RECENT OBSERVATIONS ON COSMIC ELECTRONS AND THEIR CONSEQUENCES ON DIFFERENT COSMIC RAY MODELS AND RELATED ASTROPHYSICAL QUANTITIES

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Abstract

An experiment has been carried out to study the electron component of the primary cosmic radiation at energies > 12 GeV using a hypersensitised nuclear emulsion stack, flown oriented in the east-west plane over Hyderabad, India. The results of this experiment, on the basis of 28 identified electrons of energy above 12 GeV are: (i) the integral flux of electrons above an effective energy of 16 GeV is $0 \cdot 51 \pm \cdot 10$ per m.^{2} sec. sr.; (ii) the differential energy spectrum between 12 and 300 GeV can be represented as $N(E)dE = 12 \cdot 7\ E^{-2 \cdot 1 \pm \cdot 2}\ dE$ m.$^{-2}$ sec.$^{-1}$ sr.$^{-1}$; and (iii) the fraction of positrons among the total electrons in the energy region 12 to 30 GeV has been discussed.

A critical study has been made on the applicability of different cosmic ray models by making use of the observed differential energy spectrum of electrons and the relevant astrophysical parameters associated with the confinement regions. The confinement regions considered are: (i) the universe as a whole, (ii) the super cluster to which our galaxy belongs, (iii) the galactic halo and (iv) the galactic disc. The consequences of the recently postulated universal black body radiation at 3° K. on the cosmic ray models have also been considered. Some of the crucial experiments needed to set more stringent constrains on the models which would then permit meaningful interpretation, are enumerated.

1. Introduction

THOUGH the first attempt[1] to detect electrons* amongst the cosmic ray particles was made in 1952, it was not until 1961 that definite evidence[2, 3] was obtained for their existence with an intensity of about 1% of the abundant cosmic ray protons. Since 1961 interest in this field of research has gained momentum

* The word 'electron' is used to indicate both electrons and positrons unless otherwise stated explicitly.

and many experimental measurements have been carried out during the last five years using diverse kinds of detector systems. The unique virtue of the study of cosmic electrons stems from the fact that unlike cosmic ray nuclei, the electron, owing to its very low mass, suffers significant energy losses through synchrotron radiation while traversing magnetic fields and inverse Compton scattering in radiation fields. It therefore becomes an ideal probe to study the magnetic and radiation fields existing in space traversed by cosmic rays. It is also well established now that cosmic radio emission is nothing but synchrotron radiation emitted by relativistic electrons moving in weak magnetic fields near source regions or in interstellar and intergalactic space. From this, one recognises the very intimate relation between cosmic radio emission and cosmic ray electrons.

Whereas the present experiment is the only one so far designed and carried out for electrons of energy > 12 GeV, there are many which have been made at energies < 10 GeV. When measurements are made on electrons of energy $\lesssim$ few GeV, in typical balloon flights made under a few g./cm.^{2} of air, there are two difficulties which are encountered in the proper evaluation of the data. Firstly, the cosmic electron spectrum is strongly modulated in the solar system and secondly the corrections for secondary electrons produced in the overlying atmosphere become increasingly large and uncertain with increasing residual atmosphere and decreasing energy. At energies > 10 GeV, such interfering influences in the data are small and the interpretations become more reliable. We have used in the present experiment a stack of nuclear emulsions which has two decisive advantages over other types of detectors to study electrons of energy > 10 GeV; they are (i) the possibility of identifying without ambiguity the events which are due to electrons and (ii) the comparatively reliable methods which exist for estimation of energy right up to thousands of GeV.

The first observation on electrons of energy > 12 GeV, based on a total of 12 events, was made from this Laboratory[4] (hereafter referred as Paper I) using a hypersensitised nuclear emulsion stack; the stack was flown in a balloon flight from Hyderabad, India (where the vertical cut-off rigidity for positively charged particles is 16·9 GeV) for a period of 398 minutes in April 1963 under 10·2 g./cm.^{2} of residual atmosphere. The stack was flipped through 180° when the balloon reached ceiling altitude. By orienting the stack at ceiling altitude in the east-west plane (with an accuracy of $\pm 2°$), it was possible to estimate the charge composition of the electrons of energy between 12 and 30 GeV by making use of the geomagnetic field as a magnetic analyser. The present investigation is a continuation of our earlier work described in Paper I.

2. Experimental Details

The details regarding the preparation, exposure and development of the emulsion stack have been described in Paper I. The microscope scanning of the emulsions was carried out along a line parallel to the top edge at a depth of 3·5 cm., for two or more parallel tracks separated by a distance $\lesssim 100\,\mu$m. Selected events making zenith angles $\leqslant 50°$ and dip angles $\leqslant 7{\cdot}8°$ were traced back towards the leading edge and were classified as due to (i) γ-rays, if the tracks ultimately led to an electron pair with no associated satellite tracks within 150 μm., (ii) nuclear interactions, if the associated track was found to be associated with an interaction within the emulsion stack and (iii) electrons, if the associated track entered the stack as a single track with subsequent characteristic electromagnetic multiplication. The selected electron events were then traced down the stack until they got degraded to very low energies. In this manner scanning was carried out on a total of 1050 cm. and 71 electron events of energy > 1 GeV were identified.

2.1. *Energy Estimation*

The energy of the electrons was estimated using the track count method for energies $\gtrsim 50$ GeV and by co-ordinate method of scattering, for energies < 50 GeV.[4] Above 50 GeV the errors due to measurement and fluctuations in the development of cascade is $\sim 30\%$. In order to examine the reliability of the second method in the energy region below 50 GeV identical measurements were made in an emulsion plate exposed to 3·5 GeV electrons from DESY, Hamburg, and it was shown in Paper I that the energy estimation was dependable. Since then, similar measurements carried out by us on tracks of 5·8 GeV electrons, also from DESY, have given further confidence in the reliability of this method.

The energies obtained for all the observed electrons at the top of the stack were extrapolated to the top of the atmosphere.

2.2. *Detection Probability*

In the method of scanning adopted by us, the probability P_e for the detection of an electron depends on its energy and has been calculated using the electromagnetic theory in the following way. The mean number of electron pairs, that could be detected at the scan line due to first and second generation of photons, was calculated by assuming that the separation of the electron tracks is due to multiple Coulomb scattering only and that the energy disparity in the detected pair is small. In our calculations, we define P_e as the probability for seeing at least one electron pair at the scan line. P_e

was then calculated assuming a Poissonian distribution for the electron pairs; the solid line in Fig. 1 represents P_e at a mean distance of 4 cm. from the entry point of the electron in the emulsion stack, as a function of the electron energy. It has to be noted that this calculation is valid only up to a distance the primary electron keeps its direction.

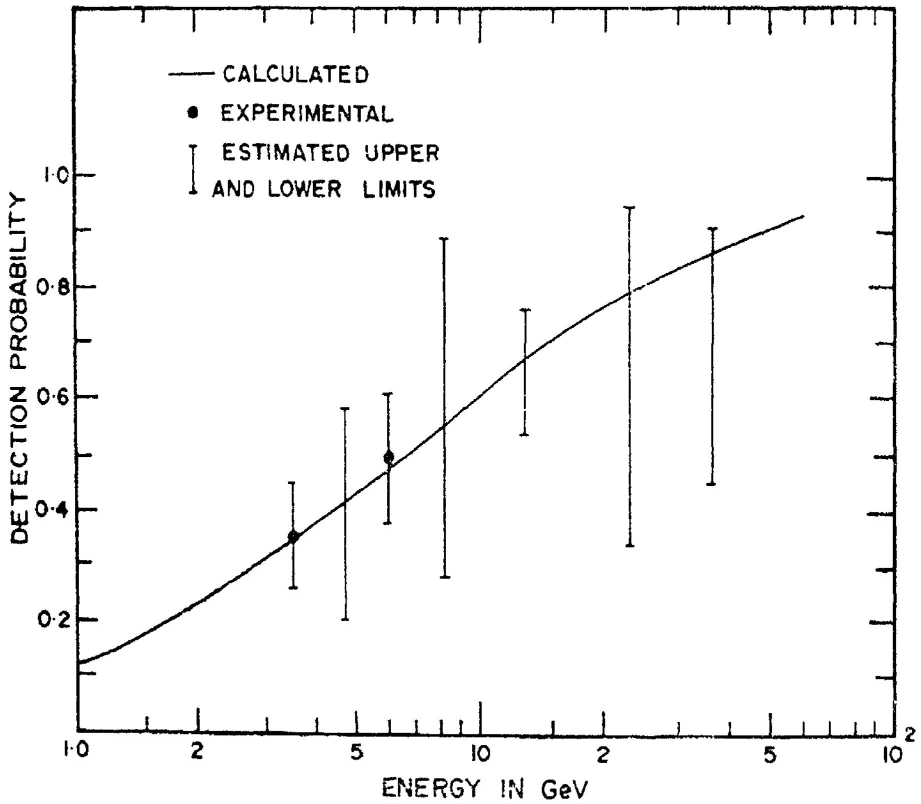

FIG. 1. Detection probability for electrons is plotted as a function of energy.

The above calculation was checked experimentally using emulsions exposed to 3·5 and 5·8 GeV electrons and as can be seen from Fig. 1, the results are consistent with the calculated curve. Also, from a careful study of the electromagnetic development of the detected cosmic ray electrons close to the scanning level, with and without the electron pair responsible for its detection, we have estimated the upper and lower limits for P_e; these values are also shown in Fig. 1. One can easily show that the true detection probability in this method of estimation should approach the upper limit as the energy increases. We feel confident that the calculated values are correct within about 10%, at all energies except below 2 GeV.

2.3. *Corrections Due to Atmospheric and Re-entrant Albedo*

It is important first to separate from the total sample of electrons, those which are produced in the overlying atmosphere due to nuclear collisions and those due to re-entrant albedo. In Fig. 2 we have plotted the energies (at the top of the atmosphere) of all the electrons with energy > 1 GeV against their arrival directions in the east-west plane. The two curves drawn in this figure are the calculated geomagnetic cut-off rigidities for the positive and negative electrons in the east-west plane using sixth degree simulation of the earth's magnetic field.[5] It can be seen from this figure that all electrons below 12 GeV should be of secondary origin and there are 43 such electrons. The next step is to estimate the number of secondary electrons in the sample of 28 with energies above 12 GeV. In order to do this, we calculated the number of electrons produced in the overlying atmosphere by assuming the

$$P_{\pi}^{\pm}(x, E)\, dE dx = C_{\pi}^{\pm}\, e^{-x/\Lambda} \frac{dx}{\lambda} \frac{dE}{E^{\gamma+1}} \quad (\text{m.}^2 \text{ sr. sec.})^{-1} \qquad (1)$$

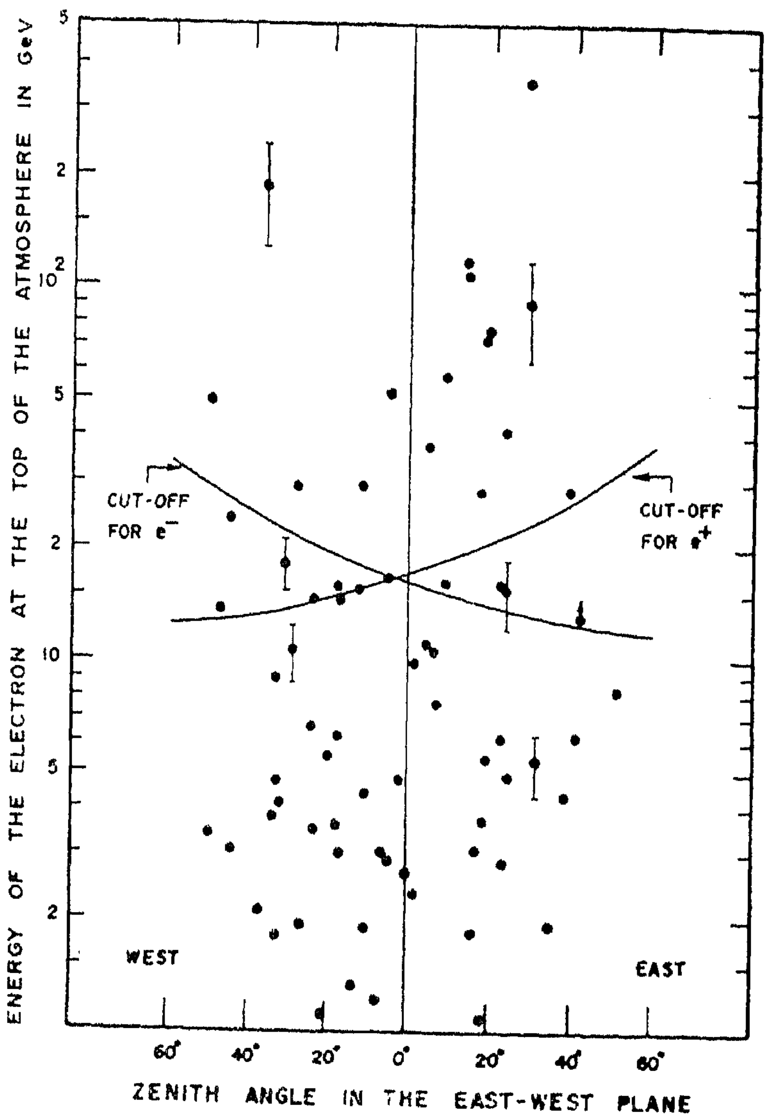

FIG. 2. Plot of electron energies at the top of the atmosphere against their arrival directions in the east-west plane. The two curves represent the calculated threshold energies for positrons and electrons as a function of zenith angles in the east-west plane.

pion-production spectrum at any depth given by Yash Pal and Peters,[6] namely where $C_{\pi^0} = C_{\pi^\pm}$ is a constant taken to be $4 \cdot 68 \times 10^2$ when E is expressed in GeV, Λ and λ are the attenuation and interaction mean free paths of nucleons in air taken to be 125 and 75 g./cm.^{2} respectively, and $\gamma = 1 \cdot 67$ is the exponent of the primary power spectrum. In Fig. 3 we have shown the calculated flux of secondary electrons (their energies extrapolated to the top of the atmosphere) resulting through the processes $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ and $\pi^\circ \rightarrow 2\gamma \rightarrow 2e^\pm$. On the basis of this calculation it is seen that there can be only 2·5 electrons above 12 GeV (taking into account the detection probability) in the sample of 28 electrons. We also estimated the contribution arising from atmospheric electrons recorded during the time of descent of the detector after the termination of the flight and over the period the stack was at the ground level in the assembled condition; this was done using the measurements on the electromagnetic component at different atmospheric depths[7, 8] and the calculation by Yash Pal and Tandon.[9] We found that this contribution is $< 1\%$ (since the stack was flipped through 180° when it just reached ceiling altitude, events recorded during ascent can easily be rejected).

In order to estimate the contribution due to re-entrant albedo, we have plotted in curve D of Fig. 3 the integral flux of all the 43 electrons below 12 GeV weighted according to their relevant detection probabilities *plus* the expected number of secondary electrons produced in the atmosphere above 12 GeV as obtained from curve C. The difference between the observed and calculated flux of electrons (D–C), has been attributed to the re-entrant albedo; this has been separately shown as curve E in Fig. 3. From this it can be noted that the flux of re-entrant albedo with energy > 3 GeV is $\approx$ 0·9 particles per m.^{2} sec. sr. The albedo electron spectrum can be represented as $N (> E) = 5 \cdot 6\, E^{-2 \cdot 0}$. Using this spectrum and the calculated cut-off rigidities for positrons and electrons[5] we estimated the number of re-entrant albedo electrons above 12 GeV to be only 0·43 and 0·38 from the east and west respectively in our total sample of 28 electrons.

It would be of interest to mention here that if a similar experiment is carried out with emulsions exposed from the same station, but under a smaller amount of atmospheric matter the contribution from secondary atmospheric electrons would decrease while that due to re-entrant albedo would remain the same. In a more recent experiment, now in progress, we hope to be able to do this and determine in a reliable manner the separate contributions from atmospheric electrons and re-entrant albedo.

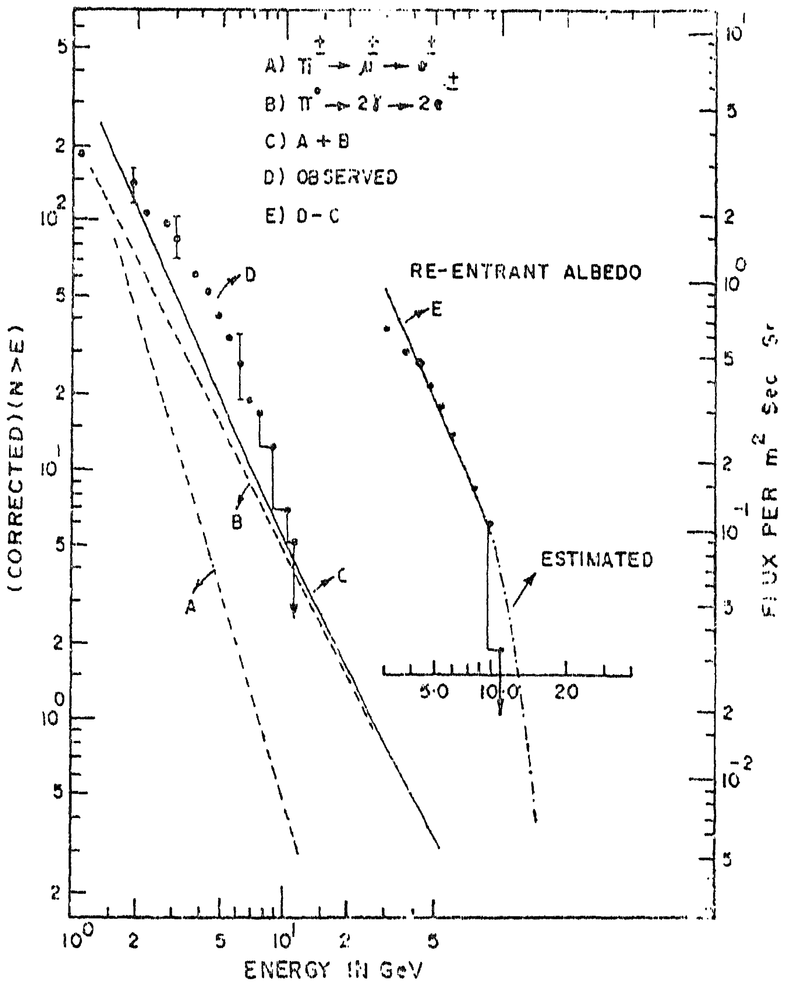

FIG. 3. The integral number and energy spectrum of electrons of secondary origin in the atmosphere. The contributions through the decay of π ð have been shown separately. The difference between the observed and the calculated atmospheric electrons is plotted separately and is attributed to re-entrant albedo.

3. RESULTS

3.1. *Flux and Energy Spectrum of Primary Electrons*

After making the corrections mentioned above, we obtained the integral flux of primary electrons at the top of the atmosphere above an effective threshold energy of 16 GeV as $0 \cdot 51 \pm 0 \cdot 10$ per m.² sec. sr., which is consistent with the value of $0 \cdot 68 \pm 0 \cdot 20$ per m². sec. sr. obtained earlier[4] with 12 events. For the sake of completeness we have shown in Table I, the integral flux of electrons above different energies. The highest energy of the electron obtained so far in our investigation is 350 ± 100 GeV.

In Fig. 4, we have shown the differential flux values of primary electrons obtained from the present experiment in the energy region between 16 and 350 GeV; this spectrum can be represented as:

$$N(E)\, dE = 12 \cdot 7 E^{-\beta}\, dE \text{ m.}^{-2} \text{ sec.}^{-1} \text{ sr.}^{-1} \quad (2)$$

TABLE I

Integral flux of primary electrons above different energy values as obtained from the present experiment

Energy in GeV	Flux per m.^{2} sec. sr.	No. of observed electrons
> 16	$0{\cdot}51 \pm 0{\cdot}10$	28
> 30	$0{\cdot}20 \pm 0{\cdot}06$	12
> 50	$0{\cdot}17 \pm 0{\cdot}05$	10
> 90	$\approx 8{\cdot}1 \times 10^{-2}$	5
>150	$\approx 3{\cdot}2 \times 10^{-2}$	2

where $\beta = 2{\cdot}1 \pm {\cdot}2$. This value of the exponent β has been compared with those obtained from other experiments at lower energies and are summarised in Table II. In Fig. 4 are also shown the differential flux values from other determinations in the energy region between 1 and 10 GeV.[10-15] The experimental points of Rubstov,[13] Bland *et al.*,[14] and Smith and Frye[15] have been estimated assuming an integral spectral index of 1·4. From Fig. 4 it is found that if some allowance is given for the suppression of the electron flux below a few GeV due to solar modulation, it is possible to fit well a single power spectrum of the type,

$$N(E)\,dE = 50E^{-2\cdot 4}\,dE \text{ m.}^{-2}\text{ sec.}^{-1}\text{ sr.}^{-1} \tag{3}$$

to all the available experimental points at energies > 1 GeV.

3.2. *Charge Composition*

The proportion of positrons among the primary electrons $R = e^+/(e^+ + e^-)$ can be deduced, in our experiment, from the ratio $N_W/(N_W + N_E)$, of the number of electrons arriving from the west to the number from the west and east together. It can be seen from Fig. 2 that a reasonably pure selection of positrons and electrons can be made by selecting events lying between the two calculated curves on the west and east of the vertical respectively. Using such events and correcting for re-entrant and atmospheric electrons, we obtain a value $R = 0{\cdot}7 \pm 0{\cdot}2$ in the energy region of about 12–30 GeV which may be compared with the value $R = 0{\cdot}35 \pm 0{\cdot}15$ obtained

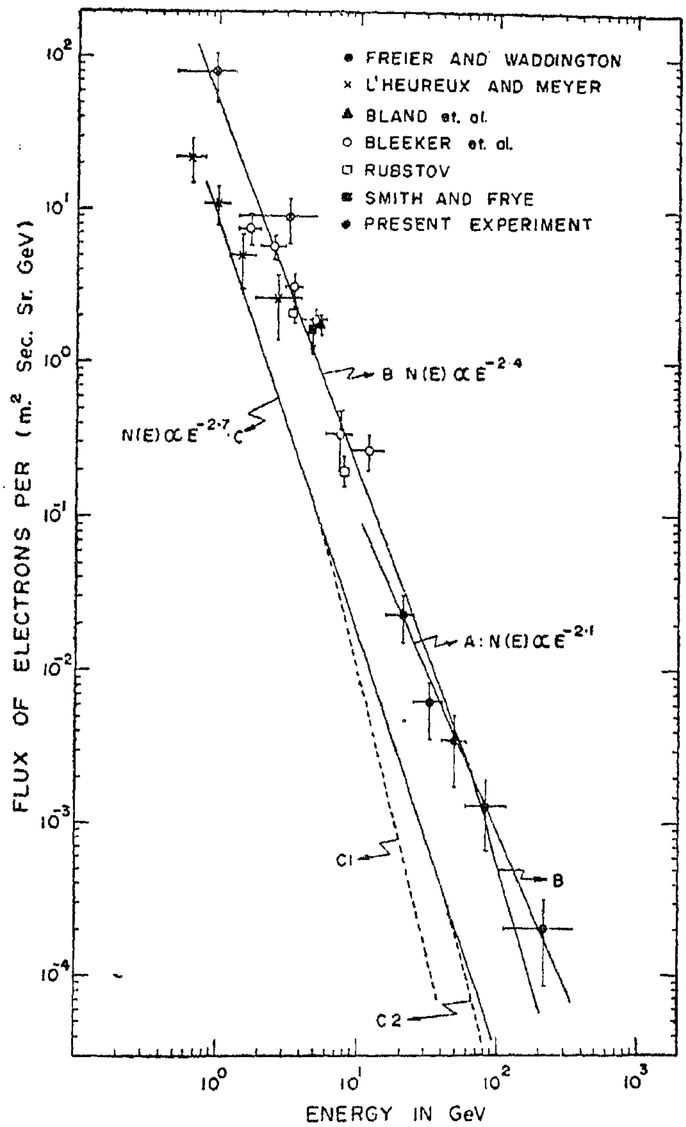

FIG. 4. Differential energy spectrum of electrons in the region 1 to 300 GeV is shown. Curve A is the spectrum fitted to the present experimental points. Curve B is the spectrum given by equation (3) with the steepening at $\sim$ 50 GeV. Curve C is the energy spectrum of electrons produced in 3 g. of hydrogen in space; the equilibrium spectra in the galactic halo with $T_h \sim 10^8$ years and in the disc with $T_d \sim 2\times10^6$ years, both without blackbody radiation at 3° K. are shown by the dotted lines C_1 and C_2 respectively.

by Hartman *et al.*[16] for energies between 100 MeV and 3 GeV and $R \leqslant 0{\cdot}15$ obtained by Bland *et al.*[14] for energies between about 5 and 10 GeV. While our results indicate a large e^+ excess at high energies, the experiments at lower energies suggest large e^- excess. The experimental errors on these values are still large and warrant greater precision of measurements; however on the basis of the existing data it seems likely that the charge composition at energies $\lesssim 5$ GeV is different from that at energies >10 GeV. If future experiments confirm our observations, it would be necessary to find an initial injection mechanism which would greatly favour positrons. Two such possibilities which are of academic interest at present are: (i) a source of antimatter and (ii) pion production by protons with a steep enough energy spectrum in the source region such that the vast majority of the pion-producing collisions occur at energies close to the threshold of meson production resulting thereby in the preferential emission of positive pions over negative ones.

TABLE II

Summary of the values of the differential energy spectral index obtained by various authors

Authors	Energy region in GeV		Year of Balloon flight
L'Heureux and Meyer[10] ..	0·5– 3·0	1·6±0·5	1963
Frier and Waddington[11] ...	0·5– 5·0	1·6	1964
Bleeker *et al.*[12]	2·0–15·0	1·9± ·4	1965
Rubstov[13]	3·5– 8·0	2·8	1964
Bland *et al.*[14]	4·6– 8·0	3·0± ·5	1965
Present Experiment	12·0–350	2·1± ·2	1963

4. GENETIC RELATION BETWEEN COSMIC RAY ELECTRONS AND THE PRIMARY NUCLEON COMPONENT

Since the flux of cosmic ray electrons is very small compared to that of the nucleon component, it is natural to enquire whether the electron component could be accounted for, as arising from the decay of charged pions produced in collisions of cosmic ray nucleons with interstellar matter. In order to attempt this, we required a knowledge of the energy spectrum of the cosmic ray nuclei responsible for the electrons, the amount of matter traversed by the cosmic rays and the characteristics of meson production at high energies, all of which are now reasonably well known. It is therefore possible, not only to calculate the flux and energy spectrum of such secondary electrons but also their charge composition and then to compare them with the observations.

Since we are interested in electron energies $\gtrsim$ few GeV, we have made use of the isobar model given by Yash Pal and Peters[6] to calculate the muon production spectrum per gram of hydrogen in space as:

$$P_\mu (E)\, dE = 12 \cdot 7\, E^{-2\cdot 67} \cdot dE. \quad (4)$$

A rigorous treatment of the energy spectrum of electrons from the decay of muons in the laboratory system of co-ordinates is given by Zatsepin and Kuzmin;[17] following this treatment we obtain the differential energy spectrum of electrons, for a traversal of 3 g./cm.^{2} of cosmic rays in interstellar space as

$$N (E)\, dE = 8 \cdot 25\, E^{-2\cdot 67}\, dE\ \mathrm{m.}^{-2}\ \mathrm{sec.}^{-1}\ \mathrm{sr.}^{-1} \quad (5)$$

In Fig. 4 is shown this calculated spectrum [equation (5)]; also shown by dotted lines are the expected equilibrium spectra in the galactic disc and galactic halo according to the calculations described in Sec. 5.

(*a*) *Electron Energies between About* 1 *and* 10 *GeV*.—It can be seen from Fig. 4 that while in this energy region the observed and calculated spectral shapes are not inconsistent, the absolute value of the observed flux is larger than the calculated one by a factor of $\sim$ 10. It is therefore obvious that the bulk of the observed electron flux cannot be due to secondary production in interstellar space. However it is found, that the best estimates for the experimental and calculated values for the differential flux of e^+ close to 2 GeV are 1 and 0·7 electrons m.$^{-2}$ sec.$^{-1}$ sr.$^{-1}$ GeV^{-1}, respectively. It seems, therefore, that while almost all the e^+ and a near equal amount of e^- can still be attributed to secondary electrons, the rest of the e^- should have a different origin, presumably direct acceleration in the source region.

(*b*) *Electron Energies* > 10 *GeV*.—It is further seen from Fig. 4 that in the energy region of 10–100 GeV also, the calculated secondary electrons can only be about 10% of the observed flux in the extreme case where these electrons do not suffer any energy degradation due to synchrotron radiation and inverse Compton scattering. Further, there is some evidence that the experimental slope of the spectrum is, if at all, flatter than the primary nucleon spectrum.

From all these considerations it is now almost certain that, contrary to earlier ideas regarding the origin of cosmic ray electrons, the bulk of them with energy $\gtrsim$ 1 GeV cannot be due to nuclear collisions of cosmic ray nucleons in space.

5. THE HISTORY OF THE ELECTRONS SAMPLED NEAR THE EARTH

The characteristics of the cosmic radiation sampled near the earth should bear the effects of its life-history near its source region, in cosmic space traversed by it and in interplanetary space. Though it seems reasonable and is always assumed, that the confinement of the nucleonic and the electronic components in any region in space would only be momentum-dependent, the modifications introduced in their characteristics would be widely different because of the large difference in their rest masses and their interaction properties. In particular it turns out that the energy spectrum of cosmic electrons is so much influenced by their leakage from the confinement region and energy losses through synchrotron radiation and inverse Compton scattering, that from a study of their spectrum near the earth, it becomes possible to make an estimate of their lifetime in the containment region by using appropriate values for the magnetic and radiation fields. Such knowledge when coupled with information obtained from a study of the nucleonic component—for instance the total amount of matter traversed by them or a direct estimate of their lifetime—could result in a fuller understanding of a variety of allied subjects. The reliability of any deduction made from such procedures can only be judged from the extent to which it is in conformity with well-founded information on associated astrophysical and cosmological parameters. We would now attempt to examine the applicability of various confinement regions for the cosmic rays sampled by us near the earth.

Equilibrium Spectrum of Electrons.—The cosmic electrons observed in the neighbourhood of the earth could in principle be either in (i) a state of equilibrium in a suitable confinement volume of space containing the earth or (ii) a state of non-equilibrium. In the case of the latter alternative it would be natural to expect large temporal variations of cosmic ray intensity near the earth in the 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 the same within $\pm 10\%$ over the last million years and within a factor of two over the past billion years.[18] Therefore in what follows we would only consider the first alternative, namely an equilibrium spectrum of electrons.

We will assume for the electrons a source (or sources) which continuously generates and injects electrons into the confinement volume with a power law spectrum of the type

$$Q(E)\, dE = KE^{-\beta}\, dE. \tag{6}$$

The electrons lose energy by various processes such as ionisation, bremsstrahlung, synchrotron radiation and inverse Compton scattering; a part of them would leak out of the containment volume. By considering the steady state conditions, wherein there is equilibrium between the rate of injection of electrons in a given energy interval and the rate of removal of electrons from the same energy interval due to energy losses and leakage, the spectral form of the equilibrium electrons has been deduced by many authors.[19-22] Assuming that there is no acceleration during the time the cosmic rays undergo diffusion in the containment volume, the electron spectrum satisfies the following continuity equation in energy space:

$$\frac{\partial}{\partial t}[\mathrm{N}(\mathrm{E}, t)\, d\mathrm{E}] + \frac{\partial}{\partial \mathrm{E}}\left[\frac{d\mathrm{E}}{dt}\mathrm{N}(\mathrm{E}, t)\, d\mathrm{E}\right] = \sum_i \mathrm{Q}_i(\mathrm{E}, t)\, d\mathrm{E}. \qquad (7)$$

The terms on the right-hand side would include all sources and catastrophic losses (mainly leakage). The quantity ($d\mathrm{E}/dt$) represents the gradual energy loss due to processes mentioned earlier. Since in the present analysis our interest relates only to electrons of energy greater than 1 GeV, the important loss processes are leakage from the confinement volume, synchrotron radiation in the magnetic field and inverse Compton scattering in the radiation field, and as will be shown later, the first one is dominant in the lower energy region (Region I) while the later two are dominant at higher energies (Region II).

For the steady state conditions, one can set $\partial/\partial t\, \mathrm{N}(\mathrm{E}, t)\, d\mathrm{E} = 0$ in equation (7) and obtain the solutions as:

$$\mathrm{N}(\mathrm{E})\, d\mathrm{E} = \mathrm{T.K.\,E}^{\beta}\, d\mathrm{E} \quad \text{for} \quad \mathrm{E} \ll \frac{1}{b\mathrm{T}(\beta - 1)} \quad \text{Region I} \qquad (8)$$

$$\mathrm{N}(\mathrm{E})\, d\mathrm{E} = \frac{\mathrm{KE}^{-(\beta+1)}\, d\mathrm{E}}{b(\beta - 1)} \quad \text{for} \quad \mathrm{E} \gg \frac{1}{b\mathrm{T}(\beta - 1)} \quad \text{Region II} \qquad (9)$$

Here T is the lifetime of electrons against leakage and

$$b\mathrm{E}^2 = -\left[\left(\frac{d\mathrm{E}}{dt}\right)_{\text{syn.}} + \left(\frac{d\mathrm{E}}{dt}\right)_{\text{comp.}}\right].$$

It is important to notice here that while in Region I the spectral index of the electrons in the confinement volumes is the same as the injection spectrum of electrons, in Region II it is steeper by one power; the energy value where the steepening, if any, occurs in the energy spectrum can be used to estimate the value of T and the absence of a steepening to set an upper limit to T.

As has been stated earlier, the measured differential fluxes of electrons available at present between 1–300 GeV can be fitted by a single power spectrum given by equation (3); there is so far no indication of a steepening of the spectrum as characterised by equation (9). From the observations summarised in Fig. 4, it is possible only to say that the lower limit for the electron energy up to which no steepening has set in is $\approx$ 50 GeV. Under these circumstances we feel that the best line of approach is to use an equilibrium energy spectrum as given by equation (3) which steepens at an energy $\gtrsim$ 50 GeV; with this spectrum one could proceed to deduce an upper limit for the lifetime of cosmic rays in different containment volumes using a reasonable set of parameters associated with the respective regions of space. This has been made for the following four regions of space: (i) universal, (ii) the super-cluster of galaxies, (iii) the galactic halo and (iv) the galactic disc; the parameters used and the corresponding lifetimes obtained for a spectral steepening at 50 GeV for these regions are summarised in Table III. We will not consider here mixed models whereby one can attempt to explain electrons at different energy intervals to be contributed by different confinement regions. We will now proceed to examine the four possibilities in detail; in each case we will consider the consequences with and without the recently postulated[23] universal black body radiation (BB) at $\approx$ 3° K. In the latter calculations we will use a photon energy density of 0·4 eV/cm.^{3} and a mean energy of 7×10^{-4} eV per photon for the 3° K. radiation field.

(i) *The Universal Model.*—We have used in this model an intergalactic magnetic field of 10^{-7} gauss and a starlight photon density of $1\cdot5\times10^{-3}$ eV/cm.^{3}, [24, 25] and obtained the upper limit for T_u as 3×10^9 years. Since this time period is comparable to the expansion time of the universe, it can be thought of as due to loss of electrons from the observable universe because of the expansion. On the other hand, in this model, the 3 g./cm.^{2} of matter traversed by the nucleonic component and the value obtained for T_u would lead to an average density of matter $\gtrsim 3/cT_u \sim 10^{-27}$ g./cm.^{2} for the intergalactic space; this value is, however, at least two orders of magnitude larger than the average density of 10^{-29} g./cm.^{2} in the universe. In all such situations where, from lifetime considerations, the expected amount of matter traversed is far too small compared to 3 g./cm.^{2}, one could get over the difficulty by ascribing all or part of the amount of matter traversed to be in the source itself. There is also another difficulty which will have to be answered in this model. It has been shown by Felton and Morrison[26] that if all space is filled with relativistic electrons to the same density as in the neighbourhood of the earth, the inverse Compton scattering would result in two high a flux of hard photons which seem excluded from data available. To our knowledge, no one has so far been able to offer serious support to this kind of a model because of the consequent difficulties it would lead to in problems of cosmology and energetics.

If the 3° K. universal black body radiation exists, then the energy losses suffered by the electrons through inverse Compton scattering dominate to such great extent that we get for T_u a value $\lesssim 2\times10^7$ years. Since this time scale is far too small compared to the dimensions of the confinement volume, this model can be dismissed straightaway if the existence of the black body radiation is confirmed.

It may be summarised that on the basis of our present knowledge, the universal model, in general, does not seem to be a promising possibility for cosmic ray containment.

TABLE III

Calculated values of T to fit the experimental observations on the electron flux for various confinement regions of cosmic rays

Confinement region	H in gauss	Starlight density in eV/cm.^{3}	Lifetime T in years	
			Without BB	With BB
(i) Universal	10^{-7}	$1\cdot5\times10^{-3}$	3×10^9	2×10^7
(ii) Super cluster of galaxies	5×10^{-7}	5×10^{-3}	5×10^8	2×10^7
(iii) Galactic halo ..	$2\cdot5\times10^{-6}$	10^{-1}	2×10^7	10^7
(iv) Galactic disc	8×10^{-6}	6×10^{-1}	$2\cdot2\times10^6$	2×10^6

(ii) *The Super-Cluster Model.*—Burbidge and Hoyle[27] have argued that if one considers the super-cluster of galaxies to which our galaxy belongs, the radio sources contained therein would be able to account for, as much energy density in the cosmic radiation in the cluster as is observed near the earth in time periods of $\sim 10^{10}$ years; the radius of the super-cluster would be $\sim 10^9$ light-years. We have therefore estimated the lifetime of the electrons in this containment volume of $\sim 10^{81}$ cm.^{3}, by assuming a magnetic field of 5×10^{-7} gauss[28] and a visible photon density of 5×10^{-3} eV/cm.^{3}, and obtained a value $T_c \lesssim 5\times10^8$ years which is too small compared with the value of 10^{10} years required by Burbidge and Hoyle.[27] As for the mean density of matter traversed, we obtain a value of $\gtrsim 6\times10^{-27}$ g./cm.^{3} which is at least one order of magnitude larger than that attributed to the cluster.[28]

We have already pointed out that this difficulty can be got over by attributing 3 g./cm.^{2} of matter traversed in the source itself.

As in the universal model, the lifetime of $\lesssim 2\times10^7$ years, in case the 3° K. radiation existed, would mean that the super-cluster model would also be untenable.

It would, therefore, seem from the foregoing considerations that the super-cluster model would also be a difficult possibility for the containment of cosmic rays.

(iii) *The Galactic Halo Model.*—The great support and wide acceptance of the galactic halo model, in which the cosmic ray particles are supposed to be freely exchanged between the disc and halo of our galaxy, are derived mainly from observations on the radio halo (synchrotron radio emission of relativistic electrons moving in chaotic magnetic fields), the energetics of supernovae in our galaxy and the isotropy of the cosmic radiation as observed on earth up to very high energies. In our calculations for the halo model we used a value of $2\cdot5\times10^{-6}$ gauss for the magnetic field obtained by using a flux of electrons in the halo as given by equation (3) and the background radio emission; the value used for the starlight density is 0·1 eV/cm.[3–22] As shown in Table III, we get $T_h \lesssim 2\times10^7$ years. Since the mean galactic matter density is thought to be $\sim 10^{-26}$ g./cm.^{2}, here again we would require the cosmic rays to traverse 3 g./cm.^{2} of matter in the source region in order to understand the cosmic ray nucleonic component. The lifetime of cosmic ray particles executing "Brownian motion" in the halo as estimated[21] by assuming "reasonable" values for magnetic inhomogeneities existing in our galaxy is $\sim 10^8$ years. If the "reasonable" values used here are really so, we have already reached a difficult situation, though not hopeless as yet, to understand the cosmic ray electrons in the halo model. As for the energy density in cosmic rays in the halo model, one finds that the energetics of supernovae explosions in our galaxy would just about permit a value of $\sim 10^{-12}$ ergs/cm.^{3} It would be appropriate to mention here of an important possibility which might develop in this field in the near future and drastically change our ideas about the halo. During the last few years, there has been a growing feeling among radio astronomers[29] that part of the background radio emission presently attributed to the halo electrons may be due to unresolved discrete radio patches. If this turns out to be true, then we would be left with a thinner halo, weaker magnetic fields and hence a lifetime which is longer than what is given in Table III; the halo model would then have a much stronger basis for it to be acceptable.

Some of the consequences of the 3° K. black body radiation on the electron component has been already discussed in a previous paper.[30] The leakage lifetime obtained with the black body radiation here is $\lesssim 10^7$ years (*see* also Cowsik *et al.* for a similar treatment[31]). Such a value would be much more difficult to compromise with the value of $\gtrsim 2 \times 10^7$ years obtained for the lifetime of the cosmic rays by a direct method[32, 33] and the calculated leakage lifetime of 10^8 years.[21] It may also be pertinent here to say that the halo model assumes for equilibrium between the halo and the disc the condition $T_d/T_h < V_d/V_h$, where V_d and V_h are the volumes of the disc and the halo respectively[34]; this would mean that $T_h \gtrsim$ few times 10^7 years because T_d is unlikely to be less than 10^6 years. These considerations have prompted us to think that the universal black body radiation would be difficult to be accommodated in the galactic halo model except by attributing the observed electron flux to a two component hypothesis.[30]

(iv) *The Galactic Disc Model.*—The magnetic fields in the galactic disc are still not well known and we have used a value of 8×10^{-6} gauss[35, 36]; for the starlight density a value of $0 \cdot 6$ eV/cm.^{3} [26] has been used. We then find that in this model, the existence or non-existence of the universal black body radiation does not make any noticeable difference in the leakage lifetime and we get $T_d \lesssim 2 \times 10^6$ years. This lifetime and the usually accepted value of $\sim 2 \times 10^{-24}$ g./cm.^{3} for the mean density of the disc, yield ~ 3 g./cm.^{2} for the amount of matter traversed by the cosmic rays, requiring thereby no necessity for the particles to traverse any matter in the source. It is thus seen that the galactic disc model would be a potential candidate for the containment of cosmic rays in spite of the existence of the black body radiation. However to be acceptable the requirements of this model will have to be consistent with the following: (*a*) In this model it seems natural to expect some anisotropy for the cosmic radiation, because the source or sources are likely to be located in the central regions of the galaxy. From observations so far made on the absence of anisotropy of the cosmic rays, a lifetime of $T_d > 10^6$ years has been set by Fujimoto *et al.*[34] Better measurements of T_d by this method in future should be in conformity with the values got from electron observations. (*b*) Direct estimates for the lifetime of cosmic rays have indicated a value $\gtrsim 2 \times 10^7$ years.[32, 33] Since these values are based on data of poor statistical weight, one would like this experiment to be repeated because of its crucial nature.

6. Summary and Future Scope

To summarise, it seems to us that from the many considerations detailed in Sec. 5, it will be hard to understand the electron component within the framework of the universal and super-cluster models. This leaves us with the galactic halo and galactic disc models; between these two models there is not sufficient data at present to favour one over the other in any significant manner. However on the basis of our present knowledge, one important difference in the consequences of the two models is that while in the halo model all the matter traversed will be in the source, in the latter it will be in interstellar space. As for the universal black body radiation at 3° K. if future experiments confirm its existence, one may then have to appeal to the two-electron-component hypothesis in the galactic halo model[30] or the galactic disc model. Regarding the existence of the 3° K. radiation field itself, we would like to refer to the observations on the flattening of the energy spectrum of cosmic rays at energies 10^{19}–10^{20} eV[37] and the existence of γ-rays of energy 10^{14} – 10^{16} eV[38, 39] which offer difficulties if the universal radiation exists.

While the difficulties in interpreting the data are to a great extent due to our inadequate knowledge of astrophysical parameters involved, it is certain that when we have reliable results from a number of experiments which are now in progress in various parts of the world, we will be able to place more stringent constraints on the models thereby permitting meaningful interpretations. In what follows we enumerate some of the crucial experiments:

(i) Experiments to prove or disprove the existence of the universal black body radiation at 3° K. by direct observations in the mm. radio wavelength region.

(ii) More detailed observations on the halo background radio emission.

(iii) Experiments to extend the energy spectrum of cosmic ray electrons to higher energies and establish the existence or otherwise of a steepening in the spectrum.

(iv) Experiments to determine accurately the proportion of positrons among the cosmic electronic component as a function of energy.

(v) Experiments to set better limit to the anisotropy of high energy cosmic rays.

(vi) Experiments to measure in a reliable manner or set reliable lower limits for the lifetime of cosmic rays based on the decay of Be^{10}.

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