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COSMIC-RAY ELECTRON LIFETIMES IN THE GALACTIC DISK AND HALO*

Reuven Ramaty and Richard E. Lingenfelter
Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California
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Recent measurements of cosmic-ray electrons of energies 12 to 350 BeV[1,2] indicate that their differential energy spectrum can be fitted by a power law with spectral index of 2.1 ± 0.2. This index is the same as that found at energies of a few billion electron volts,[3,4] which seems to be in contradiction with the expected steepening of the spectrum because of synchrotron and inverse Compton losses. As a result of this discrepancy, Daniel and Stephens[2] concluded that either the 3°K black-body radiation does not exist or there is an additional high-energy electron source with spectral index 1.1.

We propose instead that the observed high-energy electron spectrum results from a cosmic-ray mean lifetime in the galactic disk that is shorter than the lifetime against radiation losses by these electrons, but long enough to establish a measurable equilibrium flux.

The calculations of Felten and Morrison[5] show that the intergalactic electron intensity required to produce the diffuse gamma-ray background flux by the inverse Compton mechanism is more than three orders of magnitude less and of a steeper spectral shape than the electrons observed at the earth. Thus, we shall assume that the sources of the electrons, whether of primary or secondary origin, are located in the galactic disk. The electrons produced in the sources spend a time τ_d in the disk, after which they leak out into the halo, where they spend a time $\tau \gg \tau_d$ before they leak into the intergalactic medium. Since τ is much larger than τ_d, the electrons in the halo are freely exchanged[6] between disk and halo. The equilibrium density in the halo, $\eta_h(E)$, satisfies

$$\frac{\eta_h(E)}{\tau} - \frac{\partial}{\partial E}\left[\frac{dE}{dt}\eta_h(E)\right] = \frac{\eta_s(E)}{\tau_d}\frac{V_d}{V_h}, \tag{1}$$

where $\eta_s(E)$ is defined by

$$\frac{\eta_s(E)}{\tau_d} - \frac{\partial}{\partial E}\left[\frac{dE}{dt}\eta_s(E)\right] = q(E), \tag{2}$$

and where $q(E)$ is the number of electrons produced per unit volume per second in the disk, V_d and V_h are the disk and halo volumes, respectively, and dE/dt is the energy-loss rate resulting from synchrotron and inverse Compton losses. For a mean magnetic field of 3×10^{-6} G and a black-body photon density of 0.4 eV/cm^3, we obtain $dE/dt = 6 \times 10^{-17} E^2$ (BeV/sec). The equilibrium density which should be measured in the disk is

$$\eta_d(E) = \eta_s(E) + \eta_h(E).$$

Assuming that $q(E) = q_0 E^{-\Gamma}$, Eq. (2) can be solved analytically, and for $E \ll E_1 = 1.6 \times 10^{16}/\tau_d$ BeV its solution is

$$\eta_s(E) = q_0 E^{-\Gamma}\tau_d,$$

whereas for $E \gg E_1$, η_s varies as $E^{-\Gamma-1}$. Using this functional form for η_s, we can solve Eq. (1) for η_h in a similar fashion, where now the break in the spectrum comes at $E_2 = 1.6 \times 10^{16}/\tau$ BeV. Then for $E < E_2$, the disk density is

$$\eta_d(E) = q_0 E^{-\Gamma}\tau_d\left[1 + \frac{V_d}{V_h}\frac{\tau}{\tau_d}\right]. \tag{3}$$

The factor $V_d\tau/V_h\tau_d$ is the ratio of the time a halo electron spends in the disk to the disk lifetime τ_d. At energies less than E_2 where the halo leakage life is shorter than the lifetime against energy losses in the halo, this ratio is a measure of the re-entrant halo electrons in the disk. For $E_2 < E < E_1$, the energy-loss lifetime in the halo is shorter than τ but longer than τ_d; thus re-entrant electrons from the halo become negligible, and

$$\eta_d(E)=q_0E^{-\Gamma}\tau_d. \quad (4)$$

The electron measurements from 1 to 200 BeV are shown in Fig. 1. Above and below a transition region between 6 and 30 BeV, these data can be fitted by two power laws having the same spectral index but different absolute normalizations. Such a spectral behavior is expected from the present model, and the transition should begin at an energy approximately equal to E_2. Using the relation $E_2=1.6\times10^{16}/\tau$ given above, the break in the observed spectrum at 6 BeV implies that $\tau=2.7\times10^{15}$ sec. This is consistent with previous estimates of the nuclear cosmic-ray lifetime based on the amount of material traversed[7] and radioactive decay.[8] The expected displacement in absolute

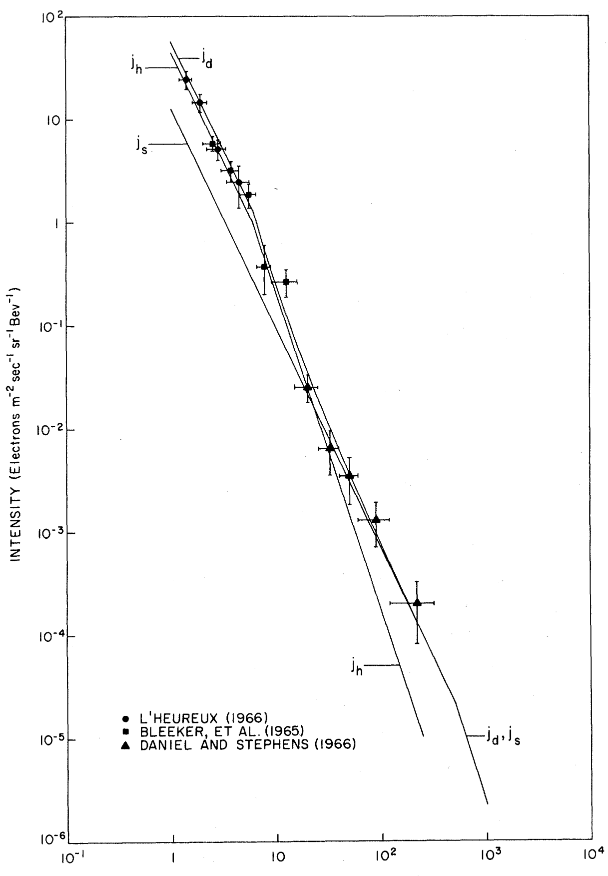

FIG. 1. Cosmic-ray electron measurements from 1 to 300 BeV [2–4] together with a schematic representation of the disk and halo electron intensities j_d and j_h from Eqs. (3) and (4) for a case where $\Gamma=2.1$, $\tau=3\times10^{15}$ sec, $\tau_d=3\times10^{13}$ sec, $V_h/V_d=30$, and $j_{d,h,s}=(c/4\pi)\eta_{d,h,s}$. Here η_s is the disk density without the contribution of re-entrant halo electrons.

normalization is the ratio of Eq. (3) to (4) and is equal to $1+(V_d/V_h)(\tau/\tau_d)$. As can be seen from the data in Fig. 1, this ratio is approximately 4.5 for $\Gamma=2.1$. Solving for τ_d, we find

$$\tau_d=0.29(V_d/V_h)\tau.$$

For a disk-to-halo volume ratio of about 1/30,[9] and $\tau=3\times10^{15}$ sec, we find a cosmic-ray electron lifetime in the disk, τ_d, of 3×10^{13} sec. In the present model we would thus expect a second steepening of the spectrum at an energy of about $E_1=500$ BeV. This is not inconsistent with the present data which show no break in the spectrum up to about 300 BeV. This value of τ_d is also consistent with present measurements of cosmic-ray anisotropy of less than 1%, provided that the electron sources are distributed throughout the disk. The degree of anisotropy depends on the cosmic-ray streaming velocity v and is given by $\delta=6(v/c)$.[10] A characteristic streaming distance of 300 pc and a τ_d of 3×10^{13} sec yield $\delta\approx0.6\%$.

In the above example we have fitted the observed data with a spectral index $\Gamma=2.1$. However, the data may be fitted by spectral indexes ranging from 1.9 to 2.6. The resulting ratios of the absolute normalization then vary from 7 to 1, respectively. These imply electron lifetimes in the disk, τ_d, ranging from about 10^{13} to 6×10^{13} sec. The upper limit on τ_d results from a ratio of 1 which corresponds to a vanishing halo contribution to the equilibrium disk electron flux at all energies. This would require a negligible re-entrance probability from the halo to the disk or the nonexistence of the halo, which would further require an alternative explanation for the nonthermal "halo" radioemission. The lower limit on τ_d resulting from the maximum ratio of 7 is required simply to give an observable electron flux at high energies where the contribution from the halo is negligible because of electron energy losses in the halo.

This range of disk lifetimes requires a second steepening of the spectrum between 300 and 1600 BeV. It is hoped that further electron measurements in this energy range will better determine this lifetime.

Finally, we would like to note that the positron-to-total electron ratio[2] of 0.7 ± 0.2 would suggest that secondary processes are of importance in producing these high-energy electrons.

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COSMIC-RAY ELECTRON SPECTRUM AND THE UNIVERSAL BLACKBODY RADIATION AT 3°K

R. F. O'Connell*
Institute for Space Studies, Goddard Space Flight Center,
National Aeronautics and Space Administration, New York, New York

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It is shown that the observed energy spectrum of cosmic-ray electrons between 1 and 350 GeV may be compatible with the existence of a universal blackbody radiation at 3°K, in contrast to the conclusion drawn by Daniel and Stephens in a recent Letter.

Daniel and Stephens[1] have shown that the differential energy spectrum of cosmic-ray electrons between 12 and 350 GeV can be represented as

$$N(E)dE = 12.7E^{-2.1\pm 0.2}dE \text{ m}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}, \quad (1)$$

where E is the electron energy in GeV. The theoretically calculated spectrum is generally written as[2,3]

$$N(E) = KE^{-\gamma}, \quad (2)$$

where the spectral index γ is determined by the particular mode of acceleration envisaged. Using Fermi's[4] statistical mode of acceleration, and neglecting processes of energy loss, one has $dE/dt = \alpha E$; one deduces that $\gamma = 1 + (\alpha T)^{-1}$ where T is the lifetime of electrons against leakage by diffusion from the acceleration region, and

$$\alpha = u^2 v/c^2 l, \quad (3)$$

where u is the velocity of the magnetic "walls" or "clouds," l is the distance between the walls, and v is the velocity of the particle along the lines of force. With the usual choice for these parameters,[2,3] γ is of the order of 2.4 to 2.5. A value of 2.5 for γ was obtained by Syrovatskii[5] from the assumption that the cosmic rays are produced in nebulae and supernova shells and that the total energy is equally distributed between the kinetic energy of turbulent motion, the magnetic field, and the cosmic rays. This value agrees well with the value of about 0.7 obtained for the spectral index $(\gamma-1)/2$ for the isotropic radio emission.[1]

For higher electron energies, losses due to synchroton radiation and losses due to Compton scattering[6] with starlight photons and 3°K blackbody radiation[7] become important. These losses (particularly the latter[1]) have the effect of increasing the spectral index to a value $\gamma + 1$ at a critical energy E_c, which is proportional[1,2,6] to T^{-1}. Taking T to be 3×10^{15} sec, Daniel and Stephens[1] arrived at a critical energy of about 10-20 GeV; thus for energies >20 GeV the calculated index is 3.4, in strong disagreement with the experimental value of 2.1 ± 0.2. This led Daniel and Stephens to cast doubt on the existence of the 3°K radiation or alternatively to postulate the existence of two separate electron components.

In this paper we will show that the value of T can be 40 times or more smaller. This will invalidate the argument of Daniel and Stephens since it has the effect of increasing E_c from 10 GeV to >400 GeV, a value beyond the range