FLUX OF COSMIC-RAY ELECTRONS BETWEEN 17 AND 63 MeV*

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The flux of cosmic-ray electrons in the energy interval of 17-63 MeV was measured in three high-altitude balloon flights during the summer 1967 near Fort Churchill, Manitoba. The average flux was found to be 0.3 ± 0.2 electrons/m^2 sec sr MeV. Implications of this result on models of the origin of galactic cosmic-ray electrons and their solar modulation are discussed.

A number of measurements of the spectrum of cosmic-ray electrons at energies above 100 MeV near the top of the atmosphere have been made using balloon-borne detector systems at high latitudes.[1-3] In the energy interval between 3 and 12 MeV, electrons have been observed from IMP satellites since 1963.[4] The energy spectrum below 12 MeV does not appear to be a simple extension of that above 100 MeV, so the intermediate energy range, between 10 and 100 MeV, is of particular interest. Furthermore, the flux of cosmic-ray electrons expected in this energy region appears to be very sensitive to proposed models for solar modulation.

In this paper we report a measurement of the primary-electron flux in the energy interval from 17 to 63 MeV. The data were taken in 1967 in high-altitude balloon flights launched from Fort Churchill, Manitoba. We have taken into account the diurnal variation of the electron flux which occurs at latitudes near Fort Churchill,[5,6] and present results derived from data of the nighttime interval only. Our own results,[6] which include a direct measurement of the splash albedo, support the interpretation of this diurnal variation given by Jokipii, L'Heureux, and Meyer[5]; therefore, we consider that these nighttime data contain primary electrons and atmospheric secondaries but no return albedo. Of several other published measurements made within the magnetosphere at these energies,[5,7-9] the only one that can be considered free of return albedo is that of Jokipii, L'Heureux, and Meyer,[5] which is an average flux measurement over the interval from 15 to 240 MeV. In addition, Fan et al. have reported a flux value for electrons between 10 and 40 MeV outside the magnetosphere.[10]

Our measurements were performed with an instrument specifically designed to detect cosmic-ray electrons. Data are derived from three high-altitude balloon flights launched at Fort Churchill on 17 June, 2 July, and 21 July 1967. For the electrons discussed here, the results from the three flights were mutually consistent and were combined for improved statistical accuracy. All ascent data were taken during the nighttime interval.

A cross section of the detector system is shown in Fig. 1. The two scintillation-telescope counters ($T1$ and $T2$) define the acceptance cone of the system, whose geometrical factor is 0.92 ± 0.02 cm^2 sr. A triple coincidence of $T1$, $T2$, and the gas Čerenkov counter (C) was required to trigger the system. The Čerenkov counter was filled with SF$_6$ at 2.2 atm absolute pressure, resulting in a velocity threshold of $0.9984c$. The spark chamber contained four lead plates as indicated in Fig. 1. The first plate had a thickness of 11.6 g/cm^2 (2 radiation lengths), and each of the others, 5.8 g/cm^2. Below each lead plate were two digitized-spark-chamber gaps

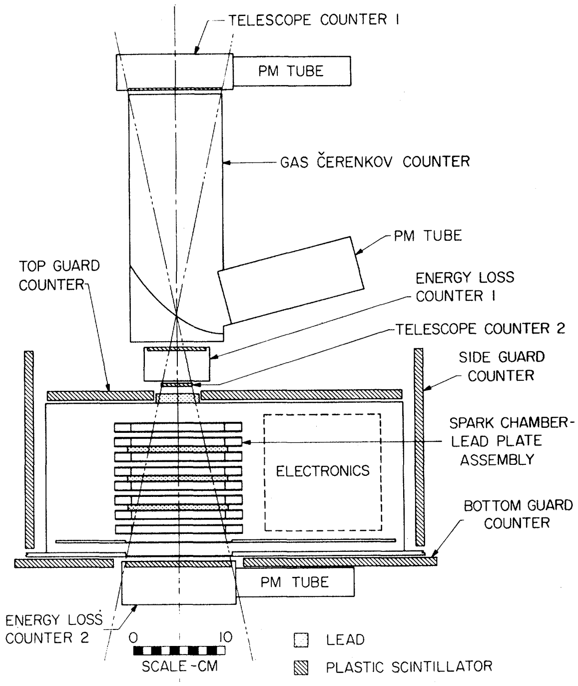

FIG. 1. Cross section of the detector system.

with magnetic-memory-core readout. The spark chamber was completely surrounded by guard counters except for apertures for the allowed particle beam. For each event, the pulse height in both energy-loss counters ($\Delta E1$ and $\Delta E2$), the position of each spark in each gap, and indicator bits for the guard counter pulses were recorded on magnetic tape.

In this paper we consider only events where a triple coincidence was accompanied by minimum ionization loss in $\Delta E1$, and where neither $\Delta E2$, nor any spark gap, nor any guard counter registered a particle. These events must be due to electrons, since any heavier particle with velocity above the Čerenkov counter threshold has a range much greater than the entire lead stack. The effective energy interval for these electrons is 12-55 MeV. This interval is determined at the lower end by the Čerenkov-counter response. The instrument was calibrated on the Caltech synchrotron in order to define the upper end.

The raw fluxes measured are corrected for the possibility that an electron of the correct energy, within the acceptance cone, may be rejected because it leaves more than $1\frac{1}{2}$ times minimum energy loss in $\Delta E1$, or it produces secondaries which trigger a guard counter. A correction is also made for the 96% Čerenkov-counter efficiency. The combined corrections amount to 25% and introduce a possible systematic error in the reported fluxes of less than 10%. An additional possibility of systematic error is introduced in the differential flux by a 10% uncertainty in the upper boundary of the effective energy interval. The lower boundary uncertainty is $\lesssim 1$ MeV.

In Fig. 2 we present the altitude dependence of the flux of electrons whose energy at the top of the detector system is between 12 and 55 MeV. The error bars indicate the statistical error only. It is clear that even at the highest altitude (2.1 g/cm^2), the measured flux contains a significant fraction of secondary electrons produced in the atmosphere. Two independent calculations of the secondary-electron flux above 10 MeV have been published.[11,12] Both consider interactions of the nucleonic component of primary cosmic rays with air nuclei and determine the flux of electrons which result from the decay of the interaction products. We have modified these calculations by adding the contribution of knock-on electrons,[13] which is important at energies $\lesssim 20$ MeV. When the predicted secondary-electron spectra are folded with the response of our instrument, we derive the dashed curves shown in Fig. 2. Curve 1 is the sum of secondary electrons from interactions, as calculated by Perola and Scarsi,[11] and knock-on electrons. Curve 2 includes interactions as calculated by Verma[12] plus knock-on electrons.

Because of the disagreement between the two calculated secondary fluxes, we have chosen to subtract secondaries using the following semiempirical method. We assumed that the altitude dependence of the total electron flux between 12 and 55 MeV, $J(d)$, has the form

$$J(d) = as(d) + bp(d), \tag{1}$$

where d is atmospheric depth, $s(d)$ is the depth dependence of the flux of secondary electrons, $p(d)$ is the depth dependence of the flux due to primary electrons, and a and b are parameters which give the magnitude of the secondary and primary contributions, respectively. We calculated the form of $p(d)$ assuming a differential electron spectrum at the top of the atmosphere of the form $E^{-0.5}$, where E is the electron energy. For $s(d)$ we used the calculated depth dependence of curve 2, which is linear. We then carried out a least-squares fit to the nine data points from 2.1 to 25 g/cm^2 to determine the two parameters a and b. The solid curve of Fig. 2 gives the resulting $J(d)$ which fits with a χ^2 of 2.9. The curves A and B give the secondary and pri-

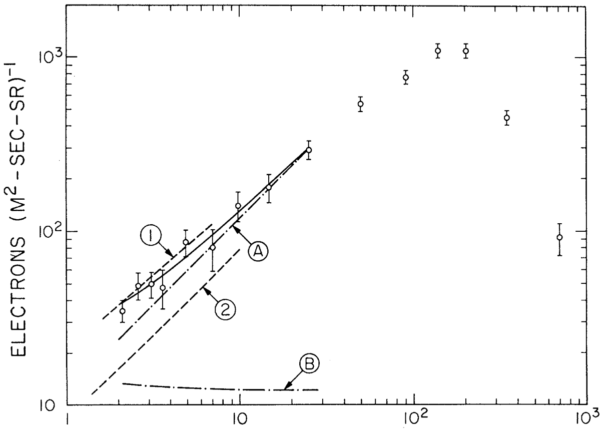

FIG. 2. Intensity versus atmospheric depth for electrons between 12 and 55 MeV. Dashed line, calculated contribution from atmospheric secondaries. Curve 1 is derived from Ref. 11 with addition of knock-on electrons. Curve 2 is derived from Ref. 12 with same addition of knock-on electrons. Solid line, least-squares fit to data using Eq. (1). Dot-dashed line, secondary (curve A) and primary (curve B) contributions to least-squares fit.

mary contributions, respectively. The primary electron contribution to the flux of 2.1 g/cm^2 resulting from this fit is 13 ± 5 electrons/m^2 sec sr. This result is very insensitive to the choice of $n = -0.5$ as the exponent in the power law of the assumed primary spectrum. It differs from this value by less than 10% for any value of n between 0 and -2.

After correcting for ionization and *bremsstrahlung* energy losses of the electrons in the 2.1 g/cm^2 above the gondola and including both the statistical errors and possible systematic errors, we derive a flux at the top of the atmosphere of 0.3 ± 0.2 electrons/m^2 sec sr MeV, between 17 and 63 MeV. If we were to assume that the depth dependence of secondaries between 2 and 25 g/cm^2 were somewhat less steep than linear (curve 1), the same process of least-squares fitting to our data would give a smaller primary flux, consistent with zero. Thus our quoted primary flux must be taken as an upper limit. In Fig. 3 we present the differential energy spectrum of the primary electrons as reported in this paper and by other experimenters.

The differential flux of electrons between 10 and 40 MeV measured by Fan *et al.*[10] outside the magnetosphere between June 1965 and March 1966 differs significantly from our result in 1967. This could be understood if a strong time variation in the electron flux near 30 MeV occurred in a period of less than 2 yr. The best flux estimates from the two experiments would indicate a decrease by a factor of 7. No other data for time variations of the electron flux in this energy interval have been published; however, at both lower and higher energies the possible time variation is much smaller than this.[4,14,15] Thus, it would be difficult to ascribe this difference to a time variation.

The difference could also be accounted for if the present understanding of the diurnal variation were incorrect, and the nighttime flux of low-energy electrons near Fort Churchill were not representative of the interplanetary flux. We believe this to be quite unlikely. The interpretation of the diurnal variation adopted in this paper is supported by several calculations.[16-18] It is also supported by diurnal variations in the geomagnetic cutoff inferred from measurements of low-energy protons.[19,20] Direct evidence that particles of rigidity near 40 MV have direct access to at least some parts of the polar-cap region comes from simultaneous observations of comparable intensities of solar protons on Mariner 4, far outside the magnetosphere, and on Injun 4 in a low polar orbit.[21] Thus we consider our measured nighttime flux to be representative of the interplanetary flux and unaffected by geomagnetic cutoffs. In the remaining paragraphs we discuss some implications of our result. In particular, we shall consider a model discussed by Ramaty and Lingenfelter (RL).[22]

The solid line in Fig. 3, calculated by RL, represents the flux of cosmic-ray electrons outside the solar system, which originates in nuclear collisions between the nucleonic cosmic rays and the interstellar gas. Two models of solar modulation are discussed by RL. The modulated flux based upon these models is shown by the dashed curves. These result from multiplying the galactic flux by a factor f given by

$$f = \exp(-\eta/R\beta) \quad \text{for } R > R_0,$$
$$f = \exp(-\eta/R_0\beta) \quad \text{for } R < R_0, \qquad (2)$$

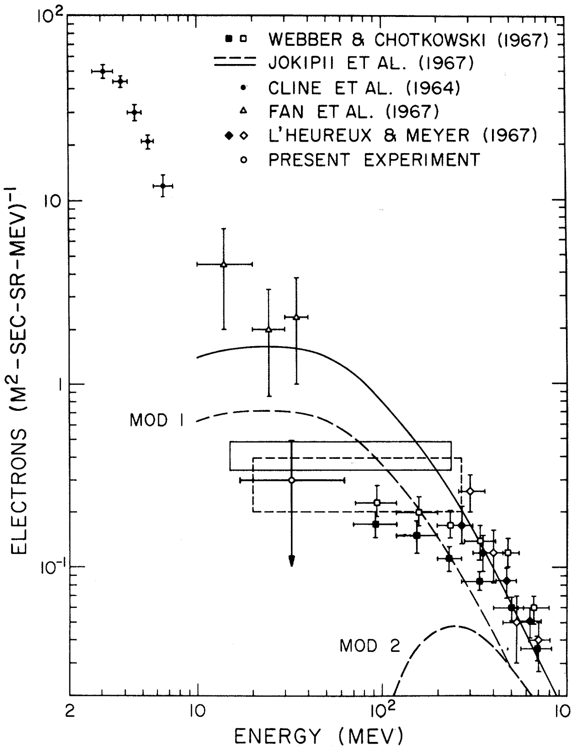

FIG. 3. Differential kinetic-energy spectrum of primary electrons. Open squares, open diamonds, and dashed rectangle represent data taken in 1965. Closed squares, closed diamonds, and solid rectangle, 1966. Solid line, galactic electron spectrum for interstellar collisions (see Ref. 21). Dashed line, modulated electron spectrum. MOD 1 and MOD 2 are obtained from the solid curve using the modulating function given by Eq. (2) with $R_0 = 0.5$ and 0 BV, respectively, and with $\eta = 0.4$ BV.

where R is the electron rigidity, βc is its velocity, and η is a time-dependent parameter independent of R and β. For the curve labeled MOD 1, $R_0 = 0.5$ BV; and for MOD 2, $R_0 = 0$. The curves are plotted for $\eta = 0.4$ BV, a value derived by RL for solar minimum. The summary of proton and helium data presented by Webber[23] shows that, while neither of these models can fully explain all observed features of modulation, below about 0.5 or 1 BV, β-dependent modulation such as MOD 1 is more likely than the $R\beta$ dependence of MOD 2. Furthermore, the lack of significant long-term variations of the electron flux above 250 MeV[15] would indicate a modulation even weaker than MOD 1.

For 1967, when our data were taken, we would expect the flux corresponding to MOD 1 to be lower than indicated in Fig. 3 for solar minimum. The change in η derived from nucleon data for a comparable period before solar minimum would result in a lowering of this flux by about 45%. Thus, if the modulation is similar to MOD 1, then the electrons which we observe could be entirely accounted for by the interstellar collision source as calculated by RL, and this would rule out a contribution from primary acceleration as large as that found by Hartman above 1 BeV (i.e., $\gtrsim 90\%$).[24]

If, on the other hand, the modulation were weaker than MOD 1, then our measured flux would fall below that calculated from the collision source of RL. This would imply that some of the galactic parameters used by RL may need revision.

Experiments now under way to measure the positron/electron ratio at these energies and to measure the long-term time variation of the electron flux will further clarify the mechanisms of production and solar modulation of electrons.

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