EVIDENCE FOR PRIMARY INTERSTELLAR COSMIC-RAY ELECTRONS

A. C. Cummings, E. C. Stone, and R. E. Vogt

Division of Physics, Mathematics, and Astronomy
California Institute of Technology
Pasadena, California (USA) 91109

We have performed a comparative study of the absolute solar modulation of cosmic-ray positrons (e⁺) and electrons (e⁺+e⁻). We find that the interstellar electron spectrum, which is described by a power-law slope at higher energies, must flatten below ~ 100 MeV, that a significant fraction of interstellar cosmic-ray electrons must originate in "primary" sources, and that the rigidity dependence of the interplanetary cosmic-ray diffusion coefficient, R₀, changes from α > 0 at higher rigidities to α ≈ -1 below ~ 60 MV.

1. Introduction. Galactic cosmic-ray electrons are produced as "primary electrons" (predominantly negatrons) in the acceleration of ambient matter in energetic sources, and as "secondary electrons" (positrons and negatrons) in the collisions of cosmic-ray nuclei with interstellar gas. There are large uncertainties in the energy spectrum and charge composition of interstellar electrons. The galactic electron spectra observed near Earth differ from the interstellar spectra since they have been modulated by the solar wind as the particles propagate through the interplanetary medium. Electron spectra deduced solely from the galactic non-thermal radio emission have large uncertainties, due to lack of detailed knowledge of other relevant galactic parameters, and cannot be extended below ~ 100 MeV, due to the interstellar absorption of radio signals. Secondary-electron fluxes calculated from collisions of the high-energy cosmic-ray nuclei with interstellar gas have uncertainties in their absolute intensities due to lacking detail on galactic parameters entering the calculations.

We shall discuss, in this paper, new information on the properties of galactic electrons which was derived from combining data from electron observations near Earth with data on interstellar electrons, derived from the non-thermal radio emission spectrum and from calculations on the production of secondary electrons. We shall develop a consistent picture of the interstellar electron spectrum from about 10 MeV - 10 GeV. We derive limits to its uncertainties, and we deduce information on the interplanetary diffusion coefficient which allows the near-Earth spectra to be related to the interstellar spectra.

2. Electron Propagation in the Interplanetary Medium. The propagation of energetic electrons in the interplanetary medium may be described in terms of a spherically symmetric transport equation:
\[
\frac{V}{r^2} \frac{\partial}{\partial r} \left( r^2 U \right) - \frac{2V}{3r} \frac{\partial}{\partial T} \left( \alpha T U \right) - \frac{1}{r} \frac{\partial}{\partial r} \left( kr^2 \frac{\partial U}{\partial r} \right) = 0
\] (1)

(see review, Jokipii, 1971), where \( V \) is the solar-wind velocity assumed independent of heliocentric radius, \( r \), \( U \) is the electron number density/unit energy, \( T \) is kinetic energy, \( \kappa \) is the radial diffusion coefficient, and \( \alpha(T) = (T+2m)/(T+m) \), where \( m \) is the particle rest energy. It has been shown (Cummings et al., 1973a) that a useful approximate solution to equation (1) for electrons is given by:

\[
j_1(T) = j_D(T) e^{-\psi(T)}
\] (2)

where \( j_1(T) \) is the intensity of electrons near 1 AU (\( j = \beta c U/4\pi, \beta c \) is the electron velocity) and \( j_D(T) \) is the interstellar electron intensity beyond the solar modulation boundary at \( r=D \), and the modulation parameter \( \psi \) is given by:

\[
\psi(T) = \int_1^D \frac{V dr}{\kappa(r,T)}
\] (3)

Given \( \psi(T) \), the interstellar electron spectrum, in principle, may be derived to a good approximation from equation (2), or more precisely through numerical solutions of equation (1), if detailed information on \( V, \kappa, \) and \( D \) can be deduced. We have derived this information by the following process. We have used an interstellar electron spectrum, newly derived from non-thermal radio data (Cummings et al., 1973b), the measured electron spectrum near Earth, and iterative numerical solutions to the transport equation (1) to deduce the cosmic-ray diffusion coefficient for energies larger than \(-100\) MeV (Cummings et al., 1973c). We derived \( \kappa \) for energies below \(-100\) MeV from a similar comparison of the calculated interstellar (secondary) positron fluxes with measured positron spectra near Earth. The interstellar positron spectrum has been calculated by several authors (e.g., Ramaty and Lingenfelter (R&L), 1968; Beedle, 1970; Araki, 1971). The independent derivations of the energy dependence of the interstellar positron spectrum by these authors are in general agreement; however, the calculated absolute intensities of positron fluxes differ by orders of magnitudes. We have resolved this uncertainty by requiring that the modulation parameters of positrons agree with those derived from the non-thermal radio data for electrons above \(-200\) MeV, an agreement found to exist most closely for the spectrum of R&L.

3. Electron and Positron Spectra in the Galaxy and at 1 AU. Figure 1a shows that the approximate range of interstellar electron spectra deduced from Figures 1b and 1c according to the analysis outlined in Section 2. The uncertainty in the interstellar electron spectrum above \(-100\) MeV is determined by uncertainties in the galactic parameters used in analyzing the radio spectrum (Cummings et al., 1973b). The uncertainties below \(-50\) MeV are due to uncertainties in the positron observations near Earth and in the absolute intensity of the R&L spectrum. The "nominal" interstellar spectrum cannot be represented by a power-law extension of the higher energy spectrum; it must flatten in order to be consistent with the observed data and the
Fig. 1a: Approximate range of interstellar electron spectra. > 70 MeV: Cummings et al., (1973b); < 50 MeV: see text. Continuous line: nominal spectrum.

Figs. 1b and 1c: Comparison of measured and calculated spectra of cosmic-ray electrons. Galactic positron spectrum: R&L (1968); galactic electron spectrum above ~ 100 MeV: Cummings et al., (1973b), below ~ 100 MeV: see text; data points:

- Fanselow et al., (1969)
- Simnett and McDonald (1969)
- Beuermann et al., (1970)
- L'Heureux et al., (1972) and Schmidt, (1972)

Lines through data points: near Earth spectra calculated from equation (1).

diffusion coefficient derived from the positron data. Figures 1b and 1c show the nominal interstellar positron and electron spectra and measurements of the modulated spectra at 1 AU made in 1965-66 and 1968. The lines through the data points represent modulated spectra calculated from a numerical solution of equation (1) (according to a technique first used by Fisk (1971)). Both positron and electron spectra at 1 AU were calculated with a solar-wind velocity of V=400 km/sec and with the same diffusion coefficient (equation (4) and Table I) for a particular year of observation:
\[ \kappa = \beta \kappa_1(r) \kappa_2(R) \]
\[ \kappa_2(R) = \begin{cases} 
R & R > R_2 \\
\sqrt{RR_2} & R_1 \leq R \leq R_2 \\
\sqrt{R_1R_2} & R_0 < R < R_1 \\
\sqrt{R_1R_2} R_0 R^{-1} & R \leq R_0 
\end{cases} \]  \hspace{1cm} (4)

and \( \kappa_1(r) \) was used in its integral form:

\[ \eta = \int \frac{Vd\tau}{\kappa_1(r)} \]

(the solutions are relatively insensitive to the radial dependence of \( \kappa \)). The values of these parameters for the years 1965/66 and 1968 are listed in Table I.

<p>| Table I: Diffusion coefficient parameters. |
|-------|-------|-------|-------|-------|</p>
<table>
<thead>
<tr>
<th>Epoch</th>
<th>( R_0 )</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965/66</td>
<td>57</td>
<td>57</td>
<td>800</td>
<td>1200</td>
</tr>
<tr>
<td>1968</td>
<td>60</td>
<td>160</td>
<td>750</td>
<td>1950</td>
</tr>
</tbody>
</table>

The calculated near-Earth spectra are in reasonable agreement with observation; no effort for further optimization was made in view of the existing observational uncertainties.

4. Primary and Secondary Galactic Electrons. Information on the sources of galactic electrons may be obtained by comparing the observed ratio \( F \) of positrons to electrons (\( F = e^+/(e^++e^-) \)) to the ratios predicted for primary electrons (\( F \approx 0 \)) and for secondary electrons (see Fig. 2). It has been suggested (Beadle, 1970) that the positron fractions, \( F \), observed near Earth may not be representative of the interstellar ratios since electrons and positrons may be modulated differently, e.g., due to the adiabatic deceleration term, \( \beta/\beta_T(aTU) \), in equation (1), which depends on the shape of the spectra. To investigate this suggestion, we have used the full numerical transport equation (which includes adiabatic deceleration) with the cosmic-ray diffusion coefficient of Section 3 to calculate the propagation of the positron fractions through the solar-modulation region. Figure 2 shows a comparison of the positron fractions of the derived spectra outside the boundary (solid) and the calculated spectra near 1 AU (dashed). The effects of adiabatic deceleration are apparent in a small shift of the 1-AU fractions.
towards lower energies with respect to the interstellar fractions. However, the shape of the curves is essentially preserved, and the differences are negligible compared to the statistical uncertainties of the data. Thus, we conclude that the positron fractions measured near Earth are representative of the interstellar fractions. Comparing the observed charge ratios in Figure 2 with those calculated for secondary electrons we conclude that interstellar electrons at energies ~ 10 MeV - 10 GeV have a significant component of electrons originating in "primary" sources, i.e., the acceleration of ambient matter in energetic "normal matter" sources.

5. **Summary.** We have made a comparative study of the absolute solar modulation of cosmic-ray positrons and electrons. By requiring a single set of modulation parameters for both components over an energy range of ~ 10 MeV - 10 GeV we have determined that: (a) the interstellar power-law type electron spectrum, derived from galactic non-thermal radio emission, must flatten considerably below ~ 100 MeV, (b) the cosmic-ray diffusion coefficient, which is an increasing function of rigidity at higher energies, \( \kappa R^2 \), must change to a decreasing function, i.e., approximately \( \kappa R^{-1} \) at rigidities below ~ 60 MV, (c) a significant fraction of interstellar electrons must originate from primary sources in the acceleration of ambient matter.

6. **References.**


Acknowledgments. This work supported by the National Aeronautics and Space Administration, Grant NGR 05-002-160. One of us (Stone) was an Alfred P. Sloan research fellow, and another (Cummings) was a NASA Trainee during this work.