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THE ENERGY SPECTRUM OF 0.16 TO 2 MeV ELECTRONS DURING SOLAR QUIET TIMES

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ABSTRACT

New observations of the quiet-time energy spectrum of 0.16 to 2 MeV electrons have been made with the Caltech Electron/Isotope Spectrometer which was launched on IMP-7 in September 1972. Earlier measurements of quiet-time electrons in this energy range by other groups have resulted in spectra differing by more than an order of magnitude in intensity. We find a minimum quiet-time flux level somewhat lower than the lowest previously reported spectra and consistent with an extrapolation of the spectrum measured at higher energies. A galactic secondary source of knock-on electrons is consistent with our results and with independent studies of the interstellar spectra of cosmic-ray nuclei provided that solar modulation does not suppress the 0.16–2 MeV electron flux by more than a factor of ~ 3. Although not required, other recently suggested sources may also contribute to the observed fluxes.

Subject heading: cosmic rays

I. INTRODUCTION

Study of the low-energy cosmic-ray electrons is of interest both for an understanding of the possible origin of these particles in such sources as supernovae, and for information on the interstellar spectrum of low-energy cosmic-ray nuclei which may be producing these electrons by interstellar knock-on processes. The electron spectrum in the $\leqslant$2-MeV energy interval is especially suitable for this study. For example, 2-MeV knock-on electrons are produced by higher-energy nuclei ($>$675 MeV per nucleon) while 0.16-MeV electrons can be produced by collisions of much lower-energy nuclei ($\geqslant$70 MeV per nucleon) which are not observable at 1 a.u. due to solar modulation effects.

Although cosmic-ray electrons of somewhat higher energy have been studied extensively (see, e.g., McDonald, Cline, and Simnett 1972), the only previously published spectra of quiet-time electrons in the 0.1- to 2-MeV energy range are those reported by Beedle *et al.* (1970), and Webber, Lezniak, and Damle (1973) from *Pioneer 8* and *Pioneer 9* during 1968–1969, and by Lin, Anderson, and Cline (1972) from two detectors on IMP-6 during 1971. Based on a spectral feature at $\sim$200 keV reported by Lin *et al.*, Ramaty, Cline, and Fisk (1972) considered a variety of electron sources, including neutron β-decay, nearby galactic sources, and acceleration at the shock transition at the boundary of the heliosphere. The 200-keV flux reported by Webber *et al.* (1973) was, however, more than an order of magnitude lower than the IMP-6 results. Thus, an understanding of the origin, propagation, and modulation of these electrons requires additional experimental results.

The new observations reported here provide the first high-resolution, low-background spectral information in the 0.16- to 2-MeV region. These observations have implications for theories of the origin of cosmic-ray electrons and provide insight into the experimental problems involved in measurements of low-energy electrons. A preliminary report of these observations has been presented by Hurford *et al.* (1973*a*).

II. THE INSTRUMENT

The Caltech Electron/Isotope Spectrometer (EIS) was launched 1972 September 22 on IMP-7 into a near circular orbit of $\sim$35 Earth radii. The EIS is designed to measure the differential energy spectra of electrons (0.16–5 MeV) and of the isotopes of H, He, Li, and Be ($\sim$2 to 40 MeV per nucleon). A cross-section of the EIS detector system is shown in figure 1. It consists of a stack of 11 fully depleted silicon surface-barrier detectors surrounded by a plastic-scintillator anticoincidence counter. Detectors D0, D1, D3, and D4 are 1-mm-thick annulars, while D5 through D10 are 1-mm-thick disks. D2 is a 50-μ-thick disk that must be traversed by particles that reach D5 through the aperture in the annular detectors. Each of the detectors D0 through D9 is pulse-height analyzed, so that the energy loss (ΔE), the total energy (E), and the range of each analyzed particle can be determined.

The EIS system has three modes of operation which are important to the present discussion. In the narrow-geometry mode, which is defined by

$$(\mathrm{D2} + \mathrm{D5})\langle \mathrm{D0D1D3D4D10D11} \rangle ,$$

where the angular brackets mean "not fired," particles entering the aperture of the annulars are analyzed in detectors D2 and D5 through D9. Because D0, D1, D3, and D4 are used as active anticoincidence elements, this mode has the best defined geometry and is most suitable for the measurement of solar-flare nuclei and electrons. Unambiguous separation of electrons and nuclei is possible in this mode because the 50-μ detector, D2, is sensitive to low-energy nuclei, but not to electrons (Lupton and Stone 1972*a*).

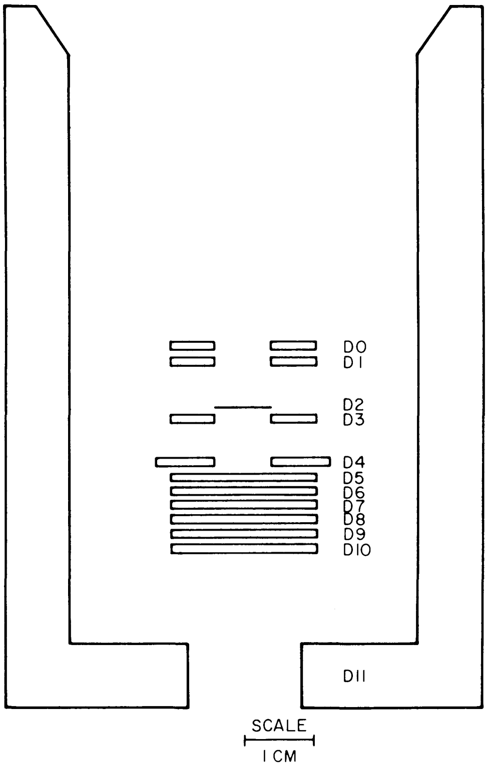

FIG. 1.—A cross-section drawing of the cosmic-ray telescope. Detectors D0 through D10 are 1 mm thick silicon surface-barrier detectors, except D2 which is 50 μm thick. D0, D1, D3, and D4 are annular devices. D11 is a plastic scintillator anticoincidence cup.

However, the combination of the small geometrical factor and the Compton electron background discussed below prevents the use of this mode for measurements of quiet-time electrons.

Low-intensity electron fluxes can be measured in the wide-geometry mode, which is defined by

$$\mathrm{D0}\langle \mathrm{D10D11}\rangle\,.$$

In this mode particles are analyzed in all of the detectors except D2, D10, and D11. Although the lowest-energy nuclei and electrons that stop in D0 cannot be separated in this mode, the narrow-geometry nuclei measurement can be used to correct the wide-geometry analysis for nuclei. During quiet times, nuclei account for less than 10 percent of the D0 events. Details of these two modes are included in table 1.

Although both the narrow-geometry and wide-geometry modes are protected against charged-particle background by the anticoincidence detectors D10 and D11, there is no protection against background due to neutral particles such as γ-rays and neutrons which may be generated by the nuclear interaction of high-energy cosmic rays in the spacecraft. For this reason, a neutral-particle mode was included in order to monitor the neutral background. In this mode, the signals in D6 through D9 are analyzed for events which satisfy the logic requirement

$$\mathrm{D7}\langle \mathrm{D0D1D3D4D5D10D11}\rangle\,.$$

Since the detectors in anticoincidence completely surround D7, any penetrating charged particle is rejected and the neutral-particle mode analyzes mainly γ-rays which penetrate undetected to D6 through D9. In silicon detectors, the γ-rays are mainly detected due to the Compton effect, provided that the Compton electron energy loss exceeds the detector threshold of $\sim$0.16 MeV. With appropriate intercalibration data, the neutral-particle analysis can be used to correct the narrow-geometry and wide-geometry analyses for neutral background. The γ-ray response of the IMP-7 instrument was calibrated for this purpose using 0.5- to 2.6-MeV γ-ray sources.

In addition to background considerations, low-energy electron measurements are complicated by the large amount of scattering which occurs at these low energies (Lupton and Stone 1972*b*), making extensive calibrations imperative to an understanding of the instrument response. The IMP-7 instrument has undergone laboratory calibrations with monoenergetic electron beams from a beta spectrometer. Data were taken at 20 energies from 0.1 to 3.3 MeV. The incidence angle of the beam with respect to the telescope axis was varied from 0° to 45°, from which response matrices appropriate to an isotropic flux were derived for each analysis mode.

TABLE 1

OPERATION AND RESPONSE CHARACTERISTICS OF THE EIS RELEVANT TO ELECTRON MEASUREMENTS

Logic Requirements	Possible Event Ranges	Particle Type	Energy Range (MeV)	Geometry Factor (cm² sr)
D0⟨D10D11⟩..................	D0–D9	Electrons	0.16–5	~2.5
		Protons	1.1–43	1.8–0.3
⟨D2⟩D5⟨D5HDY⟩.............	D5–D9	Electrons	0.2–3	~0.07
D2⟨D5DY⟩....................	D2	Protons	1.2–2.4	0.2
D2D5⟨DY⟩ or D5H⟨DY⟩.......	D5–D9	Protons	2.4–31	0.07
D7⟨D5DY⟩....................	D6–D9	Neutral particles	...	...

NOTES.—⟨DY⟩ ≡ ⟨D0D1D3D4D10D11⟩, where the angular brackets mean "not." D5H = 3.0 − MeV D5 threshold.

III. QUIET-TIME OBSERVATIONS

The observations reported here were made during the period between 1972 October and 1973 January. During this time significant variations in the wide-geometry counting rate (D0⟨D10D11⟩) were observed, while the neutral-particle counting rate (D7⟨D0D1D3D4D5D10D11⟩) was essentially constant except for a 1-day enhancement associated with high-energy solar-flare protons, followed by a small decrease associated with a Forbush decrease. Thus the time dependence of the neutral-particle counting rate was consistent with background production by the interaction of high-energy cosmic rays in the spacecraft, while the variable wide-geometry counting rate was not. Some of the D0⟨D10D11⟩ rate increases were associated with solar flare events and others with the geomagnetic tail which is traversed by IMP-7 every 13 days. These periods were removed from consideration for this study which was then restricted to six periods associated with relative minima in the D0⟨D10D11⟩ counting rate.

The D0⟨D10D11⟩ counting rate varied by a factor of ~ 3 from one quiet-time period to another. An example of the raw spectra for a typical low-rate period is shown in figure 2, in which the measured pulse-height distributions in D0 (wide geometry), D5 (narrow geometry), and D7 (neutral particles) are plotted without background corrections or spectral unfolding. The proton contribution to D0 was less than 10 percent during this period.

As shown in figure 2, the D5 and D7 pulse-height distributions are essentially identical, which is expected from laboratory calibrations of the γ-ray response. Thus, during this period the incident electron flux was too small to be measured in the narrow-geometry (D5) mode. Based on the observed D5 and D7 response and laboratory calibrations, the D0 response due to γ-rays should be ~ 25 percent higher than D5 or D7. As shown in figure 2, the D0 spectrum was ~ 3 times higher than D7, indicating the presence of a measurable electron flux. The raw D0 spectrum can thus be converted into a differential-energy electron spectrum by first subtracting the γ-ray and proton contributions and then unfolding the corrected pulse-height distribution using laboratory-determined electron response functions. A similar procedure is followed for higher-energy electrons which trigger multiple detectors. Note that the γ-ray component is constant and can therefore be determined with high statistical accuracy.

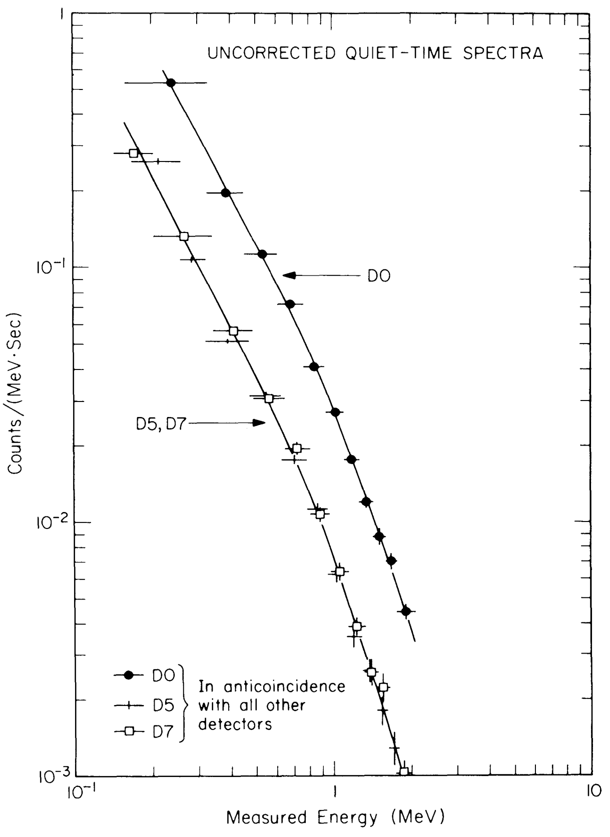

FIG. 2.—A comparison of uncorrected quiet-time energy-loss spectra measured in D0, D5, and D7 during a typical quiet-time period. Statistical uncertainties ($\pm 1\ \sigma$) are indicated when larger than the plotted point.

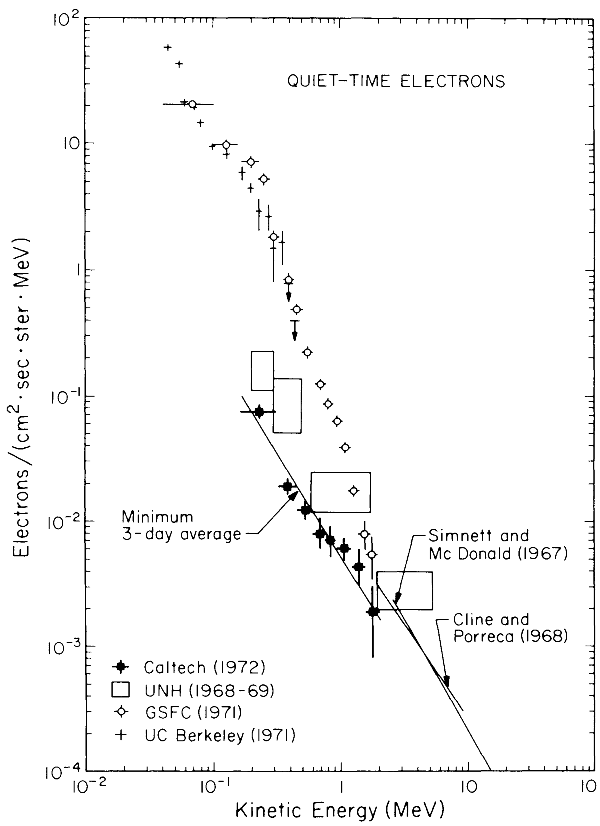

FIG. 3.—A comparison of quiet-time electron measurements by various groups. The year of each measurement is indicated. The statistical uncertainties ($\pm 1\ \sigma$) in the Caltech results include effects of unfolding the spectrum from the measured pulse-height distribution.

Electron spectra were determined during each of the following quiet-time periods: 1972 October 5–7, October 19–23, November 13–19, December 7–12, December 23–24 and 1973 January 17–20. The intensity in the 0.16- to 2.1-MeV interval varied a factor of ~ 3 during these periods. The lowest-intensity electron spectrum was observed during 1972 October 5–7, and is plotted in figure 3. This spectrum corresponds to

$$dJ/dE = (0.0054 \pm 0.0006) E^{-1.67 \pm 0.12} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1} .$$

Also shown in figure 3 are previously reported measurements by Lin *et al.* (1972) (UC Berkeley and GSFC) and Webber *et al.* (1973) University of New Hampshire (UNH) at lower energies, and Simnett and McDonald (1969) and Cline and Porreca (1970) at higher energies. The box symbols used to plot the UNH data indicate the range of observed intensity variations. The other previously reported spectra shown are long-term averages over a number of quiet-time periods. The corresponding average spectrum for the six periods analyzed here would be ~ 2 times higher than the minimum 3-day average shown in figure 3.

Further examination of figure 3 shows that our new results are in general agreement with an extrapolation of the higher-energy data reported by Simnett and McDonald (1969) and Cline and Porreca (1970). The new results are also generally consistent with the UNH spectrum, although our minimum spectrum is somewhat lower than the minimum UNH spectrum defined by the lower boundary of the box symbols, possibly because no correction for Compton electron background was applied to the UNH spectra.

Our minimum spectrum is of much lower intensity than the two independent measurements made with the UC Berkeley (UCB) and GSFC experiments on IMP-6 (Lin *et al.* 1972). As discussed by Hurford *et al.* (1973*a*) and Cline (1973), the IMP-6 experiments were susceptible to spacecraft background which prevented the observation of low electron intensities similar to those reported here.

IV. DISCUSSION

The general agreement of the quiet-time spectrum of 0.16- to 2-MeV electrons with an extrapolation of the spectrum at higher energies, and the similarity in temporal behavior (Webber *et al.* 1973), suggest that electrons with energies from 0.16 to 25 MeV have a common origin and modulation.

In the 3- to 12-MeV interval, McDonald *et al.* (1972) concluded that the quiet-time fluxes are most likely of galactic origin. Among the sources of galactic secondary electrons, knock-on electrons, which arise from the collision of cosmic-ray nuclei with ambient interstellar electrons, are expected to dominate below 15 MeV. Abraham, Brunstein, and Cline (1966) calculated the expected equilibrium spectrum for knock-on electrons which Simnett and McDonald (1969) later found to be in reasonable agreement with the observed electron spectrum in the 3- to 20-MeV energy interval.

We have extended the comparison of observation and calculation to the 0.1- to 3-MeV energy interval by appropriately modifying the original calculation of Abraham *et al.* (1966). Since the equilibrium density of knock-on electrons with less than ~ 10 MeV depends almost entirely on the spectra of the cosmic-ray nuclei which produce the knock-on electrons, and on the lifetime of the electrons as limited by ionization energy loss in the interstellar medium, these two factors have been reevaluated. At these low energies, the calculated electron density does not depend on the leakage path length of cosmic rays in the Galaxy if greater than ~ 4 g cm^{-2} or on the density of the interstellar medium.

In the original calculations, Abraham *et al.* assumed an ionization-energy loss rate independent of energy, which is a good approximation in the 3- to 20-MeV interval. Since below ~ 1 MeV, the energy loss rate increases significantly with decreasing energy, we have included the exact energy dependence of the ionization loss rate, which results in a factor of ~ 2 smaller equilibrium intensity at 0.1 MeV than is obtained with a constant-energy loss rate of 4.25 MeV cm^2 g^{-1}.

For the spectrum of cosmic-ray protons, we have assumed differential energy spectra of the form

$$j(T) = 2.0(T + km_p)^{-2.75} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1} , \quad (1)$$

where T is the proton kinetic energy (GeV), m_p is the proton rest mass, and $0 \le k \le 1$. These spectra are consistent with the measured proton spectrum at $T > 40$ GeV (Ryan, Ormes, and Balasubrahmanyan 1972; Pinkau *et al.* 1970) where solar modulation is unimportant. Spectra of the heavier cosmic rays are assumed identical, with relative abundances given by Webber, Damle, and Kish (1972) for $Z \ge 3$, with He/(C+N+O+F) = 15.5 (Shapiro, Silberberg, and Tsao 1973) and H/He = 25 as determined at high energies where there is minimum solar modulation (Ryan *et al.* 1972; Pinkau *et al.* 1970). A leakage path length of 4 g cm^{-2} was assumed, which affects the equilibrium density of electrons with energies greater than ~ 10 MeV, but has negligible effect at lower energies.

The resulting equilibrium spectrum of knock-on electrons is shown in figure 4 for $k = 0$ (kinetic-energy power-law proton spectrum), $k = 0.5$, and $k = 1$ (total-energy power law), along with our measured spectrum. It is apparent that the knock-on spectrum below ~ 2 MeV depends critically upon the spectrum of cosmic-ray nuclei at low energies. Studies of the modulation of cosmic-ray hydrogen and helium (Garrard, Stone, and Vogt 1973) are consistent with interstellar hydrogen and helium spectra with $0.5 \leqslant k \leqslant 1.0$. For spectra of these forms, a knock-on source can account for our measurements, provided that the solar modulation does not suppress the electron flux by more than a factor of ~ 3. This modulation factor for low-rigidity cosmic rays can be neither confirmed nor contradicted by our present understanding of modulation theory.

Primary electrons could also contribute to the fluxes we observe. For example, Cohen and Ramaty (1973)

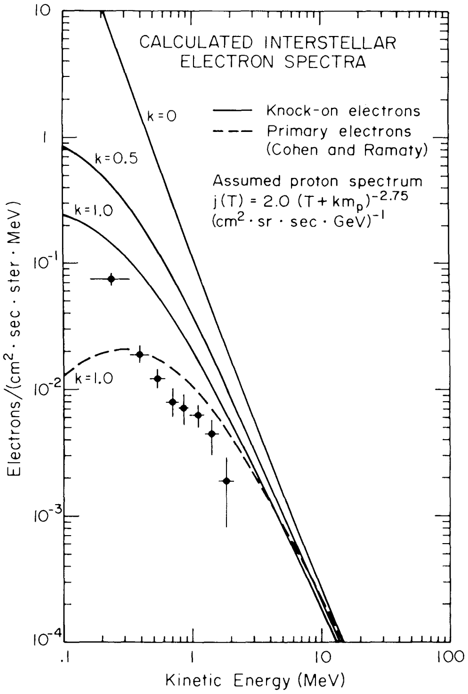

FIG. 4.—A comparison of calculated interstellar electron spectra with the observed quiet-time electron spectrum at 1 a.u.

have suggested that supernovae may produce a majority of cosmic-ray electrons below ~ 10 MeV, as well as cosmic-ray protons and alpha particles. Using arguments based on charge neutrality, they suggest that during the acceleration process there may be an equal number of protons and electrons at a given velocity. Figure 4 shows the equilibrium primary electron spectrum computed with this model assuming that the proton spectrum is given by equation (1) with $k = 1$ and that the mean path length in the Galaxy is $4\ \mathrm{g\ cm^{-2}}$. Note that with these assumptions the primary electron flux would exceed the corresponding knock-on spectrum ($k = 1$) at energies $\geqslant 3$ MeV, but would not make a significant contribution below ~ 1 MeV. The relative contribution of such a postulated primary flux would be even less significant for assumed proton spectra with $k < 1$.

Ramaty *et al.* (1972) considered several other possible low-energy electron sources in order to account for the ~ 200 keV feature reported by Lin *et al.* (1972), including neutron β-decay, nearby galactic sources such as Sco X-1 and Vela X, and particle acceleration at the solar-wind shock transition at the boundary of the heliosphere. Although contributions from these sources may be important, they are not required to account for the quiet-time intensities reported here.

Our understanding of the low-energy electron component might be clarified by a number of additional measurements. A determination of the magnitude and time dependence of the positron fraction of the total low-energy electron flux would provide important information regarding origin and modulation. A preliminary measurement of this fraction in the energy interval 0.16–1.6 MeV has yielded only an upper limit of $\leqslant 0.2$ (Hurford *et al.* 1973*b*). Measurements of the radial anisotropy may also contribute to our understanding of the origin of these electrons. Finally, additional long-term studies of the temporal behavior of the low-energy electron spectrum and its relation with other interplanetary phenomena will be required. These studies are now under way.

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