has a principal part

$$\varepsilon^2 \sqrt{\mu} \sqrt{\cos y \cos v} \sin \Phi$$

who is purely sinusoidal; hence, the relative movement of the particle consists principally in an oscillation about the thalweg.

The second approximation of u introduces, besides a term in $\cos 2\Phi$, a non periodic expression. This non periodic part of u contains the term

$$3\,\varepsilon^4 \cos^6 y\ \cos^5 v\,(1 + 2\,\mathrm{tg}^2 y)$$

which does not depend on μ and gives the first approximation of the orbit coming from the dipole; and a second term

$$-\mu \cos y \cos^4 v \left(\frac{5}{4} + 5\,\mathrm{tg}^2 y + 6\,\mathrm{tg}^4 y \right)$$

which is proportional to the square of the amplitude factor.

It shows that the oscillation takes place about the curve

$$u = \varepsilon^4 \left[3 \cos^6 y \cos^5 v\,(1 + 2\,\mathrm{tg}^2 y) - \mu \cos y \cos^4 v \left(\frac{5}{4} + 5\,\mathrm{tg}^2 y + 6\,\mathrm{tg}^4 y \right) \right]$$

which is normally more distant from the dipole than the thalweg, but which crosses the thalweg when the mirror latitude is greater than the root of the equation

$$6\,\mathrm{tg}^4 y - \mathrm{tg}^2 y - \frac{7}{4} = 0$$

or greater than

$$\mathrm{arc\,tg} \sqrt{\frac{1 + \sqrt{43}}{12}} \sim 38.4° \ .$$

[13] *Bossy* - pag. 10

It appears from (11) and (13) that the extreme values y_m of y are the roots of the equation

$$\cos^5 y_m \cos v_m = \mu \tag{14}$$

so that the relative trajectory of the particle will touch the normals to the thalweg at $+y_m$ and at $-y_m$.

If we now consider the angular movement of the meridian plane, we get from (2'), (4) and (5)

$$\frac{d\varphi}{d\sigma} = \mp (\sec^2 \lambda - e^{-x})$$

so that making use of (6) and (10) the derivative of φ with respect to σ is

$$\frac{d\varphi}{d\sigma} = \mp \cos^{-2} y \left\{ \begin{aligned} & \varepsilon^2 \sqrt{\mu} \sqrt{\frac{\cos y}{\cos v}} \sin \Phi \\ & + \varepsilon^4 \left[\begin{aligned} & 3 \cos^6 y \cos^4 v \left(1 - \frac{\mu}{2} \cos^{-5} y \cos^{-1} v \right)(1 + 2 \operatorname{tg}^2 y) \\ & + \mu \cos y \cos^3 v \left(\frac{1}{2} - 3 \operatorname{tg}^2 y - 8 \operatorname{tg}^4 y \right) \cos 2\Phi \end{aligned} \right] \\ & + o(\varepsilon^6) \end{aligned} \right\} \tag{15}$$

We see from the expressions (10) to (15) that, in the case under consideration, the family of trajectories of a defined kind of particles in a given dipole field depends on a set of 6 parameters. If we choose as initial conditions those which correspond to a certain transit through the equatorial plane, it is easy to see that this set is composed of:

a) the equatorial radius r_T of the thalweg, *b*) the amplitude factor $\sqrt{\mu}$ or the mirror latitude y_m,

c) the velocity V of the paricle or the associated STÖRMER unit L,

d) the phase constant Φ_0 of the path, or better its corresponding value τ_0 in the time scale; τ_0 is related to Φ_0 by the relation

$$d\tau_0 = \frac{r^3_T}{L^2 V^2} [1 + 2 \varepsilon^2 \sqrt{\mu} \cos \Phi_0 + o(\varepsilon^4)] \, d\Phi_0 \qquad (16)$$

At any latitude y, this relation takes the form

$$d\tau = \frac{r^3_T}{L^2 V} \cos^5 y \cos v [1+2 \varepsilon^2 \sqrt{\mu} \sqrt{\cos y \cos v} \cos v \sin \Phi + o(\varepsilon^4)] \, d\Phi \, , \qquad (16')$$

e) the corresponding longitude φ_0 of the meridian plane,

f) the epoch t_0 of the transit.

The amplitude factor $\sqrt{\mu}$ and the phase Φ_0 are connected with the components of the initial velocity vector $\mathbf{V}_0$. Using only the first approximation one obtains that:

the radial component is $V_{r0} = V\sqrt{\mu} \cos \Phi_0$,

the vertical or meridian component is $V_{m0} = V \sqrt{1 - \mu}$,

the transverse or zonal component is $V_{z0} = V\sqrt{\mu} \sin \Phi$.

The classical relation between the pitch angle θ_0 and the latitude of mirroring is consequently true as a first approximation; we find

$$\operatorname{tg}^2 \theta_0 = \frac{\|\mathbf{V}_\perp\|^2}{\|\mathbf{V}_\parallel\|^2} = \frac{\mu}{1 - \mu} \quad ; \text{ so that } \sin^2 \theta_0 = \mu = \cos^5 y_m \cos v_m$$

[13] *Bossy* - pag. 12

The approximate constancy of $\frac{1}{2} \cdot \frac{m\|\mathbf{V}_\perp\|^2}{\|\mathbf{B}\|}$ follows immediately.

With the same accuracy, the direction β of the initial relative velocity counted from the normal to the equator is defined by

$$\operatorname{tg} \beta = \sqrt{\frac{\mu}{1-\mu}} \cos \Phi_0 \quad .$$

The component $\|\mathbf{V}\|$ of the velocity of the particles has a first approximation which is independent of Φ_0 and is given by

$$\|\mathbf{V}_\parallel\| = \pm \mathrm{V} \sqrt{1 - \mu \cos^{-5} y \cos^{-1} v}$$

so that the value of $\|\mathbf{V}_\perp\|$ is

$$\|\mathbf{V}_\perp\| = \pm \mathrm{V} \sqrt{\mu \cos^{-5} y \cos^{-1} v} \quad .$$

The duration $\mathfrak{T}$ of a complete oscillation between the mirror latitudes is also independent of the phase and defined by

$$\mathfrak{T} = 4 \frac{r_\mathrm{T}}{\mathrm{V}} \int_0^{y_0} \frac{\cos^2 y}{\cos v} \frac{dy}{\sqrt{1 - \mu \cos^{-5} y \cos^{-1} v}}$$

and the period T_y of a rotation at the latitude y is given by

$$\mathrm{T}_y = 2\pi \frac{r_\mathrm{T}^3}{\mathrm{L}^2 \mathrm{V}} \cos^5 y \cos v \quad .$$

All these relations are obtained from the first terms of the expression (10), (11), (12) and (15); they coincide with the results obtainable from the ALFVÉN approach.

In the equatorial plane, our approximate expressions reduce to

$$u = \varepsilon^2 \sin \Phi + \varepsilon^4 \left(\frac{7}{4} + \frac{1}{4} \cos 2\Phi \right) + o(\varepsilon^6)$$

or

$$e^x = e^u = 1 + \varepsilon^2 \sin \Phi + 2\varepsilon^4 + o(\varepsilon^6)$$

and

$$\frac{d\varphi}{d\sigma} = \mp \left[\varepsilon^2 \sin \Phi + \varepsilon^4 \left(\frac{3}{2} + \frac{1}{2} \cos 2\Phi \right) + o(\varepsilon^6) \right]$$

with $\Phi - \Phi_0 = \sigma + o(\varepsilon^4)$.

It is easily seen that these expressions coincide, within terms in k^3, with the exact solution expressed in terms of elliptic functions.

This exact solution is, according to LIFSHITZ [6],

$$\frac{r}{r_T} = e^x = \frac{1 + k \sin^2 z}{A + (1 - A) k \sin^2 z}$$

$$\frac{d\varphi}{d\sigma} = \mp \frac{(1 - A) + A k \sin^2 z}{1 + k \sin^2 z}$$

where

$$z = \frac{1}{2} \frac{1}{\sqrt{1 + k^2}} \sigma \ , \quad \varepsilon^2 = \frac{k}{2(1 + k^2)} \text{ and } A = \frac{1 + k + \sqrt{1 + k^2}}{2\sqrt{1 + k^2}}$$

so that the modulus k is of the order of ε^2.

The period of the relative movement along the equator is given by

$$T_0 = \frac{L}{V} \sqrt{\frac{2}{k}} (K - E) = 2\pi \frac{r^3_r}{L^2 V} [1 + o(\varepsilon^4)]$$

where K and E are the complete elliptic integral of LEGENDRE and the relation between τ_0 and Φ_0 takes the form

$$d\tau_0 = \frac{r^3_T}{L^2 V} [1 - 2\varepsilon^2 \cos \Phi_0 + o(\varepsilon^4)] \, d\Phi_0 \quad .$$

3. THE DRIFT OF AN ELEMENTARY PSEUDO-PLASMA

We now take into consideration a set of charged particles describing independent trajectories in the dipole field and constituting a pseudo-plasma. Its structure depends on the types of the particles, on their energy and on the distribution of their trajectories.

This distribution will obviously much depend on the process of injection of the particles; for instance, in the case of an ARGUS type experiment there will certainly be a strongly asymmetric distribution.

In general, for a definite type of particles, the structure of the pseudo-plasma is fixed by a repartition function

$$n(r_T, \mu, V, \tau_0, \varphi_0, t_0)$$

so that

$$n(r_T, \mu, V, \tau_0, \varphi_0, t_0) \, dr_T \, d\mu \, dV \, d\tau_0 \, d\varphi_0 \, dt_0$$

gives the number of particles in a cell of the space of the initial conditions.

We will limit ourselves, to pseudo-plasmas symmetric about the dipole axis and such that n is independent of τ_0, φ_0 and t_0.

There exists then a decomposition in a family of so-called elementar pseudo-plasmas defined by the equatorial radius r_T of the thalweg common to all the trajectories, the common velocity V and the geomagnetic latitude y_m of mirroring.

The local drift velocity of an elementar pseudo-plasma can be defined as the mean transverse velocity of the particles which at a certain time cross the normal to the thalweg at the latitude y. Its value will be obtained by averaging the expression $r \cos \lambda \dfrac{d\varphi}{dt}$ in respect to τ.

If T_y is the period of gyration at the latitude y we find the mean value as

$$\overline{r \cos \lambda \frac{d\varphi}{dt}} = \frac{1}{T_y} \int_0^{T_y} r \cos \lambda \frac{d\varphi}{dt} \, d\tau = \frac{1}{T_y} \int_0^{2\pi} r \cos \lambda \frac{d\varphi}{dt} \frac{d\tau}{d\Phi} \, d\Phi$$

and we obtain, using (10), (12), (15) and (16′),

$$\overline{r \cos \lambda \frac{d\varphi}{dt}} = \mp 3 \frac{r_T^2}{L^2} V \Big[\cos^3 y \cos^4 v \, (1 + 2 \operatorname{tg}^2 y) \left(1 - \frac{1}{3} \mu \cos^{-5} y \cos^{-1} v \, \frac{1 + 2 \operatorname{tg}^2 y + 4 \operatorname{tg}^4 y}{1 + 2 \operatorname{tg}^2 y} \right) + o(\varepsilon^2) \Big]$$

so that, for an elementar pseudo-plasma confined in the equatorial plane ($\mu = 1$, $y = v = o$), the drift velocity is given by

$$\overline{r \frac{d\varphi}{dt}} = \mp 2 \frac{r_T^2}{L^2} V \left[1 + o(\varepsilon^2) \right] .$$

This value is equal to the 4/3 of the mean drift velocity of the individual particles; it agrees with the result obtainable from the exact solution in terms of elliptic functions.

It is two times greater than the one we obtained (BOSSY [7]) for the case where the elementar pseudo-plasma is considered as uniform in respect to the argument Φ_0 and not to τ_0 which is the really representative parameter.

We see that the drift of the positive particles, for instance, is directed from the East to the West as long as we have

$$1 - \frac{1}{3} \mu \cos^{-5} y \cos^{-1} v \frac{1 + 2 \operatorname{tg}^2 y + 4 \operatorname{tg}^4 y}{1 + 2 \operatorname{tg}^2 y} \geqslant 0 \ .$$

This expression can only become negative when $|y_m|$ is greater than the root of the equation

$$\operatorname{tg}^4 y - \operatorname{tg}^2 y - \frac{1}{2} = 0$$

i.e.

$$|y_m| \geqslant \operatorname{arc\,tg} \sqrt{\frac{1 + \sqrt{3}}{3}} \sim 49.5^0 \ .$$

It results that the elementar pseudo-plasmas whose mirror latitudes are greater than 49.5° exhibit a small reversed drift at their upper-most part. This effect is a maximum when y_m is near 60° and the reverse drift is then of the order of 1% of the equatorial drift. The numerical results are summarized in Fig. 3.

This mean transverse velocity differs from the one obtained from the guiding center approximation

$$V_D = \mp 3 \frac{r_T^2}{L^2} V \cos^3 y \cos^4 v (1 + 2 \operatorname{tg}^2 y) \left(1 - \frac{1}{2} \mu \cos^{-5} y \cos^{-1} v\right)$$

which is more representative for the mean motion of the individual particles.

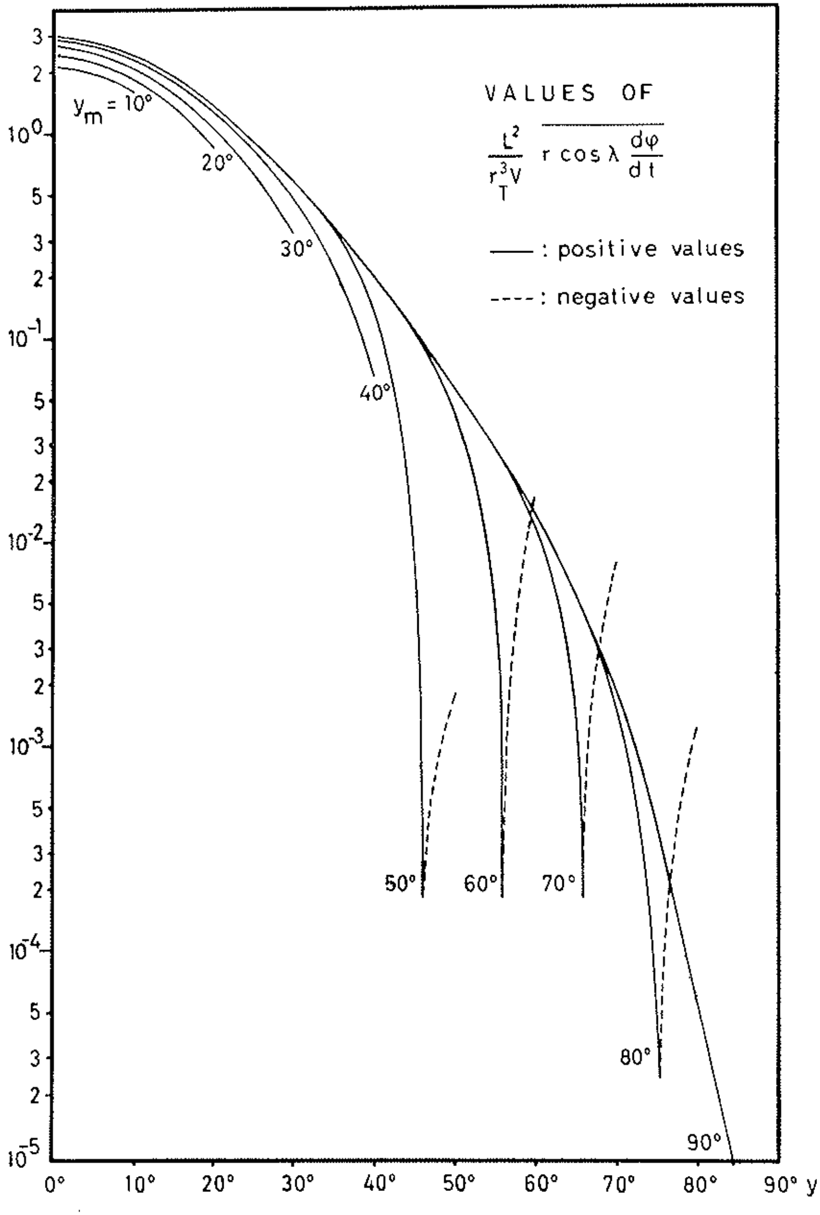


FIG. 3 — Variation of the mean transverse velocity of a pseudo-plasma with the latitude

We feel that the obtention of exact mean values of quantities related to the drift of such spiralling particles is a delicate problem which requires a careful use of the expressions of the individual trajectories.

4. The instability of an elementary pseudo-plasma

Unfortunately, the analytical representation used here has only a limited domain of validity.

This fact is evident when one considers the case of the orbits coming drom the dipole (or from infinitely near). Our results imply that the relative trajectory, characterized by $\mu = 0$, crosses normally the equator and then reaches the dipole through the other valley. But, it is well known that this is not the fact and that this relative trajectory probably never reaches the dipole again. This discrepancy is connected with the divergence of the series used.

It is then obvious that the latitude y_m is not a conservative parameter of the problem and that it is only our method of analysis which has introduced this apparent invariant.

This is an important fact for the geophysical applications, where the duration of the oscillation between the mirror points can be of the order of a few seconds, so that the particles oscillate a great number of times and the cumulative effects on y_m becomes important.

The only way to illustrate this fact consists, for the moment, in the numerical computation of individual trajectories.

Fig. 4 represents some relative trajectories starting from the intersection of the thalweg and the equator with a pitch angle equal to 70°. The values adopted for γ_1 are 1.0, 1.1, 1.3, 1.6, 2.0 and 4.0 and the dotted normals to the thalweg represent the theoretical loci of the mirror points.

We present now a more complete description of the behaviour of the mirror latitudes for the case where $\gamma_1 = 1.6$. We

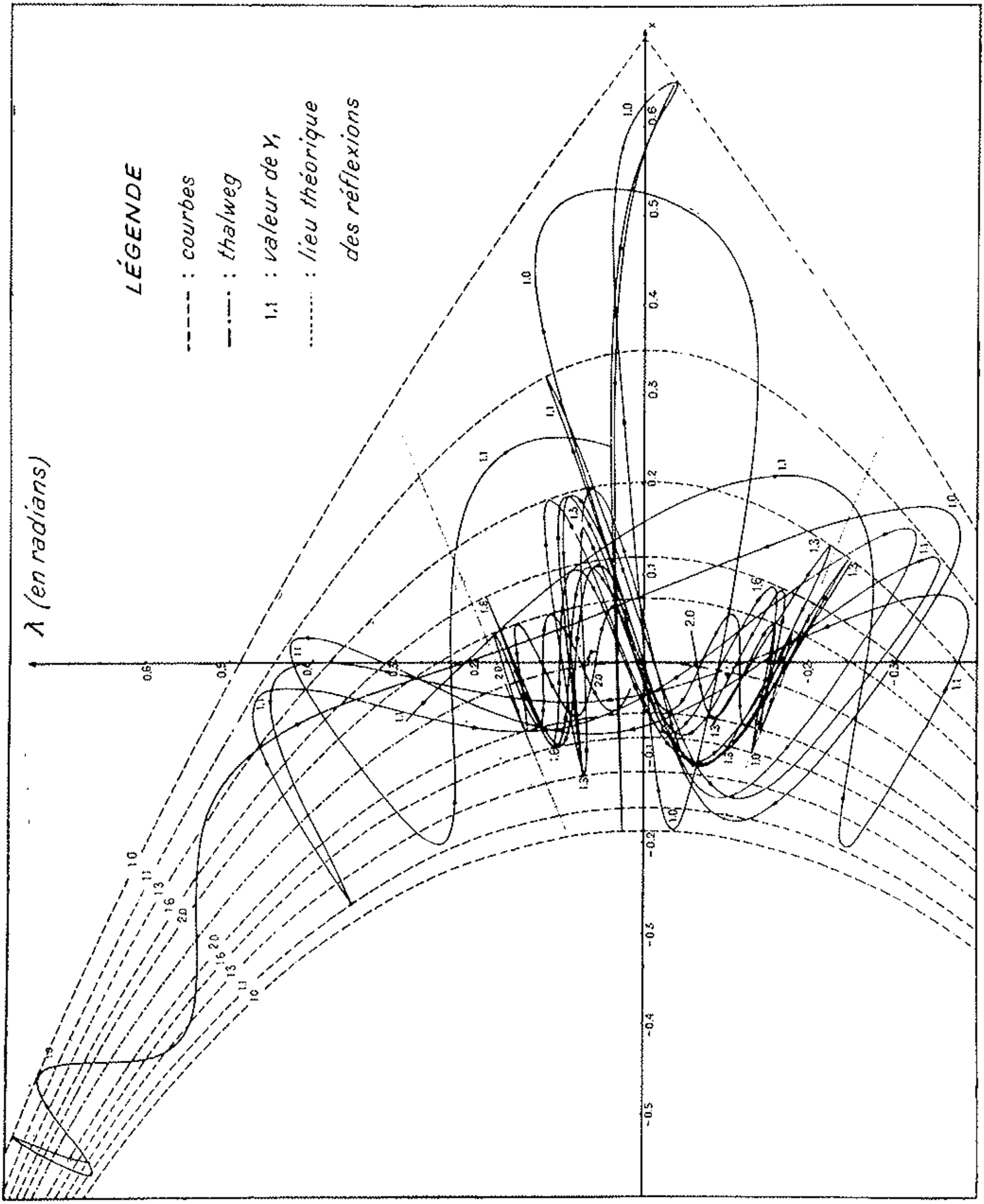


FIG. 4 — Trajectories of the family $\beta = \div 20^0$

have chosen this somewhat low value of γ_1 because the variation of μ during one quarter of an oscillation decreases rapidly when γ_1 grows and for great values of γ_1 the numerical inaccuracy would vitiate the results.

In Fig. 5, we have plotted:

a) as dotted curves, the loci of constant μ expressed by the value of the mirror latitude,

b) as full curves, the loci of the actual maximum latitude reached by the particle after a quarter of an oscillation.

The coordinates used are respectively:

a) as abscissa, the pitch angle of the trajectory and we count as positive the pitch angles corresponding to the cases where the radial velocity is positive;

b) as ordinate, the value of r/r_T at the point where the particle crosses the equator.

The equations of the movement generate a mapping of the rectangle on itself and the curves give the details of this mapping. A dotted line is the representation of a particular elementar pseudo-plasma and we see that, for instance, the particles of the elementar pseudo-plasma where $y_m = 40°$ are, after a quarter of an oscillation, distributed among elementar pseudo-plasmas where y_m varies from 25° to near 90°.

This spreading effect decreases very fast for greater values of γ_1 but it will never disappear; so that, the principal change of the process is its time scale.

This instability of the elementar pseudo-plasma plays a role in the removal of the particles trapped in the magnetic field since it brings steadily particles into high mirror latitudes *i.e.*, in regions where the particles interact with the constituents of the earth atmosphere and are removed from the set.

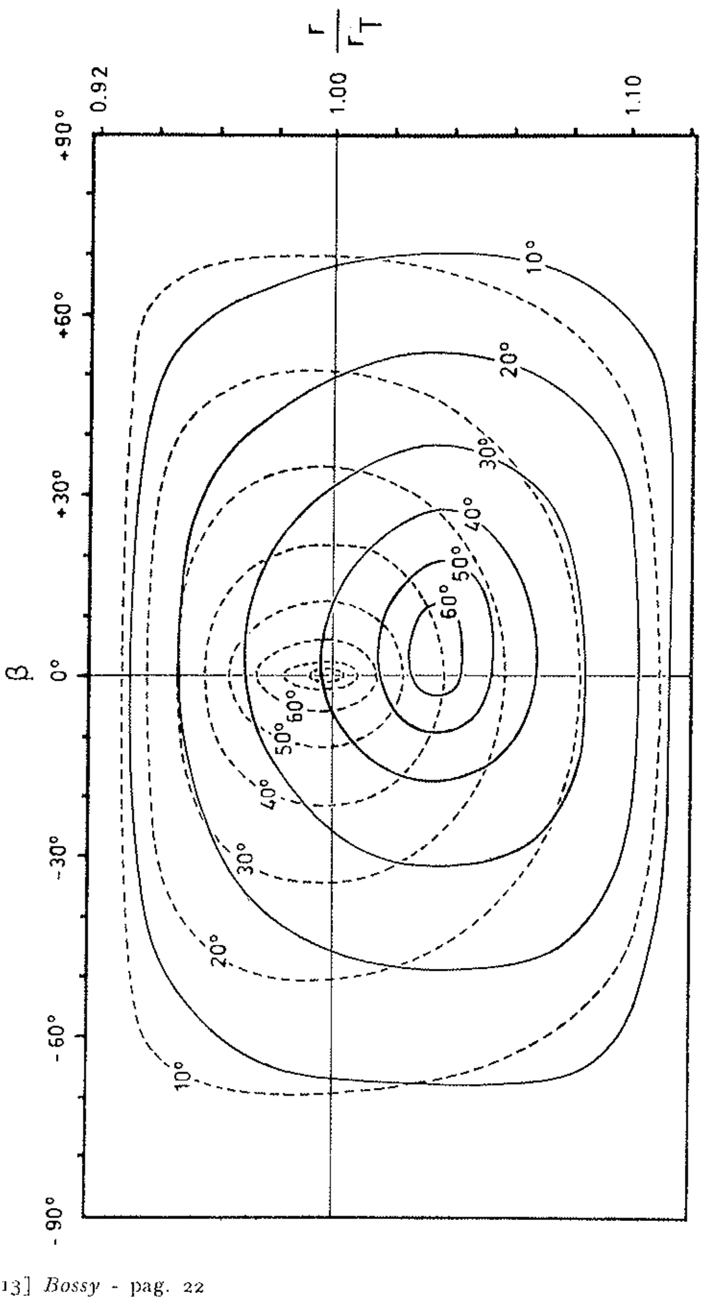


Fig. 5 — Loci of the theoretical and actual mirror latitudes

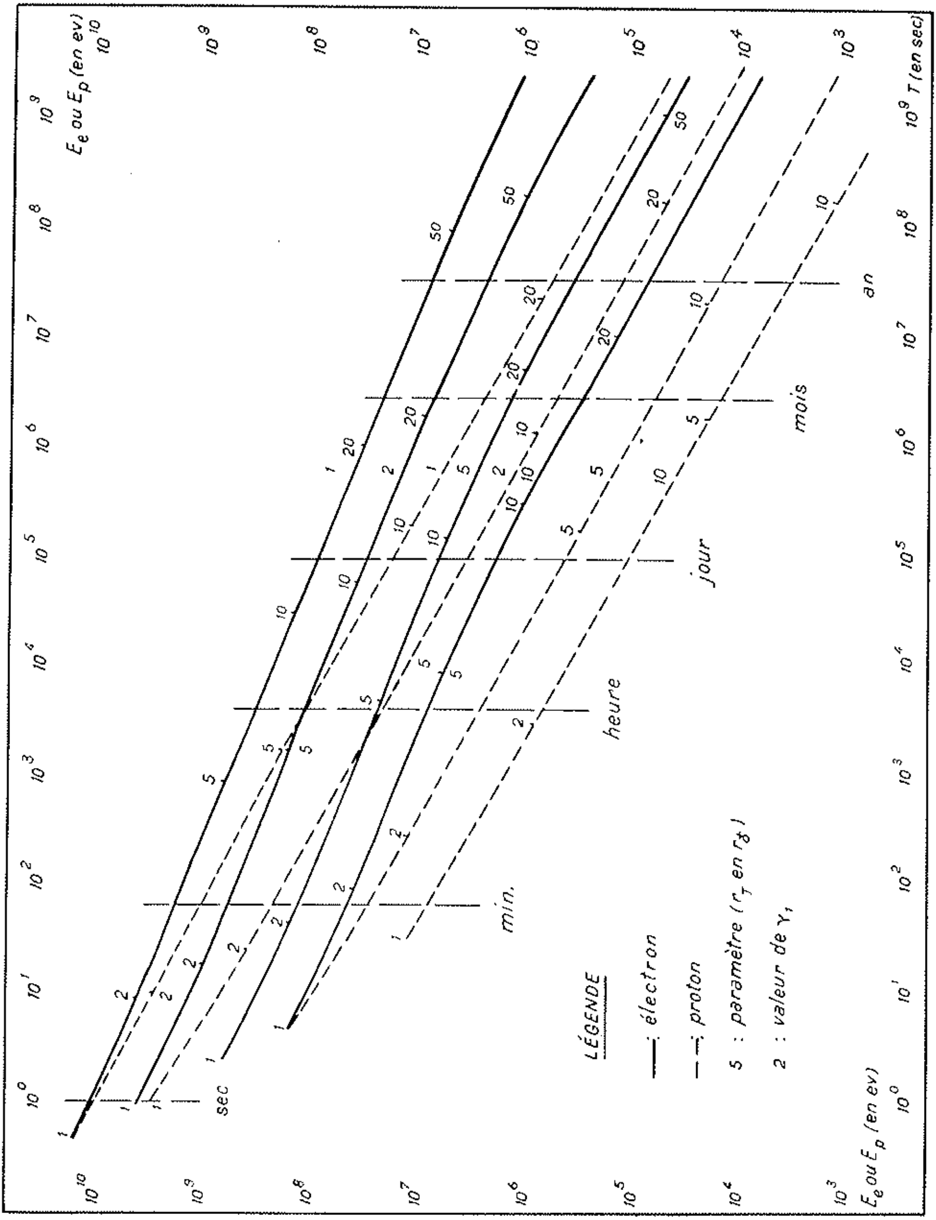


FIG. 6 — Life time of the elementar pseudo-plasmas

We have defined [6], starting from the computation of a few trajectories, a rough measure of the life time of an elementar pseudo-plasma. These results are contained in Fig. 6. They should be considered as a first and very rough attempt to descrive this phenomenon. On the other side, the time of removal of the particles of a given energy is certainly a large multiple of this life time.

The precise evaluation of those parameters in terms of the energy of the particles and of the radius of their thalweg remain to be achieved.

ACKNOWLEDGMENTS

I am very indebted to my colleague, Dr. J. VAN ISACKER, for his suggestions regarding the definition of the elementar pseudo-plasma.

REFERENCES

[1] H. ALFVÉN, *Ark. f. Mat. Astr. o. Fysik*, 27A, 1, 1939.

[2] L. BOSSY, *Contribution à l'étude des trajectoires d'une particule électrisée au voisinage d'un dipôle magnétique*. Dissertation. Université Catholique de Louvain, 1939.

[3] G. LEMAÎTRE and L. BOSSY, *Bull. Cl. Sc. Acad. Roy. de Belgique*, *31*, 357, 1946.

[4] C. STÖRMER, *The Polar Aurora*, Oxford Univ. Press, 1955.

[5] G. LEMAÎTRE and M.S. VALLARTA, *Phys. Rev.*, *43*, 87, 1933.

[6] J. LIFSHITZ, *J. Math. and Phys.*, *21*, 94, 1942.

[7] L. BOSSY, *Ann. de Geophys.*, *18*, 198, 1962.

DISCUSSION (*)

Chairman: M.S. VALLARTA

RAY

I have a question for Dr. BOSSY. You allege that this spreading effect will never go away entirely as γ increases. It seems to me that in this connection it is not at all obvious from the considerations you give in Fig. 5 that there is the tendency to walk towards this 90° value. In other words, I would expect that the displacement of the curves in this fashion should be very much less indeed for suitable larger values of γ_1, and that in order to get this steady loss effect you must have some tendency for particles that are initially what you call pseudo-plasma to walk towards 90° value; I do not think that is obvious from what you represent.

BOSSY

It is much more connected with the long-range instability considered by Prof. DE VOGELAERE. The question is certainly to know if the effect is cumulative or not. I believe it is a cumulative one.

RAY

I see, but you do not claim that you showed it.

BOSSY

No, I don't.

(*) This discussion refers both to the paper by R. DE VOGELAERE *Invariants and long-term stability* and to the paper by L. BOSSY *The motion of particles trapped in a magnetic dipole field as a special case of the Störmer problem.*

GOLD

I realize that what I want to say is not directly related to this paper; nevertheless it has an importance to the subject. In discussing the speed at which particles actually get removed from trapped orbits in the earth field, it is not clear that the precision in the orbit calculations is the important thing to know for that process. There are other physical effects taking place in the real system which are not taken into consideration in any of these discussions, and one has to be very careful, I think, in estimating the speed at which particles actually might get removed. This might be considerably faster than the speed which these orbit calculations would ever imply. Especially, I want to refer to the great importance that electric fields can play. Time variable electric fields would violate the conservation properties of these orbits in a gross way. If one were to investigate the dynamics of the low energy plasma in the earth's field at the same time as considering the orbits of fast particles, then the electric field associated with the low energy plasma will in fact have an important effect upon the orbits of the high energy particles.

DE VOGELAERE

I am quite aware of what you said. One of the points which has to be made clear is if in the model of STÖRMER we cannot easily explain instability; but it is quite clear that there are other effects, the ones you have mentioned, and also effects of magneto-hydrodynamics which come into play.

With respect to the paper of Prof. BOSSY, if my quick calculations are correct, the improved approximation that you have given only modifies the picture of these close curves which I have drawn on the blackboard; these are not sufficient to give the additional details which would correspond to the averaging equations; and it would be of very great interest to get to the next term which probably would indicate this fact. Moreover, with respect to Fig. 5, this figure is essentially related to what I said, and enables to determine the correspondance between the motion of the mirror points and that of the equatorial points of the trajectories.

Rossi

Your results, of course, refer to a perfect dipole field. I am wondering to what extent one can use them to estimate the errors that one makes by applying the ordinary methods to the real field of the earth which is not the dipole field.

De Vogelaere

The problem you mention is a very important one which has to be worked out, but which is not within reach now. We are not able to say anything about asymmetric fields. In the dipole field we have a very precious aid, the solutions which are periodic. These are not too difficult to obtain, but in the case of an asymmetric field these are extremely difficult to get.

Gold

In the same respect I should like to ask a question whether the following point is now really understood. I remember that about two or three years ago there was a discussion in the circles that discussed orbit theories of particles on whether the theorem of the conservation of the L-shell can be proved to result in a single shell that ends upon itself. As I understood it then, this point was not really proved. In the symmetric field the problem does not arise; because of the symmetry the shell closes on itself. But in the asymmetric field the particles have their guiding centres still confined to a surface in the first place, but whether that surface ends upon itself in all cases of asymmetric fields or not, is this point known? It clearly makes a big difference.

De Vogelaere

It is not known, and it is extremely difficult even to try to attack this problem rightly.

ROSSI

Dr. GOLD, are you considering particles which start from a given mirror point on a field line, or particles which start from different mirror points on the same line? Because if you consider particles which start from different mirror points, of course, the shells are different.

GOLD

Yes, but the shells are not very different. In the initial discussion the guiding centres were assumed to be near enough on the same shell, and then the question arises whether there is a gross difference the next time they come round, whether the shell is not at all re-entrant. But I agree surely, in fine detail it cannot be a simple shell anyway.

VALLARTA

I should like to ask a small question myself. As GALL has shown in a paper which appeared in the Proceedings of the Kyoto Conference, in the real case of the Van Allen belt the values of γ_1 are very high, of the order of magnitude of hundreds. Now, what conclusion can we get on the basis of this analysis which is presented here for particles which have a very high value of γ_1?

BOSSY

I believe it is more a question of time scale; for instance, the particles with high values of γ_1 would remain one year or more together in the same set of particles.

DE VOGELAERE

I would not venture to say anything for values of γ_1 as large as those you have mentioned. I believe there are other particles with γ_1 much smaller.

[13] *Bossy* - pag. 30

VALLARTA

Very few indeed.

DE VOGELAERE

I remember a discussion which I had with Mrs. GALL that there were protons with γ_1 as small as two. For values of γ_1 which are going from 1.6 up, the trend seems to be clearly towards greater and greater stability.

SINGER

I agree with this remark. For large values of γ we have particles which approach more and more what we can call the physical definition of true adiabaticity, namely the radius of curvature is extremely small compared with the scale length of the field. Therefore for such particles the trapping would be extremely good for much, much longer periods of time.

I have a question now concerning the same problem: You started off with a curve which re-entered on itself and then showed that this curve deformed into one which crosses on the unstable point and has the stable point introduced on the other side. What happens there, in the limits of large γ? Does this curve deform into a perfect closed curve?

DE VOGELAERE

I guess what happens is the following: consider the two closed curves, starting from an unstable point. I believe that for larger and larger values of γ_1 these closed curves become closer and closer together so that you can barely distinguish them from each other.

PARKER

I want to ask a question which is not clear to me: How far is the present state of the theory from giving numbers for the life of typical trapped particles with a γ of the order of 100 in a perfect dipole field?

De Vogelaere

Sorry, I cannot say anything.

Vallarta

Another small point. There is a very elaborate theory due to Bogoliubov of the adiabatic invariance of the first order, second order, third order and so on. Now, what is the relation between this theory of Bogoliubov and the results that you have shown here today?

De Vogelaere

The adiabatic invariance which is presented is of the first order, and I believe that the invariance of p_y^1 is of the second order.

Singer

I will try to answer at least partially the question raised by Dr. Parker, by using an empirical approach, that is by looking at the trapped radiation, the high energy protons as they exist round the earth, and deduce from their existence the lifetime. It is not too difficult, and I shall try to explain it this afternoon. It will involve some assumptions. This lifetime turns out to be of the order of hundreds of years, which is very long. This gives us a kind of clue as to what are the effects which eventually remove the particles. I find it very difficult to believe that hydromagnetic waves do not remove the particles, because the magnetic field is in a continuous state of perturbation; very strong storms occur very often. That is why I am so interested in the theoretical presentation this morning, because I would like very much to see what the theory tells us about the constancy of the magnetic moment in a pure dipole field. One has to start with that problem and see what it gives us before tackling the more complicated ones.

ON RING CURRENTS AND COSMIC RAY CUT-OFFS

E. C. RAY (*)

Goddard Space Flight Center - Greenbelt, Md. - U.S.A.

Abstract — A simplified technique for computing the magnetic field of an axially symmetric body of plasma trapped in the earth's magnetic field is described, and the effects of such a magnetic field on cosmic rays is discussed briefly.

1. Introduction

The idea that a circular ring of current flows about the earth with its axis aligned along the earth's dipole was proposed near the beginning of the century by BIRKELAND and STÖRMER [1] as a device for lowering cut-offs for incoming charged particles. The size and strength of current now usually discussed were introduced by CHAPMAN and FERRARO [2] in connection with their theory of the main phase of geomagnetic storms.

We will here sketch a way in which one can compute the magnetic field caused by an axially symmetric body of plasma

(*) *National Academy of Sciences fellow on leave from the department of Physics and Astronomy, the State University of Iowa, Iowa City, Iowa. Much of the work reported here was done while the author was at the Rand Corporation, Santa Monica, California. Present address: Center for Radiophysics and Space Research, Cornell University, Ithaca, N.Y.*

trapped in a dipole magnetic field, and than discuss the way in which such a magnetic field affects vertical cut-offs for incoming charged particles. These cut-offs are defined in the Störmer sense, the more elaborate penumbral problem not having been investigated. Finally we will mention some experimental results that bear on the question, together with some modifications that the cut-off theory may have to undergo.

1. A Ring Current Field

Apel [3], Dessler and Parker [4], and Akasofu and Chapman [5], among others, have made calculations of the magnetic field of a ring current. Dessler and Parker calculate the field at the earth. The others calculate the field everywhere, but adopt a straight forward procedure which results in such numerical complexity that a computer is necessary to carry out the procedure. We here indicate the source of that complexity and sketch a way of avoiding it. Fuller details will be published elsewhere.

The vector potential of the magnetic field is given by

$$\mathbf{A} = \mathbf{A}_E + (1/c)\int d\mathbf{x}' \,/\, \mathbf{x} - \mathbf{x}' \,/^{-1}\, \mathbf{j}(\mathbf{x}') \tag{1}$$

where $\mathbf{A}_E$ is that part due to sources inside the earth, c is the speed of light, $\mathbf{dx}'$ is the volume element, $\mathbf{x}$ the position vector, and $\mathbf{j}$ the current density. Parker has given a good discussion of the way of calculating $\mathbf{j}$ for a plasma imbedded in a magnetic field. When the pressure tensor can be approximated as isotropic, we have

$$\mathbf{j} = (c/B^2)\, \mathbf{B} \times \nabla p \tag{2}$$

When this is used in (1), together with $\mathbf{B} = \nabla \times \mathbf{A}$, we obtain a singular, nonlinear, integrodifferential equation for $\mathbf{A}$. It is of such complexity that numerical methods must be used in solving it. The chief difficulty with the use of numerical methods occurs because of the singularity. If one replaces the integral in (1) with a quadrature formula of the usual sort, the singularity forces the use of a large number of very small steps. Recourse must then be had to a computer, and the result is a table appropriate to a particular model. This inconvenience can be avoided by use of a quadrature formula tailored to the particular problem. A quadrature formula such as Simpson's rule can be written as

$$\int_a^b f(x)\,dx = \sum_{i=1}^{n} a_i f(x_i) + \mathrm{R}_n \}f\{$$

where the numbers a_i depend on the choice of the x_i and on n but not on $f(x)$, and $\mathrm{R}_n \}f\{$ is a functional of $f(x)$ and represents the error in replacing the integral by the sum. One can have, instead,

$$\int_a^b f(x) g(x)\,dx = \sum_{i=1}^{n} a_i f(x_i) + \mathrm{R}_n \}f\{$$

where the a_i now are functionals of $g(x)$, which function is then, in a certain sense, treated exactly. In case an integrand has one factor which is singular but can be integrated exactly and one factor which is complicated in functional form (or of unknown form, as here) but smooth, this device permits the use of a course net in spite of the singularity.

In the present problem, reasonable accuracy is obtained by using a three point formula for the colatitude, with $\vartheta = 0$, $\pi/2$, and π, and a four point formula for the integration over radial distance. The radial abscissae are those for which $p/p_m = 0.21132$, 0.78868, and p_m is the maximum value of the pressure. The longitude integration is done exactly. From the axial symmetry, the vector potential has only a longitude component. We denote that component simply by A. The result is that (1) becomes

$$A = A_E + \sum_{i=1}^{4} M_i^{-1} W_i(r, \vartheta) \tag{3}$$

The W_i can be computed, once the dependence in the equatorial plane of pressure on r is chosen, from

$$W_k = \frac{2}{p_2 - p_1} (-1)^m \int_0^{p_m} dp\, (p_j - p)\, \rho^4(p)\, V[\rho(p)/r, \vartheta] \tag{4}$$

where $m=1$ with $k \leq 2$ and $m=2$ otherwise,

and $j=2$ when $k=1$ or 4 and $j=1$ otherwise.

Also, $p_1/p_m = 0.21132$, $p_2/p_m = 0.78868$, and $\rho(p)$ is the inverse of the function giving the dependence of pressure on radial distance. When $k=1, 2$, the integrations are to be done with r less than that at $p=p_m$, otherwise with it greater. We have defined

$$V(x, \vartheta) = \begin{cases} 2x^2 \sin\vartheta & 0 \leqslant x \leqslant 1 \\ (2/x)\sin\vartheta & 1 \leqslant x \end{cases}$$

Finally, in (3), the M_i are a set of constants to be determined as follows. Put

$$M_i = r_k^3\, B(r_k, \pi/2)$$

and (3) into $\mathbf{B} = \nabla \times \mathbf{A}$. Pur $\vartheta = \pi/2$ and successively $r=r_1$, r_2, r_3, and r_4. The result is a set of four equations for the four M_i, which can then be solved for. Then (3) gives the vector potential.

3. Cosmic Ray Cut-offs

Since the field as here computed has axial symmetry, there exists a Störmer first integral to the equations of motion of a charged particle in it, and consequently Störmer cut-offs exist and can be computed. A general discussion has recently been given by Winckler and Kellogg [6]. Qualitatively the result is that the cut-off in the vertical direction is reduced, at all latitudes, below its dipole value. The fractional reduction is greatest at some latitude λ_c which depends on the spatial distribution of current, but very little on current strength. The amount of reduction depends mostly on the current strength. For the usual spatial distributions of current, λ_c is about 50° to 60°. For currents weak enough that the field is nowhere reversed from its dipole sense, the cut off is not reduced to significantly less than half its dipole value anywhere.

4. Discussion

Various people have recently made measurements that yield cut-off information. Ney and Stein [7]. They found that the cut-off at Minneapolis was normally 0.7 GV and at the time of arrival of a plasma cloud at the earth dropped below the absorption cut off due to air above their apparatus, the latter being at 0.4 GV. This behavior is probably not outside the range of applicability of the ring current model. If, however, it should turn out that the cut-off is lowered to a much smaller fraction of its undisturbed value, then the ring current model would likely go over into a regime such that mechanisms discussed in slightly different connections by Parker [8] and by Rothwell [9] should apply. One could expect that as the number of stored particles was steadily increased the field should become turbulent and rough, so that high energy particles could diffuse a certain distance through the field. At any point within such a turbulent region the allowed and forbidden regions would acquire such a fine structure that any practical detector should see many of both kinds. PARKER has discussed the effect of such a configuration on intensities at the earth, showing that they would be lowered below their extraterrestrial values. ROTHWELL has considered some of the effects on cut-offs that arise when particles of all rigidities can reach a certain distance from the dipole. It turns out that above a certain latitude the cut-offs are then zero.

REFERENCES

[1] C. STÖRMER, *The Polar Aurora*, Oxford, 1955.

[2] S. CHAPMAN and V.C.A. FERRARO, *Nature*, *126*, 129, 1930; *Terr. Magn.*, *36*, 77, 171, 1931; ibid., *37*, 147, 1932; ibid., *38*, 79, 1933; ibid., *45*, 245, 1940.

[3] J.R. APEL, Thesis, University of Maryland, 1960, and Report AFCRL-420, 1961 (unpublished).

[4] A.J. DESSLER and E.N. PARKER, *J. Geophys. Res.*, *64*, 2239, 1959.

[5] S. AKASOFU and S. CHAPMAN, *J. Phys. Soc. Japan*, *17*, Suppl. AI, 169, 1962.

[6] P.J. KELLOG and J.R. WINKLER, *J. Phys. Soc. Japan*, *17*, Suppl. AII, 408, 1962.

[7] E.P. NEY and W. STEIN, *J. Geophys. Res.*, *66*, 2550, 1961.

[8] E.N. PARKER, *Phys. Rev.*, *103*, 1518, 1956.

[9] P. ROTHWELL, *J. Geophys. Res.*, *64*, 2026, 1959.

DISCUSSION

Chairman: M. SANDOVAL VALLARTA

GOLD

This paper points out the great importance of the observation of the details of the change of intensity with latitude. One would like to know whether it is the change of the acceptance solid angle that is involved, so that in one range of directions the directional flux is the standard amount and in another range of angles it is zero, or whether one has a fine, unresolvable intermixing of allowed and forbidden regions giving the appearance of a diminished directional flux. Another possibility does not exist because of Liouville's theorem. If it was the latter, then one would know that a complex and presumably turbulent structure of a magnetic field was involved, and not merely a large-scale deformation of the dipole field. Does Prof. NEY have anything to say on the possibility of such an observation?

NEY

I think it depends on how small the solid angles are within which you say that you have to decide about structure and it is not clear to me what the scale is. The conventional equipment uses solid angles that characteristically open to a few degrees, but if you say that you have to discuss structure within hundreds of a degree, then it is very difficult.

I have another question: in this second model of a lowering cut-off which involves the line of force essentially getting out into the plasma, would you not expect that the radiation belt particles would also be affected? I think that one of the outstanding characteristics of these lower cut-offs is that while the cut-off is depressed the Van Allen belt seems to be perfectly all right at that L value.

RAY

Well, I suppose that one has to adjust the turbulence so that it does not disturb the Van Allen radiation just on the grounds you mention, but I do not suppose that is extremely difficult. Perhaps one can make the scale of the turbulence suitably large compared with the typical Larmor radius of electrons. In fact protons are seen to be essentially absent — at any rate non-thermal protons are observed to be absent — so it is an advantage to disturb the protons with their larger Larmor radii. If one adjusts the scale of the turbulence so that it is a suitable number of times larger than the Larmor radii of the electrons, I suppose they might not be so much disturbed, so that even as one goes through a hump in the magnetic field one preserves the constancy of μ. Indeed I don't see how one can be in the position of saying that such turbulence does not exist. If one just looks at a magnetogram from the main phase of a magnetic storm it clearly exhibits time dependence at any rate, which suggests such phenomena going on.

ELLIOT

I would like to put in a plea for some consideration of systems which are not axially symmetric. There is some experimental evidence, I think, for an asymmetric lowering of the threshold during magnetic storms. MARSDEN, for instance, in Leeds in studying the November 1960 event, which was a particularly good one for looking at this, has produced some evidence, which I think is quite strong, for a local-time dependent drop in thresholds at medium-latitude stations. Furthermore, it seems to me that if we are to believe the picture of a geomagnetic cavity carved out of the solar wind, one has to come sooner or later to such asymmetric changes of threshold. In particular I would like to point out that there is a way to reduce the geomagnetic threshold to zero at some point which is not the geomagnetic pole without making turbulence: if the lines of force are combed back by the solar wind, then it is possible to find some point on the longitude corresponding to the sun, where the lines of force are parted and here presumably the threshold rigidity is going to be zero.

De Vogelaere

First of all with respect to the question of intensity in the neighbourhood of the cut-off I think that the situation is perhaps more complicated than it is visualized, because it is not just a question of full intensity versus no intensity. In fact in this region, as Prof. Vallarta has observed, near some of the interesting latitudes, this cutoff is due to the shadow cone and there, one has essentially a superposition of various cones, which are energy dependent. It is not just a question of one region which is fully lighted and one region which is not. But because there is a mixture of energies the situation is extremely complicated, and I believe that measurements of energy are also important.

Ray

I fully realise the existence of the penumbra. The shadow cone itself I claim is so small as to be inappreciable in all cases. The calculation of Schremp is known to be incorrect and the cones are really very much less than the ones which he found. If you look, for example, at what Kasper calculates for a dipole field on more versatile computing equipment, and also the cone as calculated by Gall including the quadripole term, which clearly makes an appreciable difference, you find essentially the same result.

De Vogelaere

I have a small question with respect to the computations. Am I to understand first that the place where the singularity exists is known? (Ray: Yes.) Now what is the nature of this singularity?

Ray

Well, if you carry out the φ integration, the longitude integration in the volume element, then it results that you get a suitable linear combination of complete elliptic integrals, so that the singularity that occurs before the co-latitude integration is essentially that of the complete elliptic integral K.

De Vogelaere

And the position of the singularity is known?

Ray

The position of the singularity is $r=r'$ $\vartheta=\vartheta'$ where r', ϑ' are the integration values and r, ϑ are the observation values.

De Vogelaere

When you have a singularity and the position is known, it turns out that if you integrate on either side of the singularity using Gauss' method you obtain extremely good results. This is very surprising and is contrary to any intuition; but this is correct.

Ray

Yes, that's quite right. There is a variety of things that one could do with this integral if one could do anything whatever with it in an analytic way. But the integrand is so excessively complicated that in actual practice one has to resort to essentially numerical methods in any case. I think that the technique worked out here is a reasonably simple one and seems to give quite good results.

PERIODIC ORBITS IN A MAGNETIC DIPOLE FIELD (*)

RENE DE VOGELAERE
Mathematics Department, University of California
Berkeley, Cal. - U.S.A.

Abstract

DISCUSSION

Chairman: H.S. VALLARTA

RAY

I somehow missed your definition of stability, so would you repeat it, please?

DE VOGELAERE

I have been talking of two kinds of stability, a long range stability which essentially refers to regions and the stability or instability of periodic orbits which then refers to that of the first order variational equations of the trajectory; these are linear equations

(*) The text of this contribution was not received.

whose solution can be expressed as an exponential term times a periodic function.

RAY

Well, that just means that the characteristic exponents are imaginary. Is that right?

DE VOGELAERE

Yes, but it is preferable to use, instead of the characteristic exponent Ω, the cosh of the characteristic exponent times the period. Cosh Ω_T is always real; it is between -1 and $+1$ for the stable orbits, it is smaller than -1 for the odd unstable orbits, and it is larger than $+1$ for the even unstable orbits.

RAY

However, when these trajectories are stable in this sense, you still don't have any guaranty that the neighbouring trajectories remain in the vicinity of them, isn't that so?

DE VOGELAERE

They remain in the vicinity for a long time, but not for an indefinitely long time. This is so because the first order variational equation will be satisfactory for a long time, but it is clear that this is not a sufficient indication for very long range stability, but what we believe is that it is not so much the fact that these orbits are stable which is important, but the sudden transition between the stability of the periodic orbits of type δ_1, closer to the equator (crossing it nearer the earth) to the odd instability of the succeeding orbits of the same type; this is what is crucial.

WHAT DETERMINES THE LIFETIME OF TRAPPED PROTONS?

S. FRED SINGER (*)
National Weather Satellite Center
United States Weather Bureau - Washington, D.C. - U.S.A.

Abstract — Observations on high-energy trapped protons confirm the hypothesis that lifetime is controlled by the atmosphere, and additionally by breakdown of the magnetic moment invariant according to a simple theoretical model. These conclusions lend further strong support to the neutron albedo theory for the origin of trapped protons.

INTRODUCTION

The concept of « lifetime » of a trapped particle must be treated with some caution. A trapped particle, unlike a radioactive nucleus, does not have a unique lifetime; it has as many lifetimes as one may wish to define. In a static magnetic field, particles are lost from a system either *a*) by losing energy until they are undetectable, *b*) by suffering a change in equatorial pitch angle, until their mirror points fall within the more dense layers of the atmosphere whereupon they are absorbed, or *c*) by being absorbed in a nuclear interaction or some other one-shot removal process, such as charge exchange. These various processes have been discussed in detail by a number of authors (see *e.g.* Ref. [1]).

(*) On leave of absence from the University of Maryland.

Knowledge of the lifetime of trapped particles is important since it reveals the source strength and thereby sheds light on the origin of a particular group of trapped particles. The longer the lifetime, the weaker the source strength required to produce a given equilibrium concentration. Here we wish to consider only high energy protons, with energies greater than about 50 MeV and extending up to 700 MeV. The reason for this is that we suspect these protons to be due to a unique source, namely galactic cosmic ray neutron albedo [1]. Protons below 50 MeV have large contributions of SHEP (solar high energy particle) -produced neutron albedo, and perhaps also from other sources, while trapped electrons are apparently produced by a number of sources, and subject in addition to local acceleration.

The existence of such high energy protons was predicted in the initial papers on the neutron albedo theory [2], [3]; they were, in fact, found to be present a year later in the nuclear emulsion experiment of FREDEN and WHITE [4]. The early theoretical surmise was that their lifetime was controlled by the atmosphere, by energy loss rather than by scattering since the protons are relatively heavy. It was also surmised that protons would be lost when their radius of curvature became comparable to the scale of the magnetic field, so that either magnetic fluctuations or the breakdown of the adiabatic invariant in the magnetic dipole field would cause this loss. The paper, therefore, predicted a maximum of the proton intensity at some altitude between one and two earth radii because of the progressive loss of high energy protons with increasing altitude [2].

All these various features have since been confirmed, notably in the photographic emulsion experiments of FREDEN and WHITE [4], of ARMSTRONG, HARRISON, HECKMAN, and ROSEN [5], and of NAUGLE and KNIFFEN [6]. With the existence of the high energy protons thus assured, we wish in the present paper to examine various experimental evidences concerning the lifetimes of such protons. Unfortunately, there are no direct measurements, in the sense that these high energy protons have not been injected artificially, and their lifetime measured *in situ*. Instead, our conclusions must be based on inferences drawn from observations.

1. The effect of changing exospheric scale height

The initial paper on the neutron albedo theory predicted [2] that the intensity should rise rapidly in the oxygen exosphere where the scale height is of the order of 80-100 km and then much more slowly beyond 1000 km altitude where a hydrogen exosphere was believed to exist with a scale height of 1000-2000 km. This expectation has actually been borne out completely, although a comparison has not been carried out in as great detail as it should. We reproduce in Fig. 1 a comparison [1] in the vicinity of the equatorial plane, of atmospheric density with the inverse counting rate vs. altitude. The close correspondence between the two curves tends to establish that the lifetime is being controlled primarily by the density of the atmosphere.

2. Measurement of atmosphere scale height

A recent result of great importance is the experimental discovery by Heckman and Nakano [7] of the theoretically predicted east-west asymmetry of trapped protons [8]. An east-west asymmetry arises when the radius of curvature of the protons becomes comparable to the scale height of the atmosphere. The asymmetry thus is greatest for protons of highest energy, close to the surface of the earth. In fact, Heckman and Nakano were able to deduce the scale height of the atmosphere at the place of measurement and thereby can demonstrate the usefulness of radiation belts measurements to deduce scale height

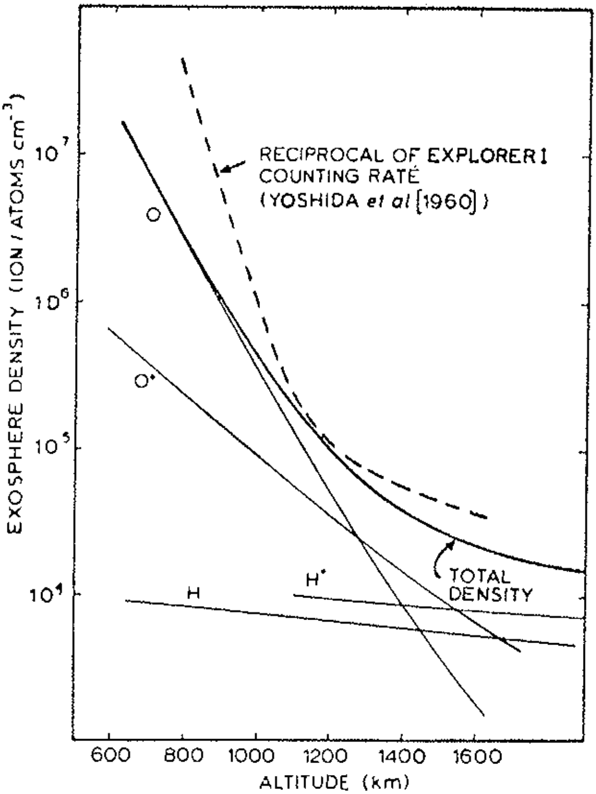


FIG. 1 — Influence of exospheric-density on trapped radiation intensity. We plot the reciprocal of the counting rate of the Geiger tube carried on Explorer I (YOSHIDA et al. [1960]). The altitude dependence of this counting rate has been obtained from plots of counting rate near the magnetic equator *vs.* magnetic field strength by using a centered dipole field. This implies the assumption that the drift averages out the eccentricity of the true field. The exospheric densities are given in atoms or ions cm^{-3} and are based on a temperature of 1500 °K at the base of the exosphere. The difference in slopes between the reciprocal radiation intensity and the total density is caused by a gradual increase of the width of the trapped angular distribution in this altitude range, due mainly to a shrinking of the loss cone with increasing altitude. Tre dominant influence of the atmosphere is clearly seen in the « break » at the altitude at which hydrogen begins to predominate over oxygen.

and temperature of the upper atmosphere. Their result gives a scale height of 62±5 km at an altitude of 364 km, over the South Atlantic magnetic anomaly.

3. Comparison with the artificial radiation belt

As can be seen by reference to Fig. 2, the lifetime of protons increases as a function of energy, and reaches a gradual plateau beyond about 400 MeV [1]. At that point, the lifetime in hydrogen is given by about 5×10^{14}, in units of sec-cm^{-3}. With an atmospheric density of the order of 5×10^3 cm^{-3}, the lifetime would become 10^{11} seconds, or as much as 3000 years (see, however, Section V). Even for protons of 100 MeV, lifetimes may be of the order of 600 years in a hydrogen exosphere.

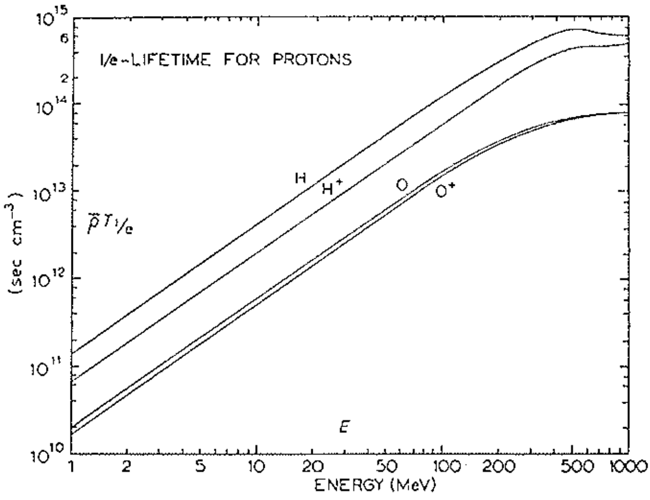


Fig. 2 — I/e-lifetime for protons. This lifetime is the time for reducing the energy to I/e of its initial value E by Coulomb collisions, or for reducing number of particles to I/e by nuclear interactions. Energy loss is computed relativistically; energy dependence of the total *p-p* cross section is included; geometric oxygen cross section is employed. By $\bar{\rho}$ we denote the true density of the respective constituent averaged over the orbit.

It is assumed here, of course, that the lifetime is directly proportional to the range of the particle. This assumption may be checked by reference to the artificial radiation belt. If we take the fragmentary data now available which indicate a lifetime of the order of one or two decades for electrons with an average energy of about 2 MeV (or range about 1 g cm^{-2}), then a 400 MeV proton having a range of about 100 g cm^{-2} should have a lifetime of the order of 1000-2000 years.

4. Low energy cut-off of protons

Observations in a scintillation counter carried on Explorer XII indicated large fluxes of protons with energies of the order of several hundred keV, at distances of several earth radii. Closer to the earth, at an L value of 2.8, there appeared to be no protons below about 500 keV, according to L. R. Davis [9]. Reference to Fig. 3 shows that this result is consistent with the hypothesis of atmospheric control over particle lifetimes, with the particles below 500 keV being removed by charge exchange. This would indicate that up to perhaps 3 earth radii the atmosphere controls particle lifetime. By the same token, the presence of a large number of 100 keV protons in the outer belt, despite their rapid renoval by charge exchange, suggests a very efficient injection mechanism, possibly based on local acceleration.

5. Breakdown of adiabatic invariance

As indicated earlier, lifetimes of 3000 years would be possible and, in fact, longer lifetimes at higher altitudes where the density is less, were it not for the loss of trapping experienced when the radius of curvature of the particle becomes comparable with the scale of the magnetic field.

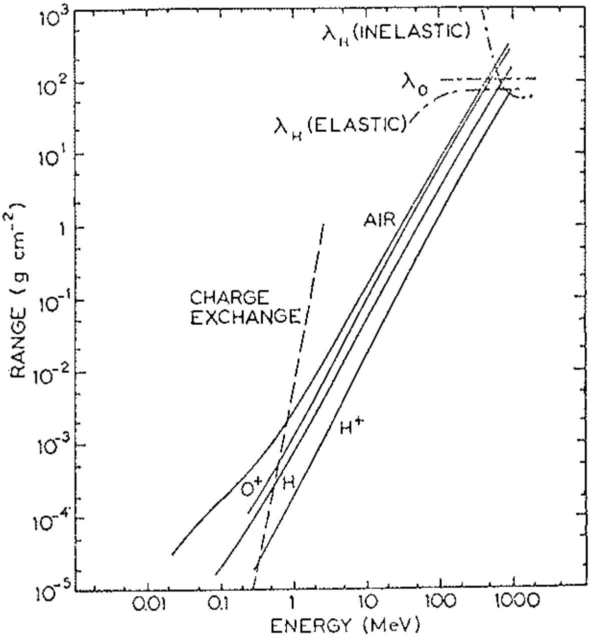


FIG. 3 — Range and mean free paths ($\lambda = A/N_0\ \sigma(E)$, N_0 = Avogadro's number, A = atomic number) for protons. For λ_H (elastic) we use the total elastic *p-p* scattering cross section; for λ_H (inelastic) we use the total inelastic *p-p* cross section; for λ_0 we use the geometric cross section. Cross section for charge exchange in hydrogen (derived from data of FITE et al. [1958] and BATES and DALGARNO [1953]).

Particles are trapped because of the constancy of their magnetic moments; however, if the gyro-radius, *a*, is not small compared to the scale of variation of B, then the magnetic moment may no longer be conserved, *i.e.*, there is a breakdown of the first adiabatic invariant. If one takes as the scale of the magnetic field the ratio (B/grad B), then one can define an « Alfvén discriminant »

$$X = a/(B/\text{grad } B)$$

It is surmised that the breakdown occurs sharply beyond a certain value of X. SINGER [10] has made an empirical determination of this critical value for the discriminant for a dipole field by using data from satellites on the altitude extent of 75 MeV protons.

The analysis proceeds as follows. In a dipole field the discriminant for a particle of fixed energy is

$$X\ (r_e) = 5 \times 10^{-5}\ pc\ (r_e/R)^{-2}$$

for pc in MeV. FAN, MEYER and SIMPSON [11] find that 75 MeV protons extend no further than $r_e/R = 2.0$. These figures give $X_c = 0.07$ or

$$p_{max}\ (r_e) = 1530\ (r_e/R)^{-2}\ \text{Mev/c}$$

The hypothesis is then made that when p exceeds $p_{max}\ (r_e)$, then the particle's mirror point becomes unstable, the particle penetrates into the dense atmosphere and is absorbed. We obtain for the maximum energy versus r_e:

$$E_0 \sim 75\ L^{-4} \qquad \text{MeV}$$

GARMIRE [12] has measured the energy spectrum of high energy protons at low altitudes in Explorer XI. Intensity and pitch angle distribution of protons with energies greater than 350 MeV were determined with a Čerenkov detector. The results are consistent with a breakdown of the magnetic moment, steepening the proton energy spectrum with increasing magnetic latitude and altitude. Assuming injection from neutron albedo, the measured intensities indicate that the spectrum is cut off at a maximum energy that varies approximately as L^{-4} in the range $L = 1.2$ to 1.4. Extrapolating these results predicts a cutoff energy of 117 MeV at $L = 2$. Numerical calculations of orbits in the dipole field [12], [13] also indicate that the trapping ability of the static dipole field decreases with increasing L. However, because of limitations on the computing techniques, it is difficult to apply these results directly to the trapped radiation.

The energy spectrum of protons trapped in the inner zone has also been measured on Explorer IV [14]. These measurements indicate that the energy spectrum can be fit by a form

$$i\ (E) = \text{constant}\ e^{-E/E_0}$$

where E_0 is proportional to L^{-4}, in good agreement with the predictions of a breakdown in the static field.

Conclusion

In view of the excellent agreement between observations and theory on high energy protons, we may regard the following hypotheses as justified: the atmosphere controls the lifetime of protons, in a manner given essentially by the range of a proton; but at higher altitudes the conservation of the magnetic moment breaks down, resulting in the removal of the high energy protons, the critical energy depends on L^{-4} in this very simple theoretical model.

As a consequence of these conclusions, we must accept the existence of a very weak injection source for these high energy protons. The source mechanism is compatible in intensity and in all other respects, with the injection resulting from the decay of cosmic ray neutron albedo.

REFERENCES

[1] S. F. Singer and A. M. Lenchek, « Geomagnetically Trapped Radiation », in *Progress in Cosmic Ray Physics* (ed. J. G. Wilson), Vol. 6, North Holland Publishing Company, Amsterdam 1962, pp. 245-335.

[2] S. F. Singer, *Phys. Rev. Letters, 1*, 171, 181, 1958.

[3] S. N. Vernov et al., *Sov. Phys. Dokl., 4*, 154, 1959.

[4] S. C. Freden and R. S. White, *Phys. Rev. Letters, 3*, 9, 1959.

[5] A. H. Armstrong, F. B. Harrison, H. H. Heckman and L. Rosen, *J. Geophys. Research, 66*, 361, 1961.

[6] J. E. Naugle and D. A. Kniffen, *Phys. Rev. Letters, 7*, 3, 1961.

[7] H. H. Heckman and G. H. Nakano, *J. Geophys. Res., 68*, 2117, 1963.

[8] A. M. Lenchek and S. F. Singer, *J. Geophys. Res., 67*, 4073, 1962.

[9] L. R. Davis, J. M. Williamson and R. A. Hoffman, *Explorer XII Symposium*, Goddard Space Flight Centre, NASA (Jan. 18, 1962).

[10] S. F. Singer, *Phys. Rev. Letters, 3*, 188, 1959.

[11] C. Y. Fan, P. Meyer and J. A. Simpson, *Space Research* (ed. E. Kallmann-Bijl), North Holland Publishing Co., Amsterdam 1960, p. 951.

[12] G. Garmire, *J. Geophys. Res., 68*, 2627, 1963.

[13] A. J. Dragt, *J. Geophys. Research, 66*, 1641, 1961.

[14] C. E. McIlwain and G. Pizzella, *J. Geophys. Res., 68*, 1811, 1963.

DISCUSSION

Chairman: S.E. Forbush

Parker

I want to ask a couple of questions. I gather from your remarks you have not yet had an opportunity to compare the declining outer side of the energetic proton belt with observation. Is that correct?

Singer

Yes; there are no suitable measurements available.

Parker

The next question I want to ask: you mentioned in your theoretical plot of the contours of the intensity of the belt that you have used the breakdown of the adiabatic invariant to determine the outer edge of the belt. Exactly what assumptions did you make there?

Singer

Exactly the ones I gave here, namely that I used the value 0.09 for the Alfvén discriminant, then the distribution with altitude comes from the theory. Just one empirical data point has been used, namely the value of the limit of the proton belt published by the Chicago group.

GOLD

Have you considered breakdowns of other adiabatic invariants, in particular the third? You remark in your paper and in your talk only about the first, and it is not at all clear to me why you were so convinced that that is the dominant one. Why not the third?

SINGER

This is a valid question. We have only considered the breakdown of the first.

GOLD

Well then, surely if we don't have any exhaustive understanding of the breakdown of invariants, we are hardly in a position to use the observational data to define the breakdown of the first invariant.

SINGER

Well, you see the breakdown of the first invariant is the one that drives the particles along the lines of force deep into the atmosphere, and therefore the one that limits lifetime. Breakdown of the third invariant would produce a spread in the radial distance, and I don't see why that should remove the high energy particles, do you?

GOLD

It will lose some to the outside, perhaps, and some to the inside, and it will also change the mirror point height. So the breakdown of the third invariant also will lose particles, and it seems to me not possible to conclude about the details of the breakdown of the first invariant by using the empirical facts, when one cannot exclude, or indeed say anything, about the possibility that the particles get removed by breakdown of the other invariants.

SINGER

Empirical evidence, *e.g.* from the Argus experiment, shows no radial spread.

BIERMANN

The breakdown of the first adiabatic invariant has been discussed also in connection with controlled thermonuclear fusion because there one is led to the same questions. Now, from what I do recall from these discussions in USA and in Göttingen one would expect a critical value of the ratio which you wrote down near unity rather than $\lesssim 0.1$ as you say. I do not, unfortunately, remember the details. Anyhow, did you investigate this point?

SINGER

Yes, I have looked into these papers; I was not able to extract any value of X from them, unfortunately.

GOLD

For the mirror machine experiments with extremely long lifetimes for electrons injected into a mirror field, which I agree is different from the dipole field, there are cases with the radii of gyration of the particles, as I recall, of the order of 1/10th of the scale of the mirror machine, and even then lifetimes of minutes for electrons going at a substantial fraction of the speed of light were observed.

PARKER

There is another question which arises here. The 0.09 for X you say was determined from the observation that at a certain distance from the earth there were no particles above 100 MeV. There still remains the question, of course, as to why they are not there, whether it is breakdown in the static field or whether it is hydromagnetic waves, not to mention violation of the second and third invariants pointed out by GOLD.

SINGER

Yes, I agree with that point and have discussed it. My work predicts a certain fall off of maximum trapped energy with altitude; one should be able to check it experimentally in the future.

I would like to say on the mirror machine; of course the situation there is different in that the background gas in the mirror machine is homogeneous, which is not the case for the earth where the density of the atmosphere changes very much. Therefore changes in the mirror points are important for lifetime; this is a very significant aspect of the problem.

DE VOGELAERE

Now an observation about the numerical errors on long trajectories. I have made a study of these errors for trajectories in the STÖRMER problem, namely for some periodic orbits because in this case we have very good solutions. It is interesting to observe that if these solutions are stable, then the errors are very small; if the periodic solutions are unstable, the errors are very large. In both cases, though, the errors for the energy integral are very small, and this confirms the warning of many, that you cannot judge errors of long trajectories by examining the energy integral.

SIMPSON

The question I am concerned with is the matter of the origin of the protons on the inside edge of the magnetosphere. Certainly one may approach the problem of lifetimes along the lines that you mention, but it might be worth raising the question of looking at the chemical abundances of the trapped particles, that is, look at the protons, alphas and perhaps heavier nuclei that may be trapped in this region. Certainly one would expect that if indeed it is all neutron decay, we would have a pure proton trapping, except for a small contamination of alphas from back scattered albedo. But on the other hand, if it is material swept up in the acceleration process, it would be characteristic of the gaseous composition of the inner portion of the magnetosphere, and it would be highly unlikely that one would find just a pure proton component. My question really is: is there any evidence one way or another regarding information on this matter?

SINGER

This is a good point and quite relevant. The evidence that I know about comes from photographic emulsion data and seems to show that the trapped high energy particles are just about pure protons. The papers of FREDEN and WHITE reported that there have been 2 or 3 tritons, and I do not think there have been any more, and I didn't know really where those came from.

I would like to make my final point again, to emphasise the fact that if we believe that the high energy protons come from neutron albedo, and if we therefore believe the very low injection rate, then it is inescapable that the lifetimes are of the order of several hundred years.

ELLIOT

I am not sure that this is a very sensible question but I shall ask it nevertheless. It concerns Prof. GOLD's question about breakdown of first, second or third adiabatic invariants. There are now present in the inner radiation belt quite a number of high energy electrons. Now, these high energy electrons have very small Larmor radii and therefore are much less likely to suffer from a breakdown in the first adiabatic invariant than the protons that are there. On the other hand, so far as the third invariant is concerned, I suppose that the protons and electrons behave in much the same way and I wonder if it is possible that one might get a line on this problem from the behaviour of those two populations of particles?

GOLD

Yes, I quite agree that it would be very valuable to make that comparison. As far as the third invariant is concerned, the type of breakdown that I can see as happening would be dependent on the energy of the particle irrespective of whether it is a proton or electron, and so it would be generally the lower energy of the injected electrons which would suffer from this.

But might I raise another point? Prof. SINGER refers to the atmospheric absorption as producing a very good fit for the inner side of the belt. Now of course it would be very important if that fit were really so sharply characteristic that one could therefore conclude that this must be the process, *i.e.* that there is nothing involved other than the injection according to the space distribution of the albedo effects and the attenuation by the atmosphere. On the other hand, it seems to me from the curve that you gave on the board as if we were told to ignore the fit beyond 400 MeV, because there the albedo data were not good. Then the central curve that was left with its margin of error, as shown, would allow a very considerable shift between the predicted and the margins of error of the experimental values.

SINGER

I can answer the question very directly. The number of protons above 400 MeV is not relevant to this problem. It is the lifetime of the *bulk* of the protons that matters here, because what was measured, of course, with the counter were the protons above 30 MeV.

GOLD

So far as the gradient is concerned, that is the only fit that we can make because for the other you just normalise with a lifetime that you assume. It is a question of the fit of the gradient over the bit over which you had it. And I cannot really see that that fit is so significantly good. I agree that it is reasonable, and I agree that it is as good as you would expect from the quality of the data, but I would not at the moment say that it is so good that it justifies the statement that by its accuracy it proves the theory.

SINGER

The protons above 400 MeV are not relevant to this problem, because there are too few to influence the counting rate. The fit is reasonably good; our work is being refined because we need to take into account the eccentricity of the dipole and a few other things, but I think the statement that the atmosphere controls the intensity of the protons is probably borne out.

VALLARTA

My remark concerns the possibility of checking up on the adiabatic invariants by means of machine calculations of particle trajectories. Now if we remember that the values of γ_1 for the particles which are caught in the radiation Van Allen belts are very high values, that means that the allowed regions of motion are extremely narrow. Therefore the trajectories oscillate a great number of times in a very small distance and the mean distance measured along the talweg that both Dr. DE VOGELAERE and Dr. BOSSY were talking about this morning is very small. I think it is possible to make a calculation for values of γ_1, let us say 5, but beyond 5 I do not believe that is possible at all. If we ever get a solution of this problem, it will have to be an analytic solution and not a numerical one. I do not believe that is possible. Now, there are a great many difficulties in the way of getting an analytical solution to this problem, so I think that we must not expect any light from this direction in the immediate future.

RAY

I would like to make one comment about YOSHIDA's graph that you exhibited: it turns out that those data are from Explorer I which had a Geiger tube on it that was well designed to steady cosmic rays but quite incompetent to cope with the level of radiations actually found. A major fraction of each of the curves that you showed was the result of a correction by up to an order of magnitude or more in the intensity from the actually observed counting rate. In a later comparison of these data with data from Explorer IV apparently it has turned out that this correction was poorly known and that in fact it varies a good deal from tube to tube. Since it had not been measured on the particular tube it is poorly known, so that the rounding over of the curves as shown in that figure probably must be taken as due to the deadtime of the counter rather than any actual physical situation.

SINGER

I would doubt this; I think the curve must turn over because the intensity stops increasing at this very high rate and increases at a much lower rate starting from some altitudes above a thousand kilometers. And this break in the slope was actually predicted in the earliest development of the neutron albedo theory.

AN EFFECT OF NON-ADIABATICITY ON THE STRUCTURE OF RADIATION BELTS

S. HAYAKAWA and H. OBAYASHI

Physical Institute, Nagoya University - Nagoya - Japan

Abstract — It has been frequently emphasized that the non-adiabaticity in the motion of particles in magnetic fields plays an important role in interpreting the structure of radiation belts. However, the implication of this statement has not been carefully investigated but seems to have been understood incorrectly, particularly concerning the mirror loss in a static magnetic field.

According to the canonical formalism of orbit theory developed by H. OBAYASHI, a set of canonical variables can be introduced so as to correspond to the intuitively known three modes and the adiabatically invariant quantities can be defined unambiguously in terms of the action integrals. In this representation the zero order Hamiltonian describes the motion that is expected from the first order orbit theory and the first order one gives the non-adiabaticity in a quantitative way. This results only in the migration of the mirror point but not in the loss of particles from a mirror, unless the mirror point lies very close to the position of the maximum field strength. In radiation belts the migration of the mirror point is very important, because even a slight shift of the turning point closer to the earth brings about a considerable increase in the collision frequency of particles with gas atoms. For a proton of 300 MeV lying near the outer edge of the inner belt and mirroring at a height of about 1000 km, the migration distance is as large as 200 km.

A more quantitative analysis of this effect and other consequences of the so-called non-adiabaticity will be discussed.

1. Introduction

The break-down of adiabatic invariance has occasionally been referred in connection with the motion of a charged particle which does not seem to follow an orbit expected from the first order orbit theory. This has been the case in the interpretations of loss of geomagnetically trapped particles. For example, the steepening of the proton spectrum at several hundreds of MeV in the inner belt and the near absence of protons in the outer belt are attributed to the break-down by some authors, because the gyration radii become comparable to the radii of curvature of magnetic lines of force in respective cases. However, it has not been fully understood, how the break-down is connected with the loss of particles. In fact, an exact numerical calculation of tracing orbits in a dipole field has revealed that particles keep being trapped within a magnetic bottle even if their radii of gyration are considerably large [1].

Recently we have investigated this problem on a more general basis [2]. In a static field of axial symmetry it has been found possible to introduce a set of canonical coordinates which correspond to three modes of motion, the gyration, the drift along a line of force and the azimuthal drift about the symmetry axis [3]. The Hamiltonian expressed in terms of these canonical variables describes complicated coupled motions of these three modes, but they can be decoupled by a perturbation method. The zero order Hamiltonian is chosen to describe the first order orbit theory and the coupling is introduced in the Born-Oppenheimer approximation to the second order of a coupling parameter, the ratio of the radius of gyration to the radius of curvature. Our canonical formalism allows us to define the adiabatically invariant quantities as the action integrals and they are evaluated to first order of perturbation. Up to this order a particle is trapped in a finite region, unless its orbit crosses over a bottle neck. However, the turning point does not coincide with the mirror point in the first order orbit theory but migrates about the mirror point depending on the phase angle of the orbit at a certain point.

This result seems to be consistent with an experimental test of adiabatic invariance by means of injecting β-rays in a magnetic bottle [4], and might be regarded as the evidence against the argument to attribute the break-down of adiabatic invariance to a cause of particle loss from the radiation belts. Nevertheless, the migration of turning points gives rise to the particle loss through the following processes.

The first process is concerned with the disturbance in the geomagnetic field, by which the phases of particles are randomized. Consequently the turning point of a particle randomly moves back and forth, and this motion is nothing but a one-dimensional random walk [5]. Therefore the turning points undergo diffusion and may reach the atmosphere.

The second process is possible even if the magnetic field is perfectly static. Then the turning point does not diffuse out but changes its position around the mirror point from one mirror oscillation to another. In this course the particle has a finite chance to go beyond the mirror point, so that it may penetrate into a low altitude, at which the gas density is considerable. Since the gas density increases very rapidly as the particle goes far from the mirror point, the probability for the particle to collide with gas atoms may be much higher than that expected for a particle to be reflected at the mirror point in the first order orbit theory.

The second process is a chief aim of our discussion in this paper. We shall illustrate how this process is significant and shall show that this is, in fact, responsible for some features of the radiation belts.

2. Migration of turning points

Since mathematics of deriving the migration of turning points is rather involved, we give only the outline of derivation and numerical results here, leaving details in separate papers [2].

In our canonical formalism the zero order motion is taken along a line, at which the kinetic angular momentum vanishes. This coincides with the trajectory of the guiding center within our approximation adopted hereafter. The zero order Hamiltonian is found to be expressed only as a function of three action variables respectively corresponding to the gyration, the longitudinal drift and the azimuthal drift modes. Therefore, these action variables are invariant, as is expected from the first order orbit theory. As is well known, this allows one to define the mirror point.

Higher order Hamiltonians are obtained by taking into account the kinetic angular momentum. The expansion parameter of obtaining higher order terms is shown to be proportional to the ratios of the radius of gyration to R, R′ and r, where R and R′ represent the radii of curvature of a magnetic line of force and of a magnetic equipotential line, respectively, and r is the distance from the symmetry axis.

In the first order Hamiltonian the three modes are coupled, but they are made decoupled by a method analogous to the Born-Oppenheimer approximation. The action and angular variables are then obtained by means of Hamilton-Jacobi equations. Fixing the rather slow motion of the second mode, the longitudinal drift mode, we obtain the first oder correction of the action variable for the first, gyration mode as

$$\delta_1 J_1 = -\left(\frac{\partial H_0}{\partial J_1}\right)^{-1} H_1 , \qquad (2.1)$$

where H_0 and H_1 are respectively the zero and first order Hamiltonians and J_1 the action variable for the gyration mode.

$\delta_1 J_1$ changes its sign depending on the phase angle of gyration φ, its detailed expression being given in reference [2].

Corresponding to $\delta_1 J_1$, the turning point of a particle is displaced from the mirror point defined by $J_1^{(o)}$ the zero order value of J_1. The average migration distance of turning points may be represented by the root mean square of $\delta_1 J_1$ over φ as

$$\Delta J_1 = \sqrt{\langle(\delta_1 J_1)^2\rangle_\varphi} . \qquad (2.2)$$

This is, in turn, connected with the average migration distance ΔR_m. Expressing the position of a mirror point by R_m and λ_m, where R is the distance from the center and λ the latitude, we obtain

$$\Delta R_m = (L\ R_E)^3\ F(\lambda_m) \quad . \qquad (2.3)$$

Here we refer to the convention introduced by the Iowa group. Namely, a magnetic line of force is represented by

$$R = L\ R_E \cos^2 \lambda \quad , \qquad (2.4a)$$

so that it intersects with the equatorial plane at

$$R_e = LR_E \ , \qquad (2.4b)$$

where R_E is the radius of the earth. As usual, all lengths are measured in Störmer units

$$l_0 = 1.56 \times 10^6 \text{ km} / \sqrt{p\ (\text{MV})}, \qquad (2.4c)$$

where p is the rigidity of a particle. Thus the numerical value of ΔR_m is obtained as

$$\Delta R_m = 1.68 \times 10^{-5}\ L^3 pF\ (\lambda_m)\ R_E = 0.107\ L^3 pF\ (\lambda_m)\ \text{km} \qquad (2.3')$$

3. Effects on trapping lifetime

The lifetime of particles in a static magnetic field may be determined by the interaction with atmospheric gas atoms at high altitude, and is known to be approximately proportional to air density at the mirror point. The migration of turning points necessitates to take the average air density over the migration distance.

The density variation near the mirror point is approximately expressed by

$$\rho(R) = \rho(R_m) \exp\left[-(R - R_m)/H_m\right] \qquad (3.1)$$

where R_m is the position of the mirror point and H_m is the scale height at $R = R_m$, approximately expressed (see ref. [6]) as

$$H_m = 57.6\ L^2 \cos^4 \lambda_m\ \text{km}\ . \qquad (3.2)$$

Since the density changes rapidly for $|R\text{-}R_m| > H_m$, ΔR_m comparable to H_m makes a considerable difference in the thickness of matter traversed by a particle and consequently in the lifetime. Therefore, the ratio, $\Delta R_m/H_m$, gives us a measure of the non-adiabatic effect. The ratio is expressed, on account of (2.3) and (3.2), as

$$\frac{\Delta R_m}{H_m} = 1.86 \times 10^{-3}\ Lp\ \frac{F(\lambda_m)}{\cos^4 \lambda_m}\ . \qquad (3.3)$$

The values of $F(\lambda_m)/\cos^4\lambda_m$ are shown in Table I. Two numerical examples are shown below.

Table 1 — *Numerical values of necessary quantities*

λ_m	$F(\lambda_m)$	$F(\lambda_m)/\cos^4 \lambda_m$
15°	0.0670	0.0772
30°	0.0408	0.0738
45°	0.0251	0.1004
60°	0.0189	0.302

Firstly, we consider protons in the inner belt. $L=1.5$ and $\lambda_m=30°$ correspond to a region near the heart of the inner belt. There we have

$$\Delta R_m/H_m = 2.05 \times 10^{-4} p \ (L=1.5, \lambda_m=30°) . \qquad (3.4)$$

At $p=1000$ MV $\Delta R_m/H_m \approx 0.2$. The steepening of the proton spectrum above 1 GV could be attributed to this effect.

Secondly we are concerned with protons in the outer belt. For $L=5$ and $\lambda_m=60°$ we have

$$\Delta R_m/H_m = 2.81 \times 10^{-3} p. \ (L=5, \lambda_m=60°) . \qquad (3.5)$$

At $p=400$ MV this ratio is as large as 1.1. This may account for the negligible proton intensity above this rigidity.

The above examples seem to indicate how important the migration of the turning points is. Although the conclusion should be reserved until we calculate higher order effects, the mechanism considered above must be kept in mind when one discusses the trapping lifetime and other static properties of radiation belts.

Up to now we have assumed that the phase of particle motion is undisturbed. Actually, however, the phase is modulated by various causes, such as magnetic disturbances and small angle scattering. If the phase modulation is random, a particle does not remain in a finite region but diffuses away. The diffusion is described by the random walk of turning points in the following way.

Now a step of the random walk is taken as ΔR_m. For the average modulation period of τ_m, the time needed to diffuse to a distance of scale height H_m is given by

$$t \approx [2 \ H_m^2/(\Delta R_m)^2] \ \tau_m . \qquad (3.6)$$

If this is comparable to or greater than the lifetime, τ_o, determined by the zero order theory, the actual lifetime would be considerably reduced.

Here again $\Delta R_m/H_m$ is an important quantity. As examples, we take $p = 400$ MV and 40 MV, for the inner and outer belts in (3.4) and (3.5) respectively, since protons of these energies are representatives of respective belts. Then t/τ_m is found to be about several hundreds in either case. Therefore, the diffusion effect would also be appreciable for modulations of periods shorter than a day.

REFERENCES

[1] R. GALL, *J. Phys. Soc. Japan*, *17*, Suppl. A II, 139, 1962.

[2] S. HAYAKAWA and H. OBAYASHI, *Lecture at the International School of Physics « Enrico Fermi »*, June 1962. See also: *Res. Rep. Inst. Plasma Physics*, Nagoya University, IPPJ-5, 1963.

[3] H. OBAYASHI, *Progr. Theor. Phys.*, *25*, 297, 1961.

[4] G. GIBSON, W.C. JORDAN and E.J. LAUER, *Phys. Rev. Lett.*, *5*, 141, 1960.

[5] S. HAYAKAWA, *J. Phys. Soc. Japan*, *17*, Suppl. A II, 612, 1962.

[6] E.C. RAY, *J. Geophys. Res.*, *65*, 1125, 1960.

Note added in proof. Some numerical results based on our idea are given in: S. HAYAKAWA and H. OBAYASHI, *J. Geoph. Res.*, *68*, 3311, 1963.

DISCUSSION

Chairman: S.E. FORBUSH

BIERMANN

A small comment concerning the importance of the density gradient. This was established also in the course of theoretical work done by HAERENDEL in our Institute in Münich. What I recall is the qualitative result which seems relevant to our discussion. HAERENDEL made, if I remember correctly, also a comparison with the observations, and the improvement of the theory appeared to be verified by the data (1).

(1) After the meeting, Prof. BIERMANN sent us the following references: G. HAERENDEL, *J. Geophys. Res.*, *67*, 1173, 1962, and *Corrigendum*, Ibidem, *67*, 1697, 1962. See also: A.M. LENCHEK and S.F. SINGER, *J. Geophys. Res.*, to be published.

MAGNETIC FIELD CONFIGURATIONS NEAR THE SUN AND IN INTERPLANETARY SPACE

T. GOLD

Center for Radiophysics and Space Research - Cornell University
Ithaca, N.Y. - U.S.A.

Abstract — The present evidence is discussed concerning the configurations of magnetic fields in interplanetary space. The maintenance of a connection to the sun, the superpositions of flow from successive outbursts and the degree of irregularity of the field lines are considered in the light of evidence from space probes and from solar cosmic ray observations.

Evidence of the magnetic field configurations that occur in interplanetary space and in the vicinity of the sun has come from astronomical observations of the corona, from magnetometer observations of space vehicles and from the study of the many effects connected with the fluxes of cosmic rays and of solar produced high energy particles. It is in this last area that the discussion is at the present time the most complex, but on the other hand, it is from this that the largest amount of information about these magnetic fields has been obtained.

The major conclusions that can be drawn from the analysis of energetic particle fluxes are as follows:

1. The Earth is usually (more than 80% of the time) in magnetic fields that connect with the sun. It is only rarely, if

at all, imbedded in galactic fields that are unconnected with the sun.

2. The field configurations in interplanetary space are such as to be capable of storing energetic particle fluxes both inside and outside of the earth's orbit.

3. The field has such distortions on an average as to give a recognizable east-west asymmetry for high energy particle events.

4. The magnetic fields drawn out by outbursts retain their connection with the sun for one day or more.

5. The interplanetary magnetic fields are uneven or turbulent and thus scatter high energy particle fluxes.

Information from space vehicles has demonstrated that the fieldstrength in space away from the earth is usually a few γ ($1\ \gamma = 10^{-5}$ gauss), and on disturbed occasions rises to a few tens of γ. The measurement of the solar surface field by the Zeeman effect and an understanding of magnetohydrostatics have made clear that the fields in the corona within, say, one solar radius above the surface, must be mostly in the range from 1 to 10 gauss. Similarly it is known that in the inner corona, say, at a height of 1/10 of a radius above the surface above sunspot regions, the fieldstrengths may rise to several hundred or a thousand gauss. On many coronal eclipse photographs arched or looped structures are seen. There is little doubt that these shapes correspond to the magnetic lines of force for it is only in directions across the field that fluctuations of temperature, density or pressure could be maintained; and it is clear that any unevenness that exists within the corona will rapidly diffuse itself into shapes which trace out the lines of force.

The polar corona usually demonstrates a field whose lines of force seem to go mostly far out into space; and for that reason, the polar field has been thought to be indicative of a general solar field. BABCOCK's magnetograph observations [1] have shown however that a more complicated interpretation is required, in which this polar field has, at least some of the time, a large quadrupole component, for the field in one hemisphere has been seen to reverse (in 1957) leaving an interval of one year before the field in the other hemisphere reversed as well.

From the evidence of comets discussed by BIERMANN [2] it is quite clear that a certain amount of outward motion from the corona of the sun takes place most or all the time. PARKER [3] has attributed this to the imbalance of a hot corona which cannot terminate statically in the low pressure of galactic space. In addition to gas which appears to be streaming out into interplanetary space from the corona, there is a considerable amount of information about gas clouds being ejected by events of which the flares are the most violent, from the depth of the chromosphere of the sun. It thus appears that there are definitely two species of gas available at different times in interplanetary space, coronal and chromospheric. Perhaps ways can be discovered of distinguishing the periods when the earth is enveloped in coronal and when it is enveloped in chromospheric gas, and perhaps this distinction will be of importance in the investigation of many phenomena.

The theoretical interpretation of the field configurations in the presence of this general outward streaming tendency of the gas presents some difficulties. Why are the loops of lines of force not stretched out indefinitely? Why does each chromospheric explosion not draw out an additional flux in the shape of an expanding arch which retains the anchored lines of force in the photosphere? Why are there not more and more lines of force drawn out from the surface of the sun increasing indefinitely the total pole strength of the sun?

There are clearly only two possible ways out of this dilemma. One would be that all the outward streaming only takes place where there are no looped lines of force. Although the inner corona has a large fraction of its volume occupied by such loops, the expansion of the corona and the origin of the solar wind would then have to lie just in the fraction of the corona which is occupied by the far-flung lines of force only. Magnetic forces would presumably then be required to prevent the outward flow in that large fraction of the corona where there is a looped structure. The total outflow from the corona would then be much reduced by this effect of the field, but since the expected rate of outflow is rather sensitively dependent upon the unknown distribution of the source of the coronal heat, no real conflict arises there. It is different however with the chromospheric eruptions, for in that case gas is seen to come up through the corona and to fly out into space from locally intensely maguetized regions. It is not possible to think that this gas is itself completely free from magnetic fields and these eruptions would therefore continue to pull new lines of force out into space. There is no indication ever of any significant return flow, and it is therefore certainly necessary to find an interpretation of these phenomena which avoids the dilemma mentioned. The only possibility seems to be that dissipative processes exist which chauge the linkage of the lines of force so that the gas of an outburst does not continue indefinitely to be magnetically connected to the surface of the suu; but that, instead, the lines of force close locally near the sun and close within the cloud of outstreaming gas.

Such a cutting off process can be understood in terms of a rapid dissipative process that must be taking place in the vicinity of surfaces of zero magnetic field. The configuration of the magnetic field of an outburst must quite generally contain a plane on which the field vanishes, and on the two sides of this plane there must be magnetic fields of opposite sense (Fig. 1). The magnetic pressure in the nearly parallel field on each side of this plane must be $\frac{HB}{8\pi}$ but the pressure must

FIG. 1 — Magnetic bulge with neutral plane.

be zero exactly on the plane (Fig. 2). The physical nature of the gas would always imply a finite thickness of a slab within which the change-over from one sense of the field to the opposite will be taking place, since current sheets cannot be infinitely thin.

Such a configuration cannot be in equilibrium. The slab cannot exert a pressure to balance the magnetic pressure on the two sides. Material will therefore flow towards this sheet, bringing lines of force with it, but the symmetry of the process does not allow a magnetic pressure to be built up. Instead, as opposing lines of force approach each other, the field would be annihilated, and a structure of short loops would be re-

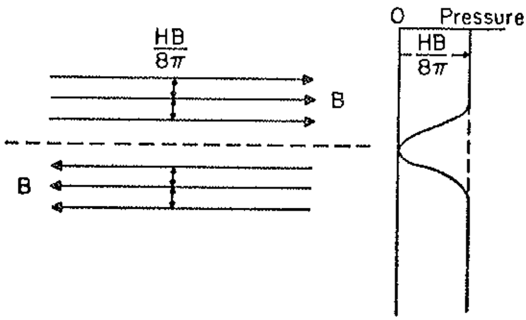


FIG. 2 — Magnetic pressure in vicinity of neutral plane.

established near the sun, and a magnetically-disconnected cloud would fly off into space. Gas pressure cannot finally balance the magnetic pressure of the system, for as soon as the gas pressure has risen in the slab, it will in turn imply a longitudinal force along the slab which is not magnetically balanced. Fig. 3 indicates the flow patterns that must be expected from such a process.

Chromospheric outbursts certainly are cut off in a period which must not be more than a few days, judging from the evidence of particle fluxes, and also from the evidence of coronal shapes. The process mentioned is almost certainly the fastest agency available. Outstreaming from the corona as a whole is however a different matter, for there we have no real knowledge that the entire corona contributes. The particularly hot regions in the corona seem, however, to be concentrated in looped coronal structures, and such structures may therefore be most liable to expansion. In that case the solar wind produced in space could not be an entirely steady phenomenon, for no steady state solution exists for an outflow in anything except an entirely combed-out field. It seems to be entirely possible, however, that an almost steady solar wind merely pulls out one cloud after another, so that the space at any time is filled with adjacent configurations like the one in Fig. 3. As each tuft

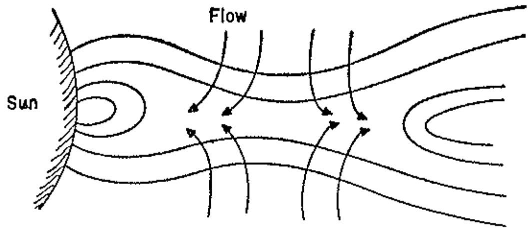


FIG. 3 — Gas flow in cutting off process.

becomes disconnected and short loops are re-established near the sun, these in turn get drawn out again by the expansion of the corona, and a new such tuft is generated. I think it most likely that this is in fact the configuration normally present in the solar system space. The very frequent occurrence of the « spiked helmet » shape in the corona is then presumably the visible part of such configurations (Fig. 4).

One might argue the case in another way. If there were uniform outstreaming and a steady state everywhere, then the field would have to be everywhere radial. But entirely radial fields must have surfaces of zero field separating regions of one sign from regions of the opposite sign. Knowing the erratic nature of the field over the solar surface, one would suppose that the division between the two senses of the radial field would itself be a surface of considerable complexity. This surface would everywhere be unstable in the manner discussed, and looped fields would be regenerated from the radial configuration.

Let us now turn to the discussion of the propagation of fast particles generated in the chromosphere during a flare. If we are concerned with protons of energies between 10 MeV and several GeV, we can immediately discuss various aspects of their propagation through space. The difficulty lies in finding which aspects are of dominant importance in the actual case.

It is clear that in the fieldstrengths that exist near the sun, no free escape of such particles is possible. On the contrary, the majority of such particles must be stored on looped tubes of force, and oscillate between mirror points in much the same manner as the particles of the radiation belts of the earth. In the case of the earth we know that particles injected at one place would soon occupy a shell encircling the earth. This shell, defined by the famous integral invariant, will however be of much more complex shape in the more erratic solar field than in the case of the earth; and indeed there is not even any reason for supposing that it remains single valued with solar

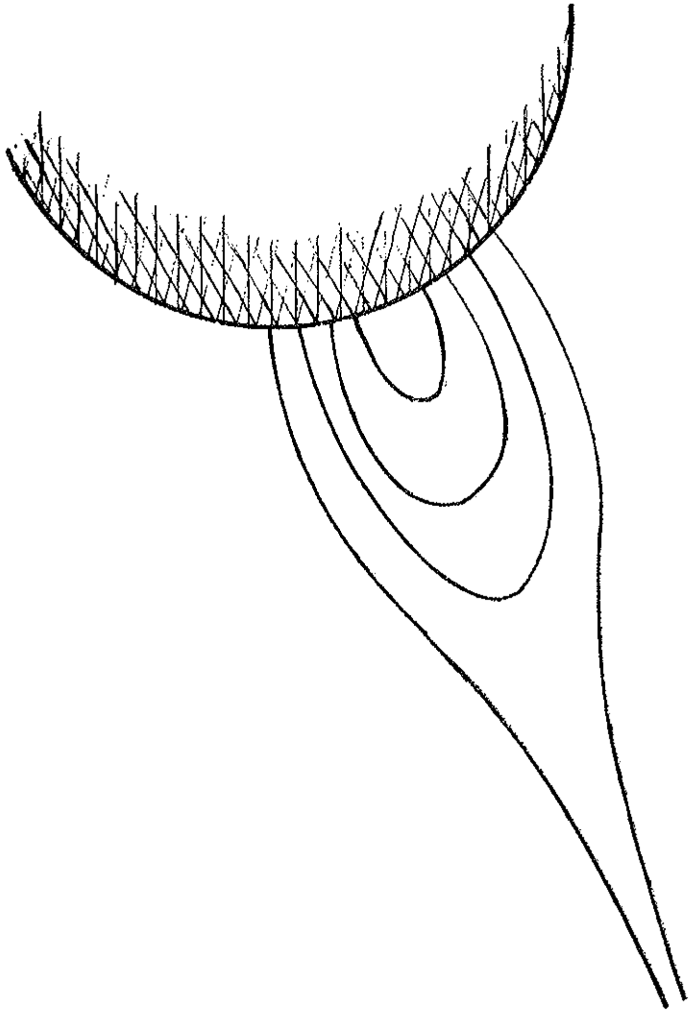


FIG. 4 — Coronal « spiked helmet ».

longitude. The particles produced in one place will thus be spreading out over such a sheet, with drift speeds normal to the field that depend on the energy of the particles, and on their pitch angles. The time scale for a large drift in longitude would be of the order of hours.

This motion would retain the guiding centers of particles on a surface and would not allow them to move out to fill a volume. On the other hand, on most occasions when energetic particles are produced near the sun, they seem to be able to reach the earth, and this fact demands a volume diffusing mechanism. One effect might be the expansion of the loops of the magnetic lines of force on which the particles are first stored; but it turns out that it is a very inefficient mechanisin to distribute particles in a volume, for if the expansion is rapid enough to be significant, then the adiabatic cooling that it provides enormously diminishes the energy of the stored particles.

In the vicinity of the sun the constant boiling of the photosphere and the frequent occurrences of instabilities in the chromosphere probably provides a high general noise level, and the corresponding Alfvén waves will be responsible for diffusing a flux initially confined to a surface into larger and larger volumes of space. This effect is likely to be largest near the sun, where the high frequency disturbances are most intense. Without time variations in the field, one could not understand how particles produced in one location could be scattered throughout a large volume.

Time variations have another effect too. Not only do particles get continuously diffused in their drift motion along a sheet, but the position of the sheet itself will change from time to time. Particles drifting along the sheet will thus be guided to different localities at different times. I take this to be of relevance to the observations reported by Prof. NEY [4] regarding the big variability in the ratio of protons to α-particles for different solar events. Protons and α-particles of the same rigidity differ in speed and in drift speed by a factor 2, and they will therefore trace their way through the complex solar field at times tens of minutes or hours apart, during which very substantial changes in this field will have taken place. They will thus not be guided around to the same places and it becomes a matter of chance whether the particular region that is magnetically well connected to the earth is better accessible for the protons or the α-particles. The proton to alpha ratio might thus be greatly changed by the propagation mechanism in either sense. The time dependent routing of the particle fluxes through the solar field would then imply in the extreme case no more correlation between the protons and the α-flux in one event than the correlation that there is from one event to another.

The distribution of particles over more and more storage orbits near the sun must be accompanied by more and more particles being also placed on the small proportion of lines of force which stretch far out into space. Some particular region on the sun will contain a line of force that reaches to the vicinity of the earth, and most of the delay time observed in the propagation of the fast particles seems to be connected with reaching this line. The direct propagation along the line to the earth, even granted that we do not know how straight the connection is, is likely to take only a small fraction of the delay time.

We know that in most events the particles reach this line of force at a distance from the sun which is much less than one astronomical unit, for only in this way can it be understood that the particles reaching here show in the first place a high degree of directionality. From studies of impact zones on the earth, McCracken [5] and others have estimated that early on in an event the particle flux approaches the earth's field from a direction which is often well defined to less than 10°, and which is often not a large angle away from the direction to the sun. This can immediately be understood if magnetic fields anchored in the sun have guided these particles here, so that in moving in a strongly diverging field, the pitch angles had been greatly steepened. Thus whatever the injection angles were on the line of force, the observed anisotropy here is then explained.

It is equally important however to account for the tendency to establish isotropy within a time like half an hour or an hour after the first arrival. The fields in our part of space cannot be taken to have changed very much in that short period, and it could certainly not be assumed that a particular change in these fields occurs every time at this phase in the event. The only alternative explanation seems to me that the particles even at this distance from the sun are still on captive orbits so that we are witnessing the filling up of a storage region. In that case, even the very small scatter in the particle pitches produced by irregularities in the field will eventually result in the storage region being filled everywhere with an isotropic flux. For the first particles arriving here this scatter would imply only a small dispersion of angle around the direction of the field. If this were as little as 10°, then already the first flux returning in the storage region and approaching now in the direction of a converging field, will have a scatter that is likely to be indistinguishable from 90°. The usual time history of the directionality of a flux is thus a natural explanation if the earth is located in a slightly diffusing storage region, which is magnetically connected to the vicinity of the sun. The quality of storage in this region must be quite good, so as to account for the fact that the intensity of the isotropic flux is only a small amount less than that of the earlier directional flux. If such storage were the consequence of a shock wave standing at some distance beyond the earth's orbit, then the shock wave would have to make a very good reflector. In terms of looped fields, the requirement means no more than that the decay of fieldstrength with distance from the sun shall usually be a little faster than $1/r^2$.

It is by no means certain that the required drift motion normal to the lines of force always occurs fairly close to the sun. If storage regions are often larger than I AU then the required longitude drift might be taking place also quite far out from the sun. One can only say that on all the occasions when events have shown a very marked anisotropy at the beginning, it is necessary for this drift to have taken place sufficiently near the sun so that enough collimation in direction would have been produced in the transmission of particles in a diverging field. On the other hand in events in which there is no marked anisotropy at the beginning this drift may well have taken place at distances even beyond that of the earth. So far as the calculations of drift speeds are concerned, both possibilities exist. It may be that one will find that in events of long time delay between the flare and the arrival, where evidently the configurations near the sun have been unfavorable, the initial arrival was not so anisotropic. One would then conclude that the longitude drift motion was executed mostly far from the sun. The initial anisotropy is likely to be a good indicator of the region in which the longitude drift took place.

The last point I would like to mention concerns the question of the sense of magnetic fields in space. OBAYASHI and others [6, 7] have demonstrated that there is a statistical tendency for the time delay of an event to be least if the originating flare is situated approximately 45° W of the central meridian of the sun. At longitudes away from this one, the time delays tend to be progressively longer. This is usually interpreted as implying that lines of force have a spiral shape, as must indeed be expected from a combination of an outward streaming with the solar rotation. The sense and angle observed fit this interpretation very well. If drift motions of particles could take place equally well in an easterly as in a westerly direction, then there ought to have been approximately as many flares situated on the back of the sun that resulted in particle events at the earth, as there were on the eastern half of the disc. This contradicts the observation that the great majority of particle events at the earth appear to have been related to a well recognizable large flare on the visible part of the sun. One cannot be quite sure at the moment how many wrong identifications of flares may be involved in these statistics, but if the statistical evidence is good, then it could only imply that particles have a much better chance of drifting by a large angle from East to West than from West to East. The field in space where this longitude drift is occurring would then have to have a tendency for a preferred direction, namely such that the component normal to the ecliptic should be more often opposite than parallel to the earth's external field. It is not clear at the moment how all this is to be related to the direction of fields as observed in sunspot regions or how this direction would change in the sunspot cycle. If this direction in space had a 22-year cycle, so that the sense changed over at each sunspot minimum, then the next sunspot cycle would give a better eastward drift for the fast particles. This in turn would mean that very many unobservable flares and far fewer observable ones would contribute to particle events at the earth (a situation which would be very inconvenient for the space program, and for the attempts of predicting damaging amounts of radiation.) There is perhaps some relation between this discussion of a possible tendency for this statistically dominant sense in drawn out solar fields, and ELLIOT's discussion [8] of a general solar field extending far out into space. It may be that some of his considerations could still be applied to a situation where there is only a statistical tendency rather than a long-lived nearly static field.

REFERENCES

[1] H.D. Babcock, *Astrophys. J.*, *130*, 364, 1959.

[2] L. Biermann, contribution to this meeting p. 477.

[3] E.N. Parker, *Space Astrophysics*, Mc Graw Hill, 1961, p. 157.

[4] E.P. Ney, contribution to this meeting p. 233.

[5] K.G. McCracken, *J. Geophys. Res.*, *67*, 423, 435, 447, 1962.

[6] T. Obayashi and Y. Hakura, *J. Geophys. Res.*, *64*, 3143, 1960.

[7] A.M. Ellison, S.M.P. McKenna and J.H. Reid, *Cosmic Ray Flares, Dunsink Observatory Publ.*, *1*, 53, 1961.

[8] H. Elliot, contribution to this meeting p. 459.

DISCUSSION

Chairman: L. BIERMANN

PARKER

First let me say that I think Prof. GOLD has given a most excellent and interesting review of the present problems and thinking in the propagation of particles in interplanetary space. I had a couple of questions that I wanted to ask to clarify in my own mind my interpretation of his remarks. First, you discussed of course the possibility that particles are detained and drift at the sun, and then that they are detained and drift in interplanetary space. It was not quite clear to me whether you regarded the detention at the sun or out in space the more important.

GOLD

I would think that more particles are delivered to the earth after having done the journey to a near line of force, to the proper one, near the sun rather than further out in space, because most events do have a substantial anisotropy to begin with.

PARKER

You say then that detention at the sun is more important than in interplanetary space. If this is the case, it follows that *on the average* the delay at the sun will be directly proportional to the rate of drift of the particles. At nonrelativistic and at extreme relativistic energies the drift rate is proportional to the particle energy. Thus the delay of arrival at the earth for particles of different energy should be proportional to the particle energy. This is true for some solar events, I am sure, but I wonder if it is true for the *average* over *many* events. My impression is that the lower energy particles are not usually so seriously delayed as this mechanism would imply. The second point is that if there is little or no diffusion in space, then each energy range of particles should be anisotropic when that energy group, no matter how long delayed, begins to arrive. It is my impression that observations show that in most cases there is only a brief anisotropy in the beginning.

GOLD

You are leading me into a confusion rapidly by using one word, delay, for both storage and delay in the transportation. Let us discuss a narrow energy range. That travels through this gradient drift system here like a wave, and it will pass the foot of this line of force at a fairly well defined time, and that is the time when we get injection into our line of force, and after that nothing. So what we see is still a fairly short pulse available at the foot of this line, even though it has got here with a fairly significant time delay. So then we have these particles in the large-scale system rattling around, and as I have said, they must be rattling around in there with fairly good storage in order to give a decay time diagram where the tail is connected to the peak. So I think that we must distinguish between these two times. The quality of storage in a sense is good near the sun because the sun will retain the particles altogether for a longish time, but it is giving a particular batch to our line of force at a fairly well-defined time. There can be a separation according to energy, if delay is mainly gradient drift, and according to velocity if path length along field dominates, or in practice anything in between.

NEY

I agree with Dr. GOLD on the evidence that very frequently the low energy particles are enormously delayed compared to the high energy ones, but I have a question somewhat related to the last one. You use the early anisotropy together with the fractionation as an argument that the switching occurs close to the sun. But the early anisotropy is measured at high energy and the fractionation is measured at low, and it is not clear to me that you can put these two together to make the argument for the fractionation occurring close to the sun.

My second question: You use the coronal shapes as observed near the sun as an argument for your cutting off mechanism, and you would then think that the cutting off would occur relatively close to the sun; but toward the end of your discussion you want the lines of force to extend far beyond the earth, and I don't see how these two are compatible.

GOLD

Your first point about the fractionation in α-particle storage: I do not want to say that I force the low and high energy particles into the same discussion. I would merely say that so far as the low energy particles are concerned (the ones that you have observed the fractionation of), I could not readily understand, if at all, how we can get such good sorting as the big variations in the ratios imply, except by arranging for the α-particles to find themselves propagated through a very differently shaped field. Since they have the same rigidity I must discriminate them on the time basis, and I will have to shape the field very differently half an hour or an hour later from what it was before; and the place where the field has a very different shape an hour later is fairly close to the sun and not far off in space. That is the only reason for assuming that the fractionation occurs in the vicinity of the sun rather than far off in space. I don't want to stress the argument any more than that. If you believe that big enough changes can occur in interplanetary space in the period of an hour, so that one set of particles are shot to one place and another set to another place, then that would be possible; but I think the evidence is that such quick effects are much more likely closer to the sun. And after all, the motion is occasioned by what is happening on the sun, and so the velocity of all the changes is of course much larger near the sun.

Your point number two: where do I have to cut the thing off? I am aware of the dilemma that you pose to this discussion, but I don't think that it is so much of a dilemma. I suppose that the cutting off occurs over the entire length of the bulge; and in this case all we can really say is that we are not stuck in cutoff clouds for more than 20% of the time, because these cannot stay hanging around for a long time, and this is consistent with the observations.

NEY

It just seems to me that the two phenomena are two orders of magnitude different in scale, that cutoff in the corona that you show on the coronal pictures is very near the sun, and the picture on the left that you drew (I wish they were both up there at the same time) are on a completely different scale. One is out beyond the earth, the other near the sun, so it is a factor of 100 in the scale that we are talking about.

GOLD

And you think it unlikely that the same phenomenon could be spanning such a great range of scale?

NEY

Yes.

ROSSI

I wonder whether you looked into the possibility that along the neutral surfaces where magnetic plasma tongues are cut off from the sun an acceleration of particles may take place? What I have in mind is that the collapse of the tongue implies the existence of an electric field; and that near the neutral surface, where $E/B > c$, the electric field does not produce a bulk motion perpendicular to E and B, but rather an acceleration in the direction of E. The question, it seems to me, is whether collisions will allow acceleration to occur, or will rather lead to energy dissipation.

GOLD

When you speak of acceleration of particles, do you have in mind high energy particles? That I think cannot be so, because of the quantities of gas that are involved. If the cutting off process works at all, then we know that through this neutral plane must flow the amount of gas that was sitting on all these lines of force that are being cut off; so we know the quantity of material that must be digested in that process. And that quantity of material is so great that if that is all treated alike, the energy per particle that can come out of it is low. This field could only heat the gas to a temperature of the order of 10 million degrees. If the process were not effective, in some way, and the cutting off did not work, then of course I could not argue like this and then you might have high energy particles. But if you believe that the cutting off happens by this process, then it is *ipso facto* not producing high energy particles.

PETERS

I wonder whether the experimental evidence, as it now stands, is already sufficient to reject the possibility that the fractionation occurs mostly during the pickup, *e.g.* in the initial stages of acceleration? The number of helium atoms accelerated will of course depend on the number of helium ions, but probably also on the ratio of doubly to singly ionized helium. This ratio will be very sensitive to temperature and may vary strongly from flare to flare. Now, if that were true, it should of course show up also in the fact that the ratio of α-particles to heavier nuclei does not stay constant. The evidence that Prof. NEY has given shows that there are less fluctuations in this ratio but not by any means that there are no fluctuations; in fact there seemed to be room for changes in the ratio of He to CNO nuclei by a factor 3. Until the question is settled whether the ratio of alphas to heavier nuclei is really constant or not, one will have to consider the possibility that fractionation occurs in the initial stages of acceleration. It should probably not be dismissed as yet.

GOLD

Yes, but the factors are evidently not so large, so I would think that what you would be allowed to say at the moment is that there may be some fractionation occurring in the flare, but I think you would want the great amount of it — that is, between alphas and protons — to be done in the transportation mechanism.

SIMPSON

I would like to comment on Prof. GOLD's interesting discussion on the trapping and diffusion of solar particles at the sun. I think that one can really put numbers into the hold-up process. As an example, let us consider the solar protons from the flare of 23 February 1956. During the period of anisotropy at the earth, one has an opportunity to look at instruments which detect particles whose trajectories extending outward from the earth cover a wide range of energy. By suitable analysis you can show that among such a group of detectors on the earth having different local geomagnetic field cutoffs the arrival time of the first solar particles is different at different detectors. For this flare, you will find the onset times distributed as shown in Fig. 5. When you analyse this effect, you discover that the first arriving 10 GV particles arrive 10 minutes earlier than the first arriving 1 GV particles. There is, of course, an additional time to be added representing the transit time. This is called a dispersion effect. Soon after these observations isotropy sets in. We then examined earlier flares and found that the dispersion effect for the November 1949 flare was 14 minutes for about the same range of particle energy. To this

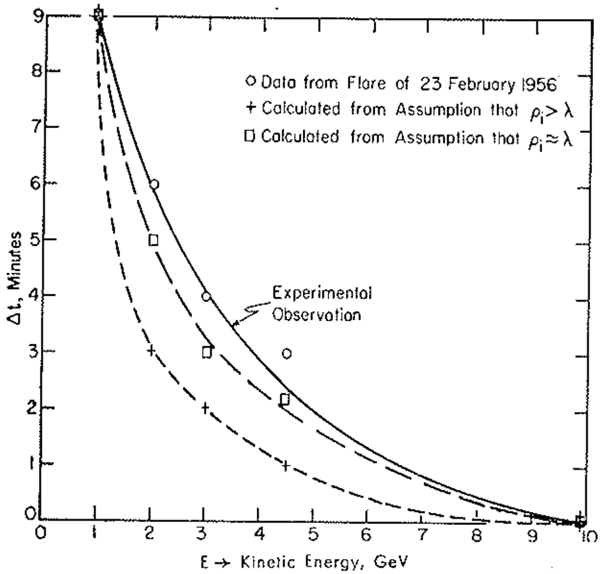


FIG. 5 — The dispersion effect. The time delays for the first-arriving particles as a function of energy. The results of calculations for diffusion through a solar dipole field with irregularities of scale size λ are shown for comparison. (From R. LÜST and J.A. SIMPSON, *Physical Review, 108*, 1563, 1957).

time must be added a base transit time — the time when the solar « gun » was fired, so to speak. Since you have to take a time zero, we chose a time near the maximum light output of the flare. This gives a transit time plus the dispersion time. It is very difficult, indeed, to explain this dispersion curve as due to the interplanetary medium; it must arise from particle diffusion near the sun. Detailed models cannot yet be given. The scale size of irregularities in the solar fields must be fairly small; the field intensities must be fairly large. A more recent case that has just come to our attention is the September 28, 1961 flare observed in Explorer XII by MACDONALD's group, in which they have seen through direct measurement the dispersive arrival of particles at much lower energies (down to approximately 2 or 3 MeV). Here the time scale is much wider, extending to $\sim$ 1000 minutes. Therefore, we observe this dispersion effect in almost all flares where the particle flux from the flare is large enough to perform an analysis.

PARKER

I want to make one comment on the first question and then ask another one. Apparently we come to different conclusions from looking at the same data, because I would come to the opposite conclusion on the basis of this kind of data.

The other question I want to ask goes back to the field configuration that you drew and discussed on the left side of the board. I worry a little about re-entrant lines of force, because if you were suitably positioned in space, you would see particles first coming from around behind you instead of from the suuward side first; the statistics are poor, but I don't think it has ever been seen.

GOLD

Well, I don't know whether that has been seen. Of course, when they come from the other side, as I say, even a little way round from the back, they will already have been isotropised because they are already going into a converging field; and it is only a little way that is needed to isotropise. So such events would not be events where you see them coming from the anti-solar direction; they are events in which you see them arrive initially isotropically, and there are such events.

PARKER

There is certainly the possibility that you should see them arriving from, say 90° between the sun and the anti-solar direction or even a little bit backward from the sun. Your point is well taken, and I would not expect this to be often, but I am a little worried that we have never seen a case like this.

GOLD

We have seen this. For example on November 15, 1960, according to McCRACKEN, we have seen particles arrive both from one direction in the sky, which was not the solar direction but one not too far from the sun, a big spike, and then we have seen half an hour later a spike which was somewhat anisotropic though not as much as the first spike, and that second spike had its preferential direction — what it had of it — in the 180° direction from the initial one. So we have seen an event where we saw particles first come from some asymptotic direction and then half an hour later from a direction which was less well-defined but was the opposite one. And that is just what one would expect. Now that can be argued easily as being the bounce particles that you see coming back, but I prefer to think of it in terms of being the particles that got into the other foot of the lines of force. I think that is statistically more probable.

PARKER

The only point I want to make is that I think one has to leave open the question of all the possible kinds of configurations and I think non re-entrant configurations may well be present frequently too.

GOLD

I do not know what you mean by non re-entrant.

PARKER

Well, not connected in two directions to the sun.

GOLD

So that the lines of force go to infinity, you mean?

PARKER

Well, let us just say some large distance, so that there is no possibility of particles going out somewhere else and coming back into you from the anti-solar directiou first without having seen them from the solar direction.

GOLD

If they stick out a very long way, then you must always have a good reflector on those lines.

PARKER

By a good reflector, just lots of perturbations would be sufficient.

GOLD

No, otherwise you get time curves where the decay is rapid first and slow later, and this is not observed.

PARKER

That is correct, but you find if you carry out a calculation that good diffusion is sufficient to do this.

GOLD

Not if it would distribute the reflected beam over more lines than it travelled out on.

BIERMANN

If I understand correctly, you associate the east-west asymmetry with a field, the polarity of which is given by the field in the polar regions. After 11 years, that is from now only six years or so, it would become apparent whether or not this is so. Now, I recall that for the big events which were observed at sea level, a similar plot was already made by ELLISON about two years ago — that was when ten big events were known. These ten events had been between 1942, when the first ones were observed by Dr. FORBUSH and Dr. EHMERT, and I think 1960. As far as I recall on this plot the asymmetry was already clearly seen and there was no indication of any change over. Perhaps you have looked at this plot too.

GOLD

There are two points to be distinguished: one is the east-west asymmetry which can be seen in the not very many observations on hand, and when you want to go a long way back in time you come to a very much smaller number of observations. In those you can still see the east-west asymmetry that there is; namely, that events of short time delay have a preference for the west side of the sun. That means only that the sense of the Archimedes spiral is being defined, and the sense of that spiral remains the same whether the lines of force have one sense or the other. But the other effect that I was discussing is whether particles when they do drift have a tendency to drift a little better westwards or a little better eastwards. And that requires a large number of observations before you can squeeze out of the data the fact that there should have been particles from flares around the back that you did not see; and it is only that latter point that suggests the preferential direction of the drift. So the Archimedes spiral could be established from the early data; but the direction of a drift can only be established — and even now perhaps not quite securely — by the bulk of all the data that we know now.

DENISSE

I am not quite clear about the way you get this drift in the east-west direction. It comes from the general solar field?

GOLD

Just suppose that there is a messy field in detail but it has a slight tendency to have the mean field superimposed on it; so it has a slight tendency to have always the sense for protons in the one way. In detail it will diffuse them in a more complicated fashion.

DENISSE

Do you think that optical evidence is for the existence of an important field of this kind down to the equatorial solar region?

GOLD

Yes, there is evidence that the solar general field still has some significance even in the low latitude zones. You do see a considerable tendency at most times in eclipse pictures for a set of loops in the equatorial zone of the sun to go over smoothly from the high latitudes. It is a common situation to see a picture which has got a sort of broad equatorial mess coming out, but you see here the plumes which certainly are quite regular and correspond to some kind of a general field, and you see this turn over smoothly into the equatorial belt on many occasions.

PARKER

For the east-west drift at the sun that you are hypothesizing, is it in the low latitude loops that one sees as you have drawn them closed over the equator? Let me tell you why I ask this question, before you answer it. It strikes me that the magnetograms would suggest that those loops vary their sense from one month to the next rather than having to wait from one sunspot cycle, so that it is not obvious tbat during any one cycle you should get a systematic shift of everything only to the east or only to the west.

GOLD

I mean, the coronal shapes do have some lines of this nature visible a large part of the time, but of course they do have a very considerable mess in detail. In any fine detail there will be a diffusion and a gradient drift in both directions. But when the particles have to go a rather large angle around, then they will often come through regions where there is a substantial contribution of the general field present too, because they do not only drift in tbe sunspot regions, not only in the messy regions, but also in clean field regions; and when you see clean field regions on the limb in an eclipse picture, then they have that kind of a tendency. So in traversing all the cleaner regions there will always be that tendency in the one sense, and not in the other sense. And perhaps that is all that we need to account for a not very perfect statistical result.

HAYAKAWA

Since I missed the comment by Prof. DENISSE during the talk, I would like to ask: is there any evidence for electrons to drift in other way than the protons?

DENISSE

I do not think that radioastronomy provides any evidence for such drift because the experiments are too crude.

COSMIC RAY INTENSITY VARIATIONS AND THE INTERPLANETARY MAGNETIC FIELD

H. ELLIOT

Imperial College of Science and Technology - London - Great Britain

Abstract — A great deal of attention has been given in recent years to the interpretation and discussion of the propagation characteristics of energetic protons emitted from solar flares, and these propagation characteristics have played an important part in the formulation of current views about the field configuration. In establishing the validity of the various models, however, it is necessary to take into account as wide a range of relevant cosmic ray phenomena as possible. This paper will attempt to summarise the experimental data at present available on the eleven-year variation, twenty-seven day variation, Forbush decrease, and solar daily variation, and to discuss these data in relation to the rather different models of the field advocated by GOLD, by PARKER and by the author.

1. INTRODUCTION

At the present time there is a considerable diversity of opinion as to the interpretation of cosmic ray intensity variations in terms of the electro-magnetic conditions prevailing in interplanetary space and in the solar corona. In view of the complexity of the problem this is hardly surprising. ALFVÉN [1], for example, has laid particular stress on the importance of electric fields, and the effects of these fields have been worked out in great detail by DORMAN [2]. MORRISON [3] was the first to propose that turbulent magnetic fields moving outwards from the sun might exercise an important influence on the cosmic ray intensity in the solar system. GOLD [4], on the other hand, has strongly advocated the presence of rather smooth tongue-like configurations of field drawn out of the photosphere by outward moving solar material at the time of enhanced activity. PARKER [5] has developed the idea first expressed by BIERMANN [6] that the outward streaming of solar material is not restricted to times of exceptional activity but takes place all the time, constituting the so-called « solar wind ». This wind stretches the photospheric fields out radially into a configuration which is relatively smooth within the earth's orbit but becomes turbulent a fraction of 1 AU beyond it. This turbulent field provides an outward moving convective barrier which impedes the arrival of cosmic ray particles from outside the solar system. SINGER [7] has pointed out that if the sun is indeed the origin of an expanding cloud of irregular magnetic field then cosmic rays inside this cloud will lose energy by an inverse Fermi process, and that this energy loss may be important for the understanding of the intensity variations. It seems likely that all these ideas will ultimately have to be incorporated to some extent into the final picture. The prohlem at the present time is to determine their relative importance.

All these proposals presuppose some measure of understanding of the magneto-hydrodynamics of the solar plasma, but it is perhaps not too unfair to say that the present diversity of views arises, in part at any rate, from our *lack* of understanding of this subject. In view of these difficulties one wondered if it might not be worthwhile to begin at the other end, so to speak, by constructing the simplest model of the magnetic field one could think of which would at the same time be capable of accounting for the known energy dependence of the 11-year variation, the Forbush decrease, and the solar daily variation — these being the three main categories of intensity variation.

In addition, it is necessary, of course, that the model should be compatible with the propagation characteristics for energetic solar particles and the established properties of the interplanetary plasma. The first question one might ask is whether the field is stationary or in motion and unfortunately this first question produces the first problem because we find that when we set about deducing the answer from cosmic ray evidence, the answer we get is not the one we expected.

If the field is in motion, in the sense that we have an outward moving convecting barrier as in PARKER's model, the 11-year modulation of the cosmic ray flux should depend on both particle rigidity and velocity. Consequently, at the lower end of the spectrum, where β is appreciably less than one, we should expect a greater depth of modulation for α-particles than for protons of the same rigidity. If, on the other hand, we are dealing with a static field, the degree of modulation should depend only on particle rigidity. The evidence at present available on this point seems to me to be rather strongly indicative of a purely rigidity dependent modulation.

2. STATIC VERSUS DYNAMIC MODELS OF THE FIELD

If this crucial evidence is correct it seems to me that it excludes any convective model for the modulation process. The experimental data on which it is based come largely from the careful measurements of the low energy proton and α-particle spectra during the past solar cycle by MCDONALD and WEBBER [8]. WEBBER [9] has summarised these data and from the table he gives we find that for particles with rigidity > 1·5 GV

$$\left[\frac{(j_p/j_\alpha)\ \text{ss. min.}}{(j_p/j_\alpha)\ \text{ss. max.}}\right]_{\text{OBS}} = 1.02 \pm 0.03$$

whereas is is possible to show that, if the modulation is such that

$$\left(\frac{\partial j}{\partial p}\right) \bigg/ \left(\frac{\partial j_\infty}{\partial p}\right) \propto \beta$$

where $\frac{\partial j}{\partial p}$ is the differential intensity at the earth, $\frac{\partial j_\infty}{\partial p}$ is the differential intensity in the galaxy and

$$\beta = v/c \ ,$$

then

$$\left[\frac{(j_p/j_\alpha) \text{ ss. min.}}{(j_p/j_\alpha) \text{ ss. max.}}\right]_{\text{CALC}} = 0.92$$

The experimental evidence, therefore, appears to favour a modulation process which does not involve β. Unfortunately, the evidence is not absolutely conclusive and it must be borne in mind that further observations might lead to different conclusions. Nevertheless, this is the way the experimental evidence points at the present time and if we accept it, it contradicts the view that the large scale interplanetary field is in continuous outward motion as is to be expected from the observed plasma flow. Since I was, in my self-imposed terms of reference, committed to try to see what can be done with a static model, such a model should in any case provide some kind of complementary picture to the dynamic models.

The very first model of the interplanetary field, proposed to explain the knee in the latitude curve, was that suggested by JANOSSY [10] round about 1937 who pointed out that if the sun had a dipole moment of 10^{34} gauss cm^3 or so this would be sufficient to produce the required effect. This suggestion was taken up and elaborated by a number of people and particularly by VALLARTA and GODART [11]. Now everyone is agreed that such a model, based as it is, on the assumption that interplanetary and coronal material is of no significance, cannot be very useful in the light of present knowledge particularly as it is in any case in disagreement with cosmic ray evidence. Nevertheless it can provide a starting point and it was on this basis that I tried, two or three years ago, to construct a static model of the field which would account for the cosmic ray intensity variations.

This model has been described in the literature [12] and there is no need to enter into details at this point. Suffice it to say that the field envisaged is an axially symmetric one, something like that of a solar dipole with its direction perpendicular to the plane of the ecliptic and parallel to that of the earth but with a field strength which falls off with increasing distance according to $1/r^2$ or $1/r^3$ or something in between. This field contains scattering centres which enable limited inward diffusion of cosmic rays to take place. Competing with this inward diffusion is absorption by the sun so that, in the steady state, the cosmic ray intensity inside the field is depressed below that prevailing outside in the Galaxy. There is no doubt that a simple field of this kind can account in a semi-quantitative way for the cosmic ray modulation processes.

I have already shown that it gives the correct energy dependence for the 11-year variation and for the Forbush decrease and this is in the literature so I don't propose to discuss it here unless someone wishes to.

I would, however, like to say a little about some recent results obtained by MATHEWS [13] in London. These, you may remember, were mentioned by Prof. AMALDI [14] the other day. They relate to observations carried out using a scintillation telescope recording μ-mesons at a depth of 60 m w.e. This recorder has semi-cubic geometry, a collecting area of 3 m^2, and a counting rate of 50,000 per hour.

Fig. 1 shows the records for three underground stations during the Forbush decrease of Nov. 11-16, 1960. Measurements of this kind are of particular interest because we are looking at the extreme upper energy limit of the modulation process. On the basis of these measurements MATHEWS

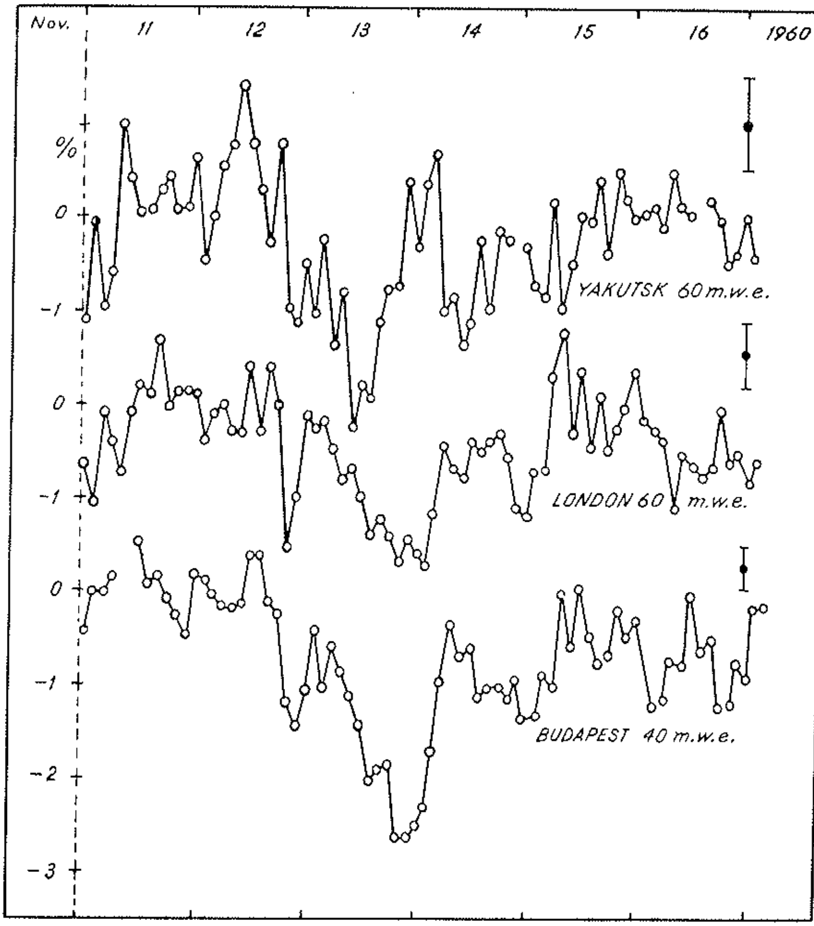


FIG. 1 — Cosmic Ray Intensity Variations recorded underground during Nov. 11-16, 1960 at Yakutsk, London and Budapest.

concludes that the Forbush decrease extends up to energies of at least 100 GeV. Furthermore he has compared the observed ratio of magnitude of the effect at different energies to that expected on the basis of these kinds of models and the results are given in Table I.

	observed	KP^{-1}	PARKER	ELLIOT
N_{SL}/μ_{SL} . . .	1.71 ± 0.01	2.41	1.90	1.64
μ_{UG}/μ_{SL} . . .	0.16 ± 0.04	0.02	0.02	0.07

MATHEWS points out that in none of the cases can the agreement be regarded as satisfactory but, cautions that anisotropies are obviously important. It may be of interest to you to note in Fig. 2 that the 27-day variation in intensity is also quite marked at these relatively high energies.

I would now like to say a little about the propagation of energetic solar particles in interplanetary space.

3. PROPAGATION OF ENERGETIC SOLAR PARTICLES

It has sometimes been argued that the arrival at the earth, in recognisable impact zones, of solar flare particles in the energy range below 20 GeV or so is incompatible with a dipole-like field of the magnitude discussed here. This is, however, not a serious objection if it is borne in mind that the inner part of the dipole field in often considerably distorted, particularly at times of great solar activity. There seems to be no reason why we could not, at such times, have a wide variety of connecting paths between the earth and the sun, having properties adequate to account for what we know about the propagation characteristics for these particles.

GOLD [15] has objected to the dipole field model on the grounds that the diffusion time for low energy particles is very

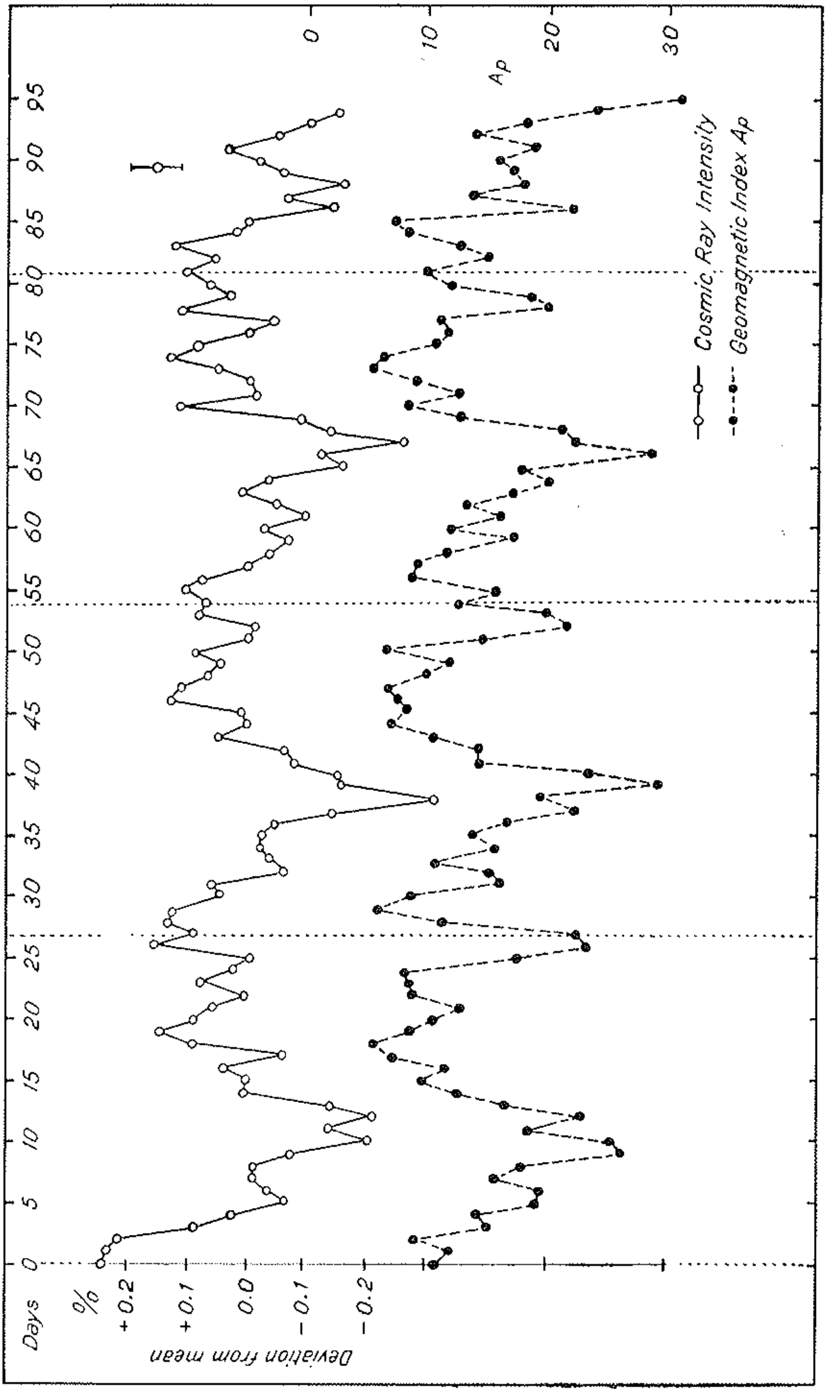


FIG. 6.2 — The 27-day variations in Cosmic Ray intensity and Geomagnetic index A_p for days of maximum Cosmic Ray Intensity recorded at 60 mwe underground.

long (of the order of a year) and that this long diffusion time would lead to a decay time for the energetic solar particle events very much longer than that which is observed.

In fact, the mode of disappearance of solar particles is very complicated. In a field of the kind under discussion the particles would be dispersed:

a) By azimuthal drift due to the field gradient;

b) By re-absorption in the sun;

c) By diffusion outwards in the same way that the galactic particles diffuse inwards; and

d) By outward convection resulting from the outward motion of field irregularities.

Assessment of the relative importance of these processes depends upon a rather detailed knowledge of the field configuration and on a knowledge of the volume initially occupied by the solar particles. *a*) and *b*) are likely to be most important in the early stages and *c*) and *d*) most important at later times. In general, we would expect the decrease in intensity of the solar particles to be most rapid in the early stages and for the highest energy particles. Characteristic times varying from hours in the early stages to perhaps a year for complete disappearance are to be expected. It is by no means certain that such times are inconsistent with observation. Indeed, the observation of an ambient flux of low energy particles under quiet solar conditions and with energies of a few hundred MeV, by Vogt [16] and by Bryant et al. [17] would seem to require storage of solar particles over long periods.

4. The gradient of cosmic ray flux in the solar system

The dipole model enables us to predict the average gradient of the cosmic ray flux to be expected in the neighbourhood of the earth, and in this connection some extremely interesting measurements have been made by the Chicago group [18] using the space probe Pioneer V. Their data are shown in Fig. 3 together with the expected gradient, and at first sight there would not seem to be any inconsistency. However, they have shown that the 10% drop in intensity, which is observed, arises from the removal of low energy particles during a Forbush decrease rather than from a steady diminution of intensity with decreasing distance from the sun and they conclude that their data are inconsistent with the value of the gradient expected on the basis of the dipole model. I believe that it is important to bear in mind that a protracted series of measurements will be necessary in order to establish the average value of the gradient. If, to take an analogy, the amplitude of the solar daily variation is really a measure of this gradient, as it would be on the dipole model, we know that this amplitude shows great variability from day to day and that many days of

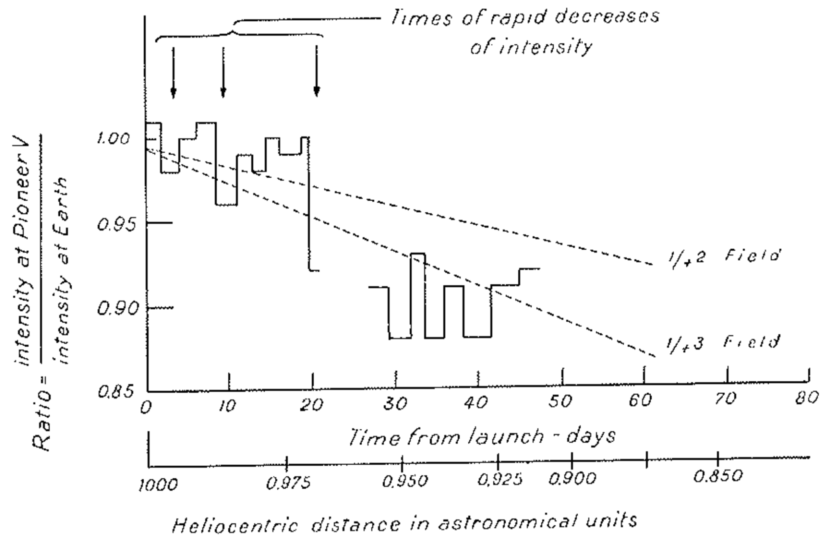


FIG. 3

[19] *Elliot I* - pag. 10

observations are required if we wish to establish a reliable average value.

This discussion is taking place at a most tantalizing time. We are waiting to hear the results of the direct measurement of the field by Mariner II and these observations will no doubt add greatly to our understanding of the field configuration. If the average field direction lies exactly in the plane of the ecliptic we shall know that the model proposed here has no validity. If, on the other hand, the average field direction deviates appreciably from that plane, the PARKER's solar wind model will be in some difficulty. If, however, there should be a field component perpendicular to the ecliptic plane, it may be quite hard to distinguish between GOLD's model and the dipole model. The test would seem to be whether or not, over a period of several solar rotations, this perpendicular component keeps the same preferred direction. If the explanation of the solar daily variation afforded by the dipole model is correct, this component should be north-pointing. On GOLD's picture it would, subject to statistical fluctuations, be north-pointing half the time and south-pointing the other half.

REFERENCES

[1] H. Alfvén, *Tellus, 6*, 252, 1954.

[2] L.I. Dorman, *Cosmic Ray Variations*, State Publ. House, Moscow, 1957.

[3] P. Morrison, *Phys. Rev., 101*, 1397, 1956.

[4] T. Gold, contribution to this meeting, p. 431.

[5] E.N. Parker, contribution to this meeting, p. 207.

[6] L. Biermann, *Z. Astrophys., 29*, 274, 1961; *Naturf., 7a*, 125, 1952.

[7] S.F. Singer, *Suppl. Nuovo Cim., 8*, 334, 1958.

[8] F.B. McDonald and W.R. Webber, *J. Phys. Soc. Japan, 17*, Suppl. A II, 428, 1962.

[9] W.R. Webber, *Progress in Elementary Particles and Cosmic Ray Physics VI*, North-Holland Publ. Co., 1962.

[10] L. Janossy, *Z. Phys., 104*, 430, 1937.

[11] M.S. Vallarta and O. Godart, *Rev. Mod. Phys., 11*, 180, 1939.

[12] H. Elliot, *Phil. Mag., 5*, 601, 1960.

[13] T. Mathews, preprint, 1962.

[14] E. Amaldi, contribution to this meeting, p. 299.

[15] T. Gold, *J. Phys. Soc. Japan, 17*, Suppl. A II, 607, 1962.

[16] R. Vogt, *Phys. Rev., 125*, 366, 1962.

[17] D.A. Bryant, T.L. Cline, U.D. Desai and F.B. McDonald, Nasa X-611-62-126, 1, 1962.

[18] J.A. Simpson, C.Y. Fan and P. Meyer, *J. Phys. Soc. Japan, 17*, Suppl. A II, 505, 1962.

[19] *Elliot I* - pag. 12

DISCUSSION

Chairman: L. Biermann

Parker

Let me say that I am very much interested in the observational results that you have presented. I have no particular comments. I am not sure that any calculations or formulas that I have ever written down can be applied as high as 200 GeV, but I do not think that that is the explanation for the discrepancy anyway. With regard to the direction of the field in space, when you said *precisely* in the plane of the ecliptic, I winced a little at the word « precisely ». Let us say that the field should show a general tendency for the plane of the ecliptic probably with lots of fluctuations. Dr. Gold and I have often wondered just what the distinction is between the two models that we proposed so far as observations from a single magnetometer in space is concerned. I don't think that we have ever come up with a clear cut conclusion. There does not seem to be any simple way of getting at it.

Gold

To take the earlier point first, I was not quite sure that one can distinguish between a static model for the 11-year cycle and a moving one quite as simply as you discussed. I do not want to say that what you said is wrong, by any means, but I only want to say that I was not sure that one can make that distinction as easily as that. In particular, what I have in mind is the kind of model whereby an outward streaming wind at this distance from the sun (always an outward stream, but of variable intensity over the 11-year cycle) may produce a slowly varying bulge in the galactic field much further out; so that there is a bulge, like a snake that has swallowed a rabbit, in the galactic field and the size of this bulge is changing with the 11-year cycle. That is a sort of almost static situation then, in which the amount of cosmic rays admitted into the interior of that bulge depends on the mirror ratio and therefore will show some kind of modulation. Now, whether that gives the right modulation and in the right ratio for the different particle rigidities and energies, I am not sure, but it gives a different effect from merely the outward convection of the field which you discussed.

Then, to come to the other point about the direction of the fields, it is true that in the view that I advocate all directions of the field are possible out here. You should in fact, if you look long enough, see them all occurring; in particular you should see fields normal or almost normal to the ecliptic occurring on occasions. But on the other hand, there should be a statistical tendency for a field which is directed somewhere to the west of the sun and not too far away in the other coordinate. If you imagine any number of these tufts coming out, then of course the proportion of time that would be in the elongated part of it would be much longer than the proportion of time that would be in the nose of one. So that it is only in the nose that you would have a large angle to the ecliptic and the rest of the time you would have a smaller angle to the ecliptic. Now, I think that so far as the evidence from solar cosmic ray events goes, that is the situation. We have had some events where preferential direction was pointing in some peculiar angle in the sky but we have the majority of events pointing to some angles not very far from 30° west of the sun.

ELLIOT

In connection with your remarks about the galactic field, I agree, but this is essentially a static field, is it not? You are relying on the break-down of the first invariant to decide the upper limit to your energy dependences. Whether or not the cosmic rays get through the trap in the field and into the cavity determines what modulation takes place. Now, such a cavity model has been tried but I think most people would agree that it gives much too steep an energy dependence. But you are in fact still agreeing with me, I think, in that this is essentially a static model that you have to deal with, and the motion of the field is not important in determining the modulation.

GOLD

Yes, I would only say that there is not a real conflict in seeing the gas moving here while we desire a static model.

ELLIOT

I agree entirely with this, and in the model I am suggesting it is the substratum of field that is not moving; the scattering centres may move, but this does not matter very much because the particles are essentially tied to the fixed field.

PETERS

I would like to ask a question on the subject which Prof. GOLD has also brought up, namely the argument you have presented in favour of a static field. It is based on the observation that the 11-year cycle maintains unchanged the ratio of protons to α-particles. Did I understand right that the experimental data apply to a rigidity range above 1.5 GV? If so, the mean energy of the protons would be above 4.5 GeV, and that of the heavy particles would be near 2.5 GeV/nucleon kinetic energy. It would then seem to be very difficult to see the velocity dependence if any existed. Maybe I misunderstood the argument.

ELLIOT

The calculation is made in this way: One takes a rigidity dependence which agrees with that observed and which is already well established from many different bits of experimental evidence. Then one adds to this a β dependence, and when one integrates over the spectrum from 1.5 GeV to infinity one can see what difference between protons and α-particles there should be, and this is the number that I have written down on the board.

PETERS

But then it depends on how much β dependence you add.

ELLIOT

Well, I have taken it to be just proportional to β, which is what one would expect from Dr. PARKER's model.

BIERMANN

What is the magnitude of the magnetic field which you would advocate in the vicinity of the earth orbit?

ELLIOT

The field strength is a function of the level of solar activity and would go up to a maximum of perhaps 8 γ. The scattering centres in the field would have a characteristic dimension of 10^{11} cm.

BIERMANN

Does this mean that there is a dependence on the square of the distance from the centre?

ELLIOT

I do not think it is possible to decide on the basis of such a model, as far as I can see, between an r^2 or r^3 dependence, except in terms of a measurement of the cosmic ray flux gradient. You will remember the picture that I showed you of the measured gradient: there are two dotted lines shown, one is for r^2 and the other for r^3. I do not think, however, that one can determine it from the energy dependence of the modulation process.

SIMPSON

In addition to the average cosmic ray intensity gradient there is a gradient for the Forbush decrease as a function of time. Although the data are limited, there are sufficient data at 0.1 AU along the sun-earth line during the Forbush decrease of 1 May 1960 to indicate that the relative cosmic ray intensity observed in Pioneer V and at the earth is essentially constant. This strongly suggests that there is a small or negligible gradient of the Forbush decrease. On the other hand, for a purely static model, such as you suggest, there should have been a large gradient effect. On the basis of the limited data available the measurements tend to be in disagreement with the static model.

ELLIOT

I am not sure what you mean by the gradient in this case. I should have thought that there was no escape from the fact that there was a gradient in the flux during the Forbush decrease, because we see tongue or blast wave travelling past the earth and as it goes past the intensity changes by the full amount of the Forbush decrease. So there must be such a gradient. I am not quite clear what you mean by gradient in this respect, I am afraid.

SIMPSON

I mean this in the sense that one waits until the intensity has dropped to the minimum value and then compares the intensities at the earth and at the position of Pioneer V.

ELLIOT

Oh, but I don't think it is possible to say anything about this. After the Forbush decrease has happened, surely the distance the space craft travels before the intensity has relaxed back to the normal value is small, is it not?

SIMPSON

There is 0.1 AU along the sun-earth line between the two positions of measurements. Is it not true in your model, that for two positions in space 0.1 AU apart, radially away from the sun, there should be at any given moment in time a difference in the gradient of the Forbush decrease?

ELLIOT

Yes, on the average a difference of 10%.

ON THE INTERPLANETARY PLASMA

L. BIERMANN

Max-Plank-Institut für Physik und Astrophysik
Institut für Astrophysik - München - Deutschland

Abstract — A discussion is given of the main properties of the interplanetary plasma and the associated magnetic fields, based on geomagnetic observations, on the observed properties of the plasma tails of comets, on the direct measurements from space vehicles, as well as zodiacal light observations and some relevant radioastronomical data.

Reference has been made in these days to the indirect evidence concerning the existence and the properties of the interplanetary plasma, specifically to that component of the interplanetary plasma which now is commonly called the « solar wind ». It is the object of my survey to discuss this evidence and to relate it to the direct measurements and to the theoretical considerations which were discussed earlier this week.

From geomagnetic data [1] we know:

1) the magnetic storms are individual large events, which are caused by plasma clouds emitted by the sun during solar flares;

2) the recurrent magnetic disturbances, which are caused by persistent particle streams emitted from certain long-lived active regions on the sun, the so-called M-regions;

3) the almost continuous presence of some corpuscular solar radiation has been inferred from the rareness of periods

without any magnetic activity and from the fact that in stations at high geomagnetic latitudes almost always some geomagnetic activity and some polar aurorae are observed..

Other types of observations which give information about interplanetary plasma are the following:

1) the polarization of the zodiacal light;

2) the effect of the appearance of the radio point sources when they are within 20° or so from the sun;

3) the acceleration of plasma tails of comets.

Only the observations of the comets' tails allow conclusions regarding the state of motion of the interplanetary plasma and the direction of its motion. I will therefore start by discussing the comets' observations and the related theoretical work.

In order to introduce the subject I have to say a few generalities about comets, their heads and their tails.

One of the several types of tails which I shall deal with in detail is the so-called type I. The direction of the type I tails is approximately along the radius vectors from the sun to the comet. In the second approximation the tail is usually lagging behind, judged from the sense of motion of the comet, around the sun, by a small angle of a few degrees of arc, just as if the tail material were accelerated by particles of 10 or 15 times the velocity of the comet (more precisely its component perpendicular to the radius vector), that is to say by particles moving with several hundred km/sec. A large number of observations of this angle were made by HOFMEISTER about 20 years ago.

The dimensions of the head are around 10^{10} cm or a bit more, those of the tails of type I are some 10^{11} cm to some 10^{12} cm in length and $\approx 10^{10}$ cm in diameter. In some cases these tails reach through the whole inner system of the planets, that is they extend over 100 million km and more.

The spectra show that these tails of type I consist of molecular ions such as CO^+, N_2^+ and CO_2^+. These surface densities are of the order of 10^{11} or more emitting molecules per cm^2;

from this figure together with the dimensions we get the total number of such molecules present in the tail at any given time.

There are reasons to believe that there are more molecules present than we see. The presence or absence of resonance bands in the ordinary photographic or visual spectral range appears to determine the selection. Owing to the dilution of solar light the degree of excitation is only 10^{-5} or so of that given by the Boltzmann formula; for this reason molecules are effectively observed only in their resonance bands. One can easily see that those molecules which one would expect in greater abundance, such as *e.g.* NH_3, are unlikely to show up because they do not have resonance bands in the accessible spectral region.

Next we turn to the velocity and the acceleration of the tail plasma, the discussion of which leads us directly into our main subject. The velocities can be found from the displacement in time of individual features. The plasma tails, in contrast to the dust tails, show a great number of structural features, such as filaments, clouds or edges, which we can follow during one night, say from hour to hour or from night to night for — in some cases — half a week. From such observations it is possible to derive velocities — which are found to be of the order of some 10 km/sec up to some hundreds km/sec — and accelerations. In the older literature it is customary to refer the accelerations to the local value of solar gravity; the fact that the plasma tails are directed almost radially away from the sun means, of course, that the acceleration is large compared with the solar gravity. The individual values range from several tens to several hundred or even $>10^3$ times solar gravity, the value of which is 0.6 cm/sec^2 at the earth's distance. The values of the acceleration may differ greatly for the same comet from night to night, also between different comets or (occasionally) between different parts of the same tail. Essential features of these tails are their richness in structures, about which I shall say more later, and their activity and variability. This is in contrast to the behaviour of the dust tails and of the heads of most comets.

The next question is how can we understand the fact that this acceleration is as large as it is. An obvious first suggestion is that the tail molecules are driven by the pressure of solar light, in other words, by the absorption and remission of solar radiation. As far as the non-ionized molecules and the dust particles are concerned, the light pressure is indeed likely to be the main force which acts upon them, the accelerations in question being only of order unity or a fraction of unity.

For the molecular ions of the plasma tails the position is rather different. The f-values for the observed bands of CO^+ are very low ($\approx 2 \times 10^{-3}$); in consequence, the acceleration by light pressure acting on these ions is only of the order of $0.1 \times$ solar gravity. Of course, one may wonder how much absorption below 3000 A and by other ions might contribute to the acceleration; but since the momentum flux in this part of the solar spectrum is much smaller than in the ordinary range, even large f-values would not yield the observed acceleration. Also one would have no explanation for the observed high degree of variability. It seems therefore that we have to look for another cause of the acceleration of these tails, and the suggestion which has been discussed in the last ten years is that plasma tails are accelerated by the solar corpuscular radiation. For the detailed justification I must refer to the original papers and to the recent review by RHEA LÜST and myself [2].

Let me just summarize some relevant observations and the theoretical position very briefly. As to the first, one would obviously expect that if the earth and the comet happen to be nearly along the same radius vector from the sun, then a geomagnetic disturbance should be likely to be accompanied by a disturbance of the plasma tail of the comet. This expectation has been checked for a number of comets and has been verified with the probability which one might expect. From this kind of observation one should be able to deduce — if the difference in radial distance is large enough — a value for the velocity of the solar particles which accelerate the tail plasma; on this basis RHEA LÜST found a velocity of the order of 300 km/sec for a case which occurred while solar activity was generally at a low level.

With regard to the theoretical aspects, we have first to enquire whether the solar corpuscular radiation has enough momentum. Using the evidence which has been described by Prof. ROSSI (which I understand is likely to be confirmed by the present measurements from the Venus probe) we have under quiet conditions a momentum flux of some 10^{-8} dyn/cm^2 in the vicinity of the earth. Using the ohserved overall densities of ions in the tails, one can show that there is sufficient momentum provided the coupling between the solar and the tail plasma is effective. With regard to the coupling there are three possibilities: first, the direct coupling by the thermal motion of the electrons. This mechanism appeared promising ten years ago, when considerably higher figures for the density of interplanetary plasma were accepted than today; but with the present values it is likely to play a more secondary role. Second, we have the possibility of coupling by magnetic fields; this possibility looked somewhat more remote in 1951, but now, as we have amply discussed, magnetic fields of the order of a few gamma are likely to be present in interplanetary space practically always; these fields should indeed help to couple together the solar plasma and the cometary plasma, though the details of this interaction require further investigation.

Finally, there is the possibility that instabilities of some kind enhance the coupling by drawing on the energy connected with the velocity difference. The subject of plasma instabilities has been rapidly developing in the last few years. Generally speaking, one should expect that the situation of the solar plasma is hitting the comet to be unstable from the points of view which are currently discussed in plasma physics; but I do not wish to express any firm opinion on this nor on the consequences of such an instability.

For the present purposes, I think it is sufficient to say that we are apparently not short of possibilities, on the basis of the general experience from plasma physics, the most likely possibility, at the present time, being the coupling of the action of magnetic fields; but I will not insist on this. From the observational side, the high degree of variability of these tails appears to be a strong general argument for ascribing the acceleration to the influence of the solar corpuscular radiation, which is known to exhibit just this character.

Let me therefore assume for the following that the plasma tails do indeed indicate the presence of moving interplanetary plasma and can be regarded as tracers for this plasma. We can then draw immediately a number of conclusions from the observations of such tails. First of all, we saw that the direction of these tails is almost radial apart from what appears to be an aberration effect reflecting the individual motion of the comet itself. This means obviously that the direction of solar wind is essentially radially away from the sun. One might ask whether there is at those distances, where one usually observes the plasma tails — that is between a few tenths and 1.5 AU — any trace of co-rotation with the sun; that is to say whether there is any visible difference between the direction of the tails of such comets which move roughly in the same sense as the sun rotates itself, and such comets which move in the opposite direction. Now, no such difference has been found, which means that if there is any component of co-rotation with the sun of the solar plasma, then it must be smaller than the usual amount of the azimuthal component of the comet velocity — that is smaller than, say, 20 or so km/sec.

Furthermore, the velocities in the solar plasma must be larger tban the largest velocity which is usually observed, which means that we need in any case some 100 km/sec in the cases of more violent motion values of the order of 1,000 km/sec.

These values are of course in the range which we believe for other reasons.

Next and perhaps most important are the following observations: If we do observe a comet to have a plasma tail in one night, then this comet is almost without exception found to possess a plasma tail also in the following nights as long as the comet is within the distance from the sun within which such tails are ordinarily observed. The dimensions, the shape and the general appearance of the tail might change greatly, but as far as I know it has never been observed that such a tail, after having been visible during one or a few nights, disappeared for the rest of the comet's period of visibility. So we have to conclude that, while the property to possess such a tail is presumably a property of the comet itself (probably connected with its size, its chemical composition and its state of evolution), the solar corpuscular radiation which accelerates the plasma must have one component which is quasi-stationary. This component has been termed the « solar wind » [3]. We have heard that this conclusion appears to have been confirmed by the direct measurements obtained until now.

Next we might enquire whether the property to have such tails is connected with the general level of solar activity, that is to say whether we observe such tails *e.g.* only if the sun is at least at a moderate level of activity or else at all times during the 11-year cycle. This question has been investigated in greater detail recently by RHEA LÜST. From a total of some 30 comets with distinct type I tails, for which good data were available, she found 4 which appeared during periods of very low solar activity. Hence, we should conclude that the solar wind is present also during minimum solar activity. In the years to come we shall have another opportunity to see whether that is really so or not. We should realise of course that we do not see all the time comets with plasma tails; the possibility that we are misled by some queer coincidences should therefore not be disregarded.

Next, we might enquire whether comets lose their plasma tails if they move at a large angle to the ecliptic plane and pass over the polar regions of the sun. Part of the comets which are known to have had such tails did indeed pass also over higher latitudes of the sun; but their general properties did not differ from those of comets moving nearer to the ecliptic plane. Hence we should conclude that the solar wind is emitted also from the polar region of the sun with a similar (though possibly smaller) intensity as from the equatorial regions. A first study of such comets has been made by PETER STUMPF [4], who got an indication that the average probability of a comet having a plasma tail appears to be somewhat lower if it is moving nearer to the ecliptic plane. If that means that the solar wind is somewhat less intense above the polar regions, one could relate this observation to some other evidence, which we shall discuss later when we turn to the observations of radio point sources.

In this connection one might enquire about the mechanism of ionization. Until some years ago, after the first rocket observations, it looked as though the photo-ionization should not contribute strongly while the solar wind was known to ionize by the exchange of charge, *e.g.* between solar protons and non-ionized CO molecules. This particular process, the result of which are CO^+ ions and H atoms, has a large cross section for the velocity range in question, its value being 3×10^{-15} cm^2, which is one of the largest cross sections for processes of this kind. At present the situation has become somewhat complex. Using HINTEREGGER's latest data [5] for the flux of ionizing quanta of solar light, it appears that the two processes are competitive and lead to time scales of ionization of probably the same order of magnitude ($\approx 10^{-6}$ sec^{-1}) [5a]. By the mechanism of charge transfer the solar wind itself contributes to the formation of a plasma tail; for this reason one would expect that the formation of a plasma tail might somewhat (but not exclusively) depend on the intensity of the solar wind.

One might furthermore enquire about the true geometrical structure of such a tail. If the interplanetary magnetic fields are essential in coupling together the solar and the tail plasma, then the tail structure might reveal something about the geometry of interplanetary magnetic fields. If for instance the magnetic fields were mainly in the equatorial plane of the sun, then one would expect the tail to have a rather flat structure because the acceleration would be largely in that plane. Now in fact the plasma tails look more or less the same from whatever angle we see them. There has been at least one case where the position of the earth was so that we looked approximately into the tail itself; in this case the comet's tail looked like a « Catherine wheel ».

This evidence appears to indicate that there is no preferential orientation in those magnetic fields which couple together the cometary plasma and the solar plasma. It tends to give support to the conception that the local interplanetary magnetic fields are fairly disordered and variable.

In this connection we might ask whether we see any structures in the comet's tails which would indicate the presence of magnetic fields. There are indeed several such indications; the first is that the plasma tails usually show very fine filaments; these filaments have a length of the order of a million kilometers or more while their diameter is only of the order of some thousand kilometers. Their lifetime is of the order of half a day or so. It is now easy to see that in order to keep the structure as sharp as it is for this length of time, either the temperature would have to be very low, of the order of only a few degrees Kelvin — a temperature which is entirely unreasonable — or else these filaments must be kept together by some force, presumably magnetic fields. In this argument it has to be realised that we do not require magnetic fields which take up the lateral pressure since the filaments might be embedded in invisible plasma; we are therefore led again to values of the magnetic fields of the order of a few gamma. As to the question of the origin of these fields, the situation is somewhat complicated.

One possibility is that the magnetic fields are carried by the solar wind and have themselves a filamentary structure; but it could also be that these filaments are created by the interaction of the solar winds with the cometary plasma.

Occasionally, we see in a tail a structure which looks like an edge, which when first observed is always near to the head, but moves further away in the course of the next days. Such an edge may be observed to move quite fast; the whole tail appears to be disrupted such that there is for a few hours a gap between the original tail, which is moving away fast, and the head of the comet itself, out of which a new tail is formed. I think this phenomenon could be associated with PARKER's conception of a blast wave in interplanetary space, which of course could take up the pressure which must arise from the compression of the tail material. Such an edge is a rather rare phenomenon but we know a number of examples of it. That we have to assume that magnetic fields are operative there follows again from the fact that such edges are sharp. In the comet Mrkos of 1957 such an edge was seen for three successive nights without any apparent diffusion. With the magnetic fields which for other reasons (see *e.g.* Prof. PARKER's discussion [3]) we believe to be connected with such shock waves the observation can be explained.

Another observation of some interest is that such a tail occasionally looks like a giant cork-screw. Similar shapes have been seen in solar prominences; the figure itself reminds us of the structure of the so-called force-free magnetic fields. One (tentative) way of looking at these structures is this: disrupted magnetic fields are carried into interplanetary space by clouds of solar plasma; if the plasma pressure falls below the magnetic pressures, the configuration must progressively become force-free.

We might ask for which reason the direction of the tails reveals nothing of the large-scale magnetic fields. As we have learnt from the cosmic ray observations, there are indications that quite often a preferential direction exists in the interplanetary magnetic fields which conforms to the garden hose angle. Now the flux of momentum of the solar plasma is larger by several orders of magnitude than the energy density of those magnetic fields of a few gamma, which are usually there; it is therefore the motion of the solar wind which governs the dynamical interaction between the tail plasma and the solar plasma, though the motion of energetic charged particles is still largely influenced by the large-scale magnetic fields.

Last, we might enquire about the masses concerned. As we heard already, there are reasons to believe that in a comet there are many molecules which are not visible. We are just in the process of investigating this question anew. It looks as though often we have gaseous matter in a similar amount by mass as we have dust. This is a suggestion which on a different basis has been made already by WHIPPLE a number of years ago, and there are independent reasons now for believing that the total production of gas on a comet is considerably larger than indicated by the amounts of visible ionized and non-ionized molecules.

The production of visible molecules is of the order of up to 10^{28} or possibly 10^{29} mol/sec. An observation which is relevant in this connection is the following: SWINGS and GREENSTEIN [6] have noted recently that there are comets which show forbidden lines of atomic oxygen, and SWINGS and Mme REMY-BATTIAU [7] have shown furthermore that this is quite a common situation. I will not try do discuss the details, but it is perhaps easy to see that the excitation probability for the appearance of the forbidden lines of oxygen is very low; taking as a guide the processes going on in the higher atmosphere of the earth, we are led to amounts of gaseus matter and molecules containing oxygen which are large, certainly larger by several power of ten than those found from the figure of 10^{28} to 10^{29} mol/sec which I gave combined with the time scales in question. I mention this here because it means that the velocity field of the solar plasma is likely to be affected by a comet out to considerably larger distances, of the order of some 10^{10} or of 10^{11} cm [8].

With regard to the mechanisms of the interaction, there is one detail which I should perhaps mention; the exchange of charge in the presence of a magnetic field has the consequence that the whole plasma is slowed down. This is a point of view which has been emphasized recently by HARWIT and HOYLE [9]. One can immediately see the following: If only 1% of the solar protons exchange their charge with molecules, then the mass per particle is increased by something like 30%, assuming that CO or N_2 are typical molecules. If we allow for conservation of momentum, then of course the mass velocity of the plasma is reduced by at least 30%; in fact the reduction must be still larger [8].

I now pass on to some other possibilities of obtaining information about the interplanetary plasma; these are based on the polarization of the zodiacal light and on the influence of the interplanetary plasma on the appearance of radio point sources. The degree of polarization of the zodiacal light is of the order of several 10%. The polarization is partly caused by the electrons, partly by the small dust particles which scatter or reflect the solar light. Unfortunately it has turned out to be very difficult to separate the contributions from these two causes. For this reason all attempts to find values for electron density in interplanetary space from the zodiacal light observations have not led to a conclusive result other than just to indicate upper limits which are $\gtrsim$ 100 electrons per cm^3, according to some authors as large as several 100 cm^{-3}.

We turn now to the observations of radio point sources in the vicinity of the sun. Owing to the motion of the earth around the sun, it often happens that a radio point source can be seen at an angular distance of less than 20° or 30°. The apparent diameter is then regularly found to increase to values of the order of several minutes of arc.

One finds from these observations [10] that in the vicinity of the equatorial plane the appearance of radio point sources indicates the presence of scattering electrons out to distances of about 100 solar radii. The observations indicate furthermore that in the direction of the poles the influence of interplanetary electrons usually does not reach quite as far. It looks as though the surfaces of equal density of the scattering electrons are somewhat flattened, possibly in the ratio 4:3 approximately. This, of course, reminds us of the work on comets moving at high heliographic latitudes; there was also an indication that the intensity of the solar wind is possibly somewhat smaller above the polar regions of the sun as compared to the equatorial belt.

Unfortunately, the radio observations were made only over a limited period of time, three months or so; it would be very important to repeat them during the whole solar cycle just to see how the properties of the electronic component of the interplanetary plasma, as far as they can be derived from these observations, change.

Other observations of radio point sources have given indications of a filamentary structure of the scattering medium stretching out approximately radially; but again it is rather difficult to conclude more than that this observation again indicates the presence of scattering electrons and some such structures in their distribution.

From the radio observations it is not possible until now to derive a value for the density of the scattering electrons, but one can check whether the observations are consistent with the values of the electron density which one derives from the direct observations. This is indeed the case if we assume a value of the order of 10^1 cm^{-3} at the earth's distance from the sun outside the geomagnetic field.

Since unfortunately most direct observations were made in the transition region between the magnetosphere of the earth and interplanetary space, it might still turn out that the true value is somewhat higher than the 10^1 cm^{-3} usually given.

Most of the comments which might be made in connection with the theoretical schemes of PARKER and GOLD have perhaps been mentioned in my discussion. I think both are compatible with the comets' observations, though it is not possible to discriminate between the two. But I have found no simple way of connecting the comet observations with the picture proposed by Prof. ELLIOT. In closing I would like to draw attention again to the general disparity which appears to exist between the momentum flux of the solar wind and the energy density of the magnetic fields which under normal circumstances are likely to be present in interplanetary space. It is the momentum flux of the former which seems to dominate in the absence of special events.

REFERENCES

[1] S. Chapman and J. Bartels, *Geomagnetism*, 2 Vols. XXVIII, 1049, 1940.
J. Bartels, *FIAT Review of German Science*, *17*, Part. I Geophysics.

[2] L. Biermann and E. Trefftz, *The Solar System*. Vol. IV, Chapter 18, p. 618; ed. B. M. Middlehurst and G.P. Kuiper, 1963.

[3] E.N. Parker's contribution to this meeting, p. 207.

[4] P. Stumpf, *A.N.*, *286*, 87, 1961.

[5] H.E. Hinteregger, *J. Geophys. Res.*, *67*, 999, 3373, 1962.

[5a] L. Biermann and E. Trefftz, *Sitz. Ber. Bayer. Akad. Wiss.*, Febr. 1963; to appeat also in *Z. Astrophys.*

[6] P. Swings and J.L. Greenstein, *C.R.*, *246*, 511, 1958.

[7] P. Swings and Remy-Battiau, *Ann. Astr.*, *25*, 165, 171, 1962.

[8] L. Biermann, B. Brosowski, H.U. Schmidt, *Sitz. Ber. Bayer. Akad. Wiss.*, July 1962.

[9] M. Harwit and F. Hoyle, *Ap. J.*, *135*, 867, 875, 1962.

[10] O.B. Slee, *M.N.*, *123*, 223, 1961.

DISCUSSION

Chairman: B. Rossi

Singer

Could you detail the interaction between the solar plasma and the cometary plasma by way of magnetic fields? Would it be possible for you to draw the magnetic field structures as you see them?

Biermann

We need to be concerned only with the component perpendicular to the motion. We assume that the solar wind carries always some lines of force, which are embedded in the plasma, so that an observer moving with the plasma sees no electric field. If now by exchange of charge or by photo-ionization of cometary molecules we get molecular ions, we have a situation in which originally the solar ions and those of cometary origin have very different mass velocities. The time scale with which the two are coupled together is then of the order of the gyration frequency of the respective ions. That can be seen by applying the ordinary three fluid equations.

Singer

Then as I understand it you always require some perpendicular component of magnetic field to give you the coupling term.

Gold

I was intending to speak on just that point. If the field is rough, then I think the situation for the acceleration is much simpler; if one required always a normal component of the field, and the field were not rough, then of course the tail would take up only the normal component of the field. If the field is rough, then an ion generated within it has a high probability of being caught in the next mirror that comes along. The next contraction point in the uneven field will catch it and it will therefore have a large tendency to move in the direction of motion of the plasma, which appears to be usually radial to the sun.

Then I wanted to ask a question about how close to the sun can you make your limit on the co-rotation? You said that you could not have a co-rotation of the gas out here, or else the directions of tails would all be wrong, but could you have co-rotation at 1/4 AU?

BIERMANN

That is somewhat difficult to say. I do not recall any detailed study of how near to the sun there is reliable evidence on the direction of the tail, but certainly down to 0.5 AU one does have observations [1]. I am not sure whether there are good observations of comets nearer to the sun which could be used for this purpose.

As to the other point, I agree that the roughness of the magnetic field of course helps to couple them together, but I do not agree that if the fields were not so rough you would get a substantial angle. The disparity of the momentum flux which I drew attention to will in any case have the consequence that the tail plasma will have to move essentially in the direction of motion of the plasma itself, because the cometary ions form lumps of conducting matter which are so to speak thrown into the solar wind.

GOLD

I do not understand that last point. If I had a radial field, then I have no effect at all in the smooth case; if I have a field which

---

(1) C. HOFFMEISTER, *Z. f. Astrophysik*, *22*, 265, 1943.

is wound up into an Archimedes spiral, then I will have an effect all right in the equatorial plane but I will have the wrong direction for any components out of the plane.

BIERMANN

The mass of cometary origin set into motion is relatively large. The lines of force of the magnetic field connected with the solar matter would then be affected roughly as for instance in the scheme which a number of years ago was proposed by ALFVÉN. Irrespective of the detailed scheme, any sort of irregularity, also of the mass distribution, which reacts on the magnetic field, will always serve to bring about some effect similar to the one which you have described.

ELLIOT

Prof. BIERMANN mentioned the incompatibility between the idea of a radial streaming field and the picture which I have advocated from time to time. I would like to say, however, that I have never disputed that the field is from time to time radial; indeed I have said so. The point at issue is whether or not there is a long time average component which is perpendicular to the plane of the ecliptic. Now I agree with you that as the solar wind becomes smoother, more comprehensive both in space and time, so it is harder and harder to believe in the plausibility of such a component, unless one has some kind of effect like the shredding of the external field by the outward streaming plasma. In fact, since the plasma has a high conductivity, any field which it did not contain at the beginning will tend to avoid it from then on. The external field would not penetrate into it, so that there is the possibility of a plasma moving outwards through substratum of field with a direction perpendicular to the plane of the ecliptic. This would mean, of course, that the wind itself had structure, and you would see it shredded in this way. Is that not perhaps what your comet tails show?

BIERMANN

In which respect do you see a confirmation of your picture from the comet's observation? I have not quite got this point.

ELLIOT

I did not intend to say that! I didn't see any confirmation. What I am saying is that if one has a large-scale steady streaming outwards of solar material which takes place all the time without pause, then the only way that I can see that this could be compatible with a field having an appreciable component perpendicular to the plane of the ecliptic would be that the wind was divided up in space into regions where it flowed and regions where it avoided the external field. This is perhaps not too inconsistent or incompatible with the pictures Prof. GOLD just showed us of comets with rather well defined streamers.

BIERMANN

That is a possibility which perhaps cannot be strictly excluded.

ELLIOT

But it is one which should be resolved quite soon when we know a little bit more about the structure of wind.

GOLD

I have one other point I forgot to make. The fact that the mass put into the field by the comet is quite significant, as you say, has of course the effect, since the stagnation pressures tend to be larger than the field in the first place, of making the field locally stronger than it was before. In the discussion I gave the other day, we considered the case of piling in the field on the surface of the moon, where it is stuck in the hard material and you cannot move it. But if you pile in the field into a gaseous body which cannot resist being taken apart, then it must have the effect of putting extra magnetic field pressure into the head of this comet, which will therefore tend also to take it apart sideways. I think that is the reason for seeing, as one clearly did on some of the pictures, that the tail is spreading and has individual streamers going off at some substantial angle from the mean direction. The fact that you have extra magnetic pressure piled into the head will mean that that will serve to give a divergence to the tail as the material is picked up.

BIERMANN

I believe the picture which you propose here is largely that one discussed by HARWIT and HOYLE (2). There are certain reasons why I hesitate to commit myself to this; part of these are connected with the time scale of the ionization — a subject which I intentionally left out of the discussion. The observational fact is that the structures which then develop into streamers are often produced in a time scale of the order of some 10^3 or 10^4 seconds only; that is hard to account for if the density of the solar particles is not higher than it is now accepted. HARWITT and HOYLE thought that the piling up of the solar material in form of the comet would lead to a local increase of the density with the result that one would have a shorter time scale than in free interplanetary space. Our own subsequent work has not confirmed the HARWIT-HOYLE point of view in this detail; it turns out that one gets a similar situation as in a fast shock, in that even with infinitely large Mach number you do not get a very large increase of the density. It is still doubtful therefore, whether one gets thereby a sufficient change of the time scale of ionization.

GOLD

The only statement I am making is that extra magnetic pressure will in any case be available for spreading out the tail.

---

(2) *Ap. J.*, *135*, 867, 875, 1962.

BIERMANN

I agree with you as far as that goes, but I wish to say that there are certain features of the situation (limiting the applicability of simple arguments based on the balance of momentum) which I intentionally left out of the discussion today because it would lead us too far away from our proper subject. Further work on those questions will appear in due course in Z.f. Astrophysik (see references [8]).

SINGER

You mentioned during your talk that the momentum flux of 10^{-8} dyn/cm^2 was adequate to produce the observed accelerations. I wonder if you could give some estimate as to what would be the *minimum* momentum flux which could produce the accelerations? I gather that 10^{-8} is more than adequate.

BIERMANN

That is somewhat difficult to do. If you just have to accelerate the matter which is visible in the form of CO^+, one could simply write down the local balance of momentum; that of the solar wind with a momentum flux of some 10^{-8} dyn/cm^2 should be adequate, though not by a very large margin. But we should also expect some transfer momentum from the side to the main body of the tail; actually a velocity field of the solar plasma will exist around the comet such that — as I said earlier — we have the full velocity only at some fairly large lateral distance (of the order of 10^{11} cm). While this makes the physical situation somewhat complicated, it helps of course to accelerate the tail plasma with a fairly low over-all flux.

SINGER

The other point I have some difficulty with is to understand why the direction should be so precisely radial when the comet is at large solar latitudes. Is not the outflow of gas from the sun controlled by the magnetic field structures we have been talking about in connection with the cosmic ray events? The main magnetic field certainly is not radial.

BIERMANN

Comets which move at a rather high angle to the ecliptic plane can usually be well observed. As far as I recall, to the first approximation, that is within a few degrees, one observes the tail having the radial direction.

PARKER

If you write down the hydrodynamic equations and put in the magnetic fields that one normally believes in, such as one gauss near the sun and a few γ far out in space, you find that the motion of the expanding corona, except perhaps very near the sun, is within a few degrees of being radial, regardless of the magnetic field structure at the sun.

BIERMANN

What is observed on the comets agrees exactly with what you expect from the theory.

ROSSI

Is not this because the energy density of the magnetic field is small compared with the kinetic energy density of the plasma?

PARKER

That is right. Anywhere beyond about fifty solar radii the magnetic energy content is very small compared to the kinetic energy density of the solar wind.

SIMPSON

Have there been any observations of comet tails following large solar bursts? The reason I ask is that, for example, in November

1960 events there was not only the low energy plasma flow (solar wind) and magnetic field changes, but also there were the higher energy protons with a total flux of about 10^9.

BIERMANN

I recall an event connected with the comet Whipple-Fedtke of 1942 which, however, was mainly visible in the early months of 1943. On March 29, 1943, there was a good sized geomagnetic storm, the largest for a fairly long period of time; this event was clearly visible in the comet tail, the structure of which was entirely unusual on that date. A similar event was seen only once before in this comet, just about one solar rotation prior to March 29, such that it looked as though there was a longer-lived active M-region. In these two cases the tail looked conspicuously turbulent, as may be seen from the pictures obtained at the Sonneberg Observatory (3).

In that case the general level of solar activity was low. The angle between the comet and the earth, as seen from the sun, was within 20° or so.

(3) *Z. f. Astrophysik*, 22, 305; 23, 8, 1943-44

HIGH ENERGY ELECTRONS IN INTERPLANETARY SPACE

S. HAYAKAWA
Physical Institute, Nagoya University - Nagoya - Japan

Abstract — Cosmic electrons of relativistic energies are expected to be produced by the collisions of cosmic ray particles with interstellar matter. Recently we have calculated the energy spectrum of the electrons down to 10 MeV on this hypothesis and found it to be not inconsistent with recent observations. If, however, various effects operative in interplanetary space are taken into account, the observed intensity of electrons should not in general be in agreement with the calculated one because of the following reasons.

The solar modulation cuts down the substantial part of electrons with energies lower than several GeV. Hence the intensity observed should be lower than the one calculated for the galactic space. This negative effect may be compensated, at least in part, by the following positive effects.

Firstly, albedo electrons are mixed to the primary ones near the cut-off energy. Secondly, there may be a contribution of electrons accelerated together with protons and heavy nuclei. Thirdly, as a special case of the second source, electrons produced by solar outbursts may also contribute to primary electrons.

These positive and negative contributions will be estimated semi-quantitavely by reference to various related phenomena including solar radio outbursts. Possible methods for investigating these effects will also be discussed. Finally it will be emphasised that observations of cosmic electrons will provide an important means to investigate not only the galactic origin of cosmic rays but also some properties of the interplanetary space.

1. Introduction

It has been well known that the primary electrons in cosmic rays have important implications in the Galactic origin of cosmic rays and in radioastronomy. In this report we discuss their importance also in the cosmic radiation in the interplanetary space. There are two main points which our discussions are concerned with. One is the interplanetary modulation and the other the solar production. Although both problems have been well investigated with protons and heavy nuclei, their effects on electrons do not only supplement our knowledge obtained by means of nuclear particles but also provide some new information which may otherwise be hardly obtained.

The modulation cuts down the Galactic electron intensity below a few GeV by a considerable factor, so that recently reported observations [1], [2] seem to give too high intensities to be accounted for in terms of the secondary electron hypothesis. According to this hypothesis, the electron spectrum can be predicted free from the ambiguity in the low energy part of the proton spectrum which is subject to considerable modulation. Therefore, the electron spectra in different periods would give us the modulation factors, if the secondary electron hypothesis were taken for granted.

The solar production of electrons is expected from the radio outbursts which are believed to be due to the synchrotron radiation. It has been pointed out by Gold [3] that these electrons responsible for the radio outbursts should survive against the radiation energy loss and would be observed together with solar protons. In fact, a recent observation by Meyer and Vogt [4] has detected such electrons after solar flares in July, 1961. Since the mass of the electron is much smaller than that of the proton, it is interesting to ask the mass dependence of the acceleration efficiency; this is not easy to see from the observation of heavy nuclei, mainly because the degree of ionization may change in the course of acceleration. If there are a considerable amount of electrons emitted from the sun, they may be trapped in the solar system, so that they contribute to the primary electrons even without association of solar flares, just as in the case of the solar component of protons [5].

Although electrons responsible for the radio outbursts are thought to be accelerated primarily, a possibility that they are the secondary products of protons has to be examined, especially for their high energy part. The relative importance of primary and secondary electrons is also an important question about Galactic electrons. This can be answered by observing the relative intensities of negatons and positons, because the latter are expected only in secondary electrons. The feasibility of distinguishing negatons and positons with the aid of the geomagnetic effect is discussed by reference to the recent work by OKUDA [6].

2. GALACTIC ELECTRONS UNDER THE SECONDARY ELECTRON HYPOTHESIS

The intensity of Galactic electrons expected under the secondary electron hypothesis has been given by many authors. Here we refer to our own calculation [7] which is mainly concerned with the low energy part of the electron spectrum.

If we pay attention to those electrons which have energies smaller than a few GeV, their intensity and energy spectrum are approximately given by

$$j\,(E)\,dE = (T_e/T_c)\,s(E)\,dE \qquad (2.1)$$

because the energy loss due to the synchrotron radiation and the inverse compton effect is negligible. s(E) dE is the source energy spectrum of electrons and can be calculated rather unambiguously by referring to the energy spectrum of nuclear particles and their pion production cross section at high energies. T_e is the mean lifetime of the electrons in the Galaxy and is supposed to be practically independent of energy at such low energies. T_c is the collision mean lifetime of nuclear particles with interstellar matter. Here we take

$$T_e/T_c = 0.06 \qquad (2.2)$$

for definiteness. Since T_c is expressed as

$$T_c = \lambda/\rho c$$

where λ is the collision mean free path, ρ the average density of interstellar matter and c the velocity of cosmic ray particles, our choice of (2.2) corresponds, say, to

$$\lambda = 50 \text{ gcm}^{-2}; \ \rho = 3 \times 10^{-26} \text{ gcm}^{-3}; \ T_e = 3 \times 10^{15} \text{ sec.}$$

The differential energy spectrum of electrons thus obtained is shown in Fig. 1, in which its high energy part is also shown by taking the energy loss processes into consideration. In the same figure the spectra of positons and negatons are given separately. Their intensities are nearly equal above 1 GeV, whereas the positon excess becomes apperciable at low energies, simply because protons are more abundant than neutrons in the nuclear particles and the multiplicity of pions is low.

The intensity and the energy spectrum of electrons given in Fig. 1 are not inconsistent with the evidence of general Galactic radio emission. Therefore, the secondary electron hypothesis as well as the values of the parameters chosen may be regarded as not far from reality. As is common to any theoretical prediction concerning the origin of cosmic rays, however, the absolute value of the electron intensity calculated cannot be accurate, say, within a factor of two, although the

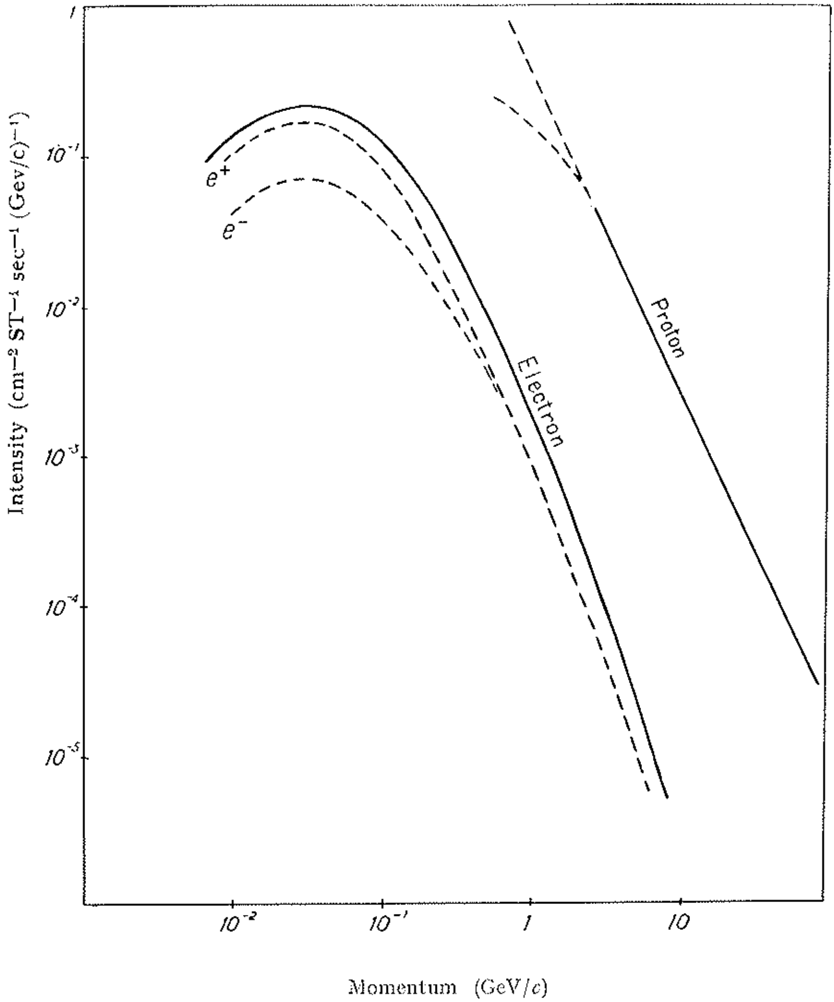


FIG. 1 — Differential momentum spectrum of « secondary » electrons. Proton: The spectrum of protons responsible for the production of electrons; e^+: The spectrum of positons; e^-: The spectrum of negatons.

shape of the spectrum is rather reliable. Hence the secondary electron hypothesis will have to be tested by comparing the relative intensities of positons and negatons, because electrons primarily accelerated are supposed to be negatons.

One of the possible methods for this purpose is the observation of the azimuthal dependence of the electron intensity. Since the azimuthal dependence practically disappears at too high latitudes, this method is applicable only at intermediate latitudes, namely for electrons of energies at several GeV. In this energy region the secondary hypothesis predicts the nearly equal intensities of positons and negatons. If this were the case, no azimuthal dependence would appear. Therefore, the azimuthal dependence will indicate the relative intensity of « primary » electrons which are assumed to consist exclusively of negatons.

On the basis of the primary electron hypothesis, in which the electron intensity given in Fig. 1 is assumed for convenience as due entirely to negatons, the azimuthal dependence at zenith angle 60° is shown in Fig. 2 [6]. On calculating this the cut-off rigidities predicted by STÖRMER's theory for the dipole field are adopted, because a more elaborate calculation by SCHWARZ [8] gives the azimuthal dependence of cut-off rigidities at latitude 40° very close to the one obtained by STÖRMER's theory. The azimuthal dependences at five latitudes given in Fig. 2 will be good enough for giving an idea on the feasibilities of such experiment.

Since no information on the « primary » electrons is yet available, our discussions in what follows will be based on the secondary hypothesis, taking it into consideration that any deviation from the secondary hypothesis will imply some indication of modulations or additional sources.

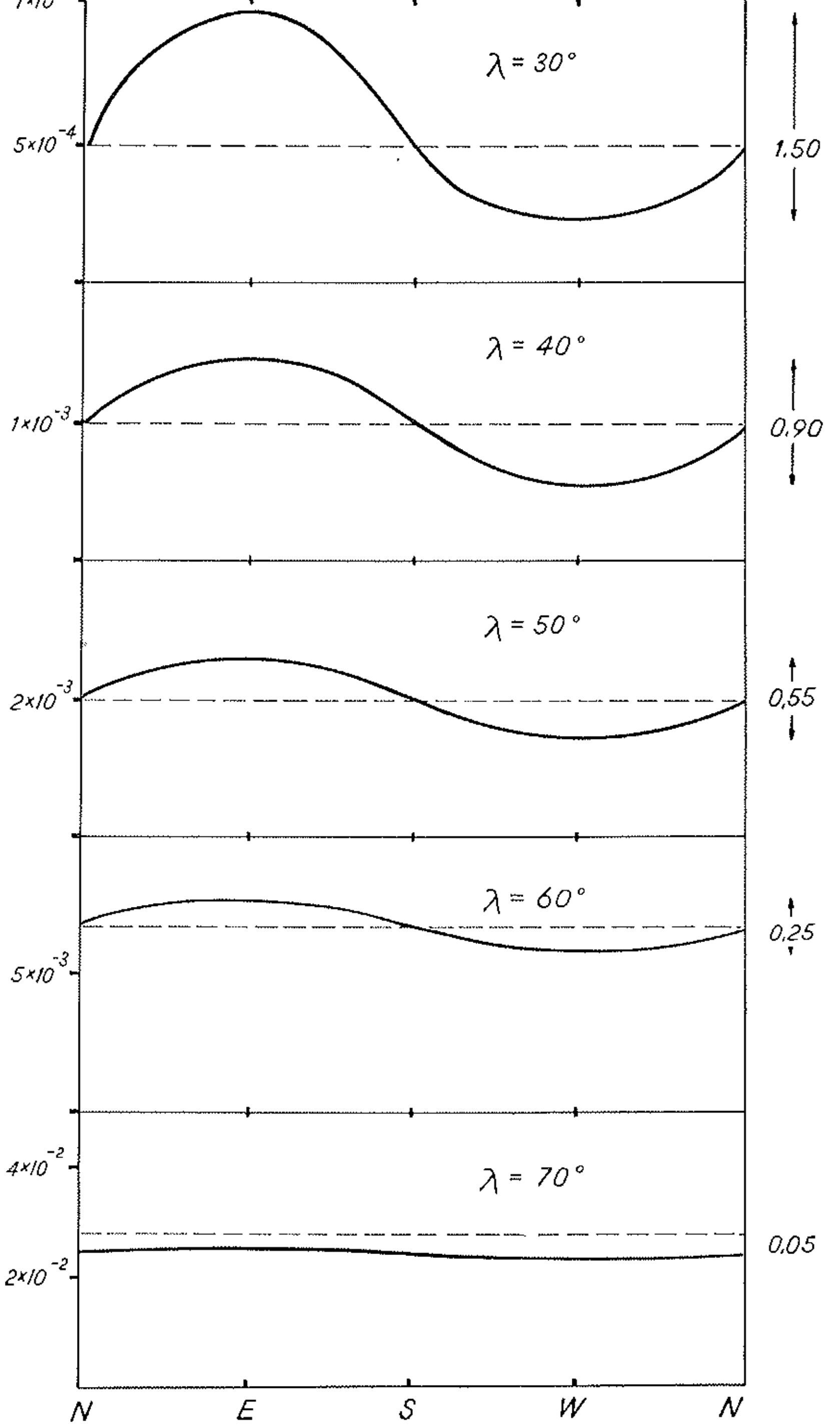


FIG. 2 — Azimuthal dependence of electrons at zenith angle 60°. Solid line: Negatons only; Dashed line: Equal amounts of positons and negatons. The electron intensities relative to the proton intensity are scaled in the left ordinate and the amplitudes for negatons alone are indicated in the right ordinate.

3. Interplanetary modulation

The variation of the energy spectra of protons and heavy nuclei is known to take place in connection with solar activities. If we consider the 11-year variation, the spectra have been well observed during the last solar cycle [9]. On deducing the modulation mechanism on the basis of these observed spectra, a difficulty lies in our ignorance on the unmodulated spectrum, since the modulation seems to be effective even in the calmest period of the sun. If, however, one refers to the electron spectrum, one would be able to obtain unambiguous information on the modulation, provided that the electrons to be observed were mainly of secondary origin.

The argument for this goes as follows. The secondary electrons in the low energy region are produced by nuclear particles of high energies, at which the modulation is unimportant. Therefore, the electron spectrum shown in Fig. 1 shows the unmodulated one, so that any difference of observed ones from it would indicate the absolute magnitude of the modulation factor.

As an illustration, we draw modulated electron spectra in Fig. 3. Here the integral spectra are compared because of their direct connection with observations. The modulation factor is assumed to be the ratio of an observed proton intensity to the extrapolated one. The extrapolation is made from the proton spectrum at high rigidities to lower values with the same power shape, *i.e.* $0.4\ p^{-1.25}\ cm^{-2}\ sr^{-1}\ sec^{-1}$, where p is in units of GV [9]. If this modulation factor is used, the electron intensity below 1 GeV is greatly reduced, as shown in Fig. 3. The observed intensities [1], [2] then turn out to be much higher than the modulated intensity. This illustration indicates how sensitive the electron intensity is to the modulation.

The discrepancy may be attributed to the following causes.

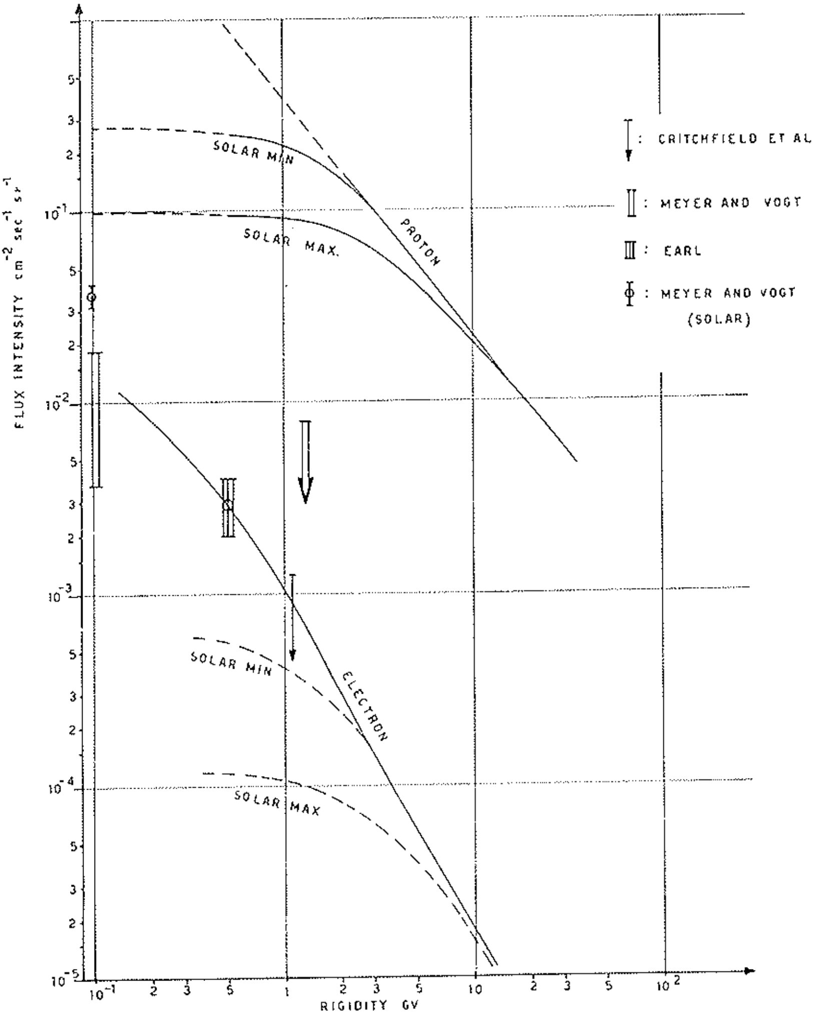


FIG. 3 — Integral rigidity spectra of protons and electrons, the solar modulation being taken into account. Experimental results are compared.

1) The modulation factors employed are too large due mainly to the error in the unmodulate proton spectrum; it may be smaller than the extrapolated one. 2) The « primary » electrons contribute significantly and preferentially to a low energy part. 3) The contribution of solar electrons is significant, preferentially again at low energies. 4) The observed electrons involve a considerable amount of albedo electrons [10]. All these effects are likely to co-exist and the separation between them does not seem to be possible at present. Among them, however, 1) and 3) are common in their nature and both contribute to the negative excess of electrons. Since 3) will be better known in relation to various solar phenomena, we shall discuss this problem in the next section.

4. Electrons accelerated at the sun

Some types of the solar outbursts of radio waves are believed to be due to the synchrotron radiation of electrons. It may be convenient for later discussions to summarize a number of important consequences of the synchrotron radiation theory.

If the electron spectrum is assumed to be of a power shape

$$N(E)\,dE = \alpha\, N_o\, (E_o/E)^{\alpha}\, dE/E, \qquad (3.1)$$

where E is the total energy of an electron, the radio spectrum observed at the earth is given by [11]

$$I(\nu) = 6.0 \times 10^{-52}\, f(\alpha)\, B_{\perp}\, N_0\, (\nu_0/\nu)^{\alpha/2}\, Wm^{-2}(c/s)^{-1} \qquad (3.2)$$

where f(α) is a numerical factor close to unity for a reasonable values of α. $B_{\perp}$ in gauss is the average magnetic field strength perpendicular to the velocity of electrons. The relation between an electron energy and a radio frequency can be seen from the most probable frequency emitted from an electrons of energy E

$$\nu_m = 1.4 \times 10^6 \ B_{\perp} \ (E/mc^2)^2, \ c/s \qquad (3.3)$$

where m is the electron mass. The half-life of electrons against the synchrotron radiation is given by

$$T_{1/2} = 0.51 \times 10^9 \ (mc^2/E) \ / \ B_{\perp}^2 \ \text{sec.} \qquad (3\text{-}4)$$

For the lifetime of electrons we have also to take the inverse Compton effect into account. This is as effective as the synchrotron radiation for the energy loss, so that

$$T_{1/2} \ (\text{Compton}) \approx 0.5 \times 10^9 \ (mc^2/E) \ \text{sec.} \qquad (3.5)$$

at the solar surface, but the scattered photons lie mainly in the soft X-ray region.

The relation between radio outbursts and high energy electrons has been analyzed by various authors in considerable details, among them by TAKAKURA and KAI [12] paying particular attention to the microwave burst. However, the correlation with the solar proton production is found better for the meter wave outburst [13], which may be called the type IVm [14]. Indeed, the source of type IVm bursts seems to extend as far as several solar radii and there may, therefore, be a high probability of association with particles emitted in the interplanetary space. Here we are mainly concerned with type IVm outburts and consider the properties of electrons injected.

First of all, as was pointed out by GOLD [3], we show that electrons responsihle for type IVm outbursts can survive for a long time after they are accelerated. Since the magnetic field strength high in the solar corona may be as low as 1 gauss, a representative frequency of $\nu \sim 10^8$ c/s corresponds to an electron energy of about 5 MeV. The half-life of the electron in this case is, according to (3.4), and (3.5) as long as one year. Even an electron of 1 GeV can survive as long as a day, whereas an outburst continues for the order of an hour. If the field strength is taken as high as 10 gauss, electrons of energies below 100 MeV can still survive without appreciable energy loss. Moreover, the energy decreases inversely proportionel to time and consequently even after ten times the half-life an electron of high initial energy may have a non-negligible energy. Once electrons are injected in the interplanetary space, their energy loss is negligible even for multi-GeV electrons, because the field strength is rarely greater than 10^{-4} gauss.

Next we compare the radio intensity of type IVm bursts. If we take $I(\nu) \sim 10^{-19}$ Wm^{-2} $(c/s)^{-1}$ as a representative value, the number of electrons responsible for the radio emission is obtained as

$$N_o \sim 10^{32} \tag{3.6}$$

This is not much different from the number of protons produced by a solar outburst. However, the energies of a proton and an electron emitted are different. The former may be of the order of 100 MeV, whereas the latter is on the average only several MeV, as expected from (3.3). If one observes protons and electrons in the same energy range, the intensity of protons may be much greater than that of electrons. This seems to be a reason why one has rarely observed solar electrons.

Recently electrons which are likely to be of solar origin have been observed [1]. Their intensity is higher than the normal electron intensity and their integral energy spectrum is represented by E^{-2} between 100 MeV and 1.3 GeV as indicated in Fig. 2. This seems to be associated with solar flares in July, 1961. Although no proton data at high altitudes are yet available, the proton intensity seems to be as small as in an event on Sept. 3, 1960, on account of the neutron data obtained at

Deep River [15]. In the September event the proton intensity of rigidities above 10 MV is about 10 cm^{-2} sr^{-1} sec^{-1} and the rigidity spectrum is slightly less steep than the electron spectrum in the July event. If these intensities are compared around 300 MV, the electron intensity is smaller by a factor of about 300. If we extrapolate the electron spectrum towards low energy with the same power shape, the electron intensity at about 10 MV would be as large as the proton intensity at about 300 MV. The shift of rigidity by a factor of several tens is in agreement with the general consideration given above.

A similar argument may apply for electrons in quiet periods. According to VOGT [5], protons which seem to be of solar origin are found to be stronger than Galactic protons below several hundreds of MV. Their intensity is only slightly higher than the electron intensity observed by VOGT and MEYER [2] in quiet periods and the same amount of rigidity shift as above would give too low an intensity of electrons. If, however, we consider a possibility of the contribution of albedo electrons, the difference would be greater. Therefore, a significant part of the electrons observed may be of the same origin as the low energy protons.

Although no quantitative conclusion can be drawn from these data, the above discussions seem to provide the evidence that electrons are injected from the sun together with protons and their intensities are of the same order of magnitude if rigidity is shifted by a factor of several tens. This factor seems to be nearly equal to the square root of the mass ratio of the proton and the electron, which is equal to the ratio of momenta of the proton and the electron in a thermal equilibrium. If thermal protons and electrons are accelerated by magnetic pumping, their momentum ratio will remain as it is.

It may be interesting to check this hypothesis by comparing the relative abundances of heavy nuclei from the sun. In the November 1960 event the above relation seems to held, while heavy nuclei are underabundant in the September 1960 event [16]. Since the September event is of rather small scale, it may be possible that the ionization of heavy atoms did not proceed fast enough, so that their effective charge to mass ratio could have been small.

Now we come back to the second point 2) mentioned towards the end of Sect. 3. It is quite likely that other cosmic ray sources eject electrons just like as in the case of solar outbursts. For example, electrons in the Crab Nebula possibly escape to the outer space [11]. If the intensity of such electrons is that expected from the rigidity shift, it turns out to be about the same order of magnitude as the intensity of secondary electrons above a few hundred MeV and would be greater at lower energies. This does not conflict other evidences now available and will be an interesting problem to look for in more detail. In this connection, we again emphasize the importance of observing the charge of electrons.

REFERENCES

[1] J. EARL, *Phys. Rev. Lett.*, *6*, 125, 1961.

[2] R. VOGT and P. MEYER, *Phys. Rev. Lett.*, *6*, 193, 1961.

[3] T. GOLD, *Space Res.*, *11*, 828, 1961.

[4] P. MEYER and R. VOGT, *Phys. Rev. Lett.*, *8*, 387, 1962.

[5] R. VOGT, *Phys. Rev.*, *125*, 366, 1962.

[6] N. OKUDA, *Rep. Ionosph. Res.* 1963, in press.

[7] S. HAYAKAWA and N. OKUDA, *Progr. Theor. Phys.*, *28*, 517, 1962.

[8] M. SCHWARTZ, *Nuovo Cim.*, *11*, 27, 1959.

[9] F.B. MCDONALD and W.R. WEBBER, *Phys. Rev.*, *115*, 194, 1959; *J. Phys. Soc. Japan*, *17*, Suppl. A II, 428, 1962.

[10] G. and C. OCCHIALINI emphasized this point so that the point observed by EARL [1] may be reduced by a factor of three and a greater reduction factor may be applied for the points by VOGT and MEYER [2].

[11] V.L. GINZBURG, *Progress in Elementary Particle and Cosmic Ray Physics* IV, North-Holland Publ. Co., 1958; S. HAYAKAWA, K. ITO and Y. TERASHIMA, *Progr. Theor. Phys.* Suppl. *6*, 1, 1958.

[12] T. TAKAKURA and K. KAI, *Publ. Ast. Soc. Japan*, *13*, 94, 1961; T. TAKAKURA, *J. Phys. Soc. Japan*, *17*, Suppl. A II, 243, 1962.

[13] S. YOSHIDA, private communication.

[14] Here we refer to the nomenclatures and general features summarized by J.P. WILD, *J. Phys. Soc. Japan*, *17*, Suppl. A II, 249, 1962.

[15] H. CARMICHAEL, *Space Science Rev.*, *1*, 28, 1962.

[16] E.P. NEY and W. STEIN, *J. Phys. Soc. Japan*, *17*, Suppl. A II, 345, 1962.

DISCUSSION

Chairman: B. Rossi

NEY

I think that the point of view that Dr. HAYAKAWA takes about the electrons is quite different from the one that STEIN and I have worked out. In particular I feel that the low energy electrons that Dr. HAYAKAWA would like to have in low magnetic fields are a kind of residue left over from the electrons that are accelerated together with the protons. The radio emission from these electrons lasts for hours after the flare. What STEIN and I considered was the radio emission that occurs during the flash phase of the flare when it is quite clear that the protons are being accelerated; we claim that the same number of electrons as protons, and with the electrons at hundreds of MeV in fields of several hundred gauss, will account for not only the radio emission but also the white light from the flare. One could not possibly get white light from electrons of 10 MeV in a field of a few gauss. The other point is that I believe the energy spectrum of the electrons, which Dr. HAYAKAWA has, will just not give the right radio frequency spectrum. What one observes in the flash phase of the flare is that the higher the frequency the higher radio wave energy goes up, whereas any power law spectrum makes the slope of the radio spectrum opposite. This is the reason we were led to a monoenergetic or exponential rigidity spectrum of the electrons in high magnetic fields and with relatively high energy electrons.

HAYAKAWA

I think Dr. NEY's comment cleared up the difference between two points of view. We have dealt with different things for different purposes.

SIMPSON

There are two experimental points that are clear from the measurements of MEYER and VOGT. One is the observation of a 40% decrease in electron intensity during the Forbush decrease of 3 September 1960. These results would be most simply explained as solar modulation of galactic electrons. But there still remains open the question of whether these were stored solar electrons that have been swept away suddenly during the event itself through the intervention of magnetic fields. The second point is based upon some unpublished results for 1962. They find that following a solar flare in July 1962, they obtain 3 electrons per 100 protons for particles of rigidity greater than 350 MV. This is a preliminary result, but it seems to be firm.

HAYAKAWA

May I ask if the July 1962 event was similar to that in last year? The electron intensities in these two events appear to me nearly the same.

SIMPSON

I do not have the numbers here at the moment to compare, but they are not greatly different.

VALLARTA

In the Störmer theory one does not have a north-south asymmetry because the Störmer cone is a circular cone with the axis along the east-west line; but in the theory of the allowed cone one does have a north-south effect. Now the interpretation of the north-south effect is difficult both from the experimental and theoretical points of view, because experiments have to be made at very high zenith angles and therefore the statistics are usually poor. There are a few experiments on the north-south effect. The interesting point that I want to bring out is this: if one compares the north-south effect with the east-west effect, then one comes out with just about the same results as have been obtained experimentally by MEYER and VOGT and by EARL. The north-south effect depends upon the sum of positives and negatives, the east-west effect depends upon their difference, and by comparing these two one can calculate the percentage of positives and negatives. Although this does not seem to be very significant I think it is worth mentioning.

REVUE SYNTHETIQUE DES TRAVAUX ET DES DISCUSSIONS

REVIEW PAPER I

NATURE, FLUX AND ENERGY DISTRIBUTION OF COSMIC RAY PARTICLES IN INTERPLANETARY SPACE

B. PETERS

Institute for Theoretical Physics - University of Copenhagen
Copenhagen - Denmark

The papers presented during this Study Week were excellent reviews of particular aspects of the problem of cosmic radiation in interplanetary space. To make a summary of these papers again, and necessarily in an abbreviated form, could hardly add to their value. Instead, I shall try to summarize by comparing the picture as it was presented in the course of this week with the state of knowledge as it existed just one year ago at the time of the International Cosmic Ray Conference in Kyoto. What new information has appeared since then and what new interpretations of the data have been attempted? I shall confine myself to questions which are related to the nature, the flux, and the energy distribution of the particles which are present in the interplanetary space. Questions connected with the influence of interplanetary plasmas and fields on these particles will be treated by Prof. ELLIOT, and the problem of the radiation belts will be discussed by Prof. SINGER.

1. EXTENSIVE AIR SHOWERS

One of the important new developments which have occurred since the Kyoto Conference is the completion of the

Chacaltaya Laboratory which has gone into operation recently and has already produced results. For the first time, one has an opportunity to carry out large air shower experiments at such great height, namely under a thickness of atmosphere exactly half way between sea level and outer space. Although the results are still preliminary, they are of considerable interest.

One of the observations reported by Prof. ESCOBAR exhibits the existence of a fairly sudden break in the integral shower size spectrum, leading to a change in the exponent of the appropriate power law from 1.4 to about 2.0. It occurs at a shower size which corresponds to a primary proton energy of about 2×10^{15} eV. This represents confirmation for the reality of a phenomenon which had been observed previously at lower altitudes only and has been reported with a gradually increasing amount of supporting evidence in 1959 at the Cosmic Ray Conference at Moscow and in 1961 at Kyoto. How should this phenomenon be interpreted? Does it represent a sudden change in the nature of the primary spectrum or a change in the nature of nucleon-nucleon interactions at very high energy?

At Kyoto it was suggested that this very steep region of the spectrum is again followed, at still greater shower size, by a flatter portion. Also at M.I.T., if I remember correctly, it was found that in the region of the very largest showers the spectrum follows a power law characterized by an exponent which is less than 2. If it is correct that this steepest portion is confined to an intermediate region of the shower size spectrum, it is almost certain that one has to ascribe it to an irregularity in the primary cosmic ray spectrum.

If one attributes the break of the spectrum to the fact that some primaries above the appropriate energy are lost because they can escape across a magnetic rigidity barrier located either in one of the accelerating sources or in some region of interstellar space, then it follows that, in the part of the spectrum which is affected by this barrier, there occurs also a fractionation, *i.e.* a change as a function of total particle energy in the chemical composition of the radiation. In this region of shower size where the spectrum is steep, it becomes therefore especially important to study all those features of air showers which depend on energy per nucleon rather than on the total energy of the primary. Such features are, for instance, the absorption coefficient of the shower core, barometric effects, zenith angle dependence of shower size, the fraction of the nuclear-active particles and μ-mesons among the shower particles, their energy spectra etc.

Another result of great interest, which may have a direct bearing on this question, was also reported by Prof. ESCOBAR. In the air showers observed at Chacaltaya, fluctuations in the ratio of μ-mesons to electrons are surprisingly small, smaller by at least a factor 3 than the fluctuations observed at lower altitudes.

Only a slight reduction is to be expected if one attributes the fluctuations in the ratio μ/e to variations in the atmospheric depth at which the incident primary suffers its first collision. A reduction of fluctuations by a factor 3 seems too large to be explained in this manner, and one might ask whether this phenomenon is not related to the observation of the increased steepness of the primary rigidity spectrum. For a given magnetic rigidity of the primary particle, the larger the atomic number, the larger the shower; therefore a steepening of the rigidity spectrum must lead to an increase in the average weight of the shower primaries, which in turn must lead to a strong decrease of fluctuations. For instance, if one substitutes α-particles for proton primaries, one reduces fluctuations in the ratio μ/e by a factor 2, since one is now dealing with the superposition of four identical nucleon-induced air showers. Thus, the observed radical reduction in the μ/e fluctuations could well be a consequence of the steepening of the magnetic rigidity spectrum and the resultant change in the composition of the air shower producing primaries.

2. Galactic γ-rays

Another recently discovered phenomenon is the occurrence of air showers which do not contain μ-mesons, or at least a much smaller fraction than ordinary showers. It is not easy as yet to decide whether these showers without μ-mesons are due to primary γ-rays or to fluctuations in the interaction products of incident nucleons. Protons making a glancing collision can be raised to an isobaric state, and may decay by emitting a neutral pion in the forward direction. This is a frequent process at lower energies ($\sim$ 25 GeV). It may also occur at very high energies, in which case a transfer to a single π^0-meson of up to 70% of the primary energy is a simple consequence of the kinematics of the process. Air showers initiated in this manner must exhibit very low μ/e ratios. Nevertheless, it is quite possible that some of the μ-meson free showers are not of this type and that one has begun to observe pure γ-ray induced air showers.

Here I would like to remind you of the interesting calculations reported by Prof. Hayakawa, who showed that if the air shower primaries with energy $\gtrsim 10^{17}$ eV are extragalactic protons, then very energetic γ-rays will be produced mainly by collision with star light. One expects then a ratio of γ-ray to proton induced showers of $\sim$ 0.2%. This is rather high and perhaps measurable. The calculations can be made fairly reliable because they are independent of the rather uncertain gas density between galaxies and instead dependent on the less speculative value of photon density between the galaxies. There exists therefore a promising experimental test for the hypothesis that cosmic rays of energy above 10^{17} eV consist predominantly of extragalactic protons.

Turning now to γ-rays of somewhat lower energies, I just would like to point out that although we have no new data on γ-rays from the galaxy since the Kyoto Conference, we do have a somewhat better understanding of the various ways in which the γ-rays observed by KRAUSHAAR and CLARK could be accounted for. Prof. HAYAKAWA has contributed to this by adding a new calculation, in which it is assumed that these γ-rays come, not from intergalactic space, but from galaxies, particularly from the radio galaxies. Assuming that cosmic radio noise is due to synchrotron radiation of electrons which are secondary to nuclear interaction, *i.e.* descendants of $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$ decays, the corresponding π^0 production was calculated and averaged over 10^{10} years, a number characteristic of the age of the galaxy. It appears that such a model can give a γ-ray flux of the right order of magnitude. One has here one more possibility, but the true origin of the γ rays observed by KRAUSHAAR and CLARK cannot be definitely established at this point.

3. COSMIC RAY ELECTRONS

We turn now to the problem of electrons in the primary radiation near the earth. The main change in the state of this problem seems to be that one has succeeded in formulating somewhat sharper the difficulties which one faces when trying to interpret experimental observations. Prof. HAYAKAWA has compared the flux of incident electrons, as measured by EARL and by MEYER and VOGT, with the galactic flux of electrons estimated either on the basis of radio emission or on the basis of pion production by nuclear collisions in the interstellar gas. He suggests that after making a reasonable allowance for the reduction of interplanetary electron flux by the solar wind, one expects near the earth fewer electrons of energy close to ~ 1 GeV than are actually observed. Therefore, the measured flux contains presumably also electrons which do not arise from $\pi - \mu - e$ decay in the galaxy.

This raises a question which no doubt will dominate research in this field during the coming years, namely how to distinguish the four different contributions to the expected electron flux:

a) electrons resulting from nuclear collisions in the galaxy;

b) primary electrons accelerated in cosmic ray sources in the same way as nucleons;

c) electrons emitted from the sun and stored in the solar system for a sufficiently long time to smooth out intensity fluctuations caused by their sporadic production in flares;

d) albedo electrons from the earth's atmosphere.

It seems not possible to make such a break-down in the observed electron flux before one has measured very carefully the latitude effect, the Forbush type decreases, and the ratio of positives to negatives. Electrons accelerated at the sun and stored in the solar environment and those accelerated from cosmic ray sources are presumably all negative, while the other two sources, namely albedo and collisions in the interstellar gas, produce electrons of both signs with a small positive charge excess.

The fact that electrons from the sun can be stored for a sufficient length of time to smooth out the flux and destroy the evidence that they were really produced in solar disturbances has also been underlined by Prof. Denisse, who reported that electromagnetic radiation due to high energy particles persists, sometimes for days after a flare has died down, and that the radiation retains the polarisation of the sun spot near which the disturbance originated. The occurrence of long-term storage of electrons after a solar flare appears to be an experimentally established fact.

4. Galactic Cosmic Ray Nuclei

Turning now to the nuclear component of galactic cosmic radiation, the principal addition to the available information since the Kyoto Conference is due to the passage of another year which brings us closer to the goal of possessing accurate intensity measurements throughout a complete solar cycle. Prof. NEHER has reviewed the balloon experiments for this period, which give information mainly on particles of energies up to about ~ 1 GeV, and Prof. SIMPSON has reviewed the neutron monitor data which depend essentially on primary nucleons in the latitude sensitive part of the spectrum. The balloon data show clearly that throughout the solar cycle there existed a « knee » in the latitude curve with the exception of the years of solar minimum, 1954-1955. This exception is a decisive piece of information, even if it should not repeat itself in future solar cycles; it means that it is not the galactic spectrum which is cut off; the low energy nuclei exist in interstellar space and we must find reasons for the existence of the knee inside the solar system. I shall not go into the various attempts to explain these data and particularly the knee which appears at a rigidity of about 800 MV; Prof. ELLIOT will no doubt refer to it when discussing the field and matter distribution.

In the balloon data there is also evidence for a time lag between the solar cycle and its modulating influence on the primary galactic radiation, an effect which was first discussed by Prof. FORBUSH. However, the numerical value of this time lag (about nine months) is somewhat larger than seems compatible with the set of data which were presented by Prof. SIMPSON and which were based on the world-wide network of neutron monitoring stations. Several new features appeared in the review which we heard on this subject. When comparing results of monitoring stations at different latitudes it appears that primaries with energies below ~ 1.4 GeV do not exhibit a time lag with respect to the general level of solar activity; the cosmic radiation intensity begins to decrease immediately after the solar minimum has been passed. However, neutron monitoring data from lower latitudes show that, as the primary energy increases, a time lag appears which amounts to several months for stations located at the equator, *i.e.* for primaries with energy about $\sim$ 14 GeV.

The data show also some other details of the 11-year variation, namely a very sudden drop in the entire cosmic ray intensity irrespective of energy when the number of sunspots reaches about 200, *i.e.* fairly close to the maximum number for that particular cycle. As has been pointed out repeatedly, the last cycle was quite unusual; it has a larger maximum than any cycle on record for the last 200 years and a lower minimum than most. While not at all typical, it is the only sunspot cycle for which data on cosmic ray flux are reasonably complete. Whether the sudden drop of cosmic ray intensity near solar maximum is a particular feature of the last cycle or a regular feature of normal and less violent sunspot cycles must be left open.

Another important feature exhibited by the neutron monitoring data was the hysteresis in the cosmic ray intensity curves; as the activity of the sun began to decrease again, the cosmic ray intensity did not recover by retracing its path in the flux versus sunspot number diagram. At first it regained strength rather slowly, but now as we approach a new solar minimum, recovery has speeded up and the loop seems to close. I shall not discuss possible interpretations of these new data. Certainly they provide much more material for understanding the 11-year cosmic ray variation than was available at the time of the Kyoto Conference.

5. Nuclei from the Quiet Sun

Another new problem of great interest has appeared in the form of a hypothesis that, apart from giving rise to particle bursts associated with flares, the sun is a steady emitter of protons in the energy range from 80 to 300 MeV. Such protons have been observed by Meyer and Vogt already during 1960, but now these measurements are more detailed and cover two years. There are two features in the observations which make it appear that these protons are of solar origin. The shape of the proton energy spectrum suggests two different sources; it drops steeply until an energy of $\sim$ 300 MeV is reached, then it rises again, reaches a maximum at $\sim$ 450 MeV and thereafter follows the well known power law of the galactic proton component. It seems reasonable to assume that the galactic spectrum goes through a maximum at 450 MeV and that at somewhat lower energy the galactic intensity becomes buried in the tail of a low energy proton flux of solar origin. This assumption receives strong support from the second feature of the observation, namely that the steep low energy part of the spectrum decreased between 1960 and 1961, while the high energy part which is attributed to galactic protons showed an increase in conformity with expectations for a period which lies on the descending branch of the sunspot cycle.

The protons in the energy region between 80 and 300 MeV are not connected with flares and seem to persist unchanged in quiet periods for a time of the order of a week. On the basis of these observations, MEYER and VOGT express the view that we are dealing here with a new phenomenon, a steady production of nuclei at the sun distinct from particle bursts connected with flares.

6. SOLAR FLARE PARTICLES

Let me now turn to high energy nuclei and electrons coming from the sun and associated with solar flares. Prof. NEY's review of this subject brought out some interesting new features in addition to strengthening evidence obtained earlier. There are more data now which show that most solar flares produce particles, although often restricted to comparatively low energy, so that they can only be observed by the blackout of galactic radio noise in the polar regions. This conclusion stands in contrast to beliefs generally held a few years ago, when it was thought that particles are emitted only by a small fraction of the solar flares. It has also been safely established now what had already been suspected, namely that the spectrum of nuclei from solar flares is not always the same but varies considerably from one burst to the next. If one expresses the spectrum by a power law, the exponent varies between 3 and 6. However, it seems that a better description of the spectrum is obtained if one expresses the energy dependence by an exponential function.

A very important addition to our information on flare particles is that in a given flare the rigidity spectra are the same for all nuclei, irrespective of their charge and mass, and still more important the discovery that the composition of the nuclei in these bursts does not represent the composition of the source region but that it is subject to considerable fractionation before the particles are emitted. The fractionation effect exhibits itself first of all in the ratio of protons to α-particles which, in the rather small sample of flare events studied so far, has reached values as low as 1 and as high as $\sim$ 30. So from flare to flare there can be an enormous difference in the relative number of protons and α-particles which are emitted.

In contrast to this large variability, the ratio between α-particles and nuclei, *i.e.* C, N and O, seems to vary little and possibly not at all. I shall come back to these data and their possible interpretation.

According to Prof. NEY there exist observations on the electromagnetic radiation from flares, suggesting that electrons are accelerated in numbers comparable to the number of protons and with similar energy spectra. Nevertheless, electrons are usnally absent in particle bursts from solar flares. An upper limit for the ratio electron/proton has been determiued as 2% and 0.3%, respectively, in two different events. These observations clearly show that there can be a strong preference for nuclei as against electrons in the emission process. But it is not clear as yet whether the observations imply that high energy electrons are never ejected during solar flares. There are observations of MEYER and his co-workers in which they do find an increased electron intensity in the energy range of about 100 MeV during a solar flare. On the basis of such preliminary evidence, one can state with some reserve that electrons usually are absent but can be present in solar flares.

It should be emphasized that the relation between the emission of electrons and of nuclei from stellar or galactic accelerators is a crucial element in the entire cosmic ray picture; our lack of information makes it the weakest link in existing theories on the origin of cosmic radiation. Except for direct measurements in the immediate vicinity of the earth, the only information which we have about cosmic radiation in various regions of space is based on electromagnetic radiation attributed to high energy electrons moving in distant magnetic fields. Yet this information is used to construct a theory of origin of a primary radiation which consists practically of nuclei only.

For instance, in GINZBURG's theory of the Supernova origin of cosmic ray, the plausible but not entirely conclusive arguments used to bridge this difficulty go as follows. One knows certain places in our galaxy where electrons are accelerated up to energies of about 10^{12} eV. One can hardly imagine a mechanism capable of accelerating electrons to such high energies which will not at the same time accelerate ions; while nuclei are subject to the same accelerating forces as electrons and subject to the same energy dissipation by atomic collisions, electrons possess additional means for losing energy, such as bremsstrahlung and synchrotron radiation. *Ergo,* whenever electrons are accelerated, nuclei will also be accelerated in comparable numbers and to at least comparable energies.

It is assumed that these nuclei finally escape but the details, in particular the fractionation which may occur in the process of releasing the high energy particles from the accelerating region, are unknown.

Therefore, it is still somewhat doubtful whether, from the data on the electromagnetic radiation emitted by electrons in certain regions of space, one can obtain information on the number of nuclei emitted from such regions. To illustrate the unsatisfactory state in which one finds oneself at present, it may be worth pointing out that if one uses Fermi acceleration mechanism as the process by which electrons and protons are accelerated (for instance in the Crab Nebula), one finds that roughly two thousand times more energy should go into the proton component than into the electron component. From optical and radio emission one can estimate the energy contained in the Nebula in the form of high energy electrons. Two thousand times as much is entirely too much energy to be contained in the Crab Nebula.

It is fortunate that processes of fractionation between electrons and nuclei during and after acceleration can be studied now at the sun. They may have relevance for galactic sources as well and may contribute to a solution of this type of difficulty.

Let me now return to solar bursts and the fractionation of nuclei at the source. The outstanding newly discovered fact is that the ratio of protons to helium varies by a factor of at least 30. The question arises whether this fractionation occurs during acceleration as a result of the difference in charge to mass ratio of the particles, or whether (as suggested by Prof. GOLD) it occurs later, during storage, and has its origin in the difference of velocity with which particles of different mass but equal magnetic rigidity propagate from the accelerating region to the point of ejection.

A more detailed study of abundance ratios among complex nuclei will be of help in solving this problem. For practically all the isotopes which are likely to be present at the solar surface in sufficient abundance to be detectable in cosmic ray experiments, the charge to mass ratio of bare nuclei is *exactly* one-half. These nuclei, when accelerated, travel on identical path with identical speed through any configuration of static or time dependent magnetic fields. Their relative abundance ratios cannot, therefore, be altered during storage or ejection. Changes in composition from one flare event to another must be attributed to fractionation in the early phases of acceleration, when ionization was incomplete and the particles still differed in their charge to mass ratio. Such changes in relative abundance, if they exist, will therefore make it possible to estimate the effectiveness of fractionation during acceleration as well as the temperature of the region in which acceleration commences. Further fractionation after stripping can affect only the abundance ratios involving elements whose most prominent isotopes have charge to mass ratios different from one-half; apart from hydrogen this applies only to nuclei of the iron group.

In closing I want to point out again that I have confined myself to a fraction only of the papers which have been presented during this Study Week; I have not touched upon any of the reports which dealt with the interpretation of observations on high energy particles in terms of particular models nor with reports which dealt with the structure of the interplanetary fields, with the interplanetary plasma or with the radiation belts.

DISCUSSION

Chairman: L. LEPRINCE-RINGUET

DENISSE

I would like to point out that the radio emissions (noise storms) which remain close to the sun after the flares can be radiated by electrons as well as by protons, if the process at work is Čerenkov radiation.

PETERS

Has any calculation been made about the density distribution in that region to show whether Čerenkov radiation is a possible mechanism for the light?

DENISSE

As far as the radio radiation is concerned, there is a calculation by M. COHEN which is published in *Phys. Rev.*, *123*, 711, 1961. The quantitative calculation is difficult because account has to be taken of the possible bunching of the particles in the plasma waves and of the conversion factor from plasma waves to radiated waves.

SINGER

It occurred to me that it is of course a very important matter in the solar production of high energy particles to decide whether:

1) the fractionation occurs at the source, that is in the acceleration process itself, or 2) in the process of migration, as was pointed out by Dr. GOLD during the meeting. I wondered if the matter cannot be settled, perhaps approached in the following way. The fractionation in migration must depend on the length of the path from the source to the line of force which connects to the earth. That is to say, if the acceleration occurs on the line of force that connects to the earth, one ought to see the distribution of elements more or less as they are accelerated, but if the flare occurs at another part of the sun and migration is very long, then there is an appreciable chance for fractionation due to different velocities. Is there any information how these particular flares that have been observed behave in this respect?

NEY

There are two well documented events. One of them is the November series in which the flares and presumably the acceleration occurred very near the foot of the lines of force that connect to the earth. We think of this as a very well connected event because all of the flares that occurred, occurred in the same region of the sun and they just got displaced as the sun rotated. In this case the beam was very rich in α-particles. The other well documented event was in September, in which case the flare occurred on the east limb and was very poorly connected to the earth, and in this case the beam was very rich in protons. I don't believe it is possible to distinguish whether the magnetic connection is important near the sun or in interplanetary space, even though there is this relationship between the two kinds.

SINGER

Well, a very simple minded interpretation of what Prof. NEY has just described would say that in the acceleration process the heavy primaries are preferred as against protons. Is this statement consistent with evidence so far?

NEY

I think a further point I should have emphasized is that in both cases the particles are observed rather late after the flash phase of the flare, so that my own interpretation would be that in the well connected event the protons had essentially leaked away leaving the beam rich in alphas and in the poorly connected event the beam was rich in protons because one was observing more the leakage than what remained.

GOLD

I would emphasize again that the discussion certainly requires time variations in the beam to get the effect at all. If there are time variations that change the connection from the source of the flare to the eventual line of force that leads to the earth, then it is not possible to make any close argument on the lines that Dr. SINGER would like, because in the different events there will be quite unknowable changes occurring between the time that the proton flux passes a certain place on the sun and the time that the α-flux passes that same place; the two fluxes will be going through the railroad shunting yard with all the switches in different places, and so I think we will just observe great variability and no very consistent pattern.

SINGER

Well, I don't think it is quite possible, if one measures a ratio of protons to alphas, to say which leaked away, the protons or the alphas, unless you know what the ratio was at the beginning. Unless you can guarantee that the ratio of protons to alphas after acceleration corresponds exactly to the abundance ratio, it is very hard to say which leaked away.

REVIEW PAPER II

INTERPLANETARY PLASMA AND MAGNETIC FIELDS

H. ELLIOT

Imperial College of Science and Technology
London - Great Britain

Like Prof. PETERS I shan't attempt to produce a series, of potted versions of the various papers that have been given. Instead I shall try to construct a table (see pag. 551) which will, I hope, show some of the areas of agreement that exist and also perhaps reveal some of the areas of disagreement.

The story of the interplanetary magnetic field begins with the fields in the photosphere of the sun. The evidence about these fields comes from a number of different sources; it comes from solar magnetograms, from a study of coronal and chromospheric shapes, and to some extent from the study of radio noise generated by electrons trapped in these fields near the photosphere. The visible aspects of flares and the radio noise which they generate have been discussed in detail by Prof. DENISSE. All this evidence is consistent with the existence in the photosphere and in the lower chromosphere of fields which vary from a few gauss — maybe even rather less — up to strengths of thousands of gauss in the biggest and most intense sunspots. In addition to these patchy fields, there is very good evidence for the existence of polar fields with strengths of the order of one or two gauss which have some kind of dipole-looking character and which in all probability show a 22-year variation similar to that shown by sunspot polarities. Up to the present time, however, only one reversal has been observed in these fields, so we should not perhaps be too sure about this last point.

These fields that are observed in the photosphere are certainly so small that if we had a vacuum between the sun and the earth they would exercise no influence whatever on the galactic cosmic radiation; they might, of course, very well generate high energy solar partcles, but they would be quite incapable of screening the earth from the galactic cosmic ray flux. So, if these fields are to play a part in modulating the galactic cosmic ray intensity, we must have something else to come to their assistance, and this of course is the interplanetary plasma. In the past the evidence concerning the nature of the interplanetary plasma has been rather indirect, and for this reason there has been a good deal of argument as to its properties and about just what it does. The situation has now crystallized very much in this respect. Evidence from the study of comet tails was discussed in detail by Prof. BIERMANN this morning. Other evidence comes from studies of the zodiacal light and from the effects of the interplanetary electrons on point radio sources. Most recently, of course, we have evidence from direct measurement in space probes. The space probes provide the firmest data that have been obtained so far and this was discussed in some detal, you remember, by Prof. ROSSI for the Explorer X space probe. I suppose that quite soon now we shall have confirmation of the rumors that we hear about what is being observed by Mariner II.

Now, on the basis of this evidence one can say with some degree of certainty, I think, that there is quite often plasma present in interplanetary space which has a temperature of perhaps a million degrees or so, and that at the orbit of the earth the density is of the order 10 per cm^3. Whether these numbers are truly representative or not one cannot say, because the observing time is as yet quite limited. The plasma probe data and the comet tail data would seem to be consistent in indicating a velocity for this plasma of perhaps a few hundred kilometers per second; this moving plasma, then, constitutes the solar wind which is alleged to blow away the comet tails and which has been discussed in considerable detail by Prof. PARKER from a theoretical point of view. The plasma, being at this high temperature, is of course highly conducting, and it is this property of the plasma which connects the interplanetary magnetic field to the photospheric fields. It is the marriage, if you like, of the photospheric fields and the plasma which is going to generate the interplanetary magnetic field.

In discussing the properties of the interplanetary magnetic field I propose to divide space into two regions, one within the earth's orbit and one outside the earth's orbit. What can we say about the interplanetary field lying between the earth and the sun? First of all, the evidence for the nature of this field again comes from a number of different sources; it comes in part from the study of shapes in the corona, as Prof. GOLD has pointed out many times; it comes in part from measurements carried out by means of satellites and space probes which have travelled beyond the limits of the geomagnetic field — and not too many measurements of this kind have been made so far, the results from only three have been published, namely those from Pioneer V, Explorer X, and Explorer XII. These observations provide information which may or may not be representative of the interplanetary magnetic field, because the measurements in two cases were made quite close to the earth, and one is really quite unsure as to what effect the geomagnetic field has in its interaction with the plasma. This is not true, of course, of the Pioneer V data. This spacecraft went to a sufficient distance from the earth to be clear of the effects of the geomagnetic field. The data collected by Pioneer V on the field *strength* were quite consistent with the information that was derived about the field from the study of the propagation of energetic solar particles from the sun to the earth and I imagine that you would be prepared to agree that in the neighbourhood of the earth the field strength is generally in the region of perhaps 1 to 10 γ, 1 γ being 10^{-5} gauss. Now this figure represents the ambient condition of the field but at times of solar disturbance this field strength may go up very considerably; it may increase by a factor of 10, certainly, during an interplanetary magnetic storm. Such an event was in fact detected and measured in Pioneer V.

This increase by a factor of 10 is, of course, a modest one compared with the kind of event that Prof. GOLD talked about when he took us on that fascinating exercise in extrapolation on Monday and discussed what might happen in a « super storm » — you may remember that at one fell swoop he demagnetized the earth, magnetized the moon, and converted an appreciable part of the Libyan desert into glass. It seemed to me rather a pity at the time that he could not have arranged simultaneously to make water on a grand scale, thereby putting out the fire and creating a few oases into the bargain!

The next question perhaps that we should ask here is how does the field strength depend on distance? If we regard the field as being of photospheric origin we know that we have to start off at the photosphere with a field which is in general going to be a few gauss. Sunspot fields of course represent extreme cases, so we would not regard them as being in any sense the fields that we have to deal with in general. Instead, it seems that we shall be dealing with the weak fields of 2 or 3 gauss and if that is so it follows that the interplanetary field must decrease from this value of 2 or 3 gauss at the sun to a few gammas at the earth. The law by which it falls off is, of course, not yet established — something like an inverse square law would perhaps be adequate — but if I write down that it falls off at something, say, between $1/r^2$ and $1/r^3$ it probably would not be very far wrong. I believe these three things that I have written down under the heading « Field

Strength » would be agreed by everyone present and I think that this represents in many ways a surprisingly satisfactory state of affairs — that we do in fact know this much about the field.

Next, though, I want to say something about the geometry of the field. On the first point, I think we would again have agreement in saying that the field between the sun and the earth is frequently radial to the sun. This is a deduction which comes from detailed study of the propagation characteristics for energetic solar particles and is, I think, based upon pretty secure evidence. This is not to say that it is always radial. The question of whether there is a uniform component of the field perpendicular to the sun-earth line, as I have advocated, is one which should quite soon be answered, assuming that the Mariner II magnetometer works properly, so I won't say any more about this particular point. There are, however, irregularities in the field and these irregularities probably have a scale size of about 10^{11} cm. These scale sizes are determined from the propagation of energetic solar particles to the earth and the degree of scattering required to render them isotropic, or nearly so.

A point which has been discussed here is whether this field, in addition to the radial component, also contains closed loops of lines of force — lines of force which have come out of the photosphere and then have been cut off somewhere between the sun and the earth's orbit. It seems, therefore, that we must bear in mind that there is a possibility of closed loops which are in outward motion. I shall indicate these by a question mark. So far as the distribution of field irregularities is concerned, I think here there is a considerable debate still. The question of whether the field close to the sun, for instance, is very turbulent or is rather smooth is not yet resolved, and I suspect that this depends very much on where you look on the solar surface. We know that if we look at the polar regions the field appears to be rather smooth; you can see this by the shapes of the coronal plumes. On the other hand, going away from the poles towards the equator, we find that the field becomes more complicated due to the presence of sunspot fields. So, although the field in the polar regions may be smooth, it seems reasonable to suppose that as one gets closer to the equator so the field become more and more complicated. There is some evidence about the degree of complication of the field from the fractionation of solar particles, which indicates rapid changes in time of these fields close to the sun — as pointed out by Prof. GOLD. By fractionation, I mean, of course, the separation of the heavy particles from the protons. However, the interpretation of these results, described Prof. NEY, is still the subject of debate in the sense that there are alternative possibilities.

The next thing we might like to know about the field is how does it depend on solar activity, how does it vary over the solar cycle? I don't think that we really know anything about this. The natural thing to suppose would be that there is in general a decrease with decreasing activity, but we don't really know, and this raises a very interesting point, which was discussed by Prof. SIMPSON, as to whether there is still some residual modulation of the galactic cosmic ray intensity at solar minimum. When I come to deal with the field outside the earth's orbit I will mention this point again. We shall, of course, eventually obtain some information about the variation over the solar cycle from the space probe magnetometer measurements, but I think that at the present time we are hardly in a position to say what happens to the interplanetary field as a function of solar activity. A point of particular interest here concerns the polar fields in the solar photosphere, in the sense that if they contribute to the fields in the interplanetary medium then there is the possibility of a large scale field reversal from one cycle to the next. Such a reversal might have an identifiable effect on the cosmic ray solar daily variation, for instance.

Let us now leave the field within the earth's orbit and go over to the field beyond 1 AU. Here we can start off with the field strength at the earth's orbit, and as we go out from the earth this value must presumably fall off to that prevailing in interstellar space, whatever that may be. Various numbers are discussed in this connection. I think that the current fashion, among some astronomers at any rate, is in favour of an upper limit of perhaps something like 3×10^{-6} gauss. This is certainly very uncertain! The way in which the field decreases as we go out from the earth's orbit to join up with the interplanetary field is not known. One thing that we can say is that the field strength increases — temporarily of course — at the time of an interplanetary magnetic storm. It is here being inferred, of course, that the increase in field observed inside the earth's orbit by Pioneer V extends out beyond the earth's orbit. This inference is strengthened by the existence of the Forbush decrease phenomenon. I should have pointed out, perhaps, that at the present time the evidence we have about the field outside the earth's orbit comes exclusively from the study of the cosmic rays. In particular, it comes from the study of the energy dependence of the 11-year variation, the Forbush decrease, and the solar daily variation. We do not have any other source of information about this field at the present time.

Now what do we know about the geometry of the field? The answer, I am afraid, is very little, hence the question mark in the diagram. Unfortunately, it is possible to account for the cosmic ray intensity variations by very different models of the field. We can take, for example, Prof. PARKER's model with the convecting outward moving barrier, or the one that I have proposed with a purely static field, and either of these two very different field configurations can be made to fit the cosmic ray evidence. It is unfortunate that the cosmic rays do not convey to us as much information as one might hope. I think it is agreed, however, that whichever field model we adopt it is necessary that the large scale field contain scattering irregularities and that the characteristic scale size of these irregularities should be somewhere in the region 10^{11} to 10^{12} cm. We cannot do much better than that.

We wish to inquire next about the extent of this field, how far away from the orbit of the earth does it stretch? Is it 4 AU, or is it 40? The answer again is that we don't know. In this connection, I think that experimental data on the upper energy limit which is involved in the 11-year variation would be a very great help — an extension, in fact, of the kind of data on the latitude dependence of the 11-year variation that Prof. SIMPSON and Prof. NEHER showed us the other day.

Finally, the question of how the field external to the earth's orbit varies over the solar cycle. Here again, as in the case of the field inside the earth's orbit, we do not know the answer. From the cosmic ray evidence we might perhaps expect it to diminish with decreasing activity on the sum. If so, does it diminish to such an extent that at solar minimum we have no longer any modulation of the cosmic ray flux so that at this time we see the undistorted galactic spectrum?

We can see from the diagram that there is, then, some appreciable measure of agreement about the magnetic field in interplanetary space, but there are still very wide areas of uncertainty. In this respect one should perhaps ask what further steps can we take to clarify the situation, what further experimental data should we try to acquire?

First of all, it is extremely important to try to decide the question which I discussed the other day, of whether the 11-year modulation process depends on particle energy or on rigidity only. A clear decision here should enable us to distinguish between an essentially static field and one in which convective removal of cosmic ray particles from the solar system predominates. Resolution of this problem would seem to be within the capability of techniques presently available, but the situation is certainly complicated by the presence of low energy solar particles.

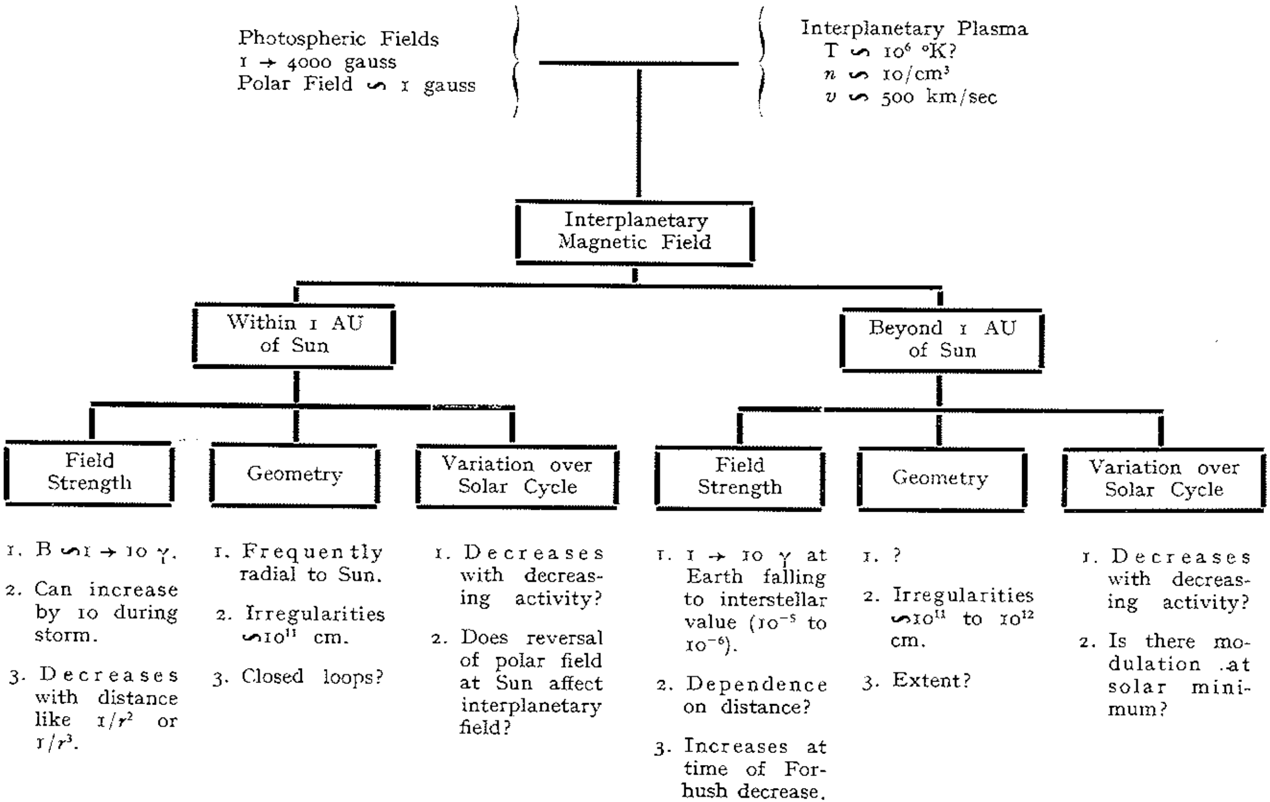
Secondly, we would like a much more detailed knowledge of the energy dependence of the 11-year variation and Forbush decrease, because this information at present provides the most direct evidence about the characteristics of the field outside the earth's orbit. In particular, we would like to know rather precisely what is the energy limit for the 11-year modulation, what is the energy limit for the Forbush decrease process?

Thirdly, it would be very nice if we could have measurements of the cosmic ray flux gradient in space. One measurement only of this important quantity has been made so far — by the Chicago group — and I personally would like to see more measurements of this because it is a quantity which can be readily compared with theory, and which is capable of giving us information about the gross structure of the interplanetary field. This information is extremely hard to get by direct observation using space probe magnetometers alone because these provide measurements along the spacecraft trajectory only and so cover a very limited region of space and time. Consequently, if we are to build up a comprehensive picture of the interplanetary field we must use these two complementary techniques — the direct measurement of the field together with the cosmic ray data.

Finally, the question of the storage of solar particles is extremely important for our understanding of the large scale properties of the field, and here one would like to know whether the flux of protons with energies of a few hundred MeV or so, observed by VOGT and also in the Explorer XII flights, are solar particles which have been trapped for a long period, or whether they represent a continuous production process at the sun. The question of the dispersal and diffusion of solar particles is one which I think could very profitably be tackled on a theoretical basis by setting up somewhat more detailed models than have been considered so far. This question bears particularly on the demarcation line which we have to draw between galactic cosmic ray particles and solar cosmic ray particles.

The main theme of this meeting was concerned with cosmic rays in the interplanetary magnetic field, and in this summary I have tried to outline some of the areas of agreement and disagreemnt and to indicate some of the things that I personally would like to see done. I am quite sure that there are many others that could be added, and indeed perhaps will be added, in the discussion which is to follow.

TABLE I — *Present knowledge about interplanetary magnetic fields.*



DISCUSSION

Chairman: L. LEPRINCE-RINGUET

ROSSI

I would like to ask on what experimental evidence you base your estimate of a million degree for the temperature of the plasma near the earth. The Explorer X data during most of the time show a rather well collimated beam, which is somewhat difficult to bring in agreement with such a high temperature. Of course, there is the question whether temperature means anything, *i.e.*, whether there is an isotropic distribution in the velocity of agitation of the particles in the frame of reference of the moving plasma.

ELLIOT

Well, may I ask the question of you? What would you estimate the temperature to be, from your plasma measurements in Explorer X?

ROSSI

From the collimation of the beam observed during most of the flight I would say, to be very conservative, that 10^6°K is an upper limit. However, in the early phase of the flight, when the magnetic field was disturbed both at the satellite and on the earth, then there is evidence for a larger spread which might agree with 10^6°K. This spread, of course, measures the « component of the temperature » perpendicular to the line of flight; the component parallel to the line of flight is reflected on the energy distribution. At the beginning of the flight there is evidence for a wide energy distribution which again would indicate a high temperature. The rumours that I have heard about the Mariner flight results is that they show a wide energy distribution, which would call for a temperature of the order of millions of degrees. My question was what experimental evidence did you use to make your estimate?

ELLIOT

You have given the answer. The number was based on your Explorer X data coupled with the rumour of even higher values from Mariner II. It seemed to me that if I wrote down 10^6, this was probably a reasonable compromise.

ROSSI

I would like to ask another question, really for my own information. We have not discussed the possible composition of interplanetary plasma. What is known about the composition of the solar atmosphere, of the chromosphere above the corona? How much helium, how much hydrogen is there?

BIERMANN

Regarding the composition of the solar atmosphere, the following may be said: The ratio of hydrogen to helium, which is somewhat difficult to determine, is by numbers probably around 1 to 7 or 1 to 6. Most of the relative abundances of the more important elements are reasonably well known from standard methods of spectral analysis. There is little reason to donbt that there is practically no separation of elements and that the composition of the solar corona and the solar atmosphere is just the same, because the former is continuously being replenished from below; so we are probably justified in taking the composition which we know from the solar atmosphere also for the corona and for the solar wind.

To come to another snbject, your statement on the temperature of the interplanetary plasma reminds me of an omission which occurred during my talk this morning. When discussing the temperature of the interplanetary plasma, one should distinguish between the ion temperature and the electron temperature. Most of what has been said in this last discussion refers to the ion temperature. While I have no comment on that, I wish to point out that with regard to the electron temperature there is certain information from the comets. If during magnetic storms the electron temperature of the solar plasma would be of the order of 10^6 °K, then one should probably see conspicuous collisional effects which, however, appear to be absent. From this upper limit I would guess the electron temperature to be in the range of 10^5 to 10^4. The best guide I know of at the present time is perhaps the theory of the solar wind. I wonder whether Prof. PARKER would give an estimate as to the loss of heat energy in the process of expansion from the solar corona or on the possibility of a separation of elements in this process.

PARKER

I think Prof. BIERMANN has summarised the situation very well. I recall that I always used to say there was no argument against any temperature between any 10^3 and 10^6°K, and I think I will stick with that.

The other point is the abundance of the heavier ions. Calculations of the downward diffusion rate of heavy ions in the solar corona, suggest that there is the barest possibility that the solar corona may be poor in heavy ions, but I think that it is rather doubtful and that the ion abundance, as Prof. BIERMANN suggested, is probably the same in the solar wind as in, say, the solar photosphere.

GOLD

We have looked a little into the question of the electron temperature out in space, and we have really not been able to find any mechanism that would keep the electrons at a higher temperature than about 10^4 °K. Magnetic fields of any shape and any roughness and turbulence in them will all nevertheless imply an adiabatic expansion that would have cooled the electrons to about 10^4 degree if they started out with the temperatures that are needed for the ions in order to make the outburst. If one assumes that in the flare there was equilibrium with the ions (and in the flare the densities are high and the time of relaxation for the electrons is fairly short, shorter than the life of the flare by a large factor), so that they started out in equilibrium, then adiabatic expansion would cool the electrons terribly. We have looked into all the processes that might heat them on the way out, and they are all quite negligible; they do not get themselves significantly heated, and so adiabatic expansion is all that I can see to be ruling the temperature that they will have out here.

PARKER

Temperatures below 10^4°K are what one expects for adiabatic cooling of the gas in the solar wind. It is conceivable that a system of waves — gravity, acoustical, hydromagnetic — propagating in the expanding corona could raise the temperature of the gas as far as the orbit of the earth to, say, 10^6°K. It is strictly hypothetical, but one can get a fair amount of energy.

OORT

I would like to discuss with Prof. ELLIOT the value he gives for the field strength in interstellar space. There are in this problem two trends of thought; one comes to values of a few times 10^{-5} gauss and the other to a few times 10^{-6}. There appears to be just as much evidence for the one as for the other, and it is not quite fair just to quote one figure.

ELLIOT

I agree with that statement entirely. I think I did say there was doubt at the time. That is why I put brackets around the number.

REVIEW PAPER III

PARTICLE ORBITS IN THE GEOMAGNETIC FIELD

S.F. SINGER (*)
National Weather Satellite Center
United States Weather Bureau - Washington, D.C. - U.S.A.

What I should like to do is to review to some extent the papers that were given earlier, referring to particle orbits in the geomagnetic field . This is an excellent time to recognize the importance of the work of LEMAÎTRE and VALLARTA, because the papers that I am reviewing here are essentially an outgrowth of this early work in two different directions. First, an extension of this work to the inclusion of the ring current; this was the paper by RAY. In the second group of papers, an extension of this work to particles of very small energy (or large values of γ, if you like), particles which are either trapped or very nearly trapped.

First, the paper about ring currents: The effect of ring currents on geomagnetic cut-offs is a very old subject, which was worked on by CHAPMAN, by TOM JOHNSON, HAYAKAWA, by TREIMAN, by RAY, and by KELLOGG and WINCKLER. But I think none of these treatments were really satisfactory until the present one which was given just the other day by Dr. RAY, who has used correctly the *diamagnetic* ring current. As he explained, the ring current is a current system consisting of both an eastward and westward current. He calculated the effect of this current on the geomagnetic cut-offs of LEMAÎTRE

(*) On leave of absence from the University of Maryland.

and VALLARTA. I think he has really solved what may be called a classical problem. The result is that there is a break at a certain *latitude* at which the effect of the ring current becomes noticeable; it is a function only of the *position* of the ring current. But the *amount* of the effect, the amount by which the cut-offs are displaced, depends on the *strength* of the current. With regard to this result it should be much easier now to analyze the geomagnetic cutoff data, experimental data obtained during geomagnetic storms and during quiet periods.

Going over the second set of papers, they concern the particles of low energy which are very nearly or completely trapped in the earth's magnetic field. This is not really an academic question; it was shown here that there are in the earth's magnetic field protons of 500 MeV; and if we can believe the neutron albedo origin of these protons, they must have lifetimes of 300 years!! To translate this into other terms, 300 years correspond to 10^{13} gyrations along the lines of force. This corresponds to a total path-length of travel of 10^{21} cm. As I mentioned many times, and I will state it again, it is intuitively very difficult to accept these long lifetimes, and I must say, I do have some slight hesitation in accepting them myself. Nevertheless, the protons are there; their presence has been shown by photographic emulsions; and what evidence we have, what analyses have been made (I gave them in some detail in my paper) seem to show that the neutron albedo theory accounts for their existence. But this then demands this very long lifetime of 300 years.

Now, with these long lifetimes experimentally demonstrated, all of the papers that were given here, which deal with the long-time stability of orbits become of a much more than academic importance. We would like to know from a theoretical point of view whether particles can exist for such a long time in orbits of this type. It is difficult to accept these long times, because of the existence of other time variations of the field, and because of the non-dipole character of the field; in fact, anything that you might think of would tend to disturb these particles.

My feeling has been that we must start with the analysis of *simple* cases. Perhaps it is useful to go back again to LEMAÎTRE and VALLARTA and ask them whether they would have undertaken their monumental work if they had known of the existence of hydromagnetic waves in the upper atmosphere, of ring currents, of the interplanetary magnetic field, and all sorts of other disturbances. Maybe they would have just thrown up their hands and not produced their beautiful theory which has been of such great value to us in the study of cosmic rays. Well, here I feel very similarly about the works which BOSSY, DE VOGELAERE, and HAYAKAWA reported. True enough, their work refers only to questions of the first invariant and its validity; and there may be many other effects which are important. But a start has to be made, and perhaps the fundamental problem to study at the present time is the instability of a particle in a purely static dipole field.

Now, the work of LEMAÎTRE and BOSSY, which was reported here by DE VOGELAERE, essentially produces the results which ALFVÉN has produced but from a different point of view; they are equivalent and give what we now recognize as the various adiabatic invariants. Then the problem attacked by BOSSY and HAYAKAWA was the question of how good the first invariant really is. They ask how constant the magnetic moment remains as a function of time in a dipole field. Both of the papers start with a hamiltonian which is divided into three parts, and both treat the problem to the first order. Both authors — I talked to them privately because the discussions were a bit difficult to follow and are highly mathematical — seem to think that it will be important to develop the theory to second order before any numerical predictions can be made, if I understand correctly. There does not seem to be quite an agreement on a fundamental point, and that is the following: HAYAKAWA feels that the change in the magnetic moment leads directly to a change in the mirror altitude of a particle, and this of course would be quite important; BOSSY feels that the magnetic moment may change during the orbit of the particle, while it bounces back and forth, and it is not guaranteed that the mirror altitude will also change.

Next, the paper by DE VOGELAERE discussed the long-term instability of periodic orbits; and this again is a theoretical problem which can be related very directly to the important experimental situation which exists with the trapped protons in the earth's magnetic field.

Finally, there is the empirical approach (SINGER) which relies on the observation of these trapped protons. An attempt was made there to develop a discriminant, which is essentially the ratio between the radius of curvature of a trapped particle and a scale length of the magnetic field, *i.e.* magnetic field divided by its gradient. As you know, the radius of curvature a of a particle of given energy is inversely proportional to the magnetic field and therefore will increase as r^3. The scale length of the magnetic field, B/grad B, for the dipole field, gives $r/3$, so the discriminant varies approximately as r^2:

$$X = \frac{a}{B/\text{grad } B} \propto \frac{r^3}{r/3} \sim r^2$$

This gives in a very direct way the relation between the maximum momentum which can remain trapped and altitude, which looks approximately like this:

$$p_m = (1800 \text{ MeV/c})\, r^{-2} .$$

The constant here is empirical. Use is made of the fact that the inner, proton radiation belt is observed to go to zero at two earth radii, and this gives the constant.

At the present time, I think, we are in a position where we must let the observations decide what ultimately removes these high energy protons at higher altitude. They are present at lower altitudes but not at high altitudes. If it is breakdown of the first invariant, then the maximum trapped energy E_m must go as $1/r^4$. If it is hydromagnetic waves, at least the theory by DRAGT gives $1/r^{11}$. There is one experimental result which I just became aware of yesterday (1): Dr. PIZZELLA has carried out an analysis of Explorer IV data, and the exponent which he gives is 5.2 ± 0.2.

To make a clear decision, what one wants to measure is the unidirectional differential flux of trapped protons as a function of energy at various distances from the centre of the earth — say in the equatorial plane — and at various pitch angles. At the present time we do not have such data available; therefore, it is perhaps a little useless to speculate. In any case, whatever the cause for the disappearance of these high energy protons, they do disappear at high altitude. But I do want to remind you of the fact that they exist, and that the very fact of their existence means that their orbits at low altitudes have a remarkable stability, which is of course an intriguing subject for theory and for future experiments.

(1) Note (added March 9, 1963): The analysis of Explorer IV data by McILWAIN and PIZZELLA shows that $E_m \sim 100\ r^{-4}$, in almost perfect agreement with the predicted behavior. (SINGER, *Phys. Rev. Letters*, *3*, 188, 1959; See also *Progress in Cosmic Ray Physics*, Vol. 6, North Holland Publishing Co., 1962, p. 300).

DISCUSSION

Chairman: L. LEPRINCE-RINGUET

SIMPSON

There were measurements by LEO DAVIS on Explorer XII which perhaps Dr. SINGER had no time to discuss but which seem to be relevant to the question of the role of hydromagnetic waves out to great distances in the magnetosphere. Specifically, his measurements show that the proton energy density for protons of 1000 to 5000 KeV energy in a region of 4 earth radii to approximately 7 earth radii is at least one-tenth the energy density of the magnetic field itself and represents the major energy component in the outer Van Allen belt. At a greater distance the proton flux suddenly disappears in a layer of the order of 100 km: presumably this being the magnetospheric boundary. In view of these observations it is important to think very carefully about what role hydromagnetic wave propagation plays in the magnetosphere. Would you care to comment on this?

SINGER

Yes, I can comment on DAVIS' data. I have analysed them as far up as 3 earth radii. At 3 earth radii, it would appear to me that the protons that DAVIS has measured which are by now quite low energy protons, of the order of 1 MeV if I recall, are under control of the atmosphere. This can be recognised by the fact that DAVIS observes a *low energy* cut-off of the protons at 500 KeV.

The cause for this, I think, is charge exchange. Charge exchange provides a very sudden limit to the lifetime of low energy protons. As soon as they slip down to 500 KeV, charge exchange cuts them off and gets them out of the magnetic field. As far as the high energy cutoff in DAVIS' data is concerned, it is consistent with the idea of breakdown of the adiabatic invariant which I discussed. I was surprised to see this, but this is the situation. I had not expected that any simple relation like this would be applicable as far out as 3-4 earth radii.

DE VOGELAERE

With respect to Dr. HAYAKAWA's paper, Prof. BOSSY has convinced me that BOSSY's results must be equivalent to Dr. HAYAKAWA's. The main reason for my conviction is that looking more closely to Dr. HAYAKAWA's paper it appears that his results are obtained by averaging using the gyration variable, and I believe it is only possible to obtain results equivalent to those obtained by the secular method if one averages for the motion in latitude from one mirror point to the other. Therefore, it would of course be of interest to carry out this averaging as I have mentioned before.

CONCLUSIONS

FINAL STATEMENT

A. — Cosmic ray particles of magnetic rigidity greater than several GV are for the most part of extra-solar origin. This conclusion is based mainly on the following evidence.

1. The inverse correlation between solar activity and cosmic ray intensity during the solar cycle. This is easily understood if cosmic rays are of extra-solar origin. If they were of solar origin, it would be necessary to postulate a storage time within the solar system of the order of several solar cycles, which seems excessive.

2. The chemical composition of solar cosmic rays differs quantitatively from that of galactic cosmic rays. The latter reflects events occurring during their travel through interstellar matter.

B. — Protons, α-particles and heavier nuclei, with energies up to several 100 MeV, occasionally several 1000 MeV are certainly produced by the sun on the occasion of large solar flares.

C. — There are indications that some of the cosmic ray particles with magnetic rigidities less than a few hundred MV that are found ordinarily in interplanetary space may be of solar origin. It is possible that such particles are emitted by the sun continuously. Alternately it is possible that they are emitted in solar flares and stored between flares.

D. — Earlier views that interplanetary space is pervaded by a moving plasma of solar origin (solar wind) have now been confirmed by direct experiment.

E. — Complex magnetic fields of solar origin transported by the solar wind in interplanetary space have a significant effect on fluxes of both solar and galactic cosmic rays in the lower energy range.

F. — There is as yet no clear comprehensive idea for the origin of the electrons and protons in the Van Allen radiation belts, nor is the broad and complicated transition region between the geomagnetic field and the solar wind understood. Further observational and theoretical exploration of these problems is needed.

AMALDI, BIERMANN, BOSSY, DENISSE, DE VOGELAERE, ELLIOT, ESCOBAR, FORBUSH, GOLD, HAYAKAWA, NEHER, NEY, PARKER, PETERS, RAY, ROSSI, SIMPSON, SINGER.

NOTE COLLECTIVE FINALE

A) Les particules des rayons cosmiques de rigidité magnétique supérieure à plusieurs GV sont pour la plupart d'origine extra-solaire. Cette conclusion s'appuie principalement sur les données expérimentales suivantes:

1) La corrélation inverse entre l'activité solaire et l'intensité des rayons cosmiques pendant le cycle solaire s'explique facilement si le rayonnement cosmique est d'origine extra-solaire. Pour une origine solaire, il faudrait postuler un temps d'emmagasinement dans le système solaire de l'ordre de plusieurs cycles d'activité, ce qui semble excessif.

2) La composition chimique des rayons cosmiques solaires est quantitativement différente de celle des rayons cosmiques galactiques, qui montrent dans leur composition l'effet dû à leur voyage à travers la matière interstellaire.

B) A l'occasion de grandes éruptions chromosphériques, le Soleil produit certainement des protons, des particules alpha et des noyaux lourds qui peuvent avoir une énergie de plusieures centaines de MeV, et parfois jusqu'à plusieurs GeV.

C) Nous avons quelques indications qu'une partie des particules des rayons cosmiques de rigidité magnétique inférieure à quelques centaines de MV, que l'on trouve ordinairement dans l'espace interplanétaire, peuvent être d'origine solaire. Il est possible que ces particules soient éjectées continuellement par le soleil. Ou bien il est possible qu'elles soient éjectées à l'occasion des éruptions solaires et emmagasinées entre une éruption et l'autre.

D) Des mesures directes ont maintenant confirmé l'existence dans l'espace interplanétaire d'un plasma en mouvement d'origine solaire, le « vent solaire ».

E) Les champs magnétiques complexes d'origine solaire transportés par le « vent solaire » dans l'espace interplanétaire ont une influence significative sur le flux des rayons cosmiques soit solaires soit galactiques dans l'intervalle des énergies plus basses.

F) Il n'existe pas encore d'idées claires pour la compréhension de l'origine des électrons et des protons présents dans les ceintures de radiation de Van Allen, et l'on n'a pas encore bien compris la large et complexe région de transition entre le champ géomagnétique et le « vent solaire ». Il est nécessaire d'explorer encore ces problèmes et du point de vue expérimental et du point de vue théorique.

AMALDI, BIERMANN, BOSSY, DENISSE, DE VOGELAERE, ELLIOT, ESCOBAR, FORBUSH, GOLD, HAYAKAWA, NEHER, NEY, PARKER, PETERS, RAY, ROSSI, SIMPSON, SINGER.

INDEX

TRAVAUX SCIENTIFIQUES

REVUE SYNTHETIQUE DES TRAVAUX ET DES DISCUSSION

CONCLUSIONS