OBSERVATIONS OF THE SCATTER-FREE SOLAR-FLARE ELECTRONS IN THE ENERGY RANGE 20-1000 keV

J. R. Wang* and L. A. Fisk
Goddard Space Flight Center, Greenbelt, Md.

R. P. Lin
Space Science Laboratory
University of California, Berkeley, Ca.

Abstract

Observations of the scatter-free electron events from solar active region McMath No. 8905 are presented. The measurements were made from Univ. of California Solar Particle Experiment and Goddard Space Flight Center Cosmic-Ray Experiment on IMP-IV satellite. The data show that more than 80% of the electrons from these events undergo no or little scattering and that these electrons travel only $\sim$ 1.5 a.u. between the sun and the earth. The duration of these events cannot be accounted fully by velocity dispersion alone. It is suggested that these electrons could be continuously injected into interplanetary medium for a time interval of $\sim$ 2 - 3 minutes. Energy spectra of these electrons which should represent the spectra near the flare site will be discussed.

1. Introduction

Solar flare particles observed near the Earth generally display an intensity-time profile which suggests a diffusion-dominant process. There are, however, some solar flare electrons which undergo very little or no scattering at all in the interplanetary medium between the sun and the earth. In this paper, we report two such events occurring in July 30, 1967. The observations were made with University of California solar electron experiment, the University of Chicago charged particle experiment (J. A. Simpson, private communication) and the GSFC galactic cosmic-ray experiment aboard the IMP-IV satellite. These experiments cover electron energy ranges of 22-45 keV (Lin, 1970a), of 170-1000 keV and 750-1600 keV (Sullivan, 1971), and of 100-400 keV and 500-1100 keV (Wang et al., 1972).

2. Observations

Figure 1 shows two typical scatter-free electron events observed on July 30, 1967 when IMP-IV was near apogee ($\sim$ 34 earth's radii). Observation of these events at low energies ($>$ 22 kev and $>$ 45 kev) was first reported by Lin (1970b). However, better understanding of these events could be achieved by addition of higher-energy observations. The electron intensity at both $\sim$ 500-1100 Kev and $\sim$ 170-1000 Kev energy windows started to increase around 1633 U.T., following the observed onset of a 1N flare at $\sim$ 1615 U.T. In contrast to the normal classical electron events (Simnett 1971; Cline and McDonald 1968) in which the decay time was generally about one order of magnitude

*NAS-NRC Research Associate

longer than the rise time (~ 30-60 min), the electron intensity rose rapidly and reached maximum within 3-5 minutes. The intensity then dropped to background level within another 5 minutes or so. On the other hand, the intensity onset for three lower-energy channels did not begin until the intensity at two higher-energy channels reached maximum. By the time when > 22 kev and > 45 kev electron intensities reached their peak values, the 500-1100 Kev and 170-1000 Kev electron intensities were already in the background level. The duration of the event varied with energy. For 500-1100 Kev, 170-1000 Kev and 100-400 Kev energy intervals, the event lasted approximately 7,10 and 12 minutes respectively; while for two lower channels at > 22 Kev and > 45 Kev, it lasted more than 20 minutes. Most of the event duration time could be accounted for by the velocity dispersion of the electrons at various energies. However, more careful analysis revealed that the duration time was consistently ~ 3-5 minutes longer than that expected from velocity dispersion alone for all energy intervals. Following the peak, there was a small fraction of the electrons which displayed a long exponentially decaying intensity-time profile similar to a classical event. We shall call the initial peak which is dominated by velocity dispersion, the scatter-free component and the long tail portion, the scattered component.

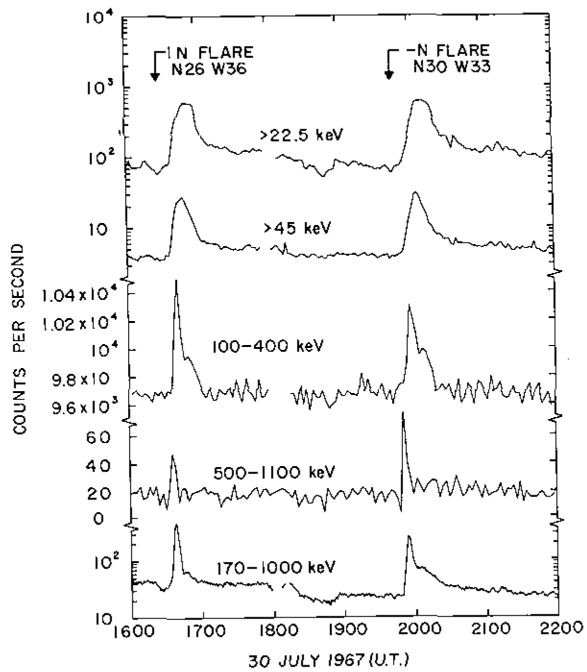

FIG. 1

Another event occurred around 2000 U.T. after a -N flare at ~ 1945 U.T. This event more or less followed the same pattern as the first one, except that the duration time was ~ 2 minutes longer at all energies and that larger fraction of electrons was scattered. To illustrate the latter point about the scattered component, we call attention to the intensity-time profile of 170-1000 Kev electrons. The intensity at this energy interval reached a maximum value of ~ 270 counts/sec at ~ 1955 U.T. After a sharp drop in intensity, there was a barely observable second maximum at ~ 2006 U.T. which was followed by an exponential decay for ~ 20 minutes. The ratio of the first and second intensity maxima for this event was ~ 4. For the first event at ~ 1640 U.T., this same ratio was ~ 7. Furthermore, the decay time of the scattered component seemed to be longer for the second event than the first one. It appears that the duration time of the scatter-free component, the fraction of the electron scattered, and the decay time of the scattered component for a given event are inter-related.

It is clear from the above description that the distinct features of these events are their rapid rise and decline in intensity - the intensity-time profile is symmetric or nearly symmetric about the time of maximum. Only a small fraction of electrons undergoes diffusion-like decay similar to classical flare event. Velocity dispersion for these events is very pronounced which excludes the possibility of these electrons as being locally accelerated near the Earth's bow shock (Fan et al., 1966; Lin and Anderson, 1966).

3. Distance traveled by Scatter-Free Electrons

The observations described above suggest that the scatter-free electrons, once released into the interplanetary medium, simply follow the magnetic field lines. Therefore, if ejected at the same time, they should travel about the same distance between the sun and the Earth, and should obey the relation

$$S = c\beta\,(T - To) \tag{1}$$

Here S is the distance traveled, c is the velocity of light, β is electron speed (in unit of c), T is the time of observation near Earth, and To is the time of electron injection at the sun. The velocity dispersion observed in Figure 3 reflects the relation between β and T, because S is a constant for a given event.

In Figure 2 we show the β vs. S/c(T - To) plot for the event at ~ 1640 U.T. For each data point plotted, we used β and T corresponding to average energy and time of peak intensity respectively. The upper and lower limits in β correspond to upper and lower bounds in energy derived from the detector responses, while those in T correspond to the times when electron intensity is half of its peak value.

It is clear from this figure that the electron transport between the sun and the earth obeys Eq. (1) quite well for this event. The time of electron injection near the sun and the distance travelled were found to be ~ 1623 U.T. and ~ 1.45 a.u. respectively. This distance was comparable to the length ~ 1.2 a.u. of Archimedean magnetic field line between the sun and the earth assuming a solar wind velocity of ~ 400 km/sec.

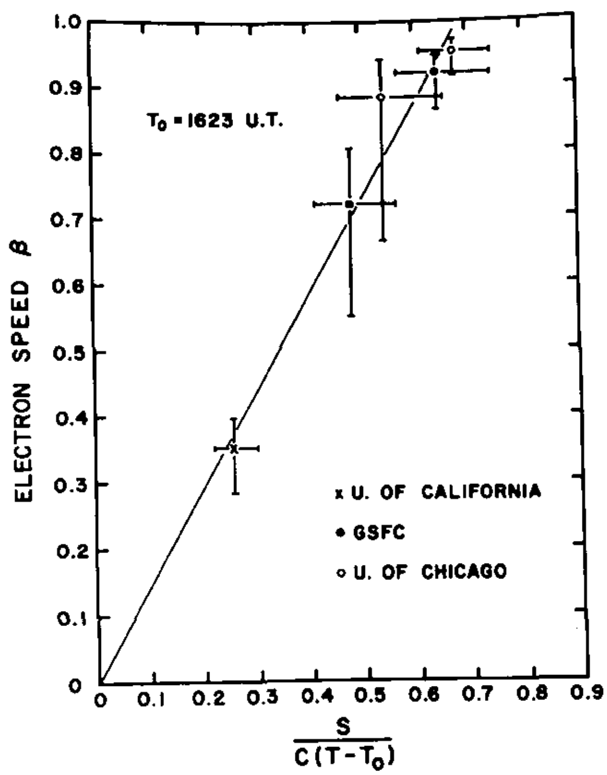

FIG. 2

When the same plot was made for the event at $\sim$ 2000 U.T., essentially the same conclusion was reached. The time of electron injection and distance travelled were $\sim$1938 U.T. and $\sim$ 1.65 a.u. respectively.

The times of electron injection at the sun derived from this approach can be compared with the times of optical flares for both events. We find that the electron injection times for both events lie in between the onset times and the times of maximum phase of the associated optical flares. This suggests that these electrons were accelerated near the times of optical flares and that after acceleration, they were immediately released into the interplanetary medium. This is in contrast to the observation of some electron events (Simnett, 1971) in which the accelerated electrons were trapped near the sun over a long time period before being released into the interplanetary space.

4. Energy Spectrum

It is clear from the previous sections that the intensity-time profile of the scatter-free electrons is characterized by velocity dispersion. Therefore, the electron energy spectrum at the point of observation varies from time to time. In order to obtain a meaningful spectrum for these electrons, we must adopt a different method from the one usually employed. Instead of calculating the average electron intensities for all energies over a fixed time interval, we simply integrate the total number of scatter-free electrons for a given event and express the results in terms of electrons/(cm^2-ster-keV). By this approach, we eliminate the difficulty due to velocity dispersion and obtain the electron energy spectrum near the flare site.

Figure 3 shows the scatter-free electron energy spectra derived in this way for the event at $\sim$ 1640 U.T. The observed electrons/(cm^2-ster-KeV) near the ecliptic plane and near the direction normal to the ecliptic plane are respectively represented by open and solid circles. Clearly, the electron intensities from both ecliptic plane and the direction normal to the ecliptic are comparable at high energies. It is also clear that the observed electron spectra near the ecliptic plane for both events is not well represented by the power law of the form $\sim E^{-\gamma}$; there appears to be a flattening in the energy spectra at energies < 600-700 KeV.

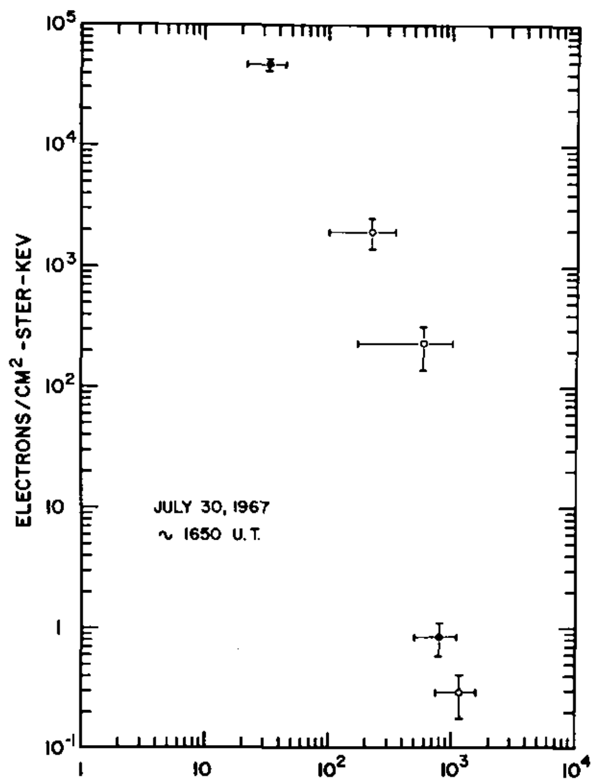

FIG. 3

This flattening in the electron energy spectra at low energies is also implied by the measurements of electrons from the direction normal to the ecliptic plane. For example, if we assume a spectrum of $\sim E^{-\gamma}$ as determined by the two solid data points in

Figure 3 and integrate the total number of electrons above ~ 45 KeV, we obtain $\sim 3 \times 10^5$ electrons/cm^2-ster. This is $\sim 40\%$ lower than the measured total > 45 KeV electrons of $\sim 5.5 \times 10^5$ electrons/cm^2-ster. Since there are not many electrons with energies > 1000 Kev, this electron excess must come from the energy range of ~ 45-1000 Kev. Thus, it appears that the electron energy spectrum is harder at lower energies. At energies $\gtrsim$ 700-800 kev, γ is $\gtrsim 6$ if power-law energy spectra are assumed. Both the hardening of electron energy spectrum at low energies and the electron cutoff at energy $\sim$ 700-800 kev is also observed for the event at $\sim$ 2000 U.T. and is probably a general characteristic of the scatter-free electron events.

The electrons of solar origin in the energy range of $\sim$ 0.5-12 MeV have been studied rather extensively by Simnett (1971) These electrons in general displayed a spectrum of the form $\sim E^{-\gamma}$ with $\gamma \simeq 3$; $\gamma > 4$ was observed only when the electrons were stored in solar neighborhood over a long time period or were originated from a backside flare. Datlowe et al. (1970) also reported measurements of solar flare electrons in the energy range of 10-200 Mev. They obtained $\gamma \simeq 3$ for two events on June 9, 1968 and February 25, 1969. The event on July 13, 1968 had a steep energy spectrum of $\sim E^{-6.7}$, but this might be attributed to long-term storage of particles in the corona (Simnett, 1971; Simnett and Holt, (1971). Clearly, all these observations suggest $\gamma \simeq 3$ for normal classical electron events, which is at least a factor of 2 smaller than that for the events we consider in this paper. Since the effect of velocity dispersion is negligible for electrons with energies ≥ 0.5 Mev, this difference in γ cannot be due to the different methods used in obtaining the electron energy spectra. Consequently, the electron cutoff at $\sim$ 700-1000 kev appears as a distinct feature of scatter-free electron events which is not shared by the normal classical electron events such as those discussed by Simnett (1971) and Datlowe et al. (1970).

5. Anisotropy

The anisotropy during the pulse-like phase of these events should be $\sim$ 100%. The electrons are all propagating in one direction, out from the Sun, undergoing little or no scattering. The diverging interplanetary magnetic fields will also collimate the pitch angles of the electrons. However, direct measurements of the anisotropy during the two events considered here, from the University of Texas experiment on IMP-IV (Allum, private communication) indicate that the anisotropy is only $\sim 30\%$. Rather than implying that there is a basic inconsistency between the scatter-free nature of these events and their observed anisotropy, we feel that these anisotropy measurements point out the inherent difficulties in making reliable anisotropy measurements from earth orbiting satellites. The bow shock was located quite close to the satellite when these measurements were made, even though the satellite was near apogee (Fairfield, private communication). There was also evidence for high frequency waves upstream from the bow shock of the type reported by Fairfield (1969), (Fairfield, private communication). Scattering of the electrons off the bow shock or by these waves could easily account for the reduced anisotropy.

6. Is Electron Emission Continuous Over a Finite Time Interval?

From a careful analysis of these events, we found that the observed duration times of the scatter-free electrons are ~ 3 min longer than the ones expected from velocity dispersion and are independent of detector energy windows. This suggests that processes other than velocity dispersion must be taken into account. When we assumed a time dependence of continuous electron release near the sun like $\sim e^{-t/to}$ and an energy spectrum shown in Figure 3, we were able to reproduce the intensity-time profiles at the point of observation and compare with the observed profiles. We found excellent agreement between the calculated and the observed intensity-time profiles when the characteristic times, to, were ~ 3 min and ~ 4 min for the events at ~ 1640 U.T. and ~ 2000 U.T. respectively. Therefore, the electron emission near the sun may be continuous over a finite time interval of ~ 3 min for these events.

7. Summary

We have reported a rare class of solar flare particle events in which the electrons were scattered near the earth's bow shock. These electrons travelled only ~ 1.5 AU between the sun and the earth. The differential energy spectrum of these electrons cannot be represented by a power law of the form $\sim E^{-\gamma}$ over the energy range of 20-1600 kev. The durations of the scatter-free component could mostly be accounted for by velocity dispersion. More careful analysis, however, revealed that these electrons might be continuously injected into the interplanetary medium over a finite time interval of ~ 3 min.

8. Acknowledgements

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