COSMIC ELECTRONS AND RELATED ASTROPHYSICS

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1. Introduction

Many exciting and important advances have been witnessed during recent years in the fields of cosmic radiation, optical, radio and X-ray astronomies, and astrophysics. In the observational side, many of the major advances have been due to unexpected, and sometimes even accidental, discoveries of the greatest importance, which are, however, the fruits of sophisticated instrumentation and new technology. Of the noteworthy ones, those of interest to us here were mainly led by the discovery of the

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cosmic ray electrons, cosmic X-rays and γ-rays, the quasi-stellar radio sources (the quasars), the pulsating radio objects (the pulsars), and the isotropic background microwave radiation corresponding to a black body temperature of 2.7 K. The new observational data that have been flowing in abundance from these and many other investigations, have stimulated considerable interest in interpretative and theoretical studies leading to great strides in our understanding of celestial objects and cosmic processes. All these advances have unmistakably established the existence of many new and intimate connections between these apparently different fields of research. In fact, such interdisciplinary cross fertilisation has already paid very rich dividends and holds immense promise and scope for our future understanding of the cosmos at large. A very important consequence of these recent developments is the synthesis of a new area of knowledge which can be truly called 'Cosmic Ray Astrophysics'. A measure of the importance of this newly emerging subject is the active interest evinced for it by scientists working, not only on cosmic radiation, but in such diverse fields as nuclear physics, astronomy, astrophysics and cosmology. It will be one of the principal aims of this article to make evident the vital contributions already made and those anticipated from a study of cosmic ray electrons to cosmic ray astrophysics.

Today we have ample and convincing evidence for the existence of relativistic electrons in various regions of cosmic space and in a variety of celestial objects. For example, we now know that cosmic electrons are present in the earth's radiation belts, the interplanetary space, the cosmic radiation, the interstellar space of our galaxy and perhaps even in the intergalactic void. As for celestial objects, we recognise that in our galaxy, novae, supernovae and pulsars are seats of cosmic electrons while the sun is known to emit them only sporadically; and in the metagalaxy, quasars and radiogalaxies are prolific sources of cosmic electrons. It is thus quite apparent that the production and propagation of cosmic electrons is of universal nature; processes of such common occurrence are also bound to play an important role in our understanding of many cosmic situations. The obvious question now arises as to how one knows about the presence of cosmic electrons in space and in discrete celestial sources, situated in regions ranging from the neighbourhood of the earth to the remotest observable parts of the universe.

The most direct evidence for the existence of cosmic electrons comes from their undisputable physical recording in detector systems sent aloft to the upper reaches of the atmosphere to study the cosmic radiation. Such experiments made in 1960 using balloon borne instruments demonstrated, for the first time, that relativistic electrons constituted about 1–3% of the cosmic ray protons. Furthermore, the ushering in of the space age has made it possible to probe the regions of space within the influence of the terrestrial magnetic field, as also the deep interplanetary space, using rockets and space vehicles. Such investigations have revealed again by direct recording, the existence of a high intensity of electrons in the radiation belts, a quiescent flux in the interplanetary space and the spewing out of large numbers of them from the sun at times of violent solar flares. Now then, what about the space beyond the solar system which could never be probed directly by man-made instruments?

Being of very small rest mass, the electrons, of all cosmic ray particles, are vulnerable to certain energy loss processes which are essentially negligible in the case of heavier particles. The two relevant electron energy loss processes of deciding importance are the synchrotron radiation (or magnetic bremsstrahlung) and the inverse Compton scattering. In cosmic situations an overwhelming fraction of the synchrotron radiation is emitted in the radio region by electrons spiralling along magnetic field lines, though in some discrete sources, and under favourable conditions, it can extend to the optical and occasionally to the X-ray region. In case of inverse Compton scattering, a fast electron collides with a soft photon, as in the radio or optical region, and elevates it to a photon of higher energy, such as X-rays and γ-rays, itself emerging with reduced energy.

When in the early fifties it was realised that an appreciable part of the cosmic radio noise studied by radio astronomers was of synchrotron origin, great interest was directed towards the study of cosmic electrons; it also simultaneously demonstrated, independently, the existence of weak magnetic fields in cosmic space. As will be evident later, more recent work has revealed the plausible origin of some cosmic X and γ radiations as due to inverse Compton scattering of cosmic electrons with soft photons in the Galaxy and probably beyond. Thus we can claim that cosmic electrons are present in almost all regions of the observable universe and that they in turn help to disclose the nature of the magnetic fields and radiation fields existing therein.

1.1. Scope of the present review

At the present stage of our knowledge, it seems convenient to consider cosmic electrons under the following major heads: (a) cosmic electrons existing in general regions of space, namely, the solar system, the interstellar space of the Galaxy and the intergalactic space, and (b) cosmic electrons residing in galactic and extragalactic discrete sources. The study of discrete sources, shining in the radio region through synchrotron emission, is a subject by itself; hence we will not attempt here to cover this topic.

Our knowledge of electrons in the solar system comes chiefly from direct measurements of the cosmic radiation in the immediate vicinity of the earth and in relatively deeper interplanetary space. It is through such observations that we are enabled to ascribe a number of important characteristics to the electrons that should exist in interstellar space, thereby permitting the inference of much important astrophysical information. Such observational data on cosmic ray electrons has been the outcome of a variety of experiments made with sophisticated instruments carried in balloons, rockets and spacecraft during recent years; the basic principles on which these instruments are based are briefly summarised in Section 2 in order to make this article complete. The observational data available at present are described in Section 3.

The discovery that a very large fraction of the background cosmic radio noise is of galactic origin, and is the synchrotron emission of relativistic electrons in interstellar space, establishes the direct link between radio astronomy and cosmic ray electrons. The first fruit of this union is that it enables one to combine our knowledge on the measured energy spectrum of cosmic ray electrons near the earth and the brightness distribution of the background radio noise, to deduce the cosmic electron spectrum in interstellar space. Thereafter, we are enabled to use this interstellar electron energy spectrum to infer information on the origin of these electrons; inferences are also made of the solar modulation of cosmic ray electrons. These are described in Section 4.

The brightness distribution of the background radio noise received from different galactic directions can, in principle, be employed to probe in a powerful way the state of interstellar space. In particular, it becomes possible to ascribe meaningful mean magnetic field strengths along some favourable galactic directions. The existence of a galactic radio halo which was sometimes acclaimed as an important discovery of our times, is being increasingly questioned by radioastronomers during recent years. In this connection our knowledge regarding cosmic electrons in the Galaxy, allows us to examine the radio data for the halo in a critical manner. All these are included in Section 5.

It has been realised that some special features of the spectral shape of the interstellar electron spectrum carry the signature of the confinement region of the cosmic rays. It now seems possible that with arguments drawn from a number of sources, one can more or less rule out the universality of cosmic rays. A model in which the cosmic rays are essentially confined within the galactic Disk seems favoured. These are critically examined in Section 6.

It is now generally believed that a small fraction of the background cosmic radio noise is of metagalactic origin. During recent years it has also been discovered that there exists a background cosmic X-radiation of isotropic nature, which is again thought to be of metagalactic origin; very recently evidence has also been obtained for an isotropic gamma ray component. It would then seem that while the former is likely to arise from synchrotron radiation emitted by electrons in the metagalaxy, the latter two possibly result from inverse Compton scattering of electrons. It is therefore evident that the connection between the isotropic radio, X and γ radiation, and the cosmic electrons in the metagalaxy, can be used as a new handle to derive information on the state of metagalactic space and/or sources, albeit with considerable speculation at present. The general scope of such investigations is briefly stated in Section 7.

2. Experimental Methods

The low intensity of electrons among the primary cosmic rays and their exclusive electromagnetic interaction properties with matter, have posed special difficulties in their identification and detailed study. It has therefore been necessary to devise specific detector systems to take advantage of their low mass, their electromagnetic interaction properties and the absence of their strong interactions, to identify individual cosmic ray electrons immersed in an overwhelming background radiation of all kinds of particles, and determine their energy and charge. In order to achieve this, a variety of ingenious instrumentations have been successfully developed during the last decade, thereby leading to rapid advances in this area of research. While the technical details of the diverse detector systems employed in these studies will be superfluous here, the basic principles involved and the associated advantages and shortcomings will, we believe, help in a better appreciation and evaluation of the results and interpretation; we also trust that such a treatment will make this article more complete. For this purpose we will summarise briefly the basic philosophy behind various kinds of instruments employed. Also, since a great majority of all experiments so far undertaken have been carried out in high flying balloons, important corrections have to be made for secondary electrons produced in the atmosphere overlying the balloon; a brief treatment of this topic is also included in this section, while the relevant calculations have been relegated to an appendix. It is hoped that the latter will be of direct interest to the cosmic ray experimenters, and the former will help others to assess the reliability in the interpretation of the observational data.

2.1. Detecting systems

2.1.1. *The Cloud Chamber Technique*

Two of the very early attempts to discover the existence of electrons in the cosmic ray beam (Critchfield *et al.*, 1950; Earl, 1961) were made by flying multiplate cloud chambers which were randomly expanded. This technique has two special merits in its favour: (i) Being a visual detector it enables almost an unambiguous identification of electrons and γ rays, and (ii) the simultaneous detection of γ rays permits corrections to be made for the contribution due to secondary electrons produced in the atmosphere above the detector. The important drawback of such experiments, however, is the small number of wanted events that can be collected using random expansions. With the introduction of other sophisticated detector devices, both visual and electronic, the cloud chamber method has since been abandoned though one last attempt was later made by Schmoker and Earl (1965) with a magnetic cloud chamber.

2.1.2. *dE/dx vs. E Detector*

At sufficiently low energies (say <100 MeV), electrons can be detected and their energies determined by the use of a comparatively simple system wherein the energy loss ($\mathrm{d}E/\mathrm{d}x$) and total energy (E) are measured in conjunction with suitable anti-coincidence counters to reject unwanted events. This method takes advantage of the fact that at these energies the electrons are still relativistic, whereas protons and heavier nuclei ionise heavily in the energy loss counter. Because of their simplicity and compactness such detector systems have been used with immense advantage in deep space probes to measure low energy electrons beyond the magnetosphere (Cline *et al.*, 1964; Fan *et al.*, 1968a; Simnett and McDonald, 1968). Mention might also be made of a variation of this method which was employed in the pioneering balloon experiments of the Chicago Group (Meyer and Vogt, 1961). A crucial requirement in these experiments is a reliable knowledge, from laboratory calibrations, of the efficiency and effective aperture of the detector as a function of energy for an omnidirectional radiation.

2.1.3. *dE/dx, E, Čerenkov Combination*

The basic principle behind a number of experiments dealing with electrons of energy between about 100 MeV and few GeV, and in some cases up to tens of GeV, is the following: In addition to the energy loss, dE/dx, and total energy, E, counters, a gas Čerenkov counter with suitable gas pressure is included in the telescope geometry such that the corresponding gas Čerenkov threshold enables an efficient rejection system for the abundant nuclear active particles. Typical examples of detector systems which take advantage of this principle are due to L'Heureux and Meyer (1965) and Webber and Chotkowski (1967). In the former experiment, 13 radiation lengths equivalent of lead glass was used as the E counter along with an appropriate anticoincidence shield, while in the latter it was only 7.2 radiation lengths. It is apparent that the depth of the E counter primarily determines the highest energies upto which electrons can be studied in this system. A modified version of such a system has been developed by Israel and Vogt (1968) for energies below 100 MeV, wherein they have replaced the lead glass E detector by a spark chamber-lead plate assembly with suitable guard counters. As in the previous class of detectors, here too it is essential to make calibration measurements for the wide range of energies involved using particles accelerated in the laboratory.

2.1.4. *Distribution of Cascade Initiation in Different Material*

There is a fourth class of detecting systems, which distinguishes between electrons and nuclear active particles on a statistical basis from their widely differing efficiency of shower production in a given thickness of producer material or in two kinds of producer materials of different Z, but same depth for nuclear interactions. The former variation has been successfully developed and used by Agrinier *et al.* (1964) and Smith and Frye (1966) by incorporating the producer material in a spark chamber assembly, while the latter has been used by Bleeker *et al.* (1966) in conjunction with a lead glass total energy spectrometer. The major drawback of this instrument is its inability to identify unambiguously individual events, thereby leading to uncertainties in the flux and energy spectrum.

2.1.5. *Nuclear Emulsions*

Of all the detector systems so far used at energies greater than a few GeV, the nuclear emulsion is the one in which the entire cascade development of the electron is visually observed. Some of the resulting advantages of this technique are almost unique: (i) individual high energy electrons can be identified without any ambiguity even in the presence of an overwhelming flux of other particles; (ii) comparatively reliable methods exist for estimating the energy of electrons right upto thousands of GeV; (iii) electron pairs resulting from the materialisation of high energy γ rays are also detected and identified with equal efficiency permitting thereby dependable corrections for atmospheric electrons. On the debit side we have the absence of time resolution for individual events because the nuclear emulsion is essentially an integrating system; the tiresome microscope scanning involved is also often considered to be a factor against its adoption. The special merits of this detector have been exploited a great deal by the Bombay Group (Daniel and Stephens, 1965; Anand *et al.*, 1968e), which has extended the electron energy spectrum upto hundreds of GeV. Even the absence of time resolution of the emulsions has been partially rectified by the use of a moving plate mechanism attempted by Freier and Waddington (1965).

2.1.6. *Charge Determining Experiments*

A very important parameter associated with the study of the electron component is its charge composition. The most successful attempt so far made towards determining this is originally due to De Shong *et al.* (1964), who made use of a permanent magnet along with two sets of spark chambers to define the trajectory of the electron, one before and one after deflection, and a shower spark chamber for electron identification. This instrument has been further improved by Hartman (1967), by the inclusion of a gas Čerenkov detector to enable the determination of the momentum and charge of electrons up to 5–10 GeV. Attempts have also been made to determine the charge ratio of electrons by taking advantage of the difference in the geomagnetic threshold energies for electrons and positrons as a function of the arrival angles (Bland *et al.*, 1966; Daniel and Stephens, 1965, 1967). At very low energies, Cline and Hones (1968) have detected positrons from the emission of characteristic γ rays associated with their annihilation in an instrument carried in a deep space probe.

2.1.7. *Future Scope*

At this stage it may be profitable to contemplate a little on the scope of future experimental systems. It seems an obvious conclusion that many future experiments will be made by the use of earth satellites and deep space probes; a great attempt in this direction has already been made by the Russian scientists in their massive satellite Proton I (Grigorov *et al.*, 1966). Many others are perhaps on the way in the U.S.A. Considerable effort is now being devoted to develop sophisticated assemblies to identify electrons, and measure their momentum and charge up to hundreds of GeV using all manner of combinations of visual and electronic detectors including the use of permanent magnets (superconducting magnets are also contemplated), wide gap spark chambers and nuclear emulsions (Smith, 1968; Cowsik *et al.*, 1969). In connection with experiments associated with the Stanford Linear Accelerator producing electrons of energy up to 20 GeV, special scintillating crystals have been successfully developed to measure electron and γ ray energies accurate to about 1% (Hofstadter *et al.*, 1969). It is certain that such developments will soon be adopted for the study of cosmic ray electrons, thereby leading to a precise determination of the energy spectrum of electrons.

2.2. Atmospheric and re-entrant electrons

In all balloon experiments designed to collect data on cosmic ray electrons, an important correction has to be made for secondary electrons produced in the terrestrial atmosphere. Though almost all recent balloon observations have been made under very small amounts of residual atmosphere ($\lesssim 5$ g/cm^2), production of secondary electrons even in this thin overlying mass of air, assumes an important proportion because of the low abundance of cosmic electrons. Two approaches have been adopted in the past to make this correction: (i) calculate quantitatively the expected contribution of electrons produced by cosmic ray particles in interactions with the constituents of air atoms, and (ii) extrapolate to the top of the atmosphere the experimentally determined growth curve for the appropriate kind of events. In this section we shall very briefly attempt to inquire how reliable are these methods in order to make the reader familiar with the uncertainties involved in the evaluation of primary electron flux.

Re-entrant albedo electrons over any geographical location are those atmospheric electrons that escape out of the atmosphere, from a conjugate location on earth, get trapped in the earth's magnetic field and are guided to the point of observation. Though the flux of re-entrant albedo is negligible at energies greater than the geomagnetic threshold, it can still be an important correction if the experimental technique involves large uncertainties in the energy estimation. For locations where the geomagnetic threshold energy is $\lesssim 1$ GeV, the flux of re-entrant electrons is of the same order as that of the primaries at energies close to the threshold. Hence large uncertainties are introduced in the evaluation of the primary flux by either of the methods. Needless to mention here that it adds further doubts under circumstances when the geomagnetic threshold energy itself is not known reliably (Hoffman and Sauer, 1968).

2.2.1. *Calculation of Atmospheric Electrons*

In the past, this method of correction has been extensively followed because of the difficulty of obtaining a reliable growth curve for electrons; such corrections are usually carried out using the only detailed calculations of Perola and Scarsi (1966), and Verma (1967a). It will be shown in Appendix I that one important uncertainty in these calculations is the deduction of the pion production spectrum over a given latitude. The pion production spectra deduced by the use of accelerator data by these authors for Fort Churchill (Canada) and Hyderabad (India) are shown in Figure 12 in Appendix I. It is evident from this figure that these calculations do not agree with one another, except in narrow energy regions; also the pion production spectrum deduced from the γ ray spectrum measured over Hyderabad in the energy region of 1–40 GeV (Stephens, 1969) has an absolute intensity significantly lower than the former calculations. We are inclined to believe that since the pion production spectrum deduced from the γ ray spectrum is comparatively straightforward, involving only the kinematics of a two body decay process, it should be reliable. It seems to us therefore that a possible reason for the discrepancy in the former calculations is the choice of extrapolated parameters of pion production in nucleon-nucleus collisions at energies far beyond the domain of the presently existing accelerators.

One can also see from Appendix I that, except at low energies, where the angular distributions of the decay products are important, the calculations of the energy spectrum of secondary electrons from the pion production spectrum are expected to be a straightforward one. However, one can notice from Figure 13 in Appendix I, that the electron spectra calculated by Perola and Scarsi (1966) and Verma (1967a) do not agree with one another, even to the degree of agreement between their pion production spectra in Figure 12. Shown, for comparison, in Figure 13 is the electron spectrum deduced from the observed γ ray flux over Hyderabad (Stephens, 1969), which was found to be consistent with the observed electron spectrum below the geomagnetic threshold energy. From these comparisons, we feel that the probable reason for the above discrepancies, apart from the uncertainty in the pion production spectrum, is due to simplified assumptions made for the energy distributions of the decay particles.

2.2.2. *Extrapolation Using the Electron Growth Curve in the Atmosphere*

The extrapolation method of determining the primary flux from the observed growth curve can be considered reliable if one can establish a satisfactory intensity altitude curve for the electron component at the desired energy interval. It can be noticed from Appendix I that the shape of the growth curve is energy dependent both for the secondary and for the primary electrons. Figure 14 in Appendix I shows that the growth curve for the secondaries becomes steeper as the energy increases, since the atmospheric depth at which the contribution from the decay of π^0-mesons (which has a steeper growth curve than that from $\pi^\pm$-decays) becomes important, decreases with increasing energy. Further, the attenuation of the primary electrons depends upon the spectral shape of the electron component at the top of the atmosphere. The experimental growth curves demonstrated in Figure 14 for similar energy intervals by different groups give clear evidence to the confused situation in this matter.

To summarise, we have shown that large uncertainties exist in the theoretical calculations on the atmospheric electrons, though the degree of accuracy claimed in individual works is better than 20%. Further, we have also shown that the extrapolation methods so far adopted require to be improved. Because of these reasons, the errors involved in the evaluation of the primary electron flux could be large especially at energies $<$ a GeV, where the magnitude of secondary corrections is comparable to the primary flux at a depth of a few g/cm^2 in the atmosphere.

3. Cosmic Electrons in the Solar System. Observational Data

The discovery of the electrons among the cosmic radiation has had an undulating history. When the charged particle nature of the radiation was first established through the latitude effect during the early thirties, it was generally believed that cosmic rays consisted predominantly of electrons. However, this attribute was abandoned, when during the forties it was demonstrated conclusively that the primary radiation consisted almost exclusively of protons and heavier nuclei. The next serious attempt made in 1950 (Critchfield *et al.*, 1950) to detect cosmic ray electrons, indicated an upper limit which was so low that it discouraged further studies until 1960. In the mean time the connection between cosmic electrons and the background radio noise had been established, thereby reviving interest to make fresh attempts with new and improved instrumentation. It was only in 1961 the first reliable evidence for the existence of a finite flux of cosmic ray electrons was reported (Earl, 1961; Meyer and Vogt, 1961). During the ensuing period of less than a decade, phenomenal progress has been achieved in obtaining observational data, which in turn has led to further developments in this field. We will now proceed to summarise the observational data available from various experiments so far carried out.

3.1. The flux and energy spectrum

The realisation that a great wealth of interpretative information can be acquired through a determination of the flux and energy spectrum of cosmic ray electrons, has been the reason for very many experiments of this nature. The result is that within a short period of time, we have a reasonably reliable knowledge of the energy spectrum from about an MeV upto a few hundred GeV. In Figure 1 all reliable measurements in the entire energy region are summarised; however, for reasons that will soon be apparent, we have included in the 100 MeV – 10 GeV region only those measurements which were made during the period of minimum solar activity 1965–66. We will now critically examine the data included in this figure under four different energy intervals. One important reason for this division of energy is that each of the intervals has associated experimental problems of differing nature and hence require different kinds of approach and treatment. Furthermore, there are also more basic reasons why such a division is called for; these will be explained as we proceed further.

3.1.1. *The 1–20 MeV Energy Regime*

If such low energy electrons are present in the near interstellar space, it seems likely that they may not encounter much difficulty to worm their way into the solar system, since their gyroradii will be very small compared to the magnetic irregularities in the solar wind (Parker, 1964). Notwithstanding this feature, it seems obvious that in order to detect these low energy galactic electrons, one will have to avoid the vicinity of the earth's upper atmosphere and even the radiation belts. It therefore follows that reliable measurements in this energy range can be made only with instruments carried in deep space probes. Such experiments have already been carried out by Cline *et al.* (1964), Cline and Hones (1968), Cline and McDonald (1968a, b), Simnett and McDonald (1968), and Fan *et al.* (1968a). For the sake of completeness it might be mentioned that attempts have also been made to measure the electron intensities below about 40 MeV using balloon borne instruments (Beedle and Webber, 1968). Of all these observations, the most recent one by Simnett and McDonald (1968) seems to

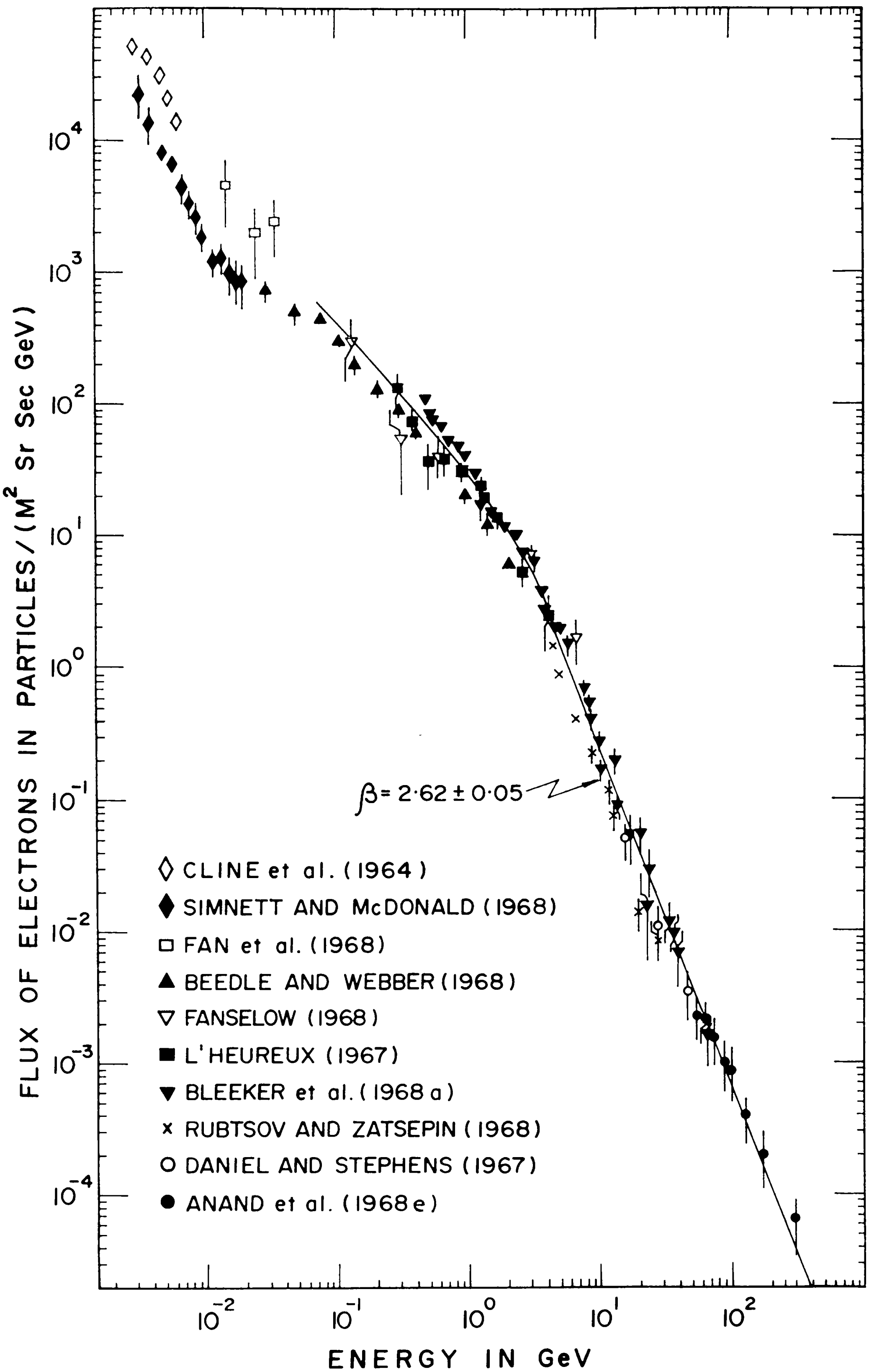

Fig. 1. The differential energy spectrum of cosmic ray electrons. The same symbols used for various investigations here, will be continued in all subsequent figures containing electron flux data.

be the most careful and reliable one. These measurements were made using a $\mathrm{d}E/\mathrm{d}x$ vs. E scintillator telescope on board the IMP-IV Satellite. The measured electron intensity in the energy interval 2.7–21.5 MeV was carried out during 1967 when the solar activity was at a low level, leading to a flux which is believed to be uncontaminated by solar electrons. The differential energy spectrum thus obtained beyond about 10^5 km from the earth is well represented by a power law of the form

$$\mathrm{d}J/\mathrm{d}E = J_0\, E^{-\beta} \text{ electrons m}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}\,\text{MeV}^{-1}, \qquad (1)$$

where $J_0 = 132$ and $\beta = 1.75$. Though all presently available data strongly indicate a galactic origin for these particles, it may not be unwise to retain some reservation about this aspect until it is so established beyond doubt. Nevertheless, in all our interpretative attempts here, we will assume that these low energy electrons are of extrasolar origin.

3.1.2. *The 20–200 MeV Energy Regime*

The greatest amount of misgivings, experimental as well as interpretative, encompass this energy region at present. Firstly, it is expected that solar modulation effects will become increasingly important in this energy interval. Secondly, it has recently been observed from balloon experiments that there exist considerable differences in the electron flux measured during day and night (Jokipii *et al.*, 1967; Webber, 1968). Thirdly, since the great bulk of data so far available at these energies are derived from stratospheric balloon ascents, there is likely to be uncertainties introduced because of atmospheric electrons. The data available up to date in this energy region is both meagre and of doubtful nature (Schmoker and Earl, 1965; Freier and Waddington, 1965; Webber and Chotkowski, 1967; Beedle and Webber, 1968). Special mention may be made here of the results of Israel and Vogt (1968), who at energies between 17 and 63 MeV get flux values far lower than that of other workers; their results are even consistent with zero flux for the primary electrons. Notwithstanding all this, it is indicated from Figure 1 that the spectrum in this energy interval is rather flat and cannot be described by a simple power law; this flatness in the spectrum also leads to a rather sharp discontinuity at either extremity of this energy interval.

3.1.3. *The 200 MeV – 10 GeV Energy Regime*

The foremost reason to have this separate energy interval is that electrons with these energies are responsible for an overwhelming fraction of the galactic background radio continuum of synchrotron origin. Though electrons with these energies are also likely to be influenced by solar modulation, not enough reliable flux data is available over a long enough period to distinguish the 11-year variations of the intensity. Nonetheless, sufficient volume of data is now available for the period of minimum solar activity (1965–66) to permit the construction of a dependable energy spectrum in this energy interval (Smith and Frye, 1966; L'Heureux, 1967; Webber and Chotkowski, 1967; Simnett, 1967; Hartman, 1967; Bleeker *et al.*, 1968a; Fanselow, 1968; Rubtsov and Zatsepin, 1968; Bland *et al.*, 1968). The observational data in this energy regime can be well represented by a smooth curve with an index continuously increasing from about -1.2 at about 200 MeV to -2.6 at 5 GeV, and thereafter remaining constant; if desired the existing data can also be, equally well, represented by two simple power law spectra one with the index ≈ -1.3 between about 200 MeV and 3 GeV and the other with ≈ -2.6 between 3 and 10 GeV.

3.1.4. *The 10–300 GeV Energy Regime*

This is the energy regime which, within the limits of present experimentation, is known to be free from effects due to the 11-year solar modulation. Consequently, we can state with confidence that the energy spectrum, and the absolute intensities which we sample near the earth should be well preserved in the near interstellar space. Existing data between 10 and 50 GeV are primarily due to the Bombay (Daniel and Stephens, 1966), the Dutch (Bleeker *et al.*, 1968a), the Russian (Rubtsov and Zatsepin, 1968), and the Japanese (Danjo *et al.*, 1968a) Groups; beyond about 50 GeV all data points available so far are due to the Bombay Group (Anand *et al.*, 1968e). It is clear from Figure 1 that the energy spectrum in this energy domain is quite well determined and can be represented by a single power law

$$(\mathrm{d}J(E))/\mathrm{d}E = 126 \quad ^{-2.62\pm0.05} \text{ electrons m}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}\text{ GeV}^{-1}. \qquad (2)$$

The spectrum at such high energies is of deciding importance to our understanding of the region of space confining the cosmic ray particles and their residence time therein; these aspects will be treated in detail later.

3.2. Temporal and Spatial Variations of Intensity

A wide variety of observations on the nucleonic components of the cosmic radiation extending over a period of about two decades has established the existence of a periodic variation of their intensities in anticorrelation with the well-known 11-year solar activity; it is also found that, even at the time of minimum solar activity, there remains an appreciable residual modulation of the galactic cosmic rays. Two of the principal objectives in such studies are: (i) to use the intensity variations of the cosmic rays as a probe to understand the state of our interplanetary space, and (ii) to deduce the intensity and energy spectrum of the radiation beyond the solar system i.e. the near interstellar space. Mention should also be made of the fact that from a comparison of the electron modulation with that of the nucleonic components, one can separate the effects due to rigidity and velocity dependent contributions, leading to definitive deductions regarding the mechanism of solar modulation and diffusion in interplanetary space. However, in view of the comparatively recent discovery of electrons, adequate flux measurements over a long enough period are not available to accomplish this. Not only that, even the limited number of observations so far made are in serious disagreement with one another. In fact there are two schools of opinion on this subject: one claiming that there is no detectable variation of intensity over the period 1960–67 and that if modulation existed it should be very small compared to that observed for the nuclear particles (Bleeker *et al.*, 1968b; L'Heureux *et al.*, 1968), and the other (Webber, 1967) claiming to have observed large variations of 20–40% during the period 1965–66. It is thus seen that the present situation here is very unclear, but it is hoped that data from electron detectors carried in earth orbiting satellites would provide decisive evidence on this issue in the near future.

It might also be appropriate here to mention about the measurement of the radial heliocentric intensity gradients for the electrons which also gives information on solar modulation and the state of interplanetary space. Though, here too, data is available for the nuclear particles, no such information is so far available for electrons; this too is an important measurement for the future.

3.3. Electron-positron charge composition

The charge ratio R, defined as the fraction of positrons among the total electron component ($R = N^+/N^+ + N^-$) is another observational parameter which is of paramount importance to understand the origin of cosmic electrons. Three experimental approaches have so far been made to determine R.

3.3.1. *The Direct Method*

Here one makes use of a magnet to reveal the sense and magnitude of the curvature of the particle trajectory and therefrom determine the charge and momentum of the electron. Such experiments have been pioneered by the Chicago Group (Deshong *et al.*, 1964; Hartman *et al.*, 1965; Hartman, 1967; Meyer, 1969); in fact until now these are the only attempts of this nature. The energy realm which has been investigated by this method ranges from about 100 MeV up to about 10 GeV.

3.3.2. *The Positron Annihilation Method*

By its very nature this method is applicable only to very low energy electrons and so far it has been successfully employed by Cline and Hones (1968) at 0–3 MeV using instruments carried in OGO-I and OGO-III satellites well beyond the region of geomagnetic influence. The basic principle of the method is to stop the positron in a beryllium well or a CsI scintillator and detect the 0.51 MeV annihilation quanta in a γ-ray spectrometer consisting of two other CsI scintillators.

3.3.3. *Method Using Geomagnetic East–West Asymmetry*

It is well known that for any location on the earth, the magnetic threshold rigidity of cosmic ray particles near the upper reaches of the atmosphere, will depend on their charge and arrival direction. The variation of the threshold rigidity as a function of zenith angle is more pronounced in the East–West plane and lower geomagnetic latitudes, the effect being opposite in sense for positive and negative particles. This feature has been taken advantage of, by Bland *et al.* (1966), who have used the gross East–West asymmetry observed, to deduce the charge composition of electrons. Since, however, in this method all electrons above the geomagnetic threshold rigidity are employed, the East–West asymmetry gets diluted by the high energy electrons, thereby reducing the sensitivity of the method.

An improved modification of this method has been attempted by Daniel and Stephens (1967), in which they have made use of the variation of the threshold rigidity for positive and negative electrons as a function of zenith angle in the East–West plane. In such a case it can be seen easily that since for any given zenith angle the threshold rigidities are different for the two kinds of electrons, those with energies between these two rigidities should have a charge same as that for the lower of the two thresholds. Though in principle this method permits unique determination of the charge, it suffers from practical difficulties. Since the energy interval within which such identification can be made is small, uncertainties in the energy estimation of individual electrons become a serious source of error; in addition the number of useful events for analysis is also very small. A variation of this method to reduce the effect due to errors in the energy estimation is to raise the upper limit of the energy region considered at the cost of slight reduction in the sensitivity of the method. This approach has been recently adopted by Stephens (1969), who has proceeded as follows. If $AE_+^{-\beta}$ and $BE_-^{-\beta}$ represent the differential energy spectra for the positive and negative electrons respectively, one can write the ratio K of all electrons from East (e) to those from West (w) as

$$K = \frac{\mathrm{N}^{\mathrm{e}}}{\mathrm{N}^{\mathrm{w}}} = \frac{A\varepsilon_+^{\mathrm{e}} + B\varepsilon_-^{\mathrm{e}}}{A\varepsilon_+^{\mathrm{w}} + B\varepsilon_-^{\mathrm{w}}}. \tag{3}$$

Here A and B are constants and $\varepsilon_+^{\mathrm{e}}$ is defined as

$$\varepsilon_+^{\mathrm{e}} = \int_\theta \int_\phi \int_{E_+{}^{e}(\theta,\,\phi)}^{E_m} E^{-\beta}\,\mathrm{d}E\,GF(\theta,\phi)\,\mathrm{d}\theta\,\mathrm{d}\phi\,,$$

where $E_+^{\mathrm{e}}\ (\theta, \phi)$ is the threshold energy for a positron arriving at a zenith angle θ to the East and an azimuthal angle ϕ, and $GF\ (\theta, \phi)\ \mathrm{d}_\theta \mathrm{d}_\phi$ is the geometrical factor at that arrival direction; other values of ε's are written in a similar manner. The charge ratio R can now be written as

$$R = \frac{K\varepsilon_-^{\mathrm{w}} - \varepsilon_-^{\mathrm{e}}}{[K\varepsilon_-^{\mathrm{w}} - \varepsilon_-^{\mathrm{e}}] + [\varepsilon_+^{\mathrm{e}} - K\varepsilon_+^{\mathrm{w}}]}. \tag{4}$$

The choice of E^m can be made to suit the errors in the energy estimation as well as the sensitivity of K with E^m. It might be mentioned here that if the energy estimation can be made more precise, this technique of charge identification can be used with great advantage up to about 40 GeV.

3.3.4. *Available Data*

At the lowest energies, namely 0.5–3 MeV, Cline and Hones (1968) have observed in the interplanetary space a finite flux of positrons. However, in the absence of any positive evidence regarding their primary nature, they have placed only an upper limit of 6×10^{-2} positrons cm^{-2} sr^{-1} sec^{-1}. We can now hopefully expect that in the near future we will have decisive data on R at these energies.

In the energy region ranging from about 100 MeV to 5 GeV, extensive measurements by the direct method, have been carried out by the Chicago Group; their latest values (Meyer, 1969) are included in Table I. Further to this, there are two attempts based on the method of East–West asymmetry. In the first, Bland *et al.* (1968) have

TABLE I
The charge composition of cosmic electrons observed and expected in the neighbourhood of the earth

Energy interval (in GeV)	Observed $R = \frac{N^+}{N^- + N^+}$	Expected $R(E)$ A	B
0.17– 0.44	0.29 $\pm$0.09	0.27	0.31
0.44– 0.86	0.10 $\pm$0.07	0.12	0.14
0.86– 1.70	0.08 $\pm$0.02	0.055	0.07
1.70– 4.2	0.046$\pm$0.018	0.04	0.05
4.2 – 8.4	0.01 $\pm$0.08	0.04	0.05
8.4 –14.3	0.15 $\pm$0.18	0.04	0.05

inferred that at about 5 GeV, their observations indicate a near absence of positrons. In the second, the Bombay Group have reported a value of $R = 0.7 \pm 0.2$, at 10–30 GeV (Daniel and Stephens, 1966); a more realistic estimate of the errors made recently has yielded a value of $0.7\,^{+0.3}_{-0.6}$ (Stephens, 1969). While the latter observations suggest an appreciable fraction of positrons at high energies, it should be treated with caution in view of the large errors, the total number of events involved being 13 only.

A careful examination of the data available on the charge composition of electrons as a function of energy reveals, that whereas its significance is unquestionably vital for our understanding of the origin of cosmic electrons – and indeed the cosmic rays in general – the only positive information we have is that at intermediate energies of 0.1–10 GeV, the dominant fraction is due to negative electrons. There is thus a very clear need for overcoming statistical and systematic errors particularly at energies $\lesssim$100 MeV and $>$10 GeV.

3.4. Relative intensities of electronic and nucleonic components

The negligibly small intensity of electrons among the cosmic rays has intrigued scientists right from the early days (Feenberg and Primakoff, 1948; Donahu, 1951) when it was recognised for the first time that the great bulk of the primary cosmic rays are protons. Though there is still no satisfactory explanation for this fact, it is well realised that it holds the key to some vital secret to the origin and propagation of the cosmic radiation; an understanding of the latter will never be complete until we can advance an acceptable explanation for the former. In what follows we will summarise our knowledge on this subject.

In Figure 2a are presented the rigidity spectra for primary electrons, protons, He-nuclei and the S-nuclei having $Z \geqslant 6$, during the period of minimum solar modu-

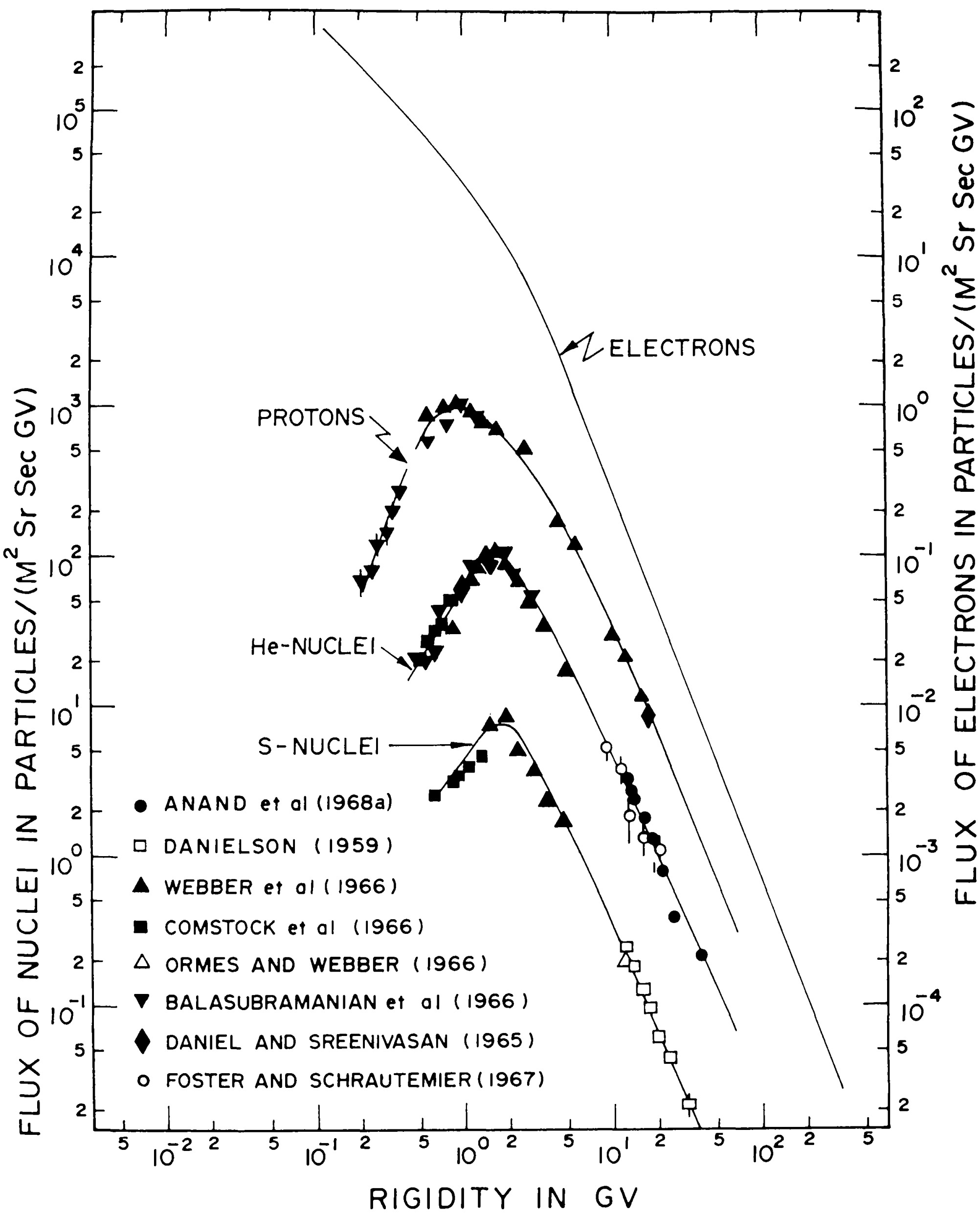

Fig. 2a. Rigidity spectra of cosmic ray electrons, protons, helium and S-nuclei ($Z \geqslant 6$) as observed during the period of minium solar modulation. The electron spectrum is taken from Figure 1.

lation (Anand *et al.*, 1968a). Two very pertinent inferences can be drawn forthright from this figure: (a) all available data which extend up to about 100 GV, show that for rigidities >5 GV, all components have power law spectra with an index ≈ -2.6; these observations are further substantiated by recent observations of Von Rosenvinge *et al.* (1969); (b) as shown in Figure 2b the electron to proton ratio, e/p, is about 4 at 200 MV, 0.2 at 500 MV, 0.02 at about 2 GV, decreasing to about 0.01 at 10 GV and remaining constant thereafter.

3.5. Solar electrons

It will be instructive at this stage to briefly summarise our knowledge on relativistic

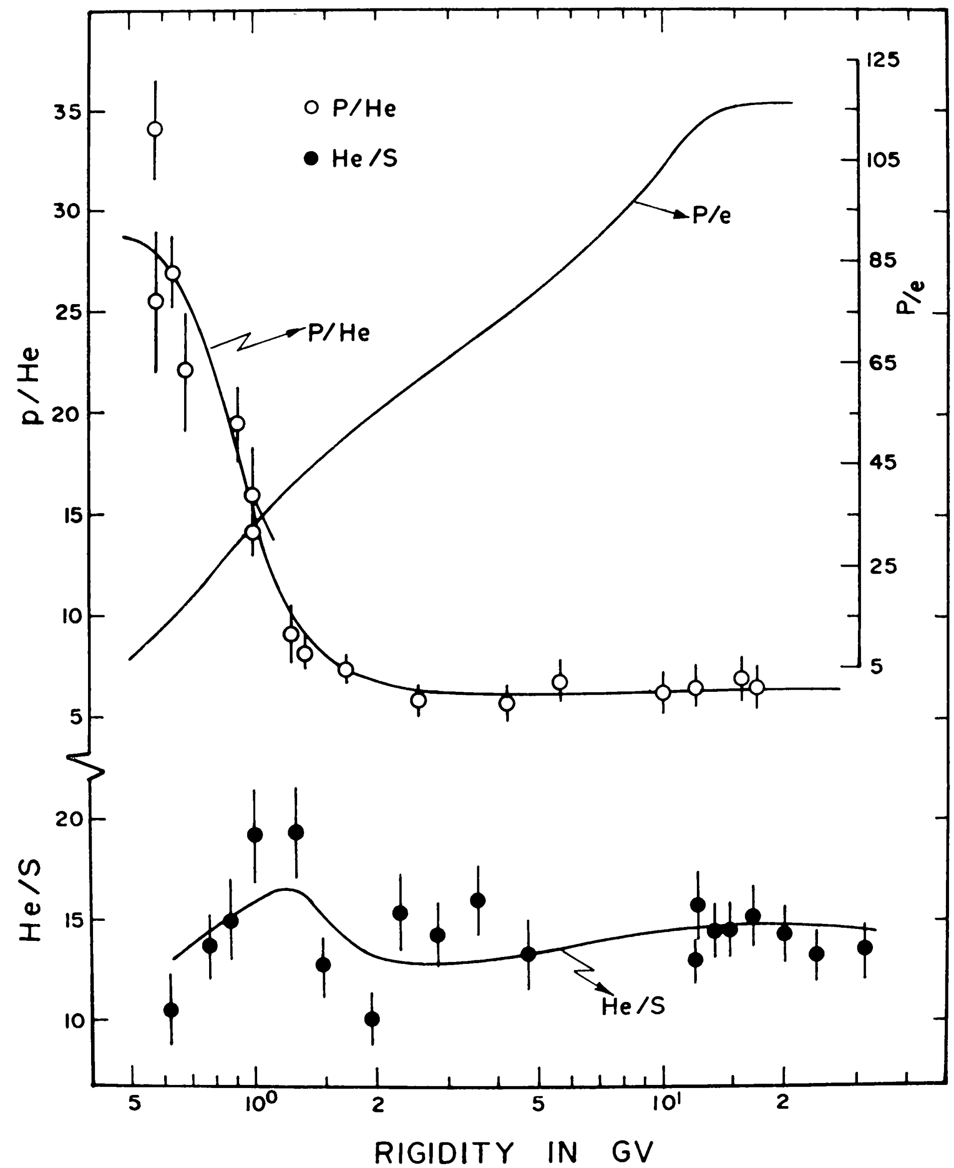

Fig. 2b. The ratios of cosmic ray protons to electrons (*P*/*e*), protons to helium nuclei (*P*/He) and helium nuclei to S-nuclei (He/S) at minimum solar modulation, as a function of rigidity.

electrons emitted from solar flares and detected in interplanetary space. It may be right to say that almost all data so far available on this subject are due to Cline and McDonald (1968a, b); they were obtained during 1963–67 from instruments carried in IMP-satellites and refer to the simultaneous observations of electrons of energy 3–12 MeV and protons of energy 16–80 MeV. Furthermore, much of the inferences drawn by these authors are rooted on a single flare event which occurred on July 7, 1966; hence the conclusions enumerated below should be treated with suitable amount of caution.

These authors find that for certain events the diffusion of particles is on a velocity basis, rather than on kinetic or total energy, or rigidity; those electrons have a power spectrum in differential energy with an index of about −3. Secondly, the electrons detected in the space craft are probably created simultaneously with the flare electrons which cause the microwave and X-ray bursts. Thirdly, it seems probable that only a small fraction of flare electrons escape into interplanetary space.

It is evident from the above that our knowledge on relativistic electrons emitted from solar flares is indeed poor; even the existing information is restricted to energies $\lesssim 10$ MeV. There is, therefore, considerable need for further work, particularly at energies much in excess of 10 MeV. Since the sun is the only celestial source of cosmic ray electrons accessible to us for direct experimentation, it calls for greater effort in this direction.

4. Cosmic Electrons in Interstellar Space

Having summarised the observational data on cosmic electrons existing in the interplanetary space, it seems natural that we should turn our interest to the situation existing in interstellar space. Three different facets of this problem seem to be of relevance here for discussion. Firstly, at energies $\gtrsim 100$ MeV one could make use of the electron spectrum observed in the neighbourhood of the earth together with information on the galactic background radio continuum, or solar modulation, to infer the interstellar spectrum. Secondly, since we now know that the high energy nucleonic component of the cosmic radiation has traversed about 3.5 g/cm^2 of matter, it should involve nuclear collisions with the ambient gas nuclei, leading to electron production through pionic decay. The electron flux arising from this source, as also their charge composition, could be calculated with confidence, thus providing a means of separating this component from the total. Thirdly, the situation at energies <100 MeV is quite unclear; nonetheless one could examine various possible mechanisms which could contribute to electrons at such low energies. All these aspects will be critically inquired in this section.

4.1. The interstellar electron spectrum at energies > 100 MeV

In principle, the interstellar electron spectrum outside the solar system, i.e. the near interstellar space, can be deduced by demodulating the observed spectrum near the earth for effects due to the diffusion and propagation of interstellar electrons into the region of influence of the solar wind, However, in order to do this one requires detailed information on the temporal variation of the electron intensity over a long enough period of the 11-year solar cycle which does not exist now. Recourse has therefore been taken to the following unique feature of the electron component. It is now well recognised that the galactic continuum radio emission arises from the synchrotron radiation of relativistic electrons spiralling along weak magnetic field lines existing in interstellar space. The continuum radio spectrum has been well determined over a wide range of frequencies for certain favourable celestial directions. Furthermore, we now have a rigorous enough treatment of the theory of synchrotron emission, to relate in a detailed manner the interstellar electron spectrum and the mean relevant magnetic fields. Such a procedure, which is described in great detail in Section 5, permits one to deduce the interstellar electron spectrum reliably for energies

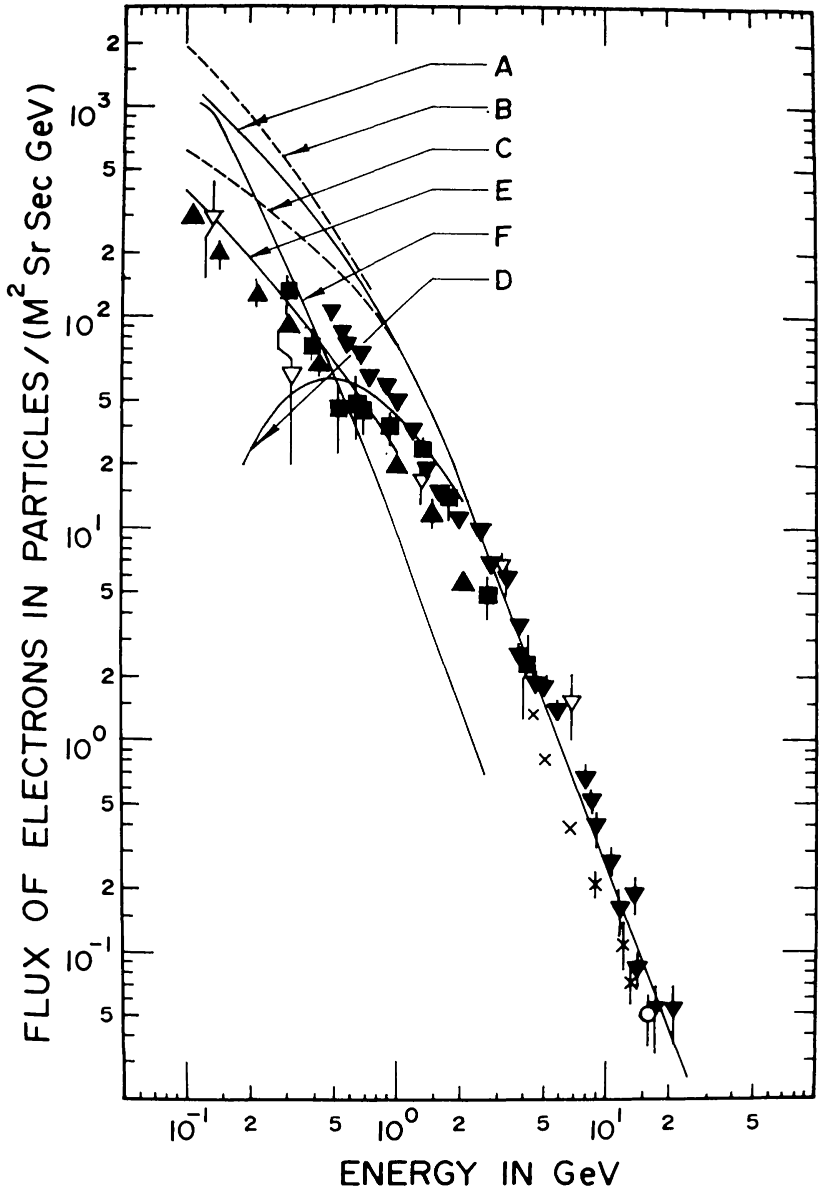

Fig. 3. The differential energy spectrum of electrons. Curves *A*, *B* and *C* are the radio emitting electrons corresponding to the radio brightness distributions *A*, A_1 and A_2 respectively of Figure 8. Curves *D* and *E* are the Rv/c and v/c dependent modulated spectra respectively of curve *A*, and curve *F* is the equilibrium secondary electrons in the Galaxy.

>100 MeV; the spectrum thus derived by Anand *et al.* (1968b) is shown as curve *A* in Figure 3. It is evident from this figure that the possibility of the same intensity of electrons seen near the earth at energies $\lesssim 1$ GeV, to exist in interstellar space, is untenable; this means that there is appreciable solar modulation present, though one could still argue about its precise magnitude.

4.1.1. *Solar Modulation of Electrons*

In Figure 3 are also shown the experimental observations made in the intermediate energies during the time of minimum solar activity 1965–66. It is evident that a comparison between the deduced interstellar radio electron spectrum (curve A of Figure 3) and the electron spectrum measured in the vicinity of the earth, permits one to infer the solar modulation of electrons. At this point it may be instructive first to recall our knowledge regarding the modulation of the nucleonic component as interpreted within the framework of the solar wind model originally suggested by Parker (1963). Firstly, for rigidities greater than about 5 GV there seems to be very little modulation. Secondly, for rigidities 0.5–5 GV the modulation function exp $(-K(t)/R(v/c)$, where K is a time dependent constant and v/c is the ratio of the velocity of the particle to the velocity of light, can best represent the observations at solar minimum with a value of K between 0.4 and 1 GV (Biswas *et al.*, 1967; Gloeckler and Jokipii, 1967; Ramaty and Lingenfelter, 1968a). Thirdly, for lower rigidities the observational data suggest that the modulation is velocity dependent (Balasubramanian *et al.*, 1965; O'Gallagher and Simpson, 1967; Durgaprasad *et al.*, 1967).

For electrons it is found from Figure 3 that (i) between about 0.5 and 5 GV, the modulation can be described equally well by an $R(v/c)$ or R dependence with a value for the constant $K \approx 0.6$ (expected shape near the earth is then given by curve D), (ii) for $0.1 \lesssim R \lesssim 0.5$ GV there is a constant modulation, which can also be understood as velocity dependent, with $K \approx 1.3$ (expected shape near the earth is then given by curve E), and (iii) at rigidities <100 MV also, a modulation similar to that in (ii) is expected to continue from a comparison of the calculated interstellar secondary electron spectrum and the observed intensities (Section 4.2). It may also be stated that at the present state of our knowledge even a modulation which is all velocity dependent or constant, cannot be ruled out. It is certain that in the near future, information will be available from satellite measurements on the solar modulation of electrons from time variation measurements of the intensity over the 11-year cycle; it will then be interesting to see how such inferences agree with that represented as curve A of Figure 3.

One might also mention here of the possibility of using the observed flux of positrons to deduce information on solar modulation. Since all available information clearly points to the fact that essentially all positrons at energies >20 MeV can be accounted for by the decay of pions produced in nuclear collisions suffered by cosmic ray nuclei traversing about 3.5 g/cm^2 of matter, one can calculate reliably the equilibrium secondary positron spectrum in interstellar space. This can then be compared with that observed near the earth to deduce information on solar modulation. Such an attempt has recently been made by Ramaty and Lingenfelter (1968b). However, since our present knowledge on positrons is not precise enough, no definitive conclusions could be derived.

4.2. 'Primary' and 'secondary' electrons in the galaxy

We have seen that the nonthermal radio continuum observations have been employed as a handle to deduce reliably the interstellar electron spectrum at energies between about 100 MeV and 10 GeV. This spectrum is then combined with the direct observations on the cosmic ray electrons above 10 GeV to yield the complete interstellar electron spectrum above 100 MeV (curve *A* of Figure 3). On the other hand no such possibility exists so far to deduce the interstellar electron spectrum at energies between 1 and 100 MeV. The best that has been attempted so far is to suggest that the solar modulation of electrons of 1–20 MeV is likely to be negligible (Parker, 1964) and hence the fluxes of such particles measured in interplanetary space should resemble closely to that in interstellar space. This leaves the region between 20 and 100 MeV as comparatively less understood.

Now, the cosmic ray electrons constitute only a few percent of the nucleonic component; also it is now widely accepted that the high energy nucleonic component has traversed about 3.5 g/cm^2 of matter. Hence it becomes important to examine what fraction of the interstellar electrons is of secondary origin in space, and what fraction of primary origin (i.e. directly from sources). Since we know reasonably well the physical processes involved in the production of secondary electrons, the flux of high energy cosmic ray nuclei in interstellar space and the mean amount of matter traversed by them, it becomes possible to calculate the equilibrium secondary electrons in space and then compare it with the total interstellar spectrum of Figure 3. Such a comparison would permit us to separate the electrons of primary and secondary origin. One could then examine whether deductions thus made are consistent with other consequences such as the dependence of the ratio R with energy. Such would be our general approach in this section.

4.2.1. *Equilibrium Secondary Electrons in Interstellar Space*

Even before the discovery of a finite flux of primary electrons in the cosmic radiation, estimates were made of the electron spectrum arising from nuclear collisions of cosmic ray nuclei with interstellar matter, in order to see whether the intensity of electrons thus produced could account for the observed background radio emission (Ginzburg, 1954; Hayakawa *et al.*, 1958; Tunmer, 1959; Ginzburg and Syrovatskii, 1961). These estimates were then revised after the discovery of the electron component of the cosmic radiation, by many workers (Hayakawa and Okuda, 1962; Ginzburg and Syrovatskii, 1964; Jones, 1963; Gould and Burbidge, 1965; Pollack and Fazio, 1965; Jones, 1965; Daniel and Stephens, 1967), and comparison made with the observed spectrum of cosmic ray electrons. In all these calculations electrons arising only from the decay of mesons created during collisions of cosmic ray nuclei with interstellar matter were taken into account. More recently, calculations have been extended to very low energies by taking into account the contribution of electrons from neutron decay and knock-on processes (Ramaty and Lingenfelter, 1966a; Abraham *et al.*, 1966; Perola *et al.*, 1967). Since in these publications much of the relevant details of calculations have been presented, we shall only summarise briefly the sources of production of secondary electrons in interstellar space without going into mathematical details. Furthermore, the general formulations for the production of secondary electrons in the atmosphere given in Appendix I, will also apply to much of the situation in interstellar space.

Secondary electrons in the MeV region arise mainly through Coulomb interactions of cosmic ray nuclei with the atomic and plasma electrons present in interstellar space. The additional contribution at these energies from processes like neutron decay and *e-e* collisions is $\lesssim 20\%$; another source of such electrons, namely, the decay of radioactive nuclei produced in spallation processes, is also expected to be unimportant compared to knock-on electrons (Verma, 1969). At energies > a few tens of MeV, secondary electrons arising through the decay of mesons created in collisions of cosmic ray nuclei with the interstellar matter, is the main source. The calculation of the high energy production spectrum of the secondary electrons in interstellar space is much simpler than that in the atmosphere, since the decay probability in interstellar space for all particles leading to electron generation can be taken as unity. It is important to point out that in the energy region of a few tens of MeV, where comparable contributions are likely to exist from knock-on and mesonic electrons, the evaluation of the total secondary electron spectrum could be in serious error unless the exact energy distribution of the decay electrons from their parent mesons is incorporated (Zatsepin and Kuzmin, 1962; Scanlon and Milford, 1965).

When once the secondary electrons are produced, they lose energy through ionisation, bremsstrahlung, synchrotron radiation and inverse-Compton scattering during their propagation in interstellar space; a part of them will also be lost by leakage. The equilibrium spectrum of these electrons can be calculated from their production spectrum by knowing the various rates of energy loss and leakage. In spite of the apparently straight forward procedures outlined above, the estimates made by different workers do not agree to the extent one would desire to have, though such calculations are continuously being revised towards more and more precise ones.

In curve *A* of Figure 4 is shown, what we consider as the most reliable equilibrium spectrum calculated for secondary electrons in the Galaxy for 3.5 g/cm^2 of matter traversed by cosmic rays; at energies relevant to this figure, synchrotron and inverse Compton losses are unimportant for cosmic ray lifetimes $\ll 10^8$ years, for which evidence will be given in Section 6.4. In this curve, the knock-on electron spectrum has been taken from Abraham *et al.* (1966) after correcting for the exact composition of heavy nuclei in the primary radiation as indicated by Brunstein (1968), and assuming that the rate of energy loss of an electron through ionisation is ≈ 4 MeV g^{-1} cm^2. The electron spectrum arising through the decay of pions at energies less than a few GeV is taken from Ramaty and Lingenfelter (1966a), while at energies greater than a few GeV the curve is reproduced from Stephens (1969), who has made use of the γ ray spectrum in the atmosphere to deduce reliably the production spectrum of pions in the energy region beyond the accelerator domain. In Figure 4 is also shown the data points for the intensities observed in the neighbourhood of the earth below 200 MeV and the radio emitting electron spectrum in the interstellar space above 100 MeV (curve *B*). The following observations can now be made from a careful scrutiny of Figure 4: (a) at energies $\gtrsim 2$ GeV the calculated equilibrium secondary electrons have a power law spectrum (curve *A*) with an index same as the interstellar electron spectrum (curve *B*), but with an intensity of only 10% that in interstellar space; (b) below 2 GeV, the two curves, *A* and *B*, gradually close in and meet one another at about 150 MeV; and (c) the data points fall below the calculated secondary curve for energies <200 MeV but become comparable in the MeV region. In what follows we shall make a careful study of these spectra to derive information on the origin of the cosmic ray electrons.

4.2.2. *The Interpretation of the Spectrum above 100 MeV*

The radio emitting electrons in the Galaxy should, in principle, represent the equilibrium spectrum of all electrons in interstellar space. Hence one can calculate at energies >100 MeV, the expected fraction of positrons among the cosmic ray electrons

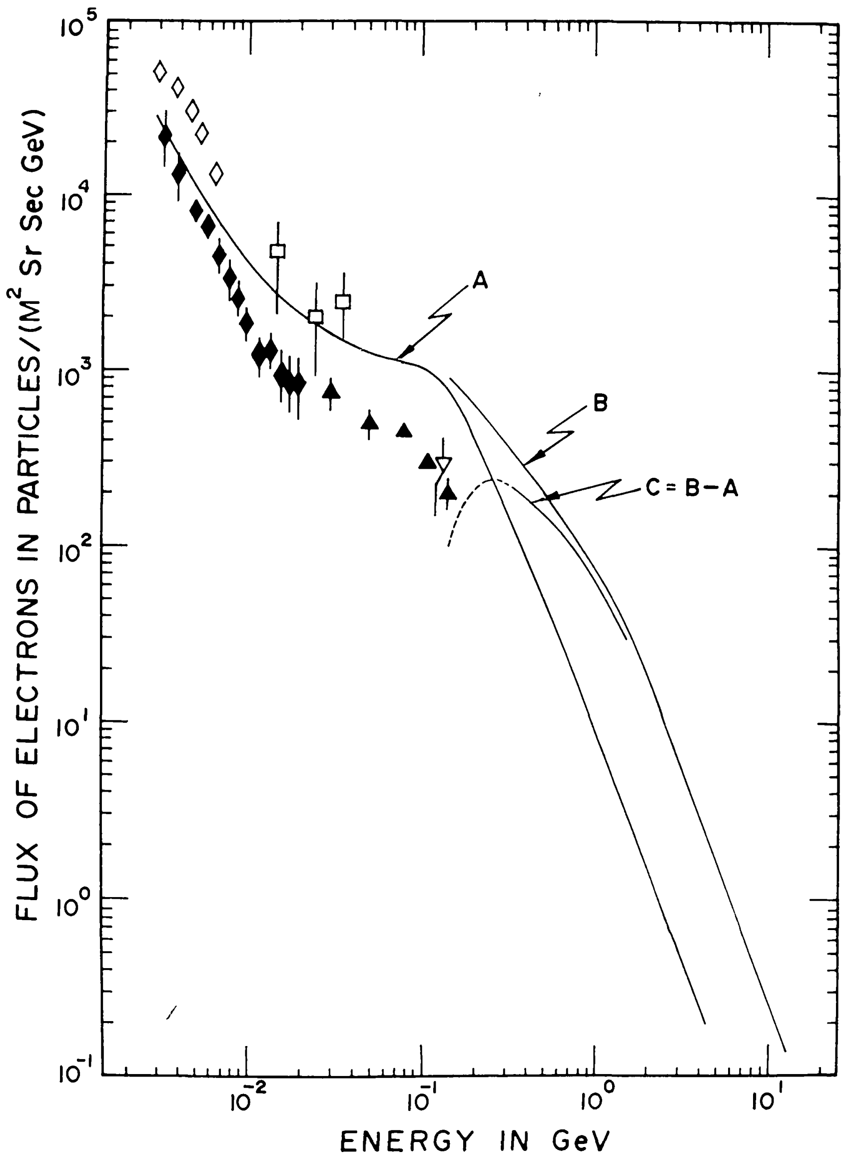

Fig. 4. The differential energy spectrum of 'Primary' and 'Secondary' cosmic electrons. Curve *A* is the equilibrium secondary electrons in the Galaxy corresponding to 3.5 g/cm^2 matter traversed by cosmic rays, curve *B* is the radio emitting electrons in the Galaxy, and curve $C = B - A$ represents the spectrum of directly accelerated electrons.

in the neighbourhood of the earth, using the estimated charge ratio of the equilibrium spectrum of secondary electrons in the Galaxy; this is carried out by assuming that positrons in the primary radiation are only due to the galactic secondaries and that the modulation mechanism is charge independent. Thus the expected fraction of positrons $R(E)$ at energy E is

$$R(E) = \frac{R_s(E)\, N_s(E)\, \mathrm{d}E}{N_t(E)\, \mathrm{d}E}, \tag{5}$$

where the subscripts s and t denote the secondary and total cosmic electrons in interstellar space respectively. The calculated values of R are shown in Table I; the two values given in columns A and B under 'expected R' correspond to values of R_s estimated by Ramaty and Lingenfelter (1966a) and Perola *et al.* (1967) respectively. It can be seen from Table I that the expected and the observed charge composition of cosmic ray electrons are in good agreement within observational errors, thus providing internal consistency for the procedures followed.

From the above discussions it is evident that the secondary electrons in the Galaxy can account for only $\approx 10\%$ of the equilibrium spectrum of all electrons in interstellar space at energies $\gg 100$ MeV. Hence, the remaining 90% should be considered to be of primary origin, which means that they have been directly accelerated in the sources along with the nucleonic component; their spectrum which is the difference between curves B and A of Figure 4 is shown by curve C. These directly accelerated electrons have a power law spectrum with a spectral index -2.6 above 2 GeV similar to the nucleonic components; the spectrum flattens below 2 GeV and attains a maximum around 200 MeV; below this there seems to be a low energy cut-off. It will be shown later that the spectrum given by curve C is likely to be the injection spectrum for interstellar space. Consequently, it can be stated that these electrons, prior to their injection into the interstellar space, are already modulated at low rigidities; perhaps electrons with rigidity <200 MV are efficiently trapped in the source region. If this is so, then one would expect a similar situation to exist for the injection of the nuclear components as well; presently available data on the nuclear components (Fan *et al.*, 1968b) though subject to considerable modifications due to large ionisation losses and solar modulation effects, is perhaps not inconsistent with this.

The observed charge composition of cosmic ray electrons is consistent with the idea that the directly accelerated electrons are negatively charged; they constitute only 1% of the nucleonic components injected into the interstellar space. The observations of Cline and McDonald (1968a) on electrons (3–12 MeV) and protons (15–80 MeV) emitted in the solar flare of July 7, 1966, also indicate that these components have similar power law spectra in rigidity with an index of about -3 and that the electron to proton ratio is $\approx 10^{-2}$ for the same equivalent rigidity interval. This encourages one to suggest that perhaps it is a general property of all explosive acceleration process to give rise to cosmic ray components, all with similar spectra and with an intensity of electrons which is only about 1% that of the nuclei.

4.2.3. *The Interpretation of the Spectrum between 1 and 20 MeV*

The first observations on electrons of energy 3–12 MeV were made by Cline *et al.* (1964) during the period November 1963 – May 1964 with instruments carried by IMP-I satellite. From short term and long term intensity variations observed during this period, these authors favoured a galactic origin for these electrons. Subsequent observations by Cline and McDonald (1968a, b), particularly from IMP-III satellite, during the period May 1965 – April 1967, showed that while short term intensities are correlated with the general cosmic ray intensity variations, no clear long term pattern was noticeable. These authors also support the hypothesis of the galactic nature of these electrons. These experimental findings suggest that the low energy electrons in interstellar space will have an intensity essentially same as that seen in interplanetary space. We would also like to draw particular attention to the IMP-IV experiment of Simnett and McDonald (1968), in which a sophisticated analysis technique was employed. For solar quiet periods, this experiment yielded a flux value in the 2.7–21.5 MeV region for July–August 1967, which is significantly lower than that observed during November 1963 (Cline *et al.*, 1964). Simnett and McDonald, however, stress that this apparent change in intensity must not be interpreted as a real time variation and that the earlier data from IMP-I are being re-analysed. Under this situation we feel inclined to consider for the present analysis the flux values seen by Simnett and McDonald as representing the intensity in interstellar space.

When the first satellite observations on the low energy electrons were made, Brunstein and Cline (1966) proposed a possible spectral neutrality of cosmic radiation on a similar velocity scale for electrons and protons. Based on this proposal, they conjectured that these electrons and protons have a common origin; they also implied a Fermi-like acceleration of protons and electrons originating from distributed, rather than discrete sources. The latter implication of their proposal was brought in to overcome the serious difficulty in understanding the source spectrum of the very low energy electrons if it has to traverse the 3.5 g/cm^2 of matter after injection. This suggestion had the attractive feature of being able to explain the low abundance of electrons when considered on an energy or rigidity basis. In spite of this, recent measurements of the electron intensities in the energy range of 20 MeV – 200 GeV, necessitate on their model a proton flux over 2 orders of magnitude larger than what is observed for a velocity corresponding to 10 GeV electrons and greater. This is graphically represented in Figure 5. We are therefore inclined to think that presently available information does not favour such a hypothesis.

The early attempt of Abraham *et al.* (1966) to understand the low energy electrons as due to knock-on process seemed to be unsatisfactory since the observational data then available (Cline *et al.*, 1964) was higher than the calculations by a factor of about 3. This led Brunstein (1968) to suggest that there might exist in the interstellar space sufficiently large flux of very heavy cosmic ray nuclei to effectively account for the electrons as due to knock-on. But again, very recent observations on nuclei of charge $\geqslant 26$ (Fowler *et al.*, 1967; Price *et al.*, 1968; Lal, 1969) do not give any credence to it. The whole situation seems to have changed with the recent observations of Simnett and McDonald (1968), whose data can now be better understood on the basis of secondary electrons in the Galaxy. If, however, it turns out that the earlier measurements of the NASA Group are correct and/or there is significant solar modulation at these energies, then one may require another weak component of primary electrons at these energies.

We have already referred to the observations of Cline and Hones (1968), who find a detectable flux of positrons below 3 MeV; since, however, this experiment leads only to an upper limit of positrons, there is as yet no serious contradiction to the knock-on origin of the low energy electrons. On the other hand, one realises the importance of measurements of the charge composition of electrons at these energies as well.

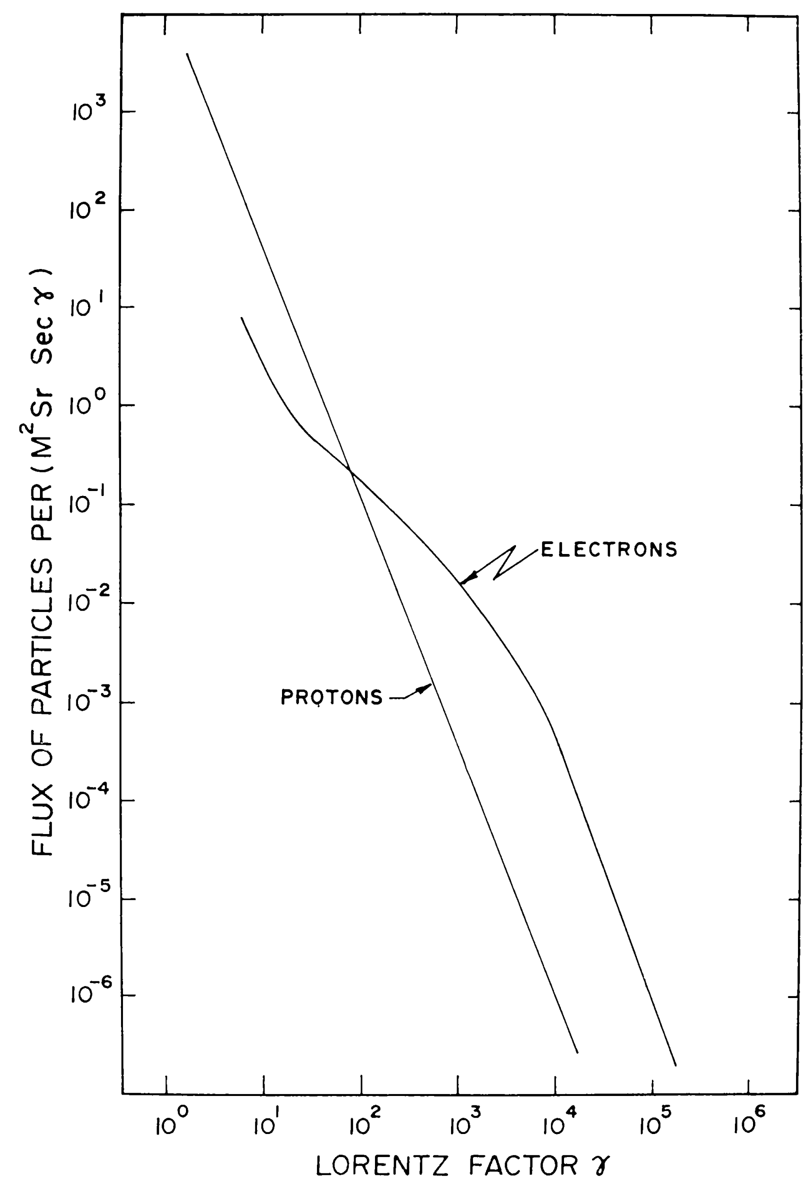

Fig. 5. Velocity spectra of cosmic ray electrons and protons.

4.3. Summary

It would have been evident that the various analyses and arguments presented in this section, have enabled us to draw a number of important and interesting conclusions, of which some are more definitive in nature while others are less so, and more speculative. It is, therefore, thought that it will be profitable to summarise them in a coherent and sequential manner to bring out and emphasise the major advances accomplished.

(i) *The interstellar electron spectrum*: It is shown that we now have a reasonably reliable knowledge of the interstellar electron spectrum right from about 1 MeV up to about 200 GeV. Of this (a) the spectrum above 10 GeV is the electron spectrum measured near the earth unaffected by solar modulation, hence it is known precisely; (b) the spectrum between 100 MeV and 10 GeV has been inferred from the galactic radio continuum, this too is therefore known reliably; (c) the region between 1 and 20 MeV is expected to be the same as that measured in deep interplanetary space; solar modulation if existing here is expected to account for a magnitude not larger than present experimental uncertainties of the measurement; and (d) the 20–100 MeV range is the one known comparatively with the least amount of reliability because of experimental and interpretative difficulties; however it too can be fixed with reasonable confidence because the points at about 20 and 100 MeV are already anchored.

(ii) *The solar modulation of electrons*: It is shown that the electrons between 100 MeV and about 2 GeV and perhaps even below 100 MeV undergo solar modulation, though there is still room for arguing about its magnitude. The existing data can be interpreted in two alternate ways: (a) that it is consistent with an R or $R(v/c)$ dependent modulation above 500 MV and a velocity dependent or constant modulation below this rigidity, or (b) the possibility of a velocity dependent or constant modulation in the entire energy domain. It is hoped that continuing satellite observations will resolve this problem in the near future.

(iii) *The interstellar equilibrium secondary electrons*: The interstellar equilibrium secondary electron spectrum between 1 MeV and few hundred GeV as calculated reliably by various workers on the assumption of 3.5 g/cm^2 of cosmic ray traversal has been graphically represented; it is then compared with the interstellar total electron spectrum described in (i). This comparison reveals that (a) above one GeV the secondary electrons which arise almost exclusively through pion production, can account for only about 10% of the total interstellar electrons, (b) below a GeV the proportion of the secondary electrons, also arising through pion production, continuously increases and accounts for almost all the interstellar electrons at about 150 MeV, (c) between 150 and 20 MeV the present situation is rather unclear, and (d) between 1 and 20 MeV again the secondary electrons which originate from knock-on and neutron decay processes seem to be able to explain all the interstellar electrons as deduced from recent NASA measurements.

(iv) *The 'primary' electrons*: When the foregoing ideas on secondary electron production are extended down to about 100 MeV, one finds that the primary electron spectrum is required to have a maximum at about 200 MeV, and then to rapidly fall off with lower energies suggesting a low energy cut off. Since this spectral shape has to represent the injection spectrum, it is indicative of some kind of modulation in the source region; one is also tempted to attribute a similar injection rigidity spectrum to the nucleonic components. The latter suggestion may not be inconsistent with our present knowledge of the nucleonic component, but may still require a second component at very low energies.

5. Cosmic Electrons and the Galactic Continuum Radio Emission

Unlike the nucleonic component, whose presence in interstellar space cannot be easily detected, the cosmic electrons unequivocally reveal themselves by emitting the characteristic synchrotron radiation as they spiral along the weak interstellar magnetic field lines. This synchrotron emission is now recognised to be the source of the galactic nonthermal background radio noise which carries with it the signature of the mean magnetic fields and the appropriate electron spectrum involved. Our problem therefore is to disentangle the information carried by the continuum radio emission by matching it suitably with the electron spectrum seen near the earth, and other astrophysical parameters. The interstellar electron spectrum, thus derived, can be employed in a variety of purposes, as will be evident as we proceed. Attempts to connect the interstellar electron spectrum and the cosmic radio continuum through galactic magnetic fields, have been made by many workers. In the earlier attempts a δ-function approximation for the spectral distribution of power radiated by an electron and a constant spectral index to the radio brightness distribution, and hence to the electron spectrum, have been assumed (Bierman and Davis, 1960; Sironi, 1965; Felten, 1966; Okuda and Tanaka, 1968). There are also other attempts in which, improved procedures have been adopted (Ramaty and Lingenfelter, 1966a; Verma, 1968; Webber, 1968b). In what follows we will describe a rigorous method followed by Anand *et al.* (1968b, c), which permits the deduction of a detailed interstellar electron spectrum from about 100 MeV up to 10 GeV. We will then use this knowledge to make further inferences on other astrophysical parameters.

5.1. The synchrotron radiation

In Appendix II the details are given of the formulation of the theory of synchrotron radiation necessary for the purposes of the present treatment. Here we present just the final relation which connects the spectral distribution of the radio emission I_ν with the energy spectrum of the electrons $N(E)\mathrm{d}E$, the line of sight distance of the emitting region L, and the mean perpendicular component of the magnetic field $\langle H_\perp \rangle$ along the emitting direction; in this formulation we have followed the procedure adopted by Ginzburg and Syrovatskii (1965):

$$I_\nu = \frac{\sqrt{3}e^3 \langle H_\perp \rangle}{4\pi mc^2} L \int_{E_1}^{E_2} G_\nu(E)\, N(E)\, \mathrm{d}E\,, \qquad (6)$$

where

$$G_\nu(E) \equiv \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\, \mathrm{d}\eta$$

through the relation

$$\nu_c = \frac{3e\langle H_\perp \rangle}{4\pi mc} \left(\frac{mc^2}{E}\right)^2 .$$

The limits of the integration E_1 and E_2 are chosen such that

$$G_\nu(E_1)\, N(E_1)\, \mathrm{d}E \approx G_\nu(E_2)\, N(E_2)\, \mathrm{d}E \ll [G_\nu(E)\, N(E)\, \mathrm{d}E]_{\max} .$$

The value of $[G_\nu(E)\, N(E)\, \mathrm{d}E]_{\max}$ would depend on the spectral shape of the electrons and can be estimated suitably.

5.2. Observational data

During the past decade or so, detailed and systematic radio surveys of the Galaxy have been carried out in a broad range of frequencies using wide angle and narrow angle beams. By making use of these surveys, one can construct the non-thermal radio spectrum for three different galactic regions of interest to us here. They are (i) the halo; in this region two general directions have been considered, viz. the direction of the North galactic pole (H) and the direction of the minimum halo radiation (H_m), (ii) the anticentre (A), and (iii) the ridge – the two directions R_1 and R_2 chosen here are towards the Centre C but clearly avoiding the nucleus, one in the plane of the Galaxy and the other normal to it. One would also notice that all these directions represent typical regions of the Galaxy for which we would be interested to derive electron spectra and mean magnetic fields. In the case of the isotropic metagalactic component of the background radiation, the radio spectrum will be deduced mainly from a few indirect estimates.

The celestial directions indicated above are shown in Figure 6, which is a schematic representation of the Galaxy in a plane perpendicular to the equatorial plane. The galactic dimensions and the location of the solar system in the Galaxy are fairly well known from optical and radio observations (Bok, 1959; Mills, 1959; Allen, 1963; Kerr and Westerhout, 1965). The sun is situated at a distance of ≈ 8 kpc from the centre and about 10 pc North of the equatorial plane. The periphery of the disk in the direction of the anticentre is ≈ 4 kpc from the sun; the thickness of the radio disk is ≈ 500 pc except close to C. Further, the sun is located close to the inner edge of the Orion arm.

5.2.1. *The North Halo*

The North halo is generally defined over a wide region of the sky corresponding to right ascension $RA \approx 10$–17 hr and declination $\delta = 20$–60°. However, there is an enhancement of the radiation due to the North Galactic spur in the region $RA \approx 12$–17 hr and $\delta \approx 20°$; this part of the sky has been excluded while evaluating the brightness spectrum of the halo. The minimum in the halo radiation occurs around $RA \approx 10$ hr and $\delta \approx 20$–$60°$. In order to deduce the spectrum in the halo region, surveys with wide angle beams in the frequency range 10–400 MHz have been used (Costain, 1960;

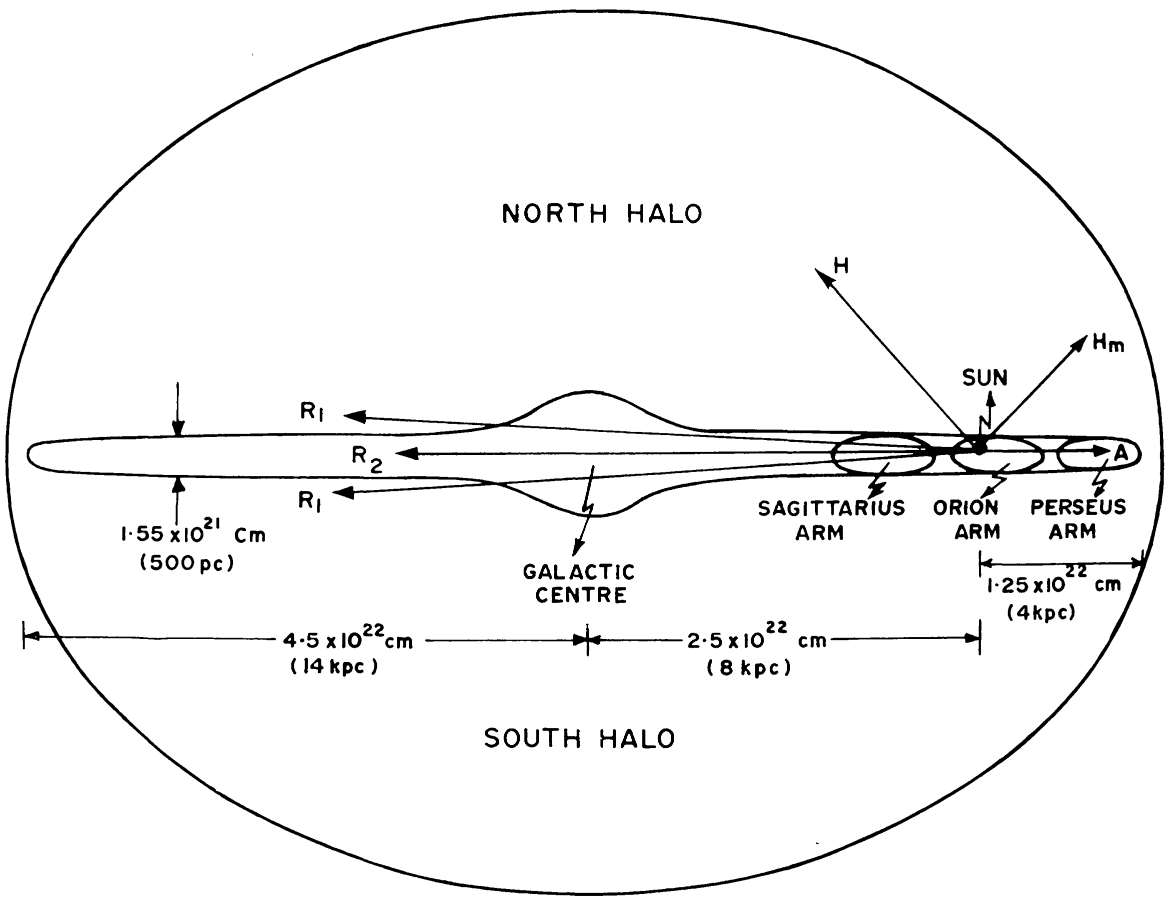

Fig. 6. Schematic drawing of the Galaxy perpendicular to its equatorial plane (not to scale).

Pauliny-Toth and Shakeshaft, 1962; Turtle *et al.*, 1962; Hartz, 1964; Parthasarathy and Lerfald, 1965; Andrew, 1966; Purton, 1966; Bridle, 1967). For surveys which do not cover the whole region, necessary corrections have been made using the recent survey by Purton (1966) at 81.5 MHz; whenever possible, relevant corrections are also made as indicated by the authors. In Figure 7 are plotted the brightness distribution thus obtained for the directions H and H_m. If the spectral form of the distribution at any frequency is expressed as $I_\nu \approx \nu^{-\alpha}$ then it is evident from this figure that the two spectra have identical shapes in the frequency region 10–400 MHz with a spectral index $\alpha \approx 0.4$ at low frequencies increasing gradually to about 0.8 at the high frequency end; the absolute intensity along H_m is about three-fourth of that along H. Data points below 10 MHz have not been considered here because galactic absorption and other effects become increasingly important (Ellis, 1964; Alexander and Stone, 1965).

5.2.2. *The Anticentre*

Using the same sky surveys from which Figure 7 was derived, one can also obtain the brightness distribution in the general direction of A. For this purpose, a broad region corresponding to $l \approx 140$–$190°$ and $b \approx 10\,°N$ to $10\,°S$ (l and b are the new galactic longitude and latitude respectively) has been chosen. The radio spectrum thus derived for the anticentre is shown in Figure 8. It is found that this spectrum is slightly, though noticeably flatter at low frequencies than that in the halo; the absolute intensity is

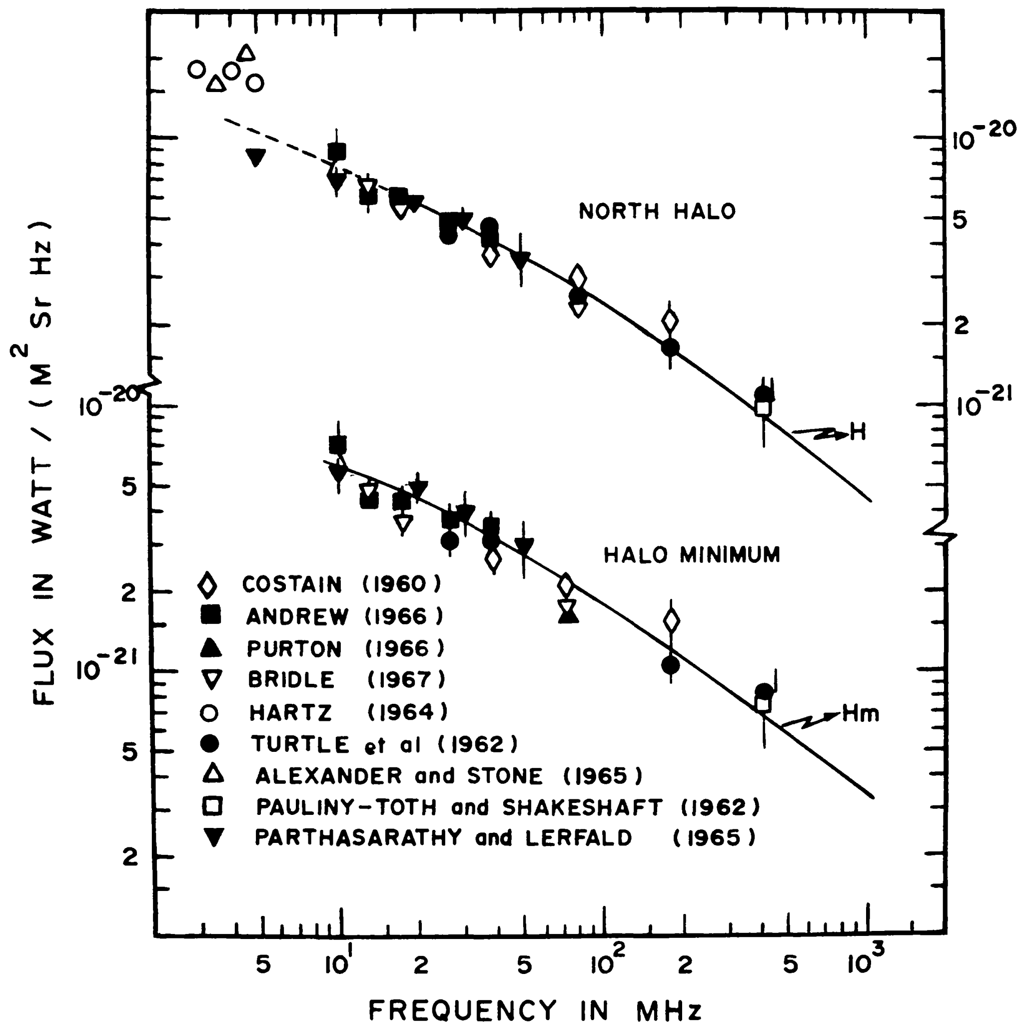

Fig. 7. Radio brightness distribution from the halo.

comparable with that towards H at about 10 MHz but about 50% larger at frequencies >100 MHz. The spectral index varies from about 0.3 at the lowest, to about 0.8 at the highest frequencies.

5.2.3. *The Ridge*

The ridge is broadly defined as the radio disk where there is a general enhancement of radio intensity as the telescope sweeps the sky. Two particular directions were

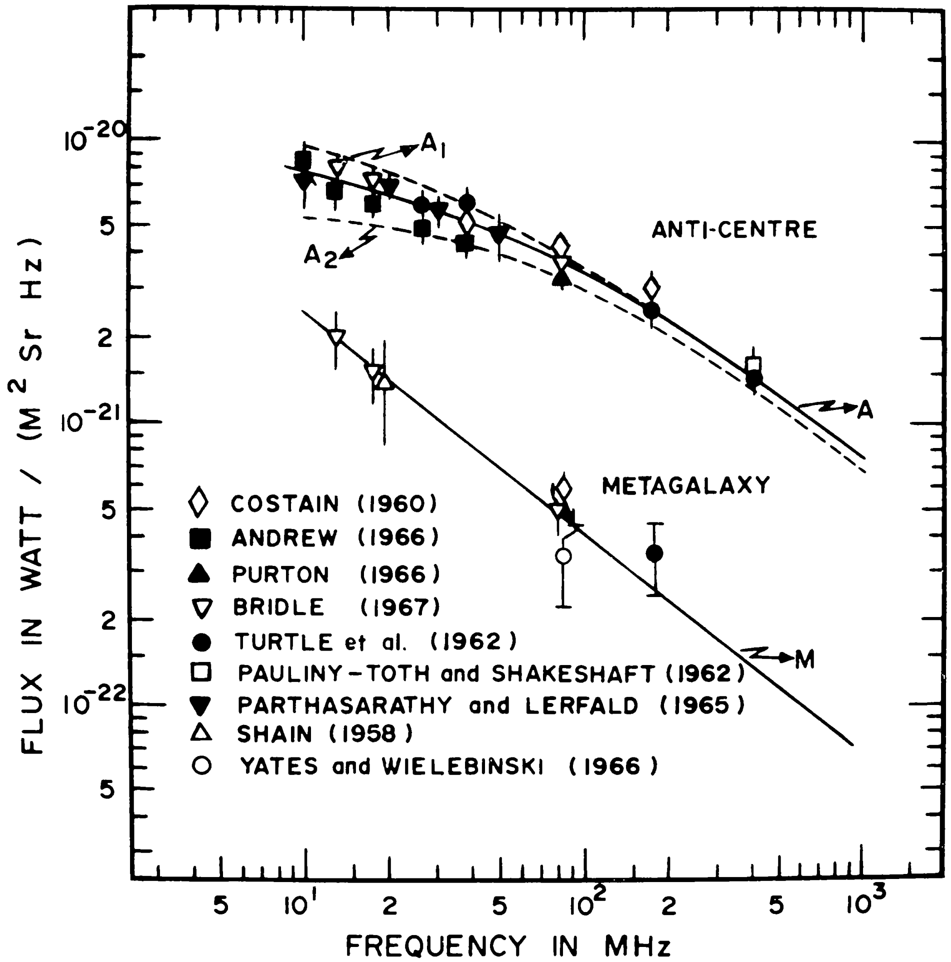

Fig. 8. Radio brightness distribution from the anticentre (curve A) and the metagalaxy (curve M); curve A_1 shows the upper bound of flux values in the direction of the anticentre, while curve $A_2 = A - M$.

chosen in the ridge towards the centre but clearly avoiding the nucleus; they are (i) $l = 0°$ and $b = 3.6$ °N and 3.6 °S (indicated as R_1), and (ii) $l = 20°$ and 340°, and $b = 0°$ (marked as R_2 in Figure 6). For the purpose of constructing the radio brightness distribution along these directions, surveys made with narrow angle beams in the frequency range 80–4080 MHz have been used (Baldwin, 1955a; Denisse *et al.*, 1955; Kraus and Ko, 1955; Piddington and Trent, 1956; Hill *et al.*, 1958; Westerhout, 1958; Seeger *et al.*, 1960; Wilson and Bolton, 1960; Large *et al.*, 1961; Mathewson *et al.*, 1962; Braccesi and Vespigani, 1964; Moron, 1965; Seeger *et al.*, 1965; Komesaroff, 1966; Penzias and Wilson, 1966; Wielebinski *et al.*, 1968). The flux values shown in Figure 9 are the mean values in the two directions $b = 3.6$ °N and 3.6 °S in case of R_1, and $l = 20°$ and 340° for R_2, except in surveys, in which data is available for only one. Relevant corrections have been made wherever possible according to the authors. It is apparent from Figure 9 that the radio spectra for R_1 and R_2 are similar in nature though one notices far greater variations in the values of individual data points for R_2 than for R_1; also the absolute intensity in the direction of R_2 is about 1.7 times that for R_1. Comparing these spectra with that obtained for the anticentre, it is seen that while they have similar shapes above 100 MHz, the spectra for R_1 and R_2 exhibit greater flattening below this frequency.

5.2.4. *Non-thermal Radio Emission of Metagalactic Origin*

It is imperative that before venturing to interpret the background radio emission as of galactic origin, one should enquire whether there could exist a substantial component of metagalactic origin in the observed radio intensities. For this purpose one could consider the metagalactic radiation to comprise of two subcomponents:

(a) The first arises from the diffuse radiation, emitted by electrons in intergalactic

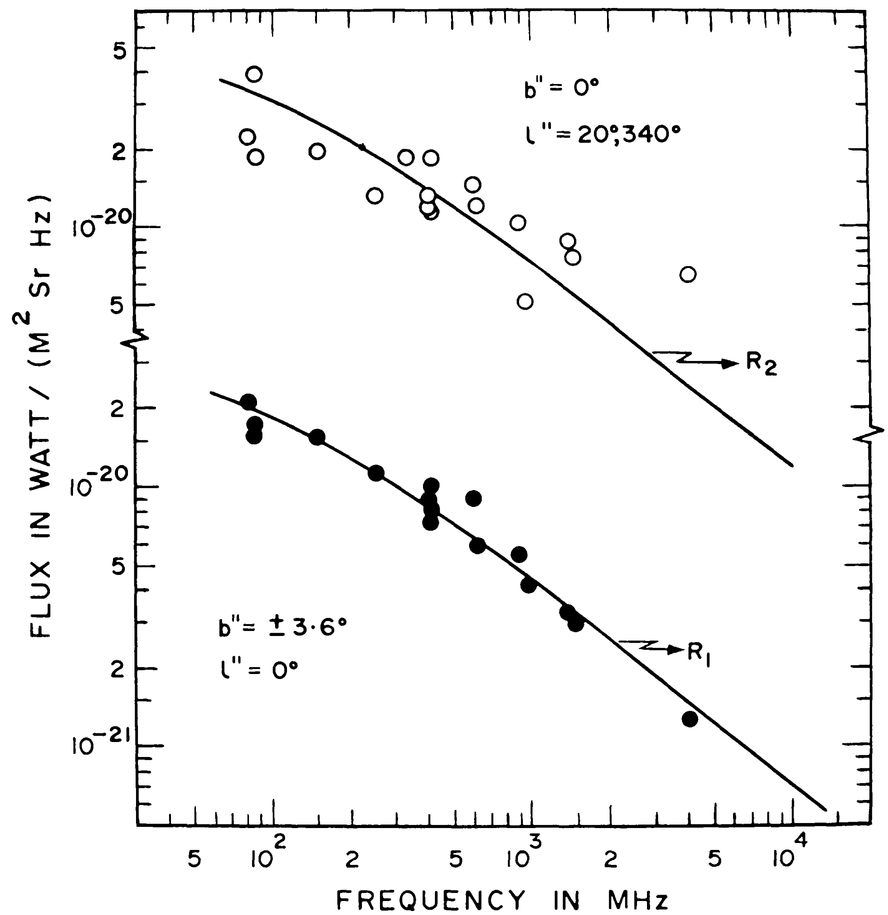

Fig. 9. Radio brightness distributions from the ridge. References for the data points are given in the text.

space. This radiation is likely to have a spectral index of −1.3 from consideration of the steepening of the equilibrium electron spectrum in the metagalaxy (Anand *et al.*, 1968d). However, since there is no reliable estimate of the flux of electrons in the metagalaxy (see Section 7) and that the total metagalactic emission cannot exceed 20% of that towards the anticentre at 10 MHz (Section 5.3), we shall ignore this contribution for the present analysis; a further justification for this would be given at the end of this section.

(b) The second component arises from the integrated radiation from radio galaxies. Spectral measurements so far carried out show that (i) between 38 and 1417 MHz, most of the sources have power law spectra (Convey *et al.*, 1963; Long *et al.*, 1966) of which majority show steepening only beyond 1417 MHz, (ii) below 38 MHz the survey of 26.3 MHz shows (Erickson and Cronyn, 1965) that more than 80% of the sources do not show any departure from a simple power law, and (iii) even at 10.3 MHz there is still no appreciable flattening of the spectra for the majority of the sources (Galt *et al.*, 1967). It is also seen that all these spectra have indices $\alpha \approx 0.2$–1.3 with a very prominent maximum between 0.7 and 0.8; furthermore, there is no evidence (Kellerman, 1966) that the spectral distribution depends on the apparent luminosity, down to about 2 flux units at 178 MHz. Hence we shall consider the contribution from radio sources as the main source of metagalactic radio emission. We shall now proceed to see whether our knowledge of cosmic electrons in the Galaxy could provide supplementary information on this.

Until now the only direct estimate made of the metagalactic radio emission is due to Shain (1958) at 19.7 MHz, who made use of the radio absorption in the Large Magellanic cloud. Other estimates which are indirect in nature depend on the assumption that the spectral shape of the metagalactic component is steeper than that of the galactic radiation (Costain, 1960; Turtle *et al.*, 1962; Purton, 1966; Yates and Wielebinsky, 1966). All these estimates are shown in Figure 8; in the case of the latter attempts we have used a spectral index of -0.75 for the metagalactic radiation. A comparison of the metagalactic spectrum with that towards the anticentre, shown in the same figure, reveals that at 20 MHz the metagalactic contribution is $\approx 20\%$ of that towards A, which reduces to $\approx 10\%$ at 400 MHz.

At this stage, one is tempted to ask whether in the region below about 20 MHz the metagalactic radiation has a spectral shape similar to that above this frequency. It will be shown in Section 5.3 that a study of the radio emitting electron spectrum corrected for the metagalactic component, together with the equilibrium spectrum of secondary electrons in the Galaxy, reveals that the contribution of metagalactic component at 10 MHz cannot be larger than 20% of that towards the anticentre. This suggests that the metagalactic radio spectrum cannot have a constant slope of -0.75 right down to 10 MHz, but should flatten below about 30 MHz. If this were so, then two interesting possibilities could be proposed. Firstly, it would indicate that in general, metagalactic sources responsible for this component have spectra which flatten at frequencies below 30 MHz, and secondly, the component arising from emission in intergalactic space has to be very small, thus justifying our earlier decision to ignore it in the present treatment.

5.3. Radio emitting electrons in the galaxy

Having summarised the observational data on the cosmic ray electrons in the vicinity of the earth, and the non-thermal radio emission from different celestial directions, the next step is to deduce the electron spectrum and mean magnetic fields in different regions of the Galaxy. For this it seems natural that one should start with conditions in the near interstellar space; our choice therefore falls on the anticentre direction because, of all the directions described earlier, it resembles closest to the region of space where the solar system is located. It should be stressed at the outset that in the present treatment, any inhomogeneities in the magnetic field or the electron intensity that might exist in the galactic direction chosen, will be averaged out. Also, the contribution due to the metagalactic component has been neglected; nonetheless it will be demonstrated later that this will not affect any of our conclusions in any significant manner.

5.3.1. *Electrons in the Anticentre Region*

Extensive investigations on the nucleonic component of the cosmic radiation have revealed that at energies $\gtrsim 5$ GeV, there is very little or no solar modulation; it has also been shown in Section 3.4 that at these energies all cosmic rays including the electrons, obey a power law spectrum in energy with $\beta \approx 2.6$. On this account it seems logical to believe that the energy spectrum of electrons, and nuclei, of energy $\gtrsim 5$ GeV detected in the neighbourhood of the earth will also be well preserved in the near interstellar space.

In order to evaluate the energy spectrum of electrons at energies less than 5 GeV in the radiating region, one has to fix the radiating distance L and mean magnetic field $\langle H_{\perp} \rangle$. Of this L_A in the direction of the anticentre has been taken to be 1.25×10^{22} cm. It is now possible to set quite meaningful constraints on $\langle H_{\perp} \rangle$ because the deduced electron spectrum at lower energies should smoothly join with that at energies $\gtrsim 5$ GeV observed near the earth. Thus it is possible to assign, a single value for $\langle H_{\perp} \rangle$ and an unique smoothly varying electron spectrum, to match the observed radio brightness distribution in the direction of the anticentre. It is apparent from Equation (6) that for a given radio spectrum which is not a simple power law (as is evident from Figure 8, and the more recent work reported by Shakeshaft (1969) of the Cambridge Group), the electron spectrum responsible can be deduced only by trial and error. It may also be pertinent to point out here that curve fitting in the high frequency end depends primarily on the magnetic field because at this frequency region $I_\nu \sim L \langle H_{\perp} \rangle^y$, where $y > 1$.

The interstellar electron spectrum deduced in this manner is shown by curve A in Figure 3 and curve B of Figure 4; the corresponding value of $\langle H_{\perp} \rangle_A$ used is 5 μg. In Table II is included the ranges of electron energy which contribute about 80% of the observed radiation at a few typical radio frequencies. It is realised that electrons of energy 200–300 MeV contribute only about 13% of the total radiation at 10 MHz; despite this fact it is unlikely that curve A in Figure 3 could be in serious error up to 100–200 MeV since a sharp change in the shape of the electron spectrum is an unlikely possibility for which there is no special indication from the radio data.

The next obvious aspect to be examined is the effect of the metagalactic component on the electron spectrum derived. If the contribution from the metagalactic component represented by curve M in Figure 8, to the observed brightness distribution from the anticentre is taken into account, one ends up with an electron spectrum given

TABLE II

Effective electron energies for radio emission at typical frequencies

Region of space	L (in cm $\times 10^{-22}$)	$\langle H_{\perp}\rangle$ (in μg)	Energy range in GeV of electrons contributing 80% of the radio flux at		
			10 MHz	400 MHz	4000 MHz
Anticentre	1.25	5.0	0.2–1.2	1.1 –4.3	–
Ridge R_1	3.9	7.2	–	0.95–4.1	2.7–11.4
R_2	6.6	7.2	–	0.95–4.1	2.7–11.4
Halo H	4.0	2.0	0.3–1.6	1.7 –6.5	–
H_m	3.0	2.0	0.3–1.6	1.7 –6.5	–

by curve C of Figure 3. Comparing this spectrum with curve F of the same figure, one notices that below about 200 MeV, the intensity of the radio emitting electrons becomes smaller than the intensity of the equilibrium interstellar secondary electrons; this seems unacceptable on our present knowledge of the propagation of cosmic radiation. From this one can easily show that at 10 MHz the metagalactic component cannot exceed 20% of the total radiation observed in the direction of the anticentre. Thus, if one sets an upper limit of 20% for the metagalactic radio emission at 10 MHz and gives a smooth shape to this spectrum, the brightness distribution towards A after correcting for the metagalactic radiation would be well within the uncertainty in the background radio measurement. When all these factors are taken into account, one is left with the belief that with the available data, curve A of Figure 3 is the best estimate of the radio electron spectrum one can deduce for the near interstellar space.

5.3.2. *Electrons in the Halo Region*

Having derived the electron spectrum in the anticentre region, it is only natural that one should, as a first step, assume its existence in the halo also, and study its consequences. Such an attempt is made with a value $L_H = 4 \times 10^{22}$ cm in the direction of the North galactic pole; the resulting radio brightness fits extremely well with the observations (curve H of Figure 7) and the required mean magnetic field is $\langle H_{\perp}\rangle_H = 2\ \mu$g. In like manner, one can use a value of $L_{H_m} = 3 \times 10^{22}$ cm for the halo minimum and obtain a radio brightness distribution which is again in good agreement with the observations using the same value for the magnetic field, viz. $\langle H_{\perp}\rangle_{H_m} = 2\ \mu$g. At this stage one is tempted to affirm that such a good fit obtained for the halo radiations with the same electron spectrum deduced for the anticentre, inspite of the noticeably different radio spectra from H and A, should be considered as a point in favour of the existence of a radio halo (Anand *et al.*, 1968d).

5.3.3. *Electrons in the Ridge*

In the case of the ridge directions too, one can start with the electron spectrum derived for the anticentre region; one then finds that a single value of mean magnetic field exists to satisfactorily explain the relevant radio spectra. In these calculations a value of $L_{R_1}=4\times10^{22}$ cm and $L_{R_2}=6.6\times10^{22}$ cm have been employed. Curves R_1 and R_2 drawn in Figure 9 have been thus obtained for a value of $\langle H_\perp\rangle_R=7.2\ \mu$g. Radio observations below about 50 MHz (Shain and Higgins, 1954; Mathewson *et al.*, 1965) indicate that the spectrum exhibits a positive slope. However, it can be seen that if the same interstellar electron spectrum, curve *A* of Figure 3, exists in the ridge directions down to 100 MeV, one should not have observed such a change in the shape of the radio spectrum. In order to understand this, Webber (1968b) has suggested that the radio emission from electrons might be relatively more important than absorption effects from interstellar H II regions in the local environment, as compared with the average along any direction in the disk.

5.4. Magnetic fields in the galaxy

Estimates of the magnetic fields in the Galaxy have been made using various methods such as (a) Zeeman effect, (b) Faraday rotation, (c) polarisation measurements, and (d) non-thermal radio emission by cosmic electrons. The first two methods yield the algebraic mean of the parallel component along the line of sight, while the third gives the algebraic mean of the normal component. The last method, on the other hand, is capable of giving the mean magnetic field along the line of sight without distinguishing the sense of orientation of the field vectors. While the magnetic fields in the halo are likely to be highly randomised, in the local spiral arm there is evidence for considerable regularity (Mathewson, 1968; Mathewson and Nichols, 1968). In spite of this, since in the present treatment the radiating distances are considerably larger than the thickness of the spiral arm, one can assume that the magnetic fields are randomly oriented and hence $\langle H\rangle=1.23\ \langle H_\perp\rangle$.

From the procedure described in Section 5.3 the mean magnetic field $\langle H\rangle$ deduced for the anticentre region is found to be $\approx 6\ \mu$g. Procedures of a similar nature but with minor modifications have been attempted by many authors; in particular Okuda and Tanaka (1968) attribute a value of 5–12 μg and Webber (1968b) a value of $\approx 8\ \mu$g for the local interstellar magnetic field. Recent observations using Zeeman effect (Verschuur, 1968; Davies *et al.*, 1968) suggest that the parallel component in the Perseus arm is as high as 7–20 μg, whereas in the Orion arm it is only about 3 μg. On the other hand, Faraday rotation measurements from Pulsars (Smith, 1968) indicate values ranging between 2 and 4 μg in regions covering both the Orion and Perseus arms. At this stage of our knowledge on this subject, it will be unwise to say that these are mutually contradictory observations; rather it calls for greater diligence to examine these matters further to see whether they will throw any light in our understanding of conditions in cosmic space.

The mean magnetic field obtained in the direction of the centre, but clearly avoiding the nucleus, is $\approx 9\ \mu$g. This may be compared with the value of 12–24 μg obtained by Okuda and Tanaka (1968) almost in the direction of the nucleus, where there could be an appreciable contribution of radio emission of thermal origin.

In the region of the halo, one obtains a value of $\approx 2.5\ \mu$g. The main uncertainties in this value would depend on (i) the contribution of the disk and metagalactic radio emission, allowance made for which would lead to a lower value of $\langle H \rangle$, (ii) the uncertainty in the dimension of the radiating region, and (iii) the possible intensity gradient for the cosmic electrons; reduction in the radiating distance, and existence of an intensity gradient which seems plausible (Section 6) would tend to give a higher value of the magnetic field. Thus it seems that the value of magnetic field derived for the halo may be considered to be realistic.

5.5. The electron intensity variation in different regions of the galaxy

It has been demonstrated that a consistent picture can be constructed to satisfactorily explain the observed non-thermal radiations from different regions of the Galaxy, by making the assumption that the electron energy spectrum is the same in all regions of the Galaxy, including the halo. At the same time it will be instructive to examine how much variations in the intensity can be tolerated without entering into serious difficulties. For this purpose let us first consider the halo. If for the sake of argument the electron intensity in the halo is reduced by a factor of 2, then in order to account for the radio brightness, a mean magnetic field of 4 μg will be required. If in addition the radiating distance used earlier is too large, then the magnetic field will have to be enhanced still further. An important consequence of this will be a shift towards lower energies of the radiating electrons, thereby requiring an electron spectrum steeper than that deduced for the near interstellar space for the same energy region. Such a situation would be difficult to understand if, as will be shown in the ensuing section, the cosmic ray confinement volume is essentially the disk. On this account, it seems unlikely that the electron intensity in the halo could be lower than that in the disk by a factor of as much as 2 or more. In a similar fashion one can also argue that the intensity in the direction of the central region of the Galaxy could not be higher by a factor of about 2 or more than that in the near interstellar space.

Recent observations of the Cambridge Group (Shakeshaft, 1969) have shown that the spectral shapes of the radio emission from the arm and interarm regions of the disk are identical. This implies that the magnetic field strengths in these two regions are not much different. These observations would also suggest that in these regions the electrons will have the same spectral shape and not very different intensities.

From the foregoing discussions it seems reasonable to suppose that the same or nearly the same electron spectrum exists in all regions of the Galaxy including the disk and the halo. In spite of this one cannot rule out at this stage the possibility of a radial intensity gradient from the nucleus towards the polar directions or the periphery of the disk.

5.6. The galactic halo

The existence of a galactic halo of near spherical shape, glowing in the radio region by the synchrotron radiation emitted by relativistic electrons spiralling in weak magnetic fields existing therein, was first postulated by Shklovsky (1952). This suggestion was made credible by Baldwin (1955b), who, on the basis of cosmic background radio observations, attributed a diameter of 20–30 kpc for this halo. One would realise that by definition, a radio halo is also a cosmic ray halo. The existence of the radio halo, which received almost universal support from observational radio astronomers, astrophysicists, and cosmic ray physicists for over a decade (Spitzer, 1956; Woltjer, 1965; Parker, 1965; Ginzburg, 1967), and was sometimes acclaimed as one of the most important discoveries of our times, is being increasingly questioned during recent years. Though the existence of the halo has direct implications in matters relating to cosmic ray storage and the dynamics of the Galaxy, the arguments so far advanced against its existence have been drawn from recent observations on the galactic background radio emission. In view of this, our present day knowledge on the existence of cosmic electrons in galactic space, enables us to examine to what extent such arguments are well founded.

The radio brightness distribution in the galactic plane ($b \approx 0$) should consist of radiation from the radio disk and the isotropic metagalactic emission, while that in the direction of H and H_m should, if the halo exists, include the radiation from the halo as well. Therefore, a convenient way of attempting to demonstrate the existence of the halo is to deduce first the magnitudes of the components from the metagalaxy and the disk in the direction of high latitudes, and then examine whether any significant residual radiation will be left for the halo. The information on the metagalactic component has already been summarised in curve M of Figure 8. The contribution of radio brightness from the disk in the direction of high latitudes can be deduced assuming that (a) the emissivity of the disk in the direction of H, H_m and A is uniform, and (b) the radio features observed in various sky surveys are in the main, large scale galactic phenomena. In justification of (a) one might refer to the recent observations of the Cambridge Group (Shakeshaft, 1969), who find the same brightness distribution for the arm and interarm regions. Assumption (b), which is sometimes questioned by radio astronomers, has been examined by Anand *et al.* (1968d), who find that with our present knowledge it is not unreasonable; further the connected argument that the North polar spur is a local phenomenon associated with the remnants of a supernova (Davies, 1964) is doubted by a reasoning advanced by Seaquist (1968). Also the claim that the galactic radio spurs can be explained by the helical field structure in the local arm (Mathewson, 1968) does not seem to be convincing because not all spur features are aligned parallel to the magnetic field (Shakeshaft, 1969). Therefore, granting these assumptions, one finds that the disk radiation contributing in the direction of A and H should depend primarily on the linear emitting dimensions involved and should be in the ratio of about 16:1. From this it follows that the disk radiation in the direction of H and H_m is unlikely to exceed 10% of that from the anticentre. In Table III are summarised the metagalactic and disk contributions thus deduced at 80 MHz for the halo directions H and H_m. From this table, it can be observed that a liberal estimate of the contributions from the disk and metagalaxy cannot exceed 50% of the total radiation from H. Hence, one feels justified to attribute the remaining half of the radiation to the halo.

There is also considerable amount of internal consistency between various observations if one accepts the existence of a radio halo. Some of these are (a) the ratio H/H_m deduced in Column 5 of Table III, (b) the spectral shapes of radio emission from H, H_m, A and R, and (c) the reasonable values of the mean magnetic fields deduced for various galactic regions. Finally, one may also refer to a recent paper

TABLE III

Components of the radio brightness towards H and H_m at 80 MHz

	Anticentre (A) Watts/m²·sr·Hz	North halo (H) Watts/m²·sr·Hz	Halo minimum (H_m) Watts/m²·sr·Hz	H/H_m
(1) Total radiation	3.7×10^{-21}	2.8×10^{-21}	2.2×10^{-21}	–
(2) After subtracting the metagalactic component	3.1×10^{-21}	2.2×10^{-21}	1.6×10^{-21}	–
(3) After subtracting the disk component (10% of A from H and H_m)	0	1.9×10^{-21}	1.3×10^{-21}	1.45
(4) After subtracting the disk component (20% of A from H and H_m)	0	1.6×10^{-21}	1.0×10^{-21}	1.6

by Yates (1968), in which he advances a minimum halo model, only to be faced with the necessity of having to make difficult-to-accept assumptions (Anand *et al.*, 1968d).

In summary it may be stated that there are certain features relating to the non-thermal background radio emission which are in favour of the halo. We will return to this subject again in the next section, where one finds that considerations of the confinement of cosmic electrons require either no halo or a leaky halo.

6. Propagation and Confinement of Cosmic Electrons

The intrinsic properties of the electron make it vulnerable to certain energy loss processes under cosmic environment, which are normally unimportant for nuclear particles. The cosmic electrons should therefore bear the characteristic imprints of the physical processes occurring in the relevant regions of space where they are produced and stored. It will be our endeavour in this section to unravel as much of such information, from a study of the cosmic ray electrons observed near the earth in conjunction with other data; these deductions will relate, in the main, to the confinement region and the residence time therein of the cosmic electrons. We will like to stress here that, since the confinement volume should be the same for nuclei and electrons, any model for cosmic ray storage should be such that it satisfactorily explains the deductions made from studies of the nuclear and electron components of the cosmic radiation. Many attempts have been made during recent years, to understand the confinement of cosmic electrons from an analysis of the electron spectrum. These include Daniel and Stephens (1966), Ramaty and Lingenfelter (1966b), O'Connell (1966), Cowsik *et al.* (1966), Daniel and Stephens (1967), Verma (1967b), Shen (1967), Anand *et al.* (1968e), Danjo *et al.* (1968b), and Tanaka (1968).

6.1. The equilibrium nature of cosmic rays

Two clear possibilities can be considered for the state of electrons observed in the terrestrial neighbourhood; they are: (i) a state of equilibrium in a suitable confinement volume of space containing the solar system, and (ii) a state of non-equilibrium. In the case of the latter alternative, it seems reasonable to expect large temporal variations of the cosmic ray intensity over the distant past. However, results from the study of radioactive and stable cosmogenic products in meteorites strongly suggest that this is not so, and that the cosmic ray intensity has remained constant within $\pm 10\%$ over the last million years and within a factor of about 2 over the past billion years (Geiss *et al.*, 1962; Geiss, 1964; Schaeffer *et al.*, 1964; Hintenberger *et al.*, 1966; Lipschutz, 1965; Lal, 1966). One would also realise that if, for any reason, one is forced to work with a state of non-equilibrium, for which no necessity has so far arisen, none of the attractive interpretations, as are possible with the former, would be feasible. Therefore, in what follows it will be implicitly assumed that the cosmic rays exist in a state of equilibrium within a region of cosmic space encompassing the solar system.

6.2. Possible confinement regions for cosmic rays

In the past, attempts have been made to understand the cosmic rays as being confined to a wide variety of regions ranging from the solar system to the universe as a whole. Nevertheless, they can all be brought under two broad categories, viz. galactic and metagalactic. We can now marshall overwhelming arguments to believe that any storage region much in excess of galactic dimensions will not be tenable. Such reasonings, apart from those strongly advocated by Ginzburg and Syrovatskii (1967) and Ginzburg (1968) in favour of a galactic model, are of two kinds:

(i) If cosmic electrons are constrained to a certain volume of space, then during their lifetime within this confinement region, they would give rise to a certain diffuse background radiation extending right from the radio regime to the γ ray regime through bremsstrahlung, synchrotron and inverse Compton scattering processes. Since there exists now evidence for finite values, or upper limits, to the flux of diffuse radiations at various frequencies, and also reasonable estimates of matter density, magnetic field and radiation field densities in various regions of space, it has become possible to employ these to deduce information on the dimensions of the emitting region.

(ii) Since the electrons are considered to be in a state of equilibrium within the storage volume, observations made on the electrons in the terrestrial neighbourhood are capable of yielding information on the residence time of the electrons; this in turn permits one to draw inferences on the dimensions of the confinement region. In the present section, we will bring together such arguments to show that one can more or less rule out the possibility of a confinement region of size very much larger than the Galaxy for holding electrons with an intensity same as that observed in the vicinity of the solar system.

6.2.1. *Argument Based on Inverse Compton Photons and the Isotropic γ Rays*

The background γ radiation arising from the inverse Compton scattering of the equilibrium electrons with photons associated with starlight and the universal black body radiation at 2.7 K, can be written respectively as:

$$J_\gamma(>E) \approx 2.3 \times 10^{-26}\ \varrho_s L \cdot E^{-0.81} \text{ photons cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1} \tag{7}$$

and

$$F_\gamma(>E) \approx 9.2 \times 10^{-26}\ \varrho_{BB} L \cdot E^{-0.81} \text{ photons cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}, \tag{8}$$

where E is expressed in MeV; ϱ_s and ϱ_{BB} are the energy densities in starlight and the 2.7 K black body radiation respectively expressed in eV/cm^3, and L the radiating distance in cm. There is now evidence for an isotropic component of γ radiation of intensity $1.1 \pm 0.2 \times 10^{-4}$ cm^{-2} sec^{-1} sr^{-1}, with energy greater than 100 MeV (Clark *et al.*, 1968), which can be used to assign a value for L. Notice here that γ rays of 100 MeV can result either from collisions of electrons of about 4 GeV with starlight photons or electrons of about 150 GeV with the black body photons. One can then use the value of ϱ_s and ϱ_{BB} summarised in Table V (in Appendix II), and calculate the radiating distance L as $\approx 2 \times 10^{23}$ cm; mention may be made here that the dominant contribution of γ rays comes from inverse Compton scattering with the photons of the universal black body radiation which is now thought to be reliably known. Furthermore, in case the flux of isotropic γ rays quoted above turns out to be an upper limit or part of it arises from other processes or sources, as is likely to be, the value of L will be correspondingly lowered. The value $L = 2 \times 10^{23}$ cm deduced above may be compared with the diameter of our Galaxy, which is $\approx 10^{23}$ cm. From this one may conclude that, subject only to the existence of the universal black body radiation at 2.7 K, one can firstly rule out models in which the whole universe is filled with cosmic rays with an intensity same as that near the solar system; even the local group of galaxies with a dimension of about 10^{24} cm, recently proposed by Hoyle (1968) as the confinement volume for cosmic rays, seems difficult to compromise with the value of L deduced above. Needless to say, then, that the super cluster model suggested by Burbidge and Hoyle (1964) with a dimension of about 10^{27} cm can also be ruled out.

6.2.2. *Arguments Based on Inverse Compton Photons and the Diffuse X-Radiation*

There also exists now reliable evidence for a finite flux of diffuse X-rays (Metzger *et al.*, 1965), which is generally thought to be of metagalactic origin. It is also thought that a likely origin of this diffuse X-rays is the inverse Compton scattering of electrons in metagalactic space with photons of the universal black body radiation (Felten and Morrison, 1966). These authors have also been able to show that on this basis, one requires at injection an intensity of metagalactic electrons about 40 times less than that in the Galaxy; a similar conclusion has since been arrived at by Anand *et al.* (1968f, g). If, however, part of the isotropic X-radiation emanates from discrete extragalactic sources, as it is very likely to be, then the metagalactic intensity of electrons will be still lower than that deduced above. In view of this, one can again discredit the possibility of a universal model for cosmic rays.

Mention may also be made here of similar attempts that one might make through the processes of bremsstrahlung and synchrotron radiations although they do not lead to as meaningful interpretations as in the case of inverse Compton scattering (Stephens, 1969).

6.2.3. *Argument Based on Residence Lifetime of Electrons*

Using methods to be described in Section 6.4, one can derive the residence time of electrons for various assumed confinement volumes through the electron spectrum obtained for interstellar space. In this manner, one is able to demonstrate the likelihood (Daniel and Stephens, 1967) that the lifetimes of electrons in the local cluster, super cluster and universal model are all in the region of 10–20 million years. Ascribing such electron residence times to these metagalactic confinement volumes seems to be inconsistent with the dimensions associated with these regions of space.

In summary one can assert that there exists now almost unsurmountable arguments to believe that the cosmic electrons, and hence cosmic rays in general, seen near the earth are confined to the galactic space only.

6.3. The energy independence of the cosmic ray residence time

In many problems relating to cosmic rays, it is generally assumed that their mean residence time τ in the confinement volume, is energy independent over a wide range of energies; this, however, applies only to particles with gyroradii $\ll$ the dimension of the confinement volume. On this basis it is thought that in the case of the Galaxy, particles with energies below 10^{15} eV can be well confined. As evidence for this, one often refers to the steepening of the energy spectrum of particles initiating extensive air showers beyond 10^{15} eV. On the other hand, below a few GeV, rigidity dependent τ has also been suggested (Cowsik *et al.*, 1967) in order to explain some otherwise difficult-to-understand observational characteristics of the nucleonic components. In the literature one finds that in the interpretation of the electron energy spectrum, it is always assumed that the confinement time is independent of energy. It therefore seems to us that before proceeding further it is crucial to examine the correctness of this assumption. In what follows, an attempt will be made to show that the mean residence time of cosmic electrons is indeed energy independent at least in the wide energy band of 10^8–10^{14} eV. Such an attempt will be made by first making two assumptions for the rigidity dependence of τ, one providing constancy above and the other below a certain rigidity, therefrom deducing limits within which τ has to be constant. The motivation for these two assumptions stems from the fact that it is now well known from studies on the intensities of Li, Be, and B nuclei, that the cosmic rays should have traversed a constant amount of about 3.5 g/cm^2 of matter in the energy region of 1–10 GeV.

In the first case let us assume that $\tau = a + b/R$, where a and b are constants. It can be shown from the continuity Equation (11), that the equilibrium spectrum of secondary electrons produced in the Galaxy can be written as

$$N_s(E)\,\mathrm{d}E = \mathrm{d}E \int_0^\infty P_s[E'(t)]\,\frac{\partial E'}{\partial E}\,\exp\left[-\int_0^t \frac{\mathrm{d}t'}{a + b/E'(t')}\right]\mathrm{d}t\,. \tag{9}$$

Here $P_s[E'(t)]\,\mathrm{d}E'$ is the rate of production of secondary electrons at E' such that, due to energy loss processes, their energy after propagation, reduces to E over a period of time t, and $\partial E'/\partial E$ is the Jacobian for the transformation from one energy interval to the other. (For electrons $E = R$.) In Figure 10 the equilibrium spectrum of

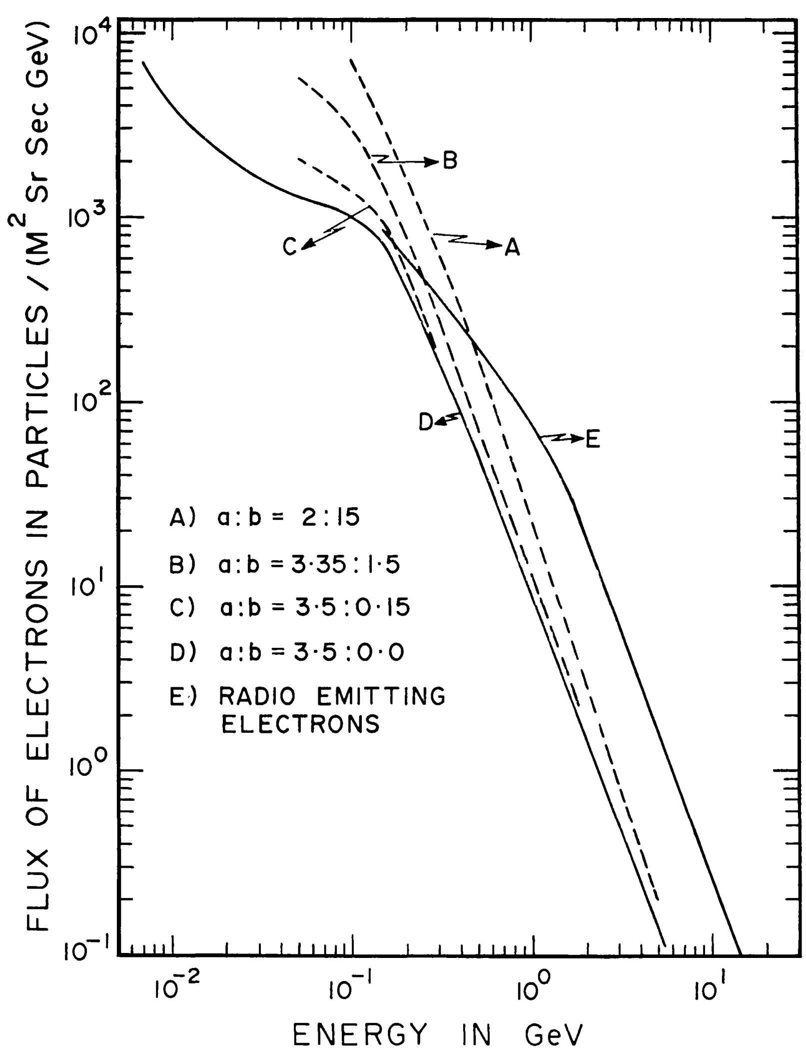

Fig. 10. Calculated energy spectra of equilibrium secondary electrons in the Galaxy with rigidity dependent time of residence of the type $\tau = a + b/R$ for various values of a and b. Curves A, B, C and D are normalised at 10 GeV assuming $\varrho c\tau = 3.5$ g/cm^2. For comparison, by curve E the energy spectrum of the radio emitting electrons in the Galaxy is shown.

secondary electrons for various values of a and b are shown, such that at $E > b/a$ the constant total matter traversed by them $x = \varrho c\tau = 3.5$ g/cm^{-2}, where ϱ and c are the matter density in the Galaxy and the velocity of light, respectively. We have also shown by curve D in the same figure, the spectrum of the secondary electrons derived in Section 4.2 for constant τ corresponding to $x = 3.5$ g/cm^{-2}, and by curve E, the radio emitting electrons in the Galaxy derived in Section 5.3. It can be seen from this figure that curve A, corresponding to $a\varrho c = 2$ and $b\varrho c = 15$, used by Cowsik *et al.* (1967), is incompatible with the radio emitting electron spectrum, and is also inconsistent with the observed charge ratio of electrons; even curve B, which has a dilution of a factor of 10 for b, is not in agreement with either the radio observations or the electron charge ratio at lower energies. A dependence of the type given by curve C, or weaker, which approaches gradually constant τ conditions, would be consistent with all observations down to about 100 MeV. Thus we have shown that at energies between about 100 MeV and a few GeV it is difficult to allow for any dependence of τ on energy. This conclusion can be considered to be consistent with the recent observations of Von Rosenvinge *et al.* (1969) on the L/M ratio of cosmic ray nuclei.

In the second case let us assume that τ is constant below a few GeV, but above this energy it is energy dependent such that $\tau = e/(d + R)$, where e and d are constants; under this assumption, when $R > d$ the cosmic ray spectrum should show a steepening by one power. Now it is known that the electron spectrum between a few GeV and 200 GeV, and the nucleonic spectrum between a few GeV and 10^{15} eV do not exhibit any indication of steepening. Therefore in this case we are left with the alternative of attributing the spectrum above a few GeV with an index of -2.6, as the spectrum steepened due to this effect. If this were so, then the equivalent rate of energy loss due to leakage will have the same form as that due to synchrotron radiation and inverse Compton scattering, wherefrom one concludes that there will be no further steepening of the electron spectrum beyond a few GeV. While one may consider this as a satisfactory situation, there are other consequences, which lead to deeper difficulties. These arise from the fact that the injection spectrum of cosmic rays should have a spectral index of -1.6, which would mean firstly the production rate of cosmic rays in the Galaxy has to be 10^4–10^5 times larger than what is thought to be at present, in order to account for the observed spectrum up to $\approx 10^{18}$ eV. Secondly, if such a situation applies to all cosmic ray sources in the universe, the leakage of cosmic rays into the metagalactic space at high energies will be highly efficient and fill up the metagalaxy with such particles much faster than at lower energies, thereby leading to a flattening of the galactic cosmic ray spectrum also at an appropriately high energy. If I_M/I_G is the ratio of the intensity of cosmic rays in metagalactic space to that in galactic space, one can, following Fujimoto *et al.* (1964), write:

$$I_M/I_G = D \times p \times t, \tag{10}$$

where D, the dilution factor, is the ratio of the volume of all galaxies to that of the universe, p, the production factor, is the ratio of the mean production rate applicable to all galaxies to that in our galaxy, and t, the lifetime factor, is the ratio of the age of the universe to the cosmic ray lifetime in the Galaxy.

Now using a rather modest value of $D \approx 10^{-7}$, $p \approx 1$, and $t \approx 10^2 (1 + R/d)$, which corresponds to $\tau \approx 10^8$ years for $R < d$, we get $I_M / I_G \approx 10^{-5} (1 + R/d)$. This means that at an energy corresponding to $R > 10^5 d$, the metagalactic component would take over and the cosmic rays should have an integral spectral index as flat as -0.6. Since no such flattening is observed at least up to 10^{18}–10^{19} eV, one can infer that there cannot be any energy dependent residence lifetime of the type we have assumed to exist up to 10^{13}–10^{14} eV.

In this manner we feel satisfied that the assumption of constancy of τ with energy for electrons of interest here is well justified.

6.4. The Injection and Equilibrium Spectrum of Cosmic Electrons

Electrons injected continuously into the confinement volume will be subject to gradual energy drain processes such as ionisation, bremsstrahlung, synchrotron emission and inverse Compton scattering, and catastrophic losses particularly through leakage out of the confinement region. If, therefore, one assumes that there is no acceleration during the time of propagation in the confinement volume, the equilibrium electron spectrum will satisfy the familiar continuity equation

$$\frac{\partial}{\partial E}\left[-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right) N(E)\,\mathrm{d}E\right] + \frac{N(E)\,\mathrm{d}E}{\tau} = Q(E)\,\mathrm{d}E\,, \tag{11}$$

where the first term on the left hand side represents the gradual energy losses, while the second one represents essentially leakage characterised by a residence lifetime τ; the term on the right hand side is the rate of injection of electrons. In Figure 15 (in Appendix II) are shown, for the metagalaxy and the disk, the typical contributions from individual energy loss processes as a function of energy, from which it is evident that at energies one deals with presently, the most important energy loss processes are due to leakage, synchrotron emission, and inverse Compton scattering. For an injection spectrum of the type $Q(E)\,\mathrm{d}E = k\,E^{-\beta}\,\mathrm{d}E$, the solution for Equation (11) can be written as

$$N(\ )\,\mathrm{d}E = \tau k E^{-\beta}\,\mathrm{d}E \quad \text{for } E \ll 1/b\tau(\beta - 1) \qquad \text{Region I} \tag{12}$$

and

$$N(E)\,\mathrm{d}E = \frac{kE^{-(\beta+1)}\,\mathrm{d}E}{b(\beta - 1)} \quad \text{for } E \gg 1/b\tau(\beta - 1)\,. \quad \text{Region II} \tag{13}$$

Here

$$bE^2 = -\left[\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{s}} + \left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{\mathrm{c}}\right], \tag{14}$$

which can be written as

$$bE^2 = [3.8 \times 10^{-18}\, H_\perp^2 + 10^{-16}(\varrho_{\mathrm{s}} + \varrho_{\mathrm{BB}})]\, E^2\,,$$

where $H_\perp$ and ϱ are expressed in μg and eV/cm^3 respectively. It is important to notice here that in Region I the spectral index of the equilibrium electrons is the same as the injection spectrum, while in Region II it is steepened by one power; if a steepening does occur in the measured energy spectrum of electrons, the energy value where it sets in can be used to deduce the value of τ and in case no steepening is observed, an upper limit can be set on the value of τ.

A close inspection of the interstellar spectrum derived in Section 4.1 at energies >100 MeV indicates that it is possible to fit two power law spectra one between 100 MeV and about 2 GeV with an index of about -1.6 and another at energies greater than 2 GeV with an index of -2.6. It has therefore been tempting to suggest an injection spectrum with a power index of -1.6 and then to attribute the steepening of the spectrum as due to the characteristic residence time in the confinement volume; such attempts resulting in values of $\tau \approx 5 \times 10^8$ years have been made in the past by Verma (1967b) and Tanaka (1968). However, an examination of the deeper implications of such an interpretation leads one into considerable difficulty. They are:

(i) A flat injection spectrum with $\beta < 2$, as in the above case, would lead to divergence in the energy content at production with increasing energy, unless the energy spectrum at productions has an arbitrary cut-off at a suitable energy. Even so, it has to extend at least up to a few thousand GeV in order to be able to account for the electrons observed up to 350 GeV. This would then mean that the cosmic ray acceleration mechanism has to be such that the electron to proton ratio which is about 5×10^{-2} at about 1 GeV should become about 10 at about 1000 GeV!

(ii) It has already been shown in Section 3.4 that the observed spectra of all nucleonic components of the cosmic rays with rigidities $\gtrsim 10$ GeV have similar spectra with $\beta \approx 2.6$; these spectra should also represent the injection spectra for these components. It would therefore be strange if the electron component alone had an injection spectrum with $\beta \approx 1.6$. However, it should be emphasised that since in the matter of the origin and acceleration of cosmic rays, our present understanding is still of a speculative nature, this point may be disputed in principle.

At this point we will like to make special reference to a possibility recently suggested by Ginzburg and Syrovatskii (1968) to explain an electron injection and source spectrum flatter than that of the nucleonic components. These authors argue that in case of Fermi type acceleration of particles, old sources, such as old supernovae, with expanding envelopes, decaying turbulence and decreasing rate of injection, can in principle, give rise to an electron spectrum with a power law spectral index between -1.5 and -2.5 at injection as well as within the source. It seems that while this model may be quite attractive to understand the age dependence of the radio spectra of supernova remnants, one seriously doubts its ability to account for the intensity and spectral shape of the cosmic ray electrons and nuclei, because of its many difficult requirements.

Also the interpretations of Verma (1967b) and Tanaka (1968) require for the halo a residence time of $\approx 5 \times 10^8$ years, a magnetic field of about 2.5 μg, and a cosmic ray intensity same as that in interstellar space. It is therefore difficult to understand how a cosmic ray energy density of about 1 eV/cm^3 can be held effectively by a magnetic field with an energy density of about 0.1 eV/cm^3, for such long time periods. There are also less important reasons, which one can adduce to the above (Anand *et al.*, 1968e), and on the whole there seem to exist enough arguments to think that the spectrum observed above 2 GeV is most likely the injection spectrum. Therefore, in what follows this will be assumed for further enquiry into the confinement of cosmic rays. However, we will like to impress most unequivocally that in problems of the kind we are dealing with here, there is always room for differing opinions and it is only through a slow process of elimination we are able to promote advancement.

6.5. Residence time of cosmic electrons in the galaxy

If the interstellar spectrum deduced in Section 4.1 is also the injection spectrum, and if the electrons are in a state of equilibrium in the storage volume, we can state that there is no steepening of the spectrum at least until about 200 GeV. One can therefore write

$$\tau \lesssim \frac{1}{bE(\beta - 1)}, \tag{15}$$

where $E = 200$ GeV. On this basis one can proceed to calculate upper limits on τ for two simple and commonly considered galactic confinement models, the halo and the disk. We recall here that we have already demonstrated in Section 6.2 of the difficulties involved in working with metagalactic confinement regions. Using the relevant astrophysical parameters summarised in Table V (in Appendix II), the values of residence time τ, and the corresponding amounts of matter traversed and cosmic ray power required, have been calculated and given in Table IV for the halo and disk models. At this stage one will like to enquire whether between the halo and disk models any preference can be found. We will therefore attempt carefully to assess the merits and demerits of each of these models to enable us to express an opinion on this crucial matter.

6.5.1. *Lifetime of Cosmic Ray Nuclei*

Before proceeding further, one may refer to the methods of deducing information on

TABLE IV

Calculated residence time, matter traversed and cosmic ray power required for halo and disk models

Parameter	Halo model	Disk model
Assumed volume V (in cm^3)	3×10^{68}	10^{67}
Residence time τ (in years)	$\gtrsim 3 \times 10^6$	$\lesssim 6 \times 10^5$
Matter traversed $\varrho c \tau$ (in g/cm^2)	$\lesssim 4 \times 10^{-2}$	$\lesssim 8 \times 10^{-1}$
Cosmic ray power[a] $\varepsilon_{cr} v/\tau$ (in ergs/sec^1)	$\gtrsim 6 \times 10^{42}$	$\gtrsim 9 \times 10^{41}$

[a] ε_{cr} is the energy density in cosmic rays and is ≈ 1 eV/cm^3.

the lifetime of cosmic ray nuclei from the amount of matter traversed by them. It has been recognised for a long time (Bradt and Peters, 1950) that since the nuclei Li, Be and B have a negligible universal abundance, their presence in the cosmic rays can be attributed to the spallation of heavier nuclei from collisions with interstellar matter, thereby permitting an estimate of x the amount of matter traversed by cosmic rays; using this method, one obtains for the observed flux of Li, Be, B nuclei in the cosmic rays, a value of $x \approx 3.5\ \mathrm{g/cm^2}$. With this information, if one adds the assumption about a confinement volume, one can make a reasonable guess about the ambient gas density ϱ and deduce a value of the residence time τ from the relation $x = \varrho c \tau$, where c is the velocity of light. Such a method leads to an estimate of $\approx 10^8$ years for the halo model and $\approx 10^6$ years for the disk model. However, it must be emphasised here that since we have no a priori knowledge so far about the contribution of matter traversed in the sources, the above lifetimes should only be considered the respective upper limits. It can now be seen that in neither model the required amount of matter traversed, as shown in Table IV, will pose any problem of understanding. In the halo model it will require that the $3.5\ \mathrm{g/cm^2}$ of matter be traversed mainly in the source region and perhaps to some extent in the disk, while in the disk model about comparable amounts of this matter traversed will be in the source region and in interstellar space or perhaps the matter density in the disk itself may be as high as 4 atoms $\mathrm{cm^{-3}}$ (Stecker, 1969).

It might also be important here to mention of a method of directly determining the lifetime of cosmic ray nuclei from a detailed study of the Li, Be and B nuclei. The relative abundance of Be nuclei among the Li, Be, B nuclei, is influenced by the radioactive decay of the Be^{10} isotope with a half life of about 4 million years; it can therefore be used as a clock to determine the lifetime of cosmic rays. An early attempt to demonstrate the feasibility of this method based on poor statistics, yielded a value of $\gtrsim 5 \times 10^7$ years (Daniel and Durgaprasad, 1966). However, it was subsequently thought that the cross sections used by these authors for the production of Be^{10} were too large (Yiou *et al.*, 1968) and hence, not only the conclusions drawn by them were unreliable, but that this method itself may not be workable (Shapiro and Silberberg, 1968). More recently two things have happened to revive interest in this topic: (i) The ratio of the intensity of Be to B nuclei in the cosmic rays has been reliably determined (Von Rosenvinge *et al.*, 1968), and (ii) there are varied indications to suggest (Goel, 1968; Von Rosenvinge *et al.*, 1968) that the relevant cross sections used by Daniel and Durgaprasad (1966) are likely to be not too wrong as indicated by the determination of Yiou *et al.* (1968). If these were so, then the new measurements of the quantity Be/B by Von Rosenvinge *et al.* (1968) would indicate a much shorter cosmic ray lifetime; even a value of 10^6 years may be consistent with the data.

6.6. The Disk Model

We will now proceed further with the examination of the halo and disk models. At the outset one must mention that the very existence of the halo, which for a long time has been considered a most appropriate volume to store and randomise cosmic rays, is being seriously questioned by radio astronomers. On the other hand, in Section 5.6 we have collected arguments to show that there is as yet no compelling reason to abandon the concept of the halo on the basis of radio continuum observations alone. The most serious obstacle in the way of accepting the halo model for cosmic rays is the short residence lifetime of 3×10^6 years in the halo. This may be compared with the generally accepted value of 3×10^8 years deduced from considerations of diffusion of particles in the halo; even conservative estimates lead to 3×10^7 years (Ginzburg and Syrovatskii, 1961, 1967). On any count this has to be reckoned as a formidable objection to this model. Therefore in what follows, we will study the disk model in detail.

The great attraction of the disk model is that the residence time deduced for it seems to be a natural attribute of the disk from considerations of the diffusion of cosmic rays within it (Parker, 1969). Nevertheless, it too has its good share of difficulties, viz. (i) the difficulty of understanding the possible existence of the halo, (ii) the high degree of isotropy of cosmic rays to the extent of 2×10^{-4} recently observed by Elliot (1968) at energies of 10^{11}–10^{12} eV, and (iii) the rather high demand of cosmic ray power generation. However, we are enabled to offer the following explanations for these three difficulties. Regarding (i) we have seen that the situation is quite unclear but that a leaky halo can in principle explain all observations. Regarding (ii) there are already attempts to explain it within the framework of a disk model in the following manner: (a) An even distribution of cosmic ray sources – this seems quite acceptable from current thinkings on this subject – all through the galactic disk will reduce the degree of anisotropy, and (b) any anisotropy of cosmic rays will excite Alfvén waves and thereby achieve isotropy by a feed back process (Rees and Sargent, 1968). Regarding (iii), there are indications from recent observations that pulsars may be very efficient sources of cosmic ray particles (Gold, 1969) sufficient to account for $\approx 10^{42}$ ergs sec^{-1} in the Galaxy; incidentally they will also explain the even distribution of sources in the disk.

After giving due consideration to all the existing uncertainties, it seems to us that in the balance the disk model has a better chance to be nearer the true situation. However, one does recognise the need for reserving the final decision, until the outcome of very many efforts to determine reliably the lifetime through the electron component (by detecting a steepening of the spectrum beyond 100 GeV) and through a study of the intensity of Be-nuclei of the nucleonic component. A final decision on this crucial, but much vexed problem is perhaps round the corner.

We have already indicated our preference to the galactic disk model on the basis of a careful scrutiny of existing data; we will therefore proceed with another implication of this model. Though one can still argue about the extent of the influence of the radio halo, since we have already indicated support for its existence, it becomes necessary to enquire whether one can retain the halo, in spite of an essential disk model for the cosmic rays. In order to explain the galactic background radio emission one requires an electron spectrum in the halo similar to the one in the disk. Since we can write $\tau_H/\tau_D < V_H/V_D$, we find $\tau_H < 2 \times 10^7$ years; here V_H and V_D are the volumes of the halo and disk respectively. This short residence time in the halo would, in turn mean that the halo is rather leaky resulting in a probable gradient of cosmic ray intensity perpendicular to the galactic plane. However, it should be impressed that a halo is not a necessary concept within the frame work of the disk model.

One should also bear in mind the possibility that the simple continuity equation used in Section 6.3, may not be sufficient to describe the electron spectrum in the disk. Instead, one may have to replace the leakage term by a diffusion term and solve the continuity equation with proper boundary conditions describing the confinement volume. A beginning in this direction has already been made by Jokipii and Meyer (1968). Finally, if one fails to detect any steepening of the electron spectrum beyond 100 GeV one may have to reconsider the whole question of the confinement of cosmic rays.

6.7. Galactic background γ and X-radiation

If cosmic ray nuclei and electrons pervade all galactic space, they must interact with the ambient matter, magnetic fields and electromagnetic radiations, to give rise to their characteristic reaction products. If these reaction products include electromagnetic radiations, they can be used as powerful probes to study not only cosmic rays in the Galaxy but also the matter, magnetic and radiation density distributions in the Galaxy. A little reflection will also indicate that such radiations will exhibit very intimate correlation with galactic directions. All this has been convincingly exemplified in the case of galactic background radio emission described in Section 5. There now exists also undisputable evidence for a background X-radiation. However, since this radiation is found to be isotropic, to the presently available limits of experimental accuracy, it has been attributed as due to metagalactic origin; it is discussed in some detail in Section 7. Yet there is bound to be at least a weak but finite galactic component immersed in this isotropic X-radiation and it is almost certain that more precise observations in the future will resolve the two components. In so far as the γ radiation is concerned, very recent satellite observations of the M.I.T. Group (Clark *et al.*, 1968) have provided strong evidence for a galactic background line intensity above 100 MeV of $\approx 5 \times 10^{-4}$ photons cm^{-2} sec^{-1} rad^{-1} in the direction of the nucleus. Nevertheless, the authors have been very cautious and have indicated that while the relative intensities are dependable, the absolute intensities should be taken with caution. Let us now attempt to understand these observations.

Clark *et al.* (1968), in their attempt to see whether their observations can be understood as due to the decay of neutral pions produced in nuclear interactions of cosmic ray particles with ambient matter, found that if the cosmic ray intensity in the disk is same as that seen near the earth at the time of solar minimum, they will contribute only about one-twentieth of the intensity observed by them. They also suggested that this discrepancy can be eased if one is willing to postulate an interstellar medium containing rather large amounts of ionised molecular or cool hydrogen and/or a greater flux of cosmic rays in the direction of the nucleus. An interesting attempt in interpreting these observations has been due to Cowsik and Yash Pal (1969) and

Shen (1969), who showed that this intensity of γ rays can be explained as due to the inverse Compton scattering of cosmic ray electrons with an intensity given by Anand *et al.* (1968e), with the photons of the intense background radiation in the mm region claimed to have been observed by Shivanandan *et al.* (1968). However, subsequent observations of Bortolot *et al.* (1969) have cast very serious doubt on the existence of a background radiation as indicated by Shivanandan *et al.* In this confused situation a very deciding evidence can be γ rays in the 10–50 MeV region, which though experimentally more difficult to detect, will permit one to draw inferences regarding the physical processes involved. This becomes possible from the fact that γ rays from neutral pion-decay show a pronounced peak at about 70 MeV, whereas the inverse Compton scattering from a power law electron spectrum will not. Apart from these two processes and bremsstrahlung, there are none which can efficiently give rise to such γ rays in the Galaxy.

6.8. Recent observations on the electron spectrum between 100 and 1000 GeV

Anand *et al.* (1969) have recently extended the electron energy spectrum beyond 100 GeV and have presented evidence which strongly suggests that the spectrum steepens at about 200 GeV. Subject to confirmation, this important observation would lead to the following interesting inferences within the framework of the Disk model. (i) The residence time of cosmic rays is $(0.5–1)\times 10^6$ years. (ii) The mean matter density in interstellar space corresponding to the above lifetime and 3.5 g.cm^{-2} of matter traversed by cosmic rays is ≈ 3 hydrogen atoms cm^{-3} compared to the value of 1 usually employed. (iii) If the intense background radiation recently observed by Shivanandan *et al.* (1968) in the sub-millimeter wavelength region exists on a galactic scale it will lead to a cosmic ray residence time of $\approx 7\times 10^4$ years. This very short cosmic ray lifetime will in turn require an interstellar gas density of about 25 hydrogen atoms cm^{-3} thereby casting serious doubt on the galactic extent of this sub-millimeter radiation.

7. Electrons in the Metagalaxy

Remembering that much of all our knowledge on cosmic ray electrons in the Galaxy described earlier in this article, has been the fruit of numerous investigations made during the last 5 years or so, it may appear to be too ambitious to attempt deductions regarding conditions in the metagalaxy. Also, by their very nature, all problems of metagalaxy are highly speculative. Yet this very speculative nature has made itself all the more attractive, and drawn the attention and interest of many scientists. From a quick examination of the papers that have appeared on this subject during the last 2 or 3 years, it seems that it is only the beginning of what is likely to grow into a most interesting area of research with intimate interplay between astronomy, astrophysics, and cosmology. Therefore, in what follows we will restrict ourselves very briefly to the general trends in this subject.

We have demonstrated, in Section 6.2, the unlikelihood of the whole universe or even the local cluster of galaxies being pervaded by cosmic rays with an intensity same as that within our Galaxy. This conclusion enables us to infer that (i) any model which invokes the possible creation of cosmic rays in a burst during a distant epoch of an evolving universe, and attributes the contemporary cosmic rays to the lingering remnants of the burst, will appear to be untenable, and (ii) one would, in a like manner, encounter considerable difficulty if the dominant source of all cosmic rays is a continuous creation in intergalactic space within or outside the framework of theories of steady state cosmology. We are thus led to speculate very favourably that the great bulk of cosmic rays in general, are generated in discrete celestial objects such as galaxies, radio galaxies, and quasistellar objects.

While our knowledge on the cosmic electrons in the Galaxy is of a more direct and reliable character, that in the metagalaxy is necessarily very indirect and as yet in a rudimentary state. From extensive observations on the non-thermal radio emission from discrete extragalactic sources, we have now undisputable evidence for the existence of varying fluxes of cosmic ray electrons in these objects. Furthermore, from general considerations, as also from those summarised in Section 6.5, there is ample room to believe that a fraction of cosmic rays generally confined to galactic volumes, leak into intergalactic space. In consequence of this, one would expect all intergalactic space to be permeated by at least a feeble flux of cosmic rays. The most direct evidence to this is the observations among cosmic rays of energy between 10^{18} and 10^{20} eV with a spectral index of $\beta \approx 2.6$, which is much flatter than that between 10^{15} and 10^{18} eV. Since, even on the most generous assumptions regarding the properties of our Galaxy, such particles cannot be confined within it, we generally accord a metagalactic origin to these particles. In view of the complete lack of information on the metagalactic nucleonic component at lower energies, one is prepared to hold even to a straw and is tempted to make a bold extrapolation from 10^{18} eV to 10^{9} eV using the same spectral index of -2.6; one then arrives at an intensity of metagalactic cosmic rays of 50–100 times weaker than that in the Galaxy in the 10 GeV region. However, in view of the enormous extrapolation made over about 10 decades, one should be cautious not to attach too much importance to this value at this stage.

An important manner in which cosmic ray electrons can reveal their existence in the metagalaxy is by the emission of electromagnetic quanta due to synchrotron radiation and inverse Compton scattering. This possibility has assumed immense importance because of three reasons: Firstly, the rapidly increasing knowledge on metagalactic objects such as radio galaxies and quasistellar radio objects has widened many possibilities. Secondly, there are sufficient reasons to believe in the existence of weak intergalactic magnetic fields, and the universal microwave radiation at 2.7 K. Thirdly, there is increasing observational evidence for the presence of isotropic, and hence metagalactic, radiations in the radio, X-ray and γ ray regions. In the interpretation and understanding of these isotropic radiations, there are two clear alternatives, namely, they arise (a) from emission by particles in the intergalactic space, and (b) from the integrated emission from all metagalactic sources. But clearly both should contribute, though their relative contributions in the different frequency regions can be much debated. It should also be borne in mind in these considerations, that our ignorance of the various parameters of relevance here is a severe handicap in deriving reliable information. Furthermore, since in all this we are dealing with physical phenomena occurring up to cosmological distances, one necessarily has to take into account effects due to cosmology. This immediately changes the whole situation and leads us to many more parameters in the form of cosmological models and the manner of evolution with time of quantities such as matter density, radiation density, magnetic fields, and source luminosities, in an evolving universe. Though at first sight the problem seems hopelessly speculative, attempts are being made, and progress is bound to come.

So far as the observational data on isotropic radiations is concerned, sufficient material is available in the X-ray region to make interpretative attempts more meaningful. Many early attempts to understand it were made, without allowing for cosmological effects; among these, the possibility of its arising from the integrated radiation from metagalactic discrete sources was investigated by Gould and Burbidge (1963), and that arising from inverse Compton scattering of electrons in intergalactic space by the universal 2.7 K microwave photons, by Felten and Morrison (1966) and Anand *et al.* (1968f, g). In this case it can be shown from observational upper limits on the flux of high energy γ rays that the electrons necessary to explain the isotropic flux of X-rays, are unlikely to be due to collisions of cosmic ray nuclei in intergalactic space (Anand *et al.*, 1968g). In both kinds of approaches the authors succeeded in arriving at reasonably satisfactory fits. However, it was soon realised that this apparently satisfactory explanation was inadequate in an evolving universe and that evolutionary effects should be taken into account. During the last 2 years, such attempts have been made, of which special mention may be made about Bergamini *et al.* (1967), Silk (1968), and Hayakawa (1969), who investigated the integrated emission from sources, and Brecher and Morrison (1967) and Rosenthal and Shukalov (1968), who have considered the emission from intergalactic space. As yet there has been no treatment which may be considered to be generally acceptable; we can only say we are trying.

Finally, we will like to make particular reference to a paper by Stecker and Silk (1969), in which they have attempted to extract information on the flux of nuclei and electrons in the metagalaxy by considering diverse physical processes to account for the observed isotropic X and γ radiations. Their results on the metagalactic electron flux are reproduced in Figure 11. The fluxes given in this figure are all upper limits and are expressed as a fraction of the flux within the Galaxy against a function of the cosmological red shift z needed to explain the observations. These calculations have been made for two cosmological models, namely an Einstein-de Sitter flat universe with mean matter density $n_0 = 10^{-5}\,\mathrm{cm}^{-3}$ and an open universe with $n_0 = 10^{-7}\,\mathrm{cm}^{-3}$, and three models of cosmic ray production. Though the authors have worked with only a restricted number of possibilities, this figure is a striking demonstration of the magnitude of the uncertainties and limitations and the extent of the task ahead of us.

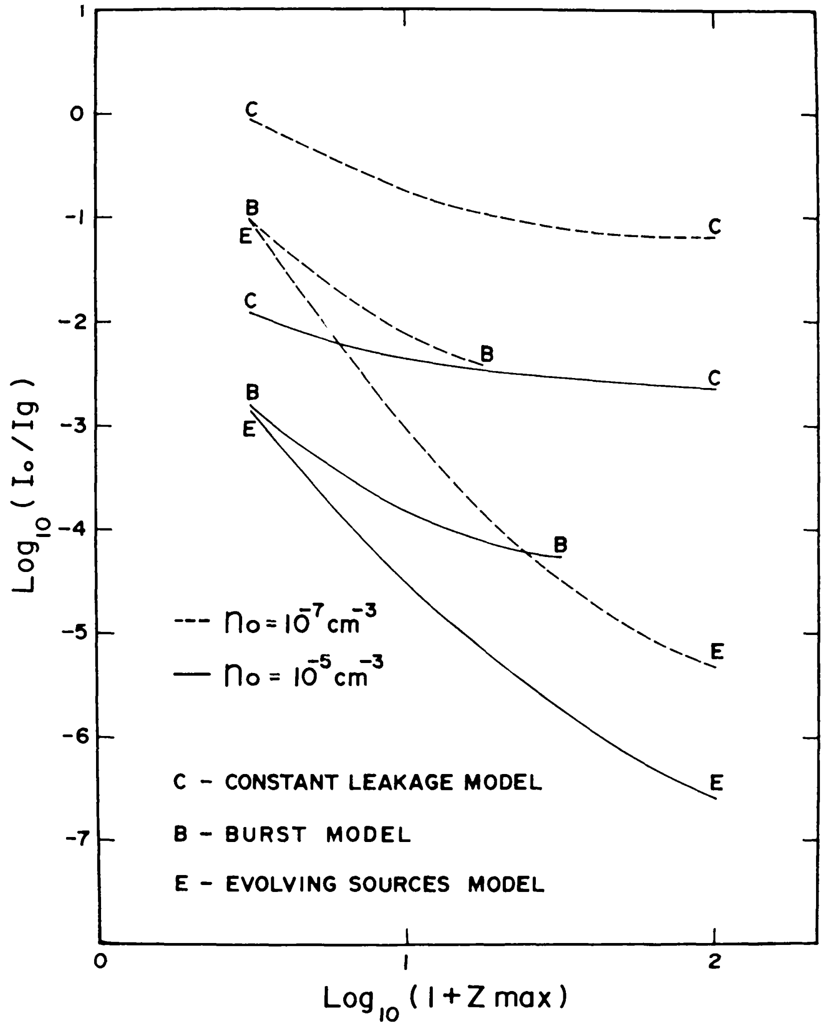

Fig. 11. Calculated upper limits of intergalactic electron intensity according to Stecker and Silk (1969).

Appendix I: Atmospheric Electrons

For small atmospheric depths, where effects due to second and higher generation interactions of nucleonic and electromagnetic components are unimportant, the main processes through which the atmospheric electrons are produced can be summarised according to their order of importance as, (a) decay of short lived particles created during collisions of cosmic ray nuclei in the atmosphere, (b) cascading of primary electrons, and (c) knock-on processes; the contribution due to the last process is negligible except at energies <50 MeV. We shall first give a general theoretical formulation to deduce the energy spectrum of electrons at a given depth in the atmosphere through these processes.

A. Electrons from the Decay of Short Lived Particles

Electrons from this process come mainly through the decay of pions

$$\pi^0 \to 2\gamma \to 2(e^+ + e^-) \tag{16}$$

and
$$\begin{array}{l}\pi^{\pm} \to \mu^{\pm} + \nu \\ \quad \hookrightarrow e^{\pm} + \nu + \bar{\nu}\,.\end{array} \tag{17}$$

The contributions from other short lived particles created during nuclear collisions can be accommodated suitably under these two. Thus it becomes essential to determine first the pion production spectrum in the atmosphere. The pion production spectrum at a depth x in the atmosphere can be written as

$$P_\pi(E, x)\,\mathrm{d}E\,\mathrm{d}x = e^{-x/\Lambda}\,Q(E)\,\mathrm{d}E\,\mathrm{d}x/\lambda \tag{18}$$

where $Q(E)\mathrm{d}E$ is the source spectrum of pions, which is determined by the energy spectrum and charge composition of the primary nucleonic component and by the characteristics of the nuclear interactions; Λ and λ are the attenuation and interaction mean free paths for nucleons in air having values 125 and 75 g/cm^2 respectively. Let us now proceed to deduce the spectrum in the atmosphere through the decay processes (16) and (17), assuming that the production spectra for charged and neutral mesons are similar with absolute intensities such that $n_{\pi_+} + n_{\pi_-} = 2n_{\pi^0}$.

(i) *Electrons through the decay of neutral pions*: Since the lifetime of neutral pions is only 1.8×10^{-16} sec, they decay instantaneously giving rise to two γ rays; the production spectrum of γ rays can then be written as

$$P_\gamma(E, x)\,\mathrm{d}E\,\mathrm{d}x = \int_{E'=\varepsilon}^{\infty} P_{\pi^0}(E', x)\,2\,\mathrm{d}E\,\frac{\mathrm{d}E'}{\Psi_\gamma(E')}\,\mathrm{d}x \tag{19}$$

where

$$\varepsilon = E + \frac{m_{\pi^0}^2}{4E} \quad \text{and} \quad \Psi_\gamma(E') = \sqrt{E'^2 - m_{\pi^0}^2}\,.$$

$$\text{Here} \quad \frac{\mathrm{d}E'}{\Psi_\gamma(E')} \approx 1, \quad \text{for} \quad E' \to m_{\pi^0}\,.$$

For a power law spectrum for pions, in the asymptotic case, P_γ becomes $\approx E^{-\beta}$ for $E > 70$ MeV, and $P_\gamma \approx E^{\beta}$ for $E < 70$ MeV, where β is the spectral index for the pion production spectrum (for detailed discussion on this, see Stecker, 1967). Note that the angular distribution of the γ rays during the decay of π^0 is important at kinetic energies $\lesssim m_{\pi^0}$. The flux of γ rays $F_\gamma(E, x)\,\mathrm{d}E$ at any depth can be described by the diffusion equation

$$\mathrm{d}\left[F_\gamma(E, x)\,\mathrm{d}E\right] = P_\gamma(E, x)\,\mathrm{d}E\,\mathrm{d}x - F_\gamma(E, x)\,\mathrm{d}E\,\frac{\mathrm{d}x}{L_c}, \tag{20}$$

where the second term on the right hand side represents the rate of conversion of γ rays in the atmosphere and $L_c = 48.5$ g/cm^2, the conversion length in air. The solution of the above equation is

$$F_\gamma(E, x)\,\mathrm{d}E = e^{-x/L_c} \int_{x'=0}^{x} P_\gamma(E, x)\,\mathrm{d}E\,e^{x'/L_c}\,\mathrm{d}x'\,. \tag{21}$$

When γ rays materialise in the atmosphere, each gives rise to a pair of electrons having a flat energy spectrum of the type $N_e(E)\,dE = (2\,dE)/E_\gamma$, which becomes zero at $E=0$ and $E=E_\gamma$. Hence the production spectrum of electrons can be written as

$$P_e(E,x)\,dE\,dx = \int_{E'=E}^{\infty} F_\gamma(E',x)\,dE' \frac{dx}{L_c}\frac{2\,dE}{E'}. \tag{22}$$

Neglecting the electromagnetic multiplication, but taking into account the radiation loss, the energy spectrum of electrons at any depth x can be given as

$$F_e(E,x)\,dE = \int_{x'=0}^{x} P_e(E',x')\,dE\,dx' \left(\frac{\partial E'}{\partial E}\right). \tag{23}$$

Here E' is the energy at x', such that at x we write $E=E'\,e^{-(x-x')/L_R}$ and $(\partial E'/\partial E)$ is the Jacobian for this transformation; $L_R=37.7\ \text{g/cm}^2$ is the radiation length in air. For a simple power law production spectrum for pions of the type $P_\pi(E,x)\,dE\,dx = C_\pi\,e^{-x/\Lambda}\,(dx)/\lambda\,(dE)/E^\beta$ the above equation becomes

$$F_e(E,x)\,dE = \frac{c_e L_R}{\lambda}\times$$
$$\times\left\{(e^{-x/\Lambda} - e^{-\gamma x/L_R})\frac{\Lambda}{\gamma_\Lambda - L_R} - (e^{-x/L_c} - e^{-\gamma x/L_R})\frac{L_c}{\gamma L_c - L_R}\right\}\frac{dE}{E^\beta} \tag{24}$$

for $E > 70$ MeV. Here

$$c_e = \frac{4c_{\pi^0}\Lambda}{\beta^2(\Lambda - L_c)}$$

and $\gamma = \beta - 1$.

When $(\beta-1)\,L_c \approx L_R$, the above expression breaks down but can be replaced by the equation

$$F_e(E,x)\,dE = \frac{c_e}{\lambda}\left\{\frac{\Lambda L_R}{\gamma_\Lambda - L_R}(e^{-x/\Lambda} - e^{-\gamma x/L_R}) - x e^{-\gamma x/L_R}\right\}\frac{dE}{E^\beta}, \tag{24'}$$

and when $(\beta-1)\Lambda \approx L_R$:

$$F_e(E,x)\,dE = \frac{c_e}{\lambda}\left\{x e^{-\gamma x/L_R} - \frac{L_c L_R}{\gamma L_c - L_R}(e^{-x/L_c} - e^{-\gamma x/L_R})\right\}\frac{dE}{E^\beta}. \tag{24''}$$

(ii) *Electrons through charged pions*: Since the charged pions (which will be indicated without sign) can interact before decay, their flux $F_\pi(E,x)\,dE$ at any depth in the atmosphere is determined from the diffusion equation

$$d\left[F_\pi(E,x)\,dE\right] = P_\pi(E,x)\,dE\,dx - F_\pi(E,x)\,dE\frac{dx}{\lambda_\pi} - F_\pi(E,x)\,dE\frac{U_\pi}{E}\frac{dx}{x}. \tag{25}$$

Here the 2nd term on the right hand side gives the number of interacting pions of energy E and the last term corresponds to the number that decay. The decay probability at depth x is given by $U_\pi/E\, \mathrm{d}x/x$, where U_π is defined as

$$U_\pi = \frac{h_0 m_\pi}{c\tau_\pi}. \tag{26}$$

Here $h_0 \approx 7$ km is the scale height of the atmosphere, and m_π and τ_π are the mass and lifetime of the pions respectively. The solution of Equation (25) is

$$F_\pi(E, x)\,\mathrm{d}E = e^{-x/\lambda_\pi} x^{-U_\pi/E} \int\limits_{x'=0}^{x} Q(E)\,\mathrm{d}E\, e^{-\left(\frac{1}{\lambda\pi} - \frac{1}{\Lambda}\right)x'} \frac{x'^{U_\pi/E}}{\lambda}\,\mathrm{d}x'. \tag{27}$$

Since $\lambda_\pi \approx \Lambda$, the above solution becomes

$$F_\pi(E, x)\,\mathrm{d}E = e^{-x/\lambda_\pi} \frac{xE}{(U_\pi + E)\,\lambda} Q(E)\,\mathrm{d}E. \tag{28}$$

When the pion decays into a muon and a neutrino, the muon production spectrum can be written as

$$P_\mu(E, x)\,\mathrm{d}E\,\mathrm{d}x = \int\limits_{E'=E+\varepsilon}^{E/f} F_\pi(E', x)\,\mathrm{d}E \frac{U_\pi}{E'} \frac{\mathrm{d}x}{x} \frac{\mathrm{d}E'}{\psi_\mu(E')}. \tag{29}$$

Here $\psi_\mu(E') = E'(1-f)$, where $f \approx 0.6$, is the minimum fractional energy the muon gets from the pion during the decay $\pi \to \mu + \nu$ and $\varepsilon \approx m_\pi - m_\mu$. Some muons decay in the atmosphere and the flux at any depth is governed by the diffusion equation

$$\mathrm{d}\left[F_\mu(E, x)\,\mathrm{d}E\right] = P_\mu(E, x)\,\mathrm{d}E\,\mathrm{d}x - F_\mu(E, x)\,\mathrm{d}E \frac{U_\mu}{E} \frac{\mathrm{d}x}{x}. \tag{30}$$

The second term in the right hand side corresponds to the number of muons of energy E that decay at depth x and U_μ is defined in a manner similar to Equation (26). The solution of the above equation is

$$F_\mu(E, x)\,\mathrm{d}E = x^{-U_\mu/E} \int\limits_{x'=0}^{x} x'^{U_\mu/E} P_\mu(E, x')\,\mathrm{d}E\,\mathrm{d}x'. \tag{31}$$

In the three body decay of muons, the electron has a distribution of energy given by the relation (Zatsepin and Kuzmin, 1962)

$$\psi_e(E_\mu, E)\,\mathrm{d}E = \left[\frac{5}{3} - 3\left(\frac{E}{E_\mu}\right)^2 + \frac{4}{3}\left(\frac{E}{E_\mu}\right)^3\right] \frac{\mathrm{d}E}{E_\mu} \tag{32}$$

and the production spectrum of electrons at a depth x can then be written as

$$P_e'(E, x)\,\mathrm{d}E\,\mathrm{d}x = \int\limits_{E'=\varepsilon}^{\infty} F_\mu(E', x)\,\mathrm{d}E' \frac{U_\mu}{E'} \frac{\mathrm{d}x}{x} \psi_e(E', E)\,\mathrm{d}E. \tag{33}$$

Here $\varepsilon = E$ for $E > m_\mu$ and $\varepsilon = m_\mu$ when $E \leqslant m_\mu$. Note that for the muon kinetic energy $\lesssim m_\mu$, the angular distribution of the decay electrons cannot be ignored. As in the case of electrons from neutral pions, the flux of electrons through the decay of charged mesons at any depth in the atmosphere is then given by Equation (23). In the case of a power law production spectrum of pions, one can express $F_e'(E, x)\,dE$ through a simple integral for a particular case, when one assumes a mean fractional energy q_1 and q_2 to be carried by the muon and the electron during the decay of pion and muon respectively ($q_1 = 0.8$ and $q_2 = 0.35$).

$$F_e'(E, x)\,dE = \int\limits_{x'=0}^{x} \frac{c_e'}{\lambda}\frac{dE}{E^\beta}\frac{e^{-(\beta-1)(x-x')/L_R}}{\left[q_1 q_2 U_\pi + E e^{(x-x')/L_R}\right]} \times \times \sum_{n=1}^{\infty} \frac{(-1)^{n-1} x'^{n-1}\,dx'}{\lambda_\pi^{n-1}\left[q_2 U_\mu + nE\, e^{(x-x')/L_R}\right]}, \tag{34}$$

where

$$c_e' = c_\pi U_\pi U_\mu q_1^\beta q_2^{\beta+1}.$$

B. CASCADE MULTIPLICATION OF PRIMARY ELECTRONS

Since the primary electrons incident at the top of the atmosphere undergo cascade multiplication, secondary electrons are produced. Let us consider here only the second generation electrons. The flux of primary electrons at any depth in the atmosphere can be written as

$$F_{ep}(E, x)\,dE = F_{ep}(E e^{x/L_R}, 0)\, e^{x/L_R}\,dE. \tag{35}$$

The electrons radiate photons through bremsstrahlung process and the production spectrum of γ rays is given by

$$P_\gamma'(E, x)\,dE\,dx = \int\limits_{E'=E}^{\infty} F_{ep}(E', x)\,dE' \frac{\varphi(E', E)}{L_R}\,dE\,dx, \tag{36}$$

where $(\varphi(E', E))\,dE/L_R$ is the differential radiation probability that an electron of energy E' radiates a photon of energy E in the interval dE and is given by

$$\frac{\varphi(E', E)\,dE}{L_R} = \frac{1}{L_R}\left[\frac{a}{E} - \frac{a}{E'} + \frac{E}{E'^2}\right] dE. \tag{37}$$

For complete screening, $a = 4/3 + 1/[9 \ln(183\, Z^{-1/3})]$. Thus knowing the production spectrum of γ rays, one can derive the flux of electrons at any depth in a manner similar to the one described above, in A.i. In the case of a power law spectrum of the type $F_{ep}(E, 0)\,dE = AE^{-\beta}\,dE$ for the primary electrons, the flux of secondary electrons at any depth can be written for energies greater than the cut-off as

$$F_e''(E, x)\,dE = c_e'' E^{-\beta}\,dE\left[\frac{L_c L_R}{\gamma L_c - L_R}\left(e^{-x/L_c} - e^{-\gamma x/L_R}\right) - x e^{-\gamma x/L_R}\right], \tag{38}$$

where

$$c_e'' = \frac{2}{\beta} \frac{A}{\gamma L_c - L_R} \left[\frac{a}{\beta - 1} - \frac{a}{\beta} + \frac{1}{\beta + 1} \right] \quad \text{and} \quad \gamma = \beta - 1 .$$

This relation breaks down when $\gamma L_c \approx L_R$ but can be written in this case as

$$F_e''(E, x)\,\mathrm{d}E = \frac{A}{\beta L_c L_R} \left[\frac{a}{\beta - 1} - \frac{a}{\beta} + \frac{1}{\beta + 1} \right] e^{-\gamma x / L_R} x^2 E^{-\beta}\,\mathrm{d}E . \tag{38'}$$

C. KNOCK-ON PROCESS

In this process, energy is transferred to electrons of the air atoms in Coulomb collisions of cosmic ray nuclei. The probability that a cosmic ray nucleus of charge Z_j and energy per nucleon E' collides with an air atom of charge Z_i and atomic mass $A_i m_p$ giving rise to a knock on electron of energy E can be written as

$$\phi_{ij}(E', E)\,\mathrm{d}E = \frac{2\pi N_0 z_i r_e^2 z_j^2 m_e}{A_i (E'^2 - m_p^2)} \times \\ \times \left[\frac{E'^2}{(E - m_e^2)^2} - \frac{2A_i m_e E' + m_e^2 + A_i^2 m_p^2}{2A_i^2 m_e (E - m_e)} + \frac{1}{2A_i^2} \right] \mathrm{d}E , \tag{39}$$

where N_0 is Avogadro's number and r_e is the classical radius of the electron. The production spectrum of knock on electrons at any depth x is then given by

$$P_e'''(E, x)\,\mathrm{d}E\,\mathrm{d}x = \int_{E' = \varepsilon}^{\infty} \sum_i \sum_j \phi_{ij}(E', E)\,\mathrm{d}E\, F_j(E', x)\,\mathrm{d}E'\,\mathrm{d}x , \tag{40}$$

where ε is defined by the equation

$$\varepsilon = m_e + \frac{2A_i^2 m_e (E'^2 - m_p^2)}{2A_i m_e E' + m_e^2 + A_i^2 m_p^2} \tag{41}$$

and the flux of electrons at any depth x is given by Equation (23). However, in this case one has to take into account the energy loss of electrons through ionisation also.

D. DISCUSSION

Estimation of the secondary electrons in the atmosphere through processes (b) and (c) are very straightforward; in case of (a) it becomes essential to determine first the source spectrum $Q(E)\,\mathrm{d}E$ of the pions. Many attempts have been made in the past (Tulinov, 1958; Subramanian and Verma, 1959; Pine *et al.*, 1959; Wolfendale, 1964; Yash Pal and Peters, 1964; Hayakawa *et al.*, 1964) to derive this at energies > a few GeV using sea level and underground measurements of the muon spectrum, and from γ ray spectrum deep in the atmosphere. A few attempts have been made recently (Okuda and Yamamoto, 1965; Perola and Scarsi, 1966; Verma, 1967a) to determine the vertical pion production spectrum in the atmosphere using the available information on the characteristics of high energy interactions at accelerator energies;

among these, the results from the works of Perola and Scrasi (1966) and Verma (1967a) have been widely used by cosmic ray workers. The charged pion production spectra at the top of the atmosphere, as deduced by these authors are shown in Figure 12 for Fort Churchill, Canada, where the geomagnetic threshold rigidity for the primary component is smaller than the threshold for the pion production, and for Hyderabad, India, where the geomagnetic threshold rigidity is very much above the threshold for pion production. One can see from this figure that the agreement between these two calculations is so poor that one is left with no choice except to question the reliability of these calculations. In the same figure is also shown the charged pion production spectrum deduced from the observed γ ray spectrum in the region 1–40 GeV over Hyderabad (Stephens, 1969); this has an absolute intensity much smaller than the former calculations. The possible reason for this discrepancy has been discussed in Section 2.2.

Considering the calculations of atmospheric electrons from the pion production spectrum, one can notice from Appendix I (A) that it is essential to take into account the energy distribution of decay particles at all energies; also for determining the vertical intensity at any depth one cannot ignore the angular distribution of the decay

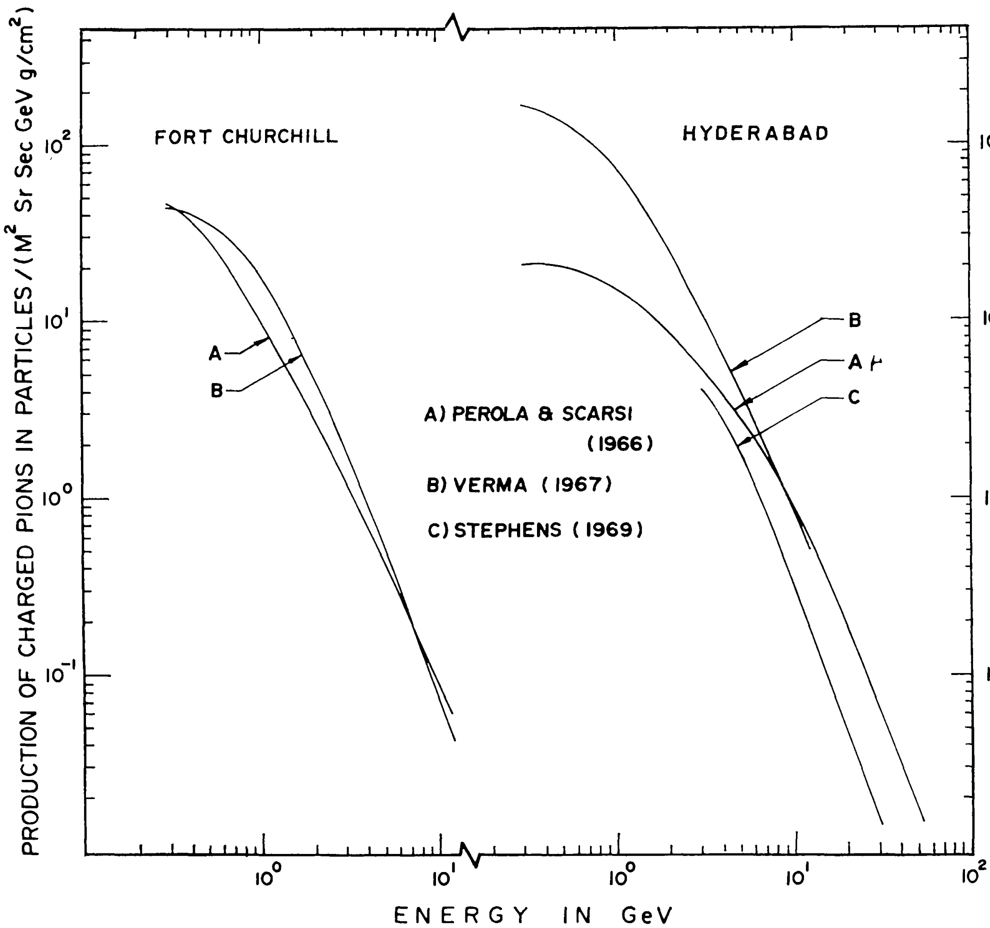

Fig. 12. The vertical production spectra of charged pions per g/cm² at the top of the atmosphere over Fort Churchill, Canada, and Hyderabad, India.

particles at low energies. However, it is often the case that such simplified assumptions are introduced in these calculations to make the computations easier. In Figure 13 is shown the estimated vertical secondary electron spectrum at an atmospheric depth of 4 g/cm^2 (Perola and Scarsi, 1966; Verma, 1967a) over Fort Churchill and

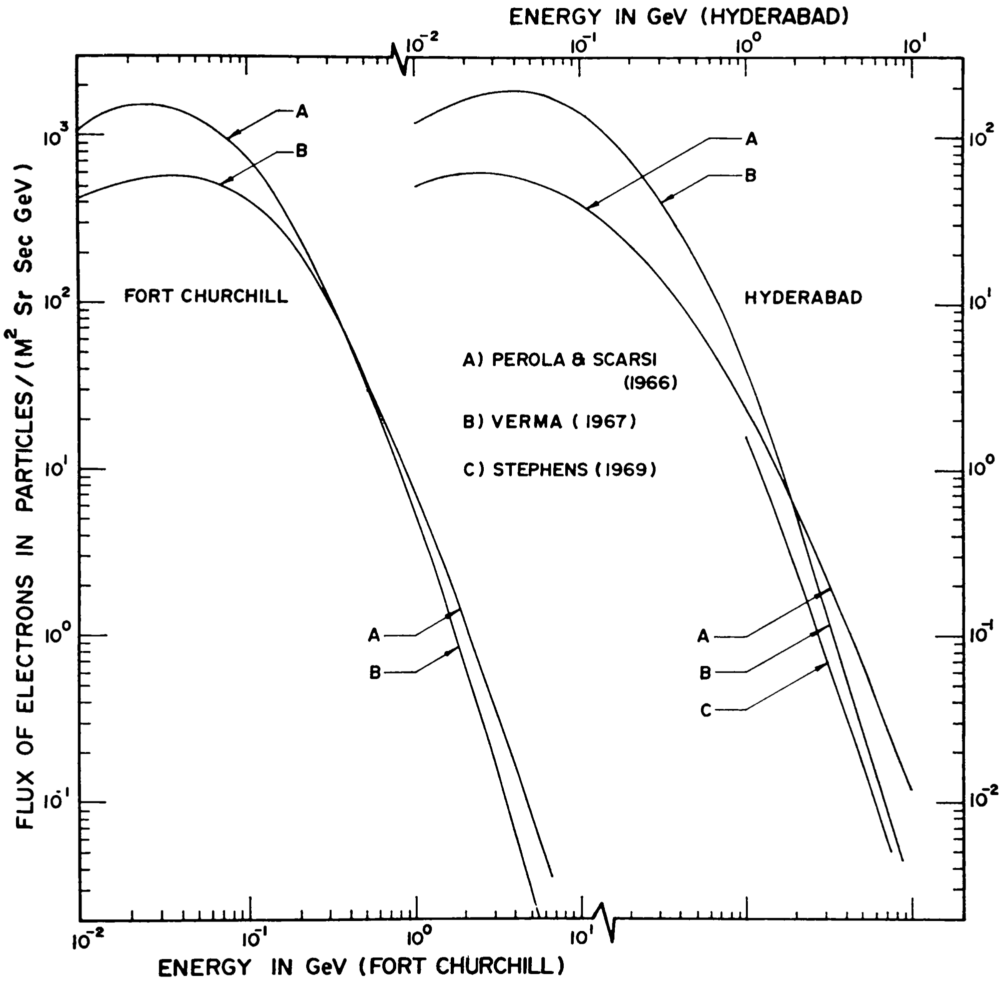

Fig. 13. The vertical differential energy spectra of atmospheric electrons at 4 g/cm^2 of atmospheric depth over Fort Churchill and Hyderabad.

Hyderabad. For comparison, we have also shown the electron spectrum deduced from the observed γ ray flux over Hyderabad (Stephens, 1969), which was found to be consistent with the observed electron spectrum below the geomagnetic threshold energy. The striking feature of Figures 12 and 13 is that the relative disagreement between the calculations is not similar to that for pions, suggesting new differences that have crept in between pion production and electron production. Mention may be made here that in these calculations, the energy loss of electrons during their traversal in the atmosphere after production, and the contribution due to the cascading of primary electrons have not been taken into account.

Another feature that comes from the calculations, is the growth of secondary electrons in the atmosphere. It can be seen from Equation (24) that the growth of electrons through neutral pion decay has a higher x dependence, but is independent of the energy. On the other hand, Equation (34) suggests that the growth of electrons from the decay of charged mesons is linear at small atmospheric depths but later decreases, as the depth and the energy increase. Because of this reason, the growth curve of the secondary electrons, which consist mainly of electrons from these decay processes, depends on the energy of the electrons. The shape appears to be linear at very small atmospheric depths due to the dominant contribution from the charged mesons but becomes steeper as the electrons from the neutral pions take over; the depth at which this change takes place depends on the energy. In order to demonstrate the above effect typical growth curves, in arbitrary units for 300 and 500 MeV, are shown in Figure 14; one can show easily that if similar calculations are made for electrons of energy ≈ 5 GeV the electrons from neutral pions dominate over those from charged pions even at about 2 g/cm^2. We have also shown in the same figure the measurements of Bleeker *et al.* (1968a), Webber and Chotkowski (1967), and L'Heureux (1967) at similar energy intervals. From this figure one can see that no two experimental growth curves agree at depths above a few g/cm^2, though they all indicate the existence of an extraterrestrial component. It is interesting to point out that the measurements of Bleeker *et al.* (1968a) in the energy interval correspond-

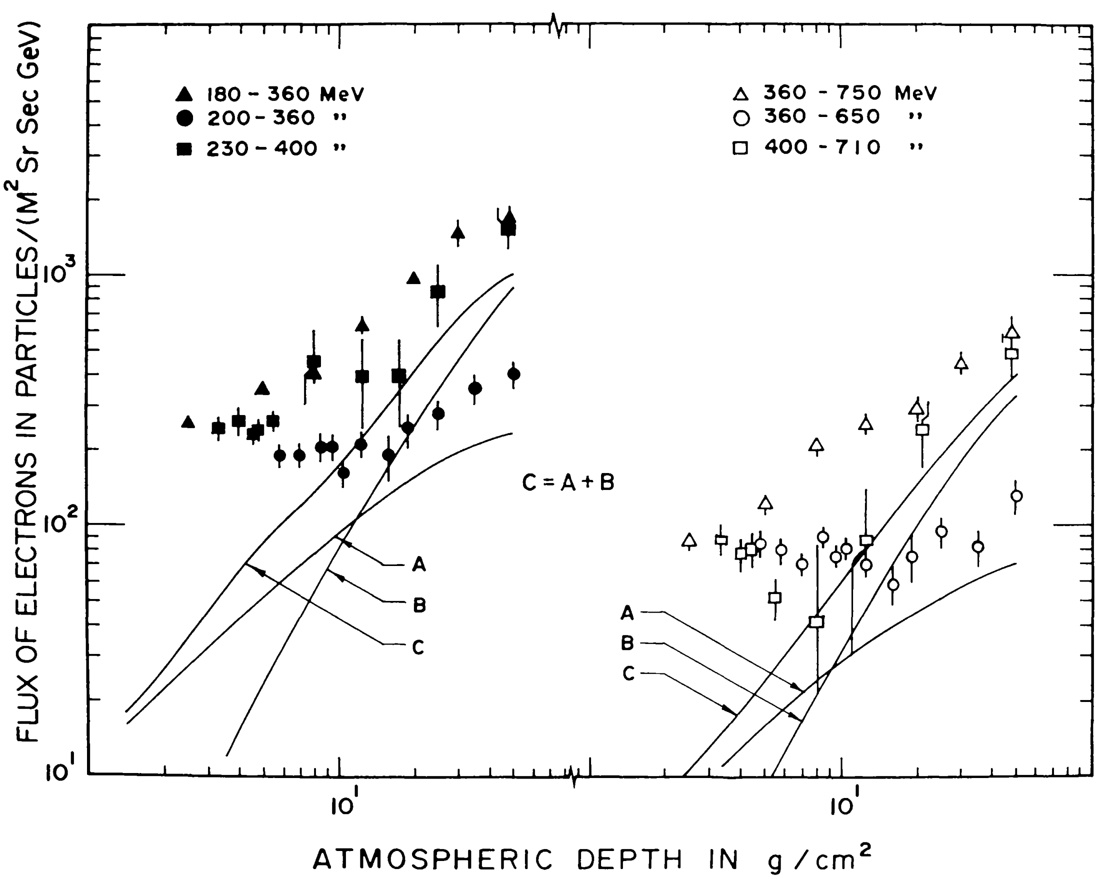

Fig. 14. Atmospheric growth curves for secondary electrons. Curves *A* and *B* are those due to the decay of charged and neutral pions respectively. The triangles, circles and squares are due to Webber and Chotkowski (1967), Bleeker *et al.* (1968a) and L'Heureux (1967) respectively.

ing to 300 MeV which is below the geomagnetic threshold energy in their experiments, gives the same flux value obtained by others over stations where the threshold energy is below 300 MeV at about 4 g/cm^2. This strongly suggests that the flux of re-entrant electrons at these energies is of the same magnitude as the primary electrons.

Appendix II: Interaction of Electrons with Matter, Magnetic Fields and Radiation Fields Existing in Space

The main processes through which a relativistic electron loses energy during its propagation in cosmic space are (a) ionisation, (b) bremsstrahlung, (c) synchrotron radiation, and (d) inverse-Compton scattering. In this appendix, we shall summarise the relations relevant to this article and illustrate the relative magnitudes of the rates of energy loss through these processes as a function of energy in two typical cosmic environments, viz. the disk and the metagalaxy.

A. IONISATION

When an electron makes Coulomb collisions with atomic hydrogen existing in space, it loses energy by ionisation, and the rate of energy loss at relativistic energies can be written as

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_I \approx 7.6\times10^{-18}\, n\left\{3\ln\frac{E}{mc^2}+18.8\right\}\text{GeV sec}^{-1}, \tag{42}$$

where n is the number of hydrogen atoms per cm^3 and E and mc^2 are the energy and mass of electron. For a mixture of 10% helium, the ionisation loss is about 10% higher than that for pure hydrogen. For a completely ionised medium, the energy loss due to ionisation is given by

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_I \approx 7.6\times10^{-18}\, n\left\{\ln\frac{E}{mc^2}-\ln n+73.4\right\}\text{GeV sec}^{-1}. \tag{42$'$}$$

B. BREMSSTRAHLUNG

The rate of energy loss due to bremsstrahlung in atomic hydrogen for complete screening is

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_B \approx 8\times10^{-16}\, nE\ \text{GeV sec}^{-1}, \tag{43}$$

and for ionised medium this becomes

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_B \approx 1.4\times10^{-16}\, nE\left\{\ln\frac{E}{mc^2}+0.36\right\}\text{GeV sec}^{-1}. \tag{43$'$}$$

C. SYNCHROTRON RADIATION

An electron while traversing magnetic fields loses energy by radiating photons in a wide spectrum of energies. The total power radiated by a single electron in a homogeneous magnetic field and hence its rate of energy loss is given by

$$S(E) = -\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_S = \frac{2e^4 H_\perp^2}{3m^2c^3}\left(\frac{E}{mc^2}\right)^2$$
$$\approx 3.8 \times 10^{-18}\, H_\perp^2 E^2 \text{ GeV sec}^{-1}, \tag{44}$$

where $H_\perp$ in μg is the component of the magnetic field perpendicular to the direction of motion of the electron and e is the charge of the electron. The spectral distribution of the power radiated from a single electron is given by

$$S(\nu) = \frac{\sqrt{3}\, e^3 H_\perp}{mc^2} \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\, \mathrm{d}\eta\,. \tag{45}$$

Here $S(\nu)$ is the power radiated at a frequency ν and ν_c is defined as

$$\nu_c = \frac{3eH_\perp}{4\pi mc}\left(\frac{E}{mc^2}\right)^2. \tag{46}$$

The spectral shape is determined by the function $F(\nu/\nu_c) = \nu/\nu_c \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\, \mathrm{d}\eta$, which has a maximum at a frequency $\nu_m = 0.29\nu_c = 4.6 \times 10^6 H_\perp E^2$, and the intensity of radiation at this frequency is $S(\nu_m) = 2.16 \times 10^{-35} H_\perp$ W Hz^{-1}.

When we consider electrons with a spectrum of energies, the power radiated at a given frequency comes from electrons with a wide range of energies. For isotropic distribution of electrons, the intensity of radiation can be evaluated from the relation

$$I_\nu = \frac{1}{4\pi} \int_{r=0}^{L} \int_{E=mc^2}^{\infty} S(\nu)\, N(E, r)\, \mathrm{d}E\, \mathrm{d}r\,, \tag{47}$$

where L is the dimension of the radiating region along the line of sight and $N(E, r)\,\mathrm{d}E$ is the number of electrons per unit volume at r having random directions of motion with energy E. Since $F(\nu/\nu_c)$ is a function of E and $H_\perp$ through Equation (46), we shall define a function $G_\nu(E, r) = F(\nu/\nu_c)$ for a given frequency and the above expression thus becomes

$$I_\nu = \frac{\sqrt{3}\, e^3}{4\pi mc^2} \int_0^L \mathrm{d}r \int_{mc^2}^{\infty} H_\perp(r)\, G_\nu(E, r)\, N(E, r)\, \mathrm{d}E\,. \tag{48}$$

Here $H_\perp(r)$ in gauss is the component of the magnetic field at r perpendicular to the line of sight. In general it is difficult to take into account the spatial distribution of magnetic field and electron intensity; we can re-write the above relation for a mean magnetic field and electron intensity approximated to a homogeneous case as

$$I_\nu = \frac{\sqrt{3}\, e^3}{4\pi mc^2} \langle H_\perp \rangle\, L \int_{mc^2}^{\infty} G_\nu(E)\, N(E)\, \mathrm{d}E\,. \tag{49}$$

For a particular case when the electron spectrum is a power law of the type

$N(E)\,\mathrm{d}E = AE^{-\beta}\,\mathrm{d}E$, where E is expressed in ergs, and the magnetic field has random orientations, the above expression reduces to

$$I_\nu = 1.35 \times 10^{-22} f(\beta)\, LA \langle H \rangle^{\frac{\beta+1}{2}} \times \times \left(\frac{6.26 \times 10^{18}}{\nu}\right)^{\frac{\beta-1}{2}} \mathrm{erg\ cm^{-2}\ sr^{-1}\ sec^{-1}\ H_Z{}^{-1}}. \tag{50}$$

Here $\langle H \rangle$ is expressed in gauss and the value of $f(\beta)$ varies from 0.283 at $\beta = 1$ to about 0.073 at $\beta = 4$.

D. Inverse Compton Scattering

In this process a high energy electron collides with a soft photon to which it imparts some or most of its energy and itself emerges with low energy. The rate of energy loss of an electron in a radiation field can be written as

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_\mathrm{c} = \tfrac{4}{3}\sigma_\mathrm{T} c \varrho_\mathrm{ph} (E/mc^2)^2 \approx 10^{-16}\, \varrho_\mathrm{ph} E^2 \ \mathrm{GeV\ sec^{-1}}. \tag{51}$$

Here σ_T is the Thomson cross-section, and ϱ_ph is the energy density of the radiation in eV/cm^3. Since the mean energy of the scattered photon is $\bar{E}_\gamma = 4/3\ \bar{\varepsilon}(E/mc^2)^2$, where $\bar{\varepsilon}$ is the mean energy of the photon, the above relation is valid only for energies $E \ll mc^2/\bar{\varepsilon}$, while for energies $E \gg mc^2/\bar{\varepsilon}$, the rate of energy loss is given by

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_\mathrm{c} \approx 2.9 \times 10^{-12} \frac{\varrho_\mathrm{ph}}{\bar{\varepsilon}^2} [\ln(\bar{\varepsilon}E) - 6 \cdot 1]\ \mathrm{GeV\ sec^{-1}}, \tag{51'}$$

where $\bar{\varepsilon}$ is expressed in eV.

For an electron spectrum $N(E)\,\mathrm{d}E$ and a photon concentration $n(\varepsilon)\,\mathrm{d}\varepsilon$, the intensity of scattered photon over a path length L, is given by

$$I_\gamma(E_\gamma)\,\mathrm{d}E_\gamma = L \int_0^\infty n(\varepsilon)\,\mathrm{d}\varepsilon \int_{E_\mathrm{min}}^\infty \sigma(E, \varepsilon, E_\gamma)\, N(E)\,\mathrm{d}E. \tag{52}$$

Here, $\sigma(E, \varepsilon, E_r)$ is the cross-section for an electron of energy E to scatter a photon, of energy ε to an energy E_γ, and $E_\mathrm{min} = mc^2\,(E_\gamma/4\varepsilon)^{1/2}$. When the electron spectrum is a power law and the radiation field is a black body one, the above relation can be evaluated as

$$I_\gamma(E_\gamma)\,\mathrm{d}E_\gamma = f'(\beta)\, \tfrac{2}{3}\sigma_\mathrm{T} L \varrho_\mathrm{ph} (mc^2)^{1-\beta} \left(\tfrac{4}{3}\bar{\varepsilon}\right)^{\frac{\beta-3}{2}} AE_\gamma^{-\frac{\beta+2}{2}}\,\mathrm{d}E_\gamma, \tag{53}$$

Here the value of $f'(\beta)$ varies from 0.84 at $\beta = 1$ to 1.4 at $\beta = 4$.

E. Relative Magnitudes of the Energy Loss Processes in Cosmic Space

The relative importance of the energy loss processes described earlier, depends upon the astrophysical conditions such as the matter density, intensity of magnetic field, and radiation density. In Table V these parameters for three different regions of cosmic space are summarised, viz. the disk, the halo and the metagalaxy. The mean energies of the starlight and the universal black body photons are 1 eV and 6.3×10^{-4} eV respectively.

TABLE V

Astrophysical parameters relating to cosmic space

Region of space	Matter density (in atom cm^{-3})	Magnetic field (in μg)	Radiation density (in eV/cm^3) Starlight	Black body–2.7K
The disk	1	7	0.5	0.25
The halo	10^{-2}	2.5	0.1	0.25
The meta-galaxy	10^{-5}	0.1	10^{-2}	0.25

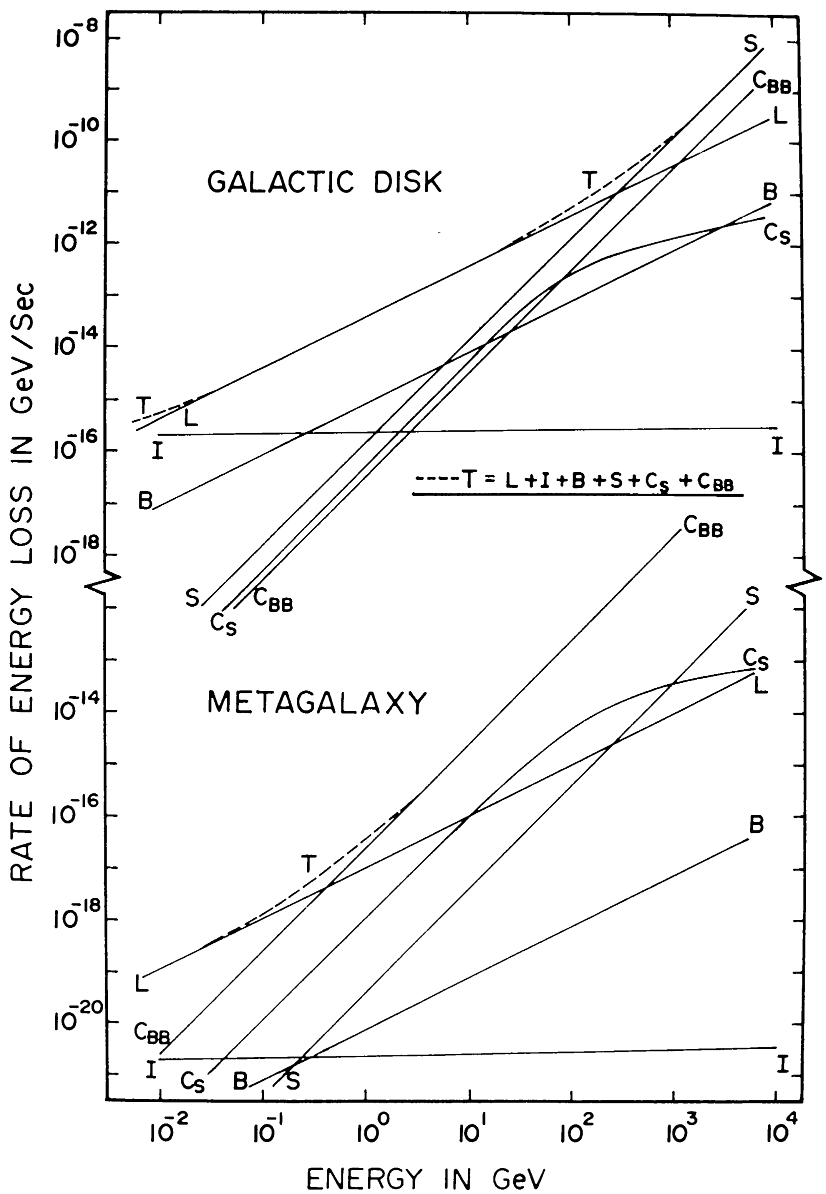

Fig. 15. Rates of energy loss of electrons through ionisation (I), bremsstrahlung (B), synchrotron radiation (S), inverse Compton scattering with star light (C_S) and black body radiation (C_{BB}) and leakage L, for the galactic disk and the metagalaxy.

Apart from the energy loss processes, the electron can sometimes be lost from the confinement volume due to leakage and the equivalent rate of energy loss can be written as

$$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_L = \frac{E}{\tau}\ \mathrm{GeV\ sec}^{-1}, \tag{54}$$

where τ is the residence time for electron in a confinement region of space. In the case of the universe, since particles are not lost by leakage, the equivalent residence time is taken to be about a third of the expansion time of the universe.

In Figure 15 are shown the rates of energy loss due to various processes in the disk and the metagalaxy using Equations (42), (43), (44), (51) and (54) taking 10^6 and 3×10^9 years as the residence time in the disk and metagalaxy respectively and assuming that the matter in cosmic space consists of only hydrogen. It can be seen from this figure that for the disk, the ionisation loss dominates at energies $\approx$ a few MeV, and at energies >100 GeV, the synchrotron radiation dominates, while in the intermediate energies the leakage of particle is the important mode of energy loss. However, in the metagalaxy, the inverse-Compton scattering of electrons with the universal black body radiation at 2.7 K dominates above 100 MeV while the loss due to expansion dominates at lower energies.

References

Abraham, P. B., Brunstein, K. A., and Cline, T. L.: 1966, *Phys. Rev.* **150**, 1088.

Agrinier, B., Koechlin, Y., Parlier, B., Boella, G., Antoni, G. D., Dilworth, C., Scarsi, L., and Sironi, G.: 1964, *Phys. Rev. Letters* **13**, 377.

Alexander, J. K. and Stone, R. G.: 1965, *Astrophys. J.* **142**, 1327.

Allen, C. W.: 1963, *Astrophysical Quantities*, Athlene Press, University of London.

Anand, K. C., Daniel, R. R., Stephens, S. A., Bhowmik, B., Krishna, C. S., Aditya, P. K., and Puri R. K.: 1968a, *Proc. Indian Acad. Sci.* **67**, 138.

Anand, K. C., Daniel, R. R., and Stephens, S. A.: 1968b, *Nature* **217**, 25.

Anand, K. C., Daniel, R. R., and Stephens, S. A.: 1968c, *Proc. Indian Acad. Sci.* **67**, 267.

Anand, K. C., Daniel, R. R., and Stephens, S. A.: 1968d, *Proc. Indian Acad. Sci.* **68**, 219.

Anand, K. C., Daniel, R. R., and Stephens, S. A.: 1968e, *Phys. Rev. Letters* **20**, 764.

Anand, K. C., Daniel, R. R., and Stephens, S. A.: 1968f, in *Proc. 10th Symp. Cosmic Rays, Aligarh, India*, p. 217.

Anand, K. C., Daniel, R. R., and Stephens, S. A.: 1968g, *Can. J. Phys.* **46**, S484.

Anand, K. C., Daniel, R. R., and Stephens, S. A.: 1969, *Nature* (in press).

Andrew, B. H.: 1966, *Monthly Notices Roy. Astron. Soc.* **132**, 79.

Balasubrahmanyan, V. K., Boldt, E., and Palmeira, R. A. R.: 1965, *Phys. Rev.* **140**, B1157.

Balasubrahmanyan, V. K., Hagge, D. E., Ludwig, G. H., and McDonald, F. B.: 1966, in *Proc. 9th Int. Conf. Cosmic Rays*, London, vol. I, p. 427.

Baldwin, J. E.: 1955a, *Monthly Notices Roy. Astron. Soc.* **115**, 684.

Baldwin, J. E.: 1955b, *Monthly Notices Roy. Astron. Soc.* **115**, 690.

Beedle, R. E. and Webber, W. R.: 1968, *Can. J. Phys.* **46**, S1014.

Bergamini, R., Londrillo, P., and Setti, G.: 1967, *Nuovo Cimento* **52B**, 495.

Biermann, L. and Davis, L.: 1960, *Z. Astrophys.* **51**, 19.

Biswas, S., Ramadurai, S., and Sreenivasan, N.: 1967, *Phys. Rev.* **159**, 1063.

Bland, C. J., Boella, G., Degli Antoni, G., Dilworth, C., Scarsi, L., Sironi, G., Agrinier, B., Koechlin, Y., Parlier, B., and Vasseur, J.: 1966, *Phys. Rev. Letters* **17**, 813.

Bland, C. J., Boella, G., Antoni, G. D., Dilworth, C., Scarsi, L., Sironi, G., Agrinier, B., Koechlin, Y., Parlier, B., and Vasseur, J.: 1968, *Nuovo Cimento* **55A**, 451.

Bleeker, J. A. M., Burger, J. J., Scheepmaker, A., Swanenburg, B. N., and Tanaka, Y.: 1966, in *Proc. 9th Int. Conf. Cosmic Rays, London*, vol. I, p. 327.
Bleeker, J. A. M., Burger, J. J., Deerenberg, A. J. M., Scheepmaker, A., Swanenburg, B. N., and Tanaka, Y.: 1968a, *Can. J. Phys.* **46**, S522.
Bleeker, J. A. M., Burger, J. J., Deerenberg, A. J. M., Scheepmaker, A., Swanenburg, B. N., and Tanaka, Y.: 1968b, *Can. J. Phys.* **46**, S911.
Bok, B. J.: 1959, *Observatory* **79**, 58.
Bortolot, V. J., Clauser, J. F., and Thaddeus, P.: 1969, *Phys. Rev. Letters* **22**, 307.
Braccesi, A. and Vespigani, G.: 1964, *Nuovo Cimento* **31**, 310.
Bradt, H. L. and Peters, B.: 1950, *Phys. Rev.* **80**, 943.
Brecher, K. and Morrison, P.: 1967, *Astrophys. J.* **150**, L61.
Bridle, A. H.: 1967, *Monthly Notices Roy. Astron. Soc.* **136**, 219.
Brunstein, K. A.: 1968, *Nature* **218**, 649.
Brunstein, K. A. and Cline, T. L.: 1966, *Nature* **209**, 1186.
Burbidge, G. R. and Hoyle, F.: 1964, *Proc. Phil. Soc.* **84**, 141.
Clark, G. W., Garmire, G. P., and Kraushaar, W. L.: 1968, *Astrophys. J.* **153**, L203.
Cline, T. L. and Hones, E. W.: 1968, *Can. J. Phys.* **46**, S527.
Cline, T. L. and McDonald, F. B.: 1968a, *Can. J. Phys.* **46**, S761.
Cline, T. L. and McDonald, F. B.: 1968b, *Solar Phys.* **5**, 507.
Cline, T. L., Ludwig, G. H., and McDonald, F. B.: 1964, *Phys. Rev. Letters* **13**, 786.
Comstock, G. M., Fan, C. Y., and Simpson, J. A.: 1966, *Astrophys. J.* **146**, 51.
Convey, R. G., Kellermann, K. I., and Long, R. J.: 1963, *Monthly Notices Roy. Astron. Soc.* **125**, 261.
Costain, C. H.: 1960, *Monthly Notices Roy. Astron. Soc.* **120**, 248.
Cowsik, R., and Yash Pal: 1969, *Phys. Rev. Letters* **22**, 550.
Cowsik, R., Yash Pal, Tandon, S. N., and Verma, R. P.: 1966, *Phys. Rev. Letters* **17**, 1298.
Cowsik, R., Yash Pal, Tandon, S. N., and Verma, R. P.: 1967, *Phys. Rev.* **158**, 1238.
Cowsik, R., Damle, S. V., Yash Pal, Rengarajan, T. N., Tandon, S. N., and Verma, R. P.: 1969, Tata Institute Technical Report.
Critchfield, C. L., Ney, E. P., and Oleska, S.: 1950, *Phys. Rev.* **79**, 402.
Daniel, R. R. and Durgaprasad, N.: 1966, *Progr. Theoret. Phys.* **35**, 36.
Daniel, R. R. and Srinivasan, N.: 1965, *Nuovo Cimento* **35**, 391.
Daniel, R. R. and Stephens, S. A.: 1965, *Phys. Rev. Letters* **15**, 769.
Daniel, R. R. and Stephens, S. A.: 1966, *Phys. Rev. Letters* **17**, 935.
Daniel, R. R. and Stephens, S. A.: 1967, *Proc. Indian Acad. Sci.* **65**, 319.
Danielson, R. E.: 1959, *Phys. Rev.* **113**, 1311.
Danjo, A., Hayakawa, S., Makino, F., and Tanaka, Y.: 1968a, *Can. J. Phys.* **46**, S530.
Danjo, A., Hayakawa, S., Makino, F., and Obayashi, H.: 1968b, *Can. J. Phys.* **46**, S533.
Davies, R. D.: 1964, *Monthly Notices Roy. Astron. Soc.* **128**, 133.
Davies, R. D., Booth, R. S., and Wilson, A. J.: 1968, *Nature* **220**, 1207.
Denisse, J. F., Leroux, E., and Steinberg, J. L.: 1955, *Compt. Rend.* **240**, 278.
Deshong, J. A., Hildebrand, R. H., and Meyer, P.: 1964, *Phys. Rev. Letters* **12**, 3.
Donahue, T. M.: 1951, *Phys. Rev.* **84**, 972.
Durgaprasad, N., Fichtel, C. E., and Guss, D. E.: 1967, *J. Geophys. Res.* **72**, 2765.
Earl, J. A.: 1961, *Phys. Rev. Letters* **6**, 125.
Elliot, H.: 1968, Conference on the Composition and Origin of Cosmic Rays, Cambridge, U.K., reported in *Nature* **219**, 1005.
Ellis, G. R. A.: 1964, *Nature* **204**, 171.
Erickson, W. C. and Cronyn, W. M.: 1965, *Astrophys. J.* **142**, 1156.
Fan, C. Y., Gloeckler, G., Simpson, J. A., and Verma, S. D.: 1968a, *Astrophys. J.* **151**, 737.
Fan, C. Y., Gloeckler, G., and Simpson, J. A.: 1968b, *Can. J. Phys.* **46**, S548.
Fanselow, J. L.: 1968, *Astrophys. J.* **152**, 783.
Feenberg, E. and Primakoff, H.: 1948, *Phys. Rev.* **73**, 449.
Felten, J. E.: 1966, *Astrophys. J.* **145**, 589.
Felten, J. E. and Morrison, P.: 1966, *Astrophys. J.* **146**, 686.
Foster, F. and Schrautemier, B. E.: 1967, *Nuovo Cimento* **X47**, 189.
Fowler, P. H., Adams, R. A., Cowen, C. G., and Kidd, J. M.: 1967, *Proc. Roy. Soc.* **A301**, 39.

Freier, P. S. and Waddington, C. J.: 1965, *J. Geophys. Res.* **70**, 5753.
Fujimoto, Y., Hasegawa, H., and Taketani, M.: 1964, *Progr. Theoret. Phys.* Suppl. **30**, 32.
Galt, J. A., Purton, C. R., and Scheuer, P. A. G.: 1967, *Publ. Don. Obs.* **25**, No. 10.
Geiss, J.: 1964, in *Proc. 8th Int. Conf. Cosmic Rays, Jaipur*, vol. III, p. 434.
Geiss, J., Oeschger, H., and Schwarz, U.: 1962, *Space Sci. Rev.* **1**, 197.
Ginzburg, V. L.: 1954, *Dokl. Akad. Nauk SSSR* **99**, 703.
Ginzburg, V. L.: 1967, in *Proc. I.A.U. Symp.*, vol. 31, p. 365.
Ginzburg, V. L.: 1968, *Astrophys. Space Sci.* **1**, 125.
Ginzburg, V. L. and Syrovatskii, S. I.: 1961, *Progr. Theoret. Phys.*, Suppl. **20**, 1.
Ginzburg, V. L. and Syrovatskii, S. I.: 1964, *The Origin of Cosmic Rays*, Macmillan & Co., New York.
Ginzburg, V. L. and Syrovatskii, S. I.: 1965, *Ann. Rev. Astron. Astrophys.* **3**, 297.
Ginzburg, V. L. and Syrovatskii, S. I.: 1967, in *Proc. I.A.U. Symp.*, vol. 31, p. 411.
Ginzburg, V. L. and Syrovatskii, S. I.: 1968, *Astrophys. Space Sci.* **1**, 442.
Gloeckler, G. and Jokipii, J. R.: 1957, *Astrophys. J.* **148**, L41.
Goel, P. S.: 1969, Preprint.
Gold, T.: 1969, To appear in the *Proc. of the 4th Texas Symposium on Relativistic Astrophysics.*
Gould, R. J. and Burbidge, G. R.: 1963, *Astrophys. J.* **138**, 969.
Gould, R. J. and Burbidge, G. R.: 1965, *Ann. Astrophys.* **28**, 171.
Grigorov, N. L., Nesterov, V. E., Radoport, I. D., Savenko, I. A., and Skuridin, G. A.: 1966, in *Proc. 9th Int. Conf. Cosmic Rays, London*, vol. I, p. 50.
Hartman, R. C.: 1967, *Astrophys. J.* **150**, 371.
Hartman, R. C., Meyer, P., and Hildebrand, R. H.: 1965, *J. Geophys. Res.* **70**, 2713.
Hartz, T. R.: 1964, *Nature* **203**, 173.
Hayakawa, S.: 1969, in *Proc. Colloq. Cosmic Ray Studies, Bombay*, p. 105.
Hayakawa, S. and Okuda, H.: 1962, *Progr. Theoret. Phys.* **28**, 517.
Hayakawa, S., Ito, I., and Terashima, Y.: 1958, *Progr. Theoret. Phys.* Suppl. **6**, 1.
Hayakawa, S., Nishimura, J., and Yamamoto, Y.: 1964, *Progr. Theoret. Phys.*, Suppl. **32**, 104.
Hill, E. R., Slee, O. B., and Mills, B. Y.: 1958, *Australian J. Phys.* **11**, 530.
Hintenberger, H., Voshage, H., and Sarkar, H.: 1966, in *Proc. 9th Int. Conf. Cosmic Rays, London*, vol. I, p. 602.
Hofmann, D. J. and Sauer, H. H.: 1968, *Space Sci. Rev.* **8**, 750.
Hofstadter, R., Hughes, E. B., Lakin, W. L., and Sick, I.: 1969, *Nature* **221**, 228.
Hoyle, F.: 1968, Conference on the Composition and Origin of Cosmic Rays, Cambridge, U.K., reported in *Nature* **219**, 1005.
Israel, M. H. and Vogt, R. E.: 1968, *Phys. Rev. Letters* **20**, 1053.
Jokipii, J. R. and Meyer, P.: 1968, *Phys. Rev. Letters* **20**, 752.
Jokipii, J. R., L'Heureux, J., and Meyer, P.: 1967, *J. Geophys. Res.* **72**, 4375.
Jones, F. C.: 1963, *J. Geophys. Res.* **68**, 4399.
Jones, F. C.: 1965, *Phys. Rev. Letters* **15**, 512.
Kellermann, K. I.: 1966, *Astrophys. J.* **146**, 621.
Kerr, F. J. and Westerhout, G.: 1965, *Galactic Structure* (ed. by A. Blaauw and M. Schmidt), University of Chicago Press, Chicago.
Komesaroff, M. M.: 1966, *Australian J. Phys.* **19**, 75.
Kraus, J. D. and Ko, H. C.: 1955, *Nature* **175**, 159.
Lal, D.: 1966, in *Proc. 9th Int. Conf. Cosmic Rays, London*, vol. I, p. 81.
Lal, D.: 1969, in *Proc. of Colloquium on Cosmic Ray Studies*, Tata Institute of Fundamental Research, Bombay, p. 65.
Large, M. I., Mathewson, D. S., and Haslam, C. G. J.: 1961, *Monthly Notices Roy. Astron. Soc.* **123**, 113.
L'Heureux, J.: 1967, *Astrophys. J.* **148**, 399.
L'Heureux, J. and Meyer, P.: 1965, *Phys. Rev. Letters* **15**, 93.
L'Heureux, J., Meyer, P., Verma, S. D., and Vogt, R.: 1968, *Can. J. Phys.* **46**, S896.
Lipschutz, M. E., Singner, P., and Anders, E.: 1965, *J. Geophys. Res.* **70**, 1473.
Long, R. F., Smith, M. F., Stewart, P., and Williams, P. J. S.: 1966, *Monthly Notices Roy. Astron. Soc.* **134**, 371.
Mathewson, D. S.: 1968, *Astrophys. J.* **153**, L47.
Mathewson, D. S. and Nichols, D. C.: 1968, *Astrophys. J.* **154**, L11.

Mathewson, D. S., Healey, J. R., and Rome, J. M.: 1962, *Australian J. Phys.* **15**, 354.
Mathewson, D. S., Broton, N. W., and Cole, D. J.: 1965, *Australian J. Phys.* **18**, 665.
Metzger, A. E., Anderson, E. C., Van Dilla, M. A., and Arnold, J. R.: 1964, *Nature* **204**, 766.
Meyer, P.: 1969, *Ann. Rev. Astron. Astrophys.* **7** (in press).
Meyer, P. and Vogt, R.: 1961, *Phys. Rev. Letters* **6**, 193.
Mills, B. Y.: 1959, *Publ. Astron. Soc. Pacific* **71**, 267.
Moron, M.: 1965, *Monthly Notices Roy. Astron. Soc.* **129**, 447.
O'Connel, R. F.: 1966, *Phys. Rev. Letters* **17**, 1232.
O'Gallagher, J. J. and Simpson, J. A.: 1967, *Astrophys. J.* **147**, 819.
Okuda, H. and Tanaka, Y.: 1968, *Can. J. Phys.* **46**, S642.
Okuda, H. and Yamamoto, Y.: 1965, *Rep. Ionosph. and Space Res. Japan* **19**, 322.
Ormes, J. F. and Webber, W. R.: 1966, in *Proc. 9th Int. Conf. Cosmic Rays, London*, vol. I, p. 349.
Parker, E. N.: 1963, *Interplanetary Dynamical Processes*, Interscience Publishers, Inc., New York.
Parker, E. N.: 1964, *J. Geophys. Res.* **69**, 1755.
Parker, E. N.: 1965, *Astrophys. J.* **142**, 584.
Parker, E. N.: 1969, *Proc. Colloq. Cosmic Ray Studies*, Tata Institute of Fundamental Research, Bombay, p. 202.
Parthasarathy, R. and Lerfald, G. M.: 1965, *Monthly Notices Roy. Astron. Soc.* **129**, 395.
Pauliny-Toth, I. I. K. and Shakeshaft, J. R.: 1962, *Monthly Notices Roy. Astron. Soc.* **124**, 61.
Penzias, A. A. and Wilson, R. W.: 1966, *Astrophys. J.* **146**, 666.
Perola, G. C. and Scarsi, L.: 1966, *Nuovo Cimento* **46**, 718.
Perola, G. C., Scarsi, L., and Sironi, G.: 1967, *Nuovo Cimento* **52B**, 455, and **53B**, 459.
Piddington, J. A. and Trent, G. H.: 1956, *Australian J. Phys.* **9**, 481.
Pine, J., Davisson, R. J., and Greisen, K.: 1959, *Nuovo Cimento* **14**, 1181.
Pollack, J. B. and Fazio, G. G.: 1965, *Astrophys. J.* **141**, 730.
Price, P. B., Rajan, R. S., and Tamhane, A. S.: 1968, *Astrophys. J.* **151**, L109.
Purton, C. R.: 1966, *Monthly Notices Roy. Astron. Soc.* **133**, 463.
Ramaty, R. and Lingenfelter, R. E.: 1966a, *J. Geophys. Res.* **71**, 3687.
Ramaty, R. and Lingenfelter, R. E.: 1966b, *Phys. Rev. Letters* **17**, 1230.
Ramaty, R. and Lingenfelter, R. E.: 1968a, *Can. J. Phys.* **46**, S627.
Ramaty, R. and Lingenfelter, R. E.: 1966b, *Phys. Rev. Letters* **20**, 120.
Rees, M. J. and Sargent, W. L. W.: 1968, *Nature* **219**, 1005.
Rosenthal, I. and Shukalov, L.: 1968, *Can. J. Phys.* **46**, S620.
Rubtsov, V. I. and Zatsepin, V. I.: 1968, *Can. J. Phys.* **46**, S518.
Scanlon, J. H. and Milford, S. N.: 1965, *Astrophys. J.* **141**, 718.
Schaeffer, O. A., Davis, R., Stoenner, R. W., and Heymann, D.: 1964, in *Proc. 8th Int. Conf. Cosmic Rays, Jaipur*, vol. III, p. 480.
Schmoker, J. W. and Earl, J. A.: 1965, *Phys. Rev.* **138**, B300.
Seaquist, E.R.: 1968, *Observatory* **88**, 269.
Seeger, C. L., Stumpers, F. L. H. M., and Harch, N.: 1960, *Philips Tech. Rev.* **21**, 317.
Seeger, C. L., Westerhout, G., Conway, R. G., and Hockema, T.: 1965, *Bull. Astron. Inst. Neth.* **18**, 11.
Shain, C. A.: 1958, in *Proc. Symp. Rad. Astr. Paris*, p. 328.
Shain, C. A. and Higgins, C. S.: 1954, *Australian J. Phys.* **7**, 130.
Shakeshaft, J. R.: 1969, in *Proc. Colloq. Cosmic Ray Studies*, Tata Institute of Fundamental Research, Bombay, p. 131.
Shapiro, M. M. and Silberberg, R.: 1968, *Can. J. Phys.* **46**, S561.
Shen, C. S.: 1967, *Phys. Rev. Letters* **19**, 399.
Shen, C. S.: 1969, *Phys. Rev. Letters* **22**, 568.
Shivanandan, K., Houck, J. R., and Harwit, M. O.: 1968, *Phys. Rev. Letters* **21**, 1460.
Shklovsky, I. S.: 1952, *Astron. Zh. SSSR.* **29**, 418.
Silk, J.: 1968, *Astrophys. J.* **151**, L19.
Simnett, G. M.: 1967, Imperial College of Science and Technology, London, Preprint.
Simnett, G. M. and McDonald, F. B.: 1968, NASA Preprint X-611-68-450.
Sironi, G.: 1965, *Nuovo Cimento* **39**, 372.
Smith, F. G.: 1968, *Nature* **220**, 891.
Smith, L. H.: 1968, in *Proc. 10th Int. Conf. Cosmic Rays, Calgary*, Part A, p. 506.

Smith, L. H. and Freye, G. M.: 1966, *Phys. Rev.* **149**, 1013.
Spitzer, L.: 1956, *Astrophys. J.* **124**, 70.
Stecker, F. W.: 1967, *Smithsonian Astrophys. Obs. Spl. Report 260.*
Stecker, F. W.: 1969, *Nature* (in press).
Stecker, F. W. and Silk, J.: 1969, *Nature* **221**, 1229.
Stephens, S. A.: 1969, Ph.D. Thesis, Bombay University.
Subramanian, A. and Verma, S. D.: 1959, *Nuovo Cimento* **13**, 572.
Tanaka, Y.: 1968, *Can. J. Phys.* **46**, S536.
Tulinov, V. E.: 1958, *Sov. Phys. JETP*, **6**, 894.
Tunmer, H.: 1959, *Monthly Notices Roy. Astron. Soc.* **119**, 184.
Turtle, A. J., Pugh, J. F., Kenderdine, S., and Pauliny-Toth, I. I. K.: 1962, *Monthly Notices Roy. Astron. Soc.* **124**, 297.
Verma, S. D.: 1967a, *Proc. Indian Acad. Sci.* **66**, 125.
Verma, S. D.: 1967b, *Phys. Rev. Letters* **18**, 253.
Verma, S. D.: 1968, *Astrophys. J.* **152**, 537.
Verma, S. D.: 1969, *Astrophys. J. Letters* (in press).
Verschuur, G. L.: 1968, *Phys. Rev. Letters* **21**, 775.
Von Rosenvinge, T. T., Ormes, J. F., and Webber, W. R.: 1969, *Astrophys. Space Sci.* **3**, 80.
Webber, W. R.: 1967, *J. Geophys. Res.* **72**, 5949.
Webber, W. R.: 1968a, *J. Geophys. Res.* **73**, 4905.
Webber, W. R.: 1968b, *Australian J. Phys.* **21**, 845.
Webber, W. R. and Chotkowski, C.: 1967, *J. Geophys. Res.* **72**, 2783.
Webber, W. R., Ormes, J. F., and Von Rosenvinge, T. T.: 1966, in *Proc. 9th Int. Conf. Cosmic Rays, London*, vol. I, p. 407.
Westerhout, G.: 1958, *Bull. Astron. Inst. Neth.* **14**, 215.
Wielebinski, R., Smith, D. H., and Cardenas, X. G.: 1966, *Australian J. Phys.* **21**, 185.
Wilson, R. W. and Bolton, J. G.: 1960, *Publ. Astron. Soc. Pacific* **72**, 331.
Wolfendale, A. W.: 1964, in *Proc. 8th Int. Conf. Cosmic Rays, Jaipur*, vol. VI, p. 3.
Woltjer, L.: 1965, *Stars and Stellar Systems*, University of Chicago Press, Chicago.
Yash, Pal and Peters, B.: 1964, *Mat. Fys. Medd. Dansk Vid. Selsk.* **33**, No. 15.
Yates, K. W.: 1968, *Australian J. Phys.* **21**, 167.
Yates, K. W. and Wielebinsky, R.: 1966, *Australian J. Phys.* **19**, 389.
Yiou, F., Dufaure de Citres, J., Frehel, F., Gradsztajn, E., and Bernas, R.: 1968, *Can. J. Phys.* **46**, S557.
Zatsepin, G. J. and Kuzmin, U. K.: 1962, *Sov. Phys. JETP* **14**, 1294.