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THE ENERGY SPECTRUM OF 0.16 TO 3 MeV ELECTRONS DURING SOLAR QUIET TIMES

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New observations of the quiet-time energy spectrum of 0.16 to 3 MeV electrons have been made with the Caltech Electron/Isotope Spectrometer which was launched on IMP-7 in September 1972. Recent 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 similar to 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 provided that there is negligible solar modulation. Although not required, other recently suggested sources may also contribute to the observed fluxes.

1. Introduction. Although cosmic-ray electrons of somewhat higher energy have been studied extensively (see, e.g., McDonald et al., 1972), the only previous measurements of quiet-time electrons in the 0.1 to 3 MeV energy range are those reported by Beedle et al. (1970), and Webber et al. (1973) from Pioneer 8 and 9 during 1968-9, and by Lin et al. (1972) from two detectors on IMP-6 during 1971. Based on the spectral feature at ~ 200 keV reported by Lin et al., Ramaty et al. (1972) considered a variety of electron sources, including neutron β-decay, nearby galactic sources such as Sco X-1 and Vela X, 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 must be preceded by an understanding of the large difference in the reported spectra.

The new observations reported here provide the first high-resolution, low-background spectral information in the 0.16 to 3 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.

2. The Instrument. The Caltech Electron/Isotope Spectrometer (EIS) was launched 22 September 1972 on IMP-7 into a near circular orbit of ~ 35 earth radii. The EIS is designed to measure the differential energy spectra of electrons (0.16 - 3 MeV) and the isotopes of H, He, Li, and Be (~ 2 to 40 MeV/nucleon). A cross section of the EIS detector system is shown in Figure 1. It consists of a stack of eleven fully-depleted silicon surfacebarrier detectors surrounded by a plastic-scintillator anti coincidence 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 μm 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 (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, 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. 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. These low-intensity electron fluxes can be measured in the Wide-Geometry mode. In this mode signals from all of the detectors except D2, D10 and D11 are analyzed for particles which enter D0 without penetrating either D10 or D11. Although the lowest-energy nuclei and electrons 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 % of the D0 events. Details of these two modes are included in Table I.

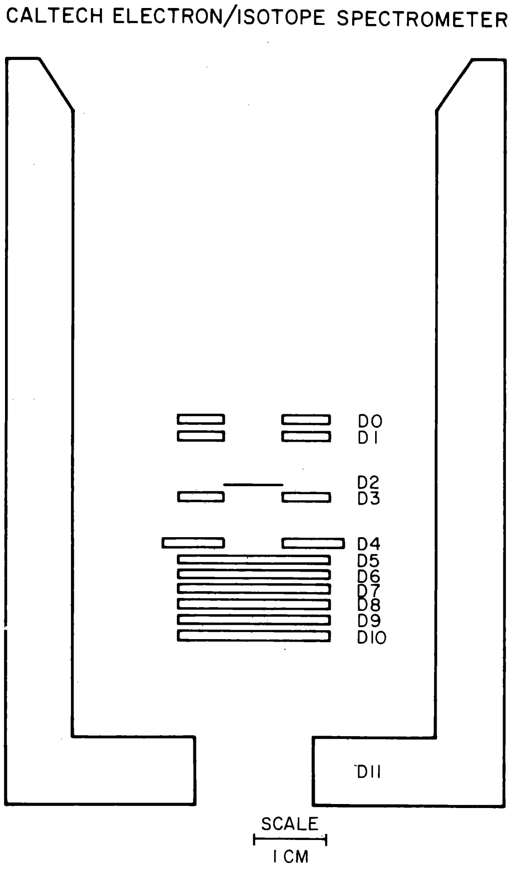

Fig. 1. A cross section drawing of the cosmic-ray telescope. Detectors D0 through D10 are silicon detectors, while D11 is a plastic scintillator.

TABLE I

Operation and Response Characteristics of the EIS
Relevant to Electron Measurements

Logic Requirements	Possible Event Ranges	Particle Type	Energy Range (MeV)	Geometry Factor (cm^2. ster)
$D0\ \overline{D10}\ \overline{D11}$	D0 - D9	Electrons	.16 - 3	~ 2.5
		Protons	1.1 - 43	1.8 - .3
$\overline{D2}\ D5\ \overline{D5H}\ \overline{Y}$	D5 - D9	Electrons	.2 - 3	~ .07
$D2\ \overline{Y}$	D2, D5	Protons	1.2 - 2.5	.22, .07
$D7\ \overline{D5}\ \overline{Y}$	D6 - D9	Neutral Particles		

$\overline{Y} \equiv \overline{D0}\ \overline{D1}\ \overline{D3}\ \overline{D4}\ \overline{D10}\ \overline{D11}$
D5H = 3.0-MeV D5 threshold

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 detected in D7 which are not detected in D0, D1, D3, D4, D5, D10, or D11. Since these latter detectors completely surround D7 and would reject any penetrating charged particle, the Neutral-Particle mode analyzes mainly γ-rays and neutrons which can penetrate undetected to D6 through D9. In silicon detectors, the γ-rays would be detected due to the Compton effect, provided that the Compton electron energy loss exceeded the detector threshold of ~160 keV. 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 both the IMP-7 and an identical IMP-J instrument was calibrated for this purpose using 0.5 to 4.3 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, 1971a, 1971b), making extensive calibrations imperative to an understanding of the instrument response. Both the IMP-7 and IMP-J instruments have 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^o to 80^o, from which response matrices appropriate to an isotropic flux were derived for each analysis mode.

3. Quiet-Time Observations. The observations reported here were made during the period between 1 October 1972 and 1 February 1973. During this time significant variations in the Wide-Geometry counting rate (D0 $\overline{\text{D10}}$ $\overline{\text{D11}}$) were observed, while the Neutral-Particle counting rate (D7 $\overline{\text{D0}}$ $\overline{\text{D1}}$ $\overline{\text{D3}}$ $\overline{\text{D4}}$ $\overline{\text{D5}}$ $\overline{\text{D10}}$ $\overline{\text{D11}}$) 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 high-energy cosmic rays, while the variable Wide-Geometry counting rate was not. Some of the D0 $\overline{\text{D10}}$ $\overline{\text{D11}}$ 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 further restricted to periods when all counting rates were relatively constant for at least 24 hours.

The D0 $\overline{\text{D10}}$ $\overline{\text{D11}}$ counting rate varied by a factor of ~ 3 from one quiet-time period to another. An example of the raw spectra for one of the lowest rate periods 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% 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

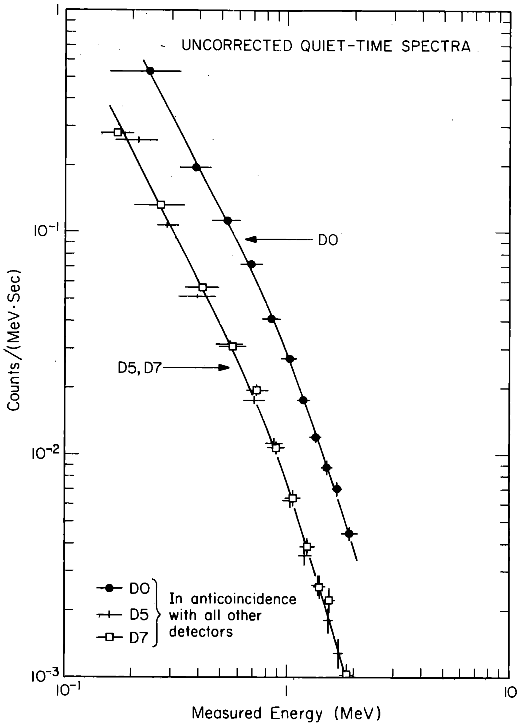

Fig. 2. A comparison of uncorrected quiet-time energy-loss spectra measured in D0, D5, and D7.

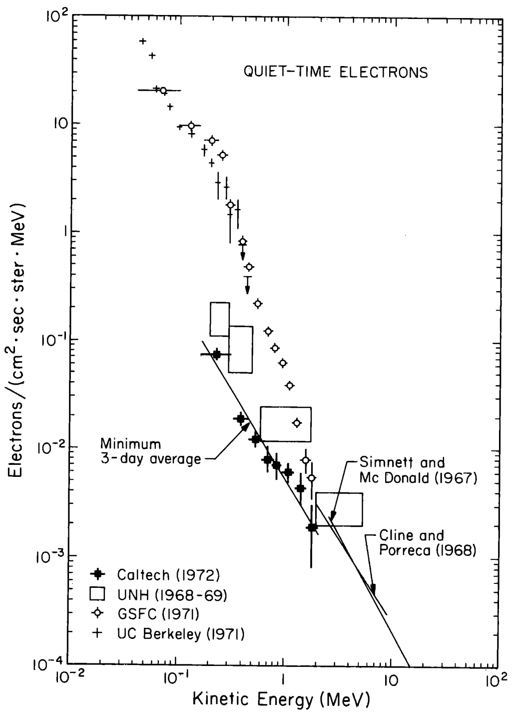

Fig. 3. A comparison of quiet-time electron measurements. The year of measurement is indicated.

to γ-rays should be ~ 25% higher than D5 and 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 the laboratory-determined electron response function.

Electron spectra were determined for each of 6 quiet-time periods. The lowest intensity electron spectrum was observed during Oct. 5-7, 1972, and is plotted in Figure 3. This spectrum corresponds to

$$dJ/dE = (0.54 \pm 0.06)\ E^{-1.67 \pm 0.12}\ \mathrm{cm^{-2}sec^{-1}sr^{-1}MeV^{-1}}$$

Also shown in Figure 3 are previously reported measurements by Lin et al. (1972) (UC Berkeley and GSFC) and Webber et al. (1973) (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 are long-term averages over a number of quiet-time periods. The corresponding average spectrum for the six periods analyzed here would be ~ 2 x 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 a 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 and GSFC experiments on IMP-6 (Lin et al., 1972). The flux measured by both the IMP-6 experiments was essentially constant and exhibited none of the quiet-time intensity variations reported here and by the UNH group. Such a steady flux would be expected if there was a substantial background contribution to the UCB and GSFC counting rates. Because of the larger mass of the GSFC detector, the Compton-electron rate at low energies should be ~ 5 times higher than the D5 rate in Figure 2. In addition, the geometrical factor of the GSFC detector for detecting cosmic-ray electrons is a factor of ~ 2 smaller than for D0, so that the background rate would be significantly larger than the rate of cosmic-ray electrons corresponding to the spectrum reported here.

The steady flux measured with the UCB detector is likely of a different origin since the small mass of that detector system results in a much smaller Compton-electron rate. Lin et al. (1972) point out that because their detector does not have complete anticoincidence shielding, a significant background correction is required at energies greater than 100 keV to account for cosmic-ray nuclei which penetrate the side of the detector. However, a background of comparable size is due to secondary charged particles from cosmic-ray interactions in the spacecraft. Subtracting this contribution would undoubtedly lower the reported flux significantly.

4. Discussion. The general agreement of the quiet-time spectrum of 0.16 to 3 MeV electrons with an extrapolation of the spectrum at higher energies, and the similarity in temporal behaviour (Webber et al., 1973), suggests 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 are expected to dominate below ~ 15 MeV and should have a spectrum similar to that reported here (Abraham et al., 1966). However, a knock-on source is capable of accounting for our measurements only if one assumes negligible solar modulation. Contributions from other sources (Ramaty et al., 1972) may be important, but are not required to account for the quiet-time intensities reported here.

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