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Onsets of Invariant Spectra of E $>$ 0.3 MeV Electron Intensities in Solar Energetic Particle Events

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Abstract

Using simultaneous observations from two Helios spacecraft we examined the intensity-time profiles of E $>$ 0.3 MeV electrons during the decay phases of 17 gradual solar energetic particle (SEP) events. As previously found for the SEP event ions, the electron spectra and decay times were nearly invariant over large spatial regions. For SEP events associated with solar flares at increasingly eastern longitudes from the spacecraft, we find invariance onset times with increasing time delays following the shock arrival times. For associated flares at increasingly western longitudes the invariance onset times are increasingly advanced ahead of the shock arrival times.

1 Introduction

According to the current paradigm (e.g., Cane, 1997) large gradual solar energetic particle (SEP) events are produced not in solar flares but in shocks driven by fast coronal mass ejections (CMEs). After Kahler et al.(1984) found a good correlation between the peak proton intensities in SEP events and their associated CME speeds, further evidence supporting a relationship between CMEs and the protons and ions of SEP events was obtained (e.g., Kahler, 1996). The relationship between the SEP event electron components and CME-driven shocks is not so clear as in the case of protons and ions (Kahler, 1996), but examining time scales of energetic electron intensity enhancements, such as the delay from the associated solar flare or CME time to t_{on}, the time of the electron event onset, and T_r, the time of electron intensity rise to its maximum, we have found evidence of energetic electron acceleration at CME-driven shocks (Stolpovskii et al., 1995, 1997, 1998).

Recently Reames et al.(1996) found that late in SEP events proton intensities were nearly identical over longitude intervals of up to 160° and that the proton intensities at all energies from 1 to 100 MeV declined with the same e-folding times. They suggested that the particles originated in large "quasi-trapping" regions between the converging magnetic field near the Sun and moving shells of strong scattering downstream from the travelling shocks. Later Reames et al.(1997) showed evidence of spatial and temporal invariance in the energy spectra of 1 to 100 MeV protons in the decay phases of large gradual SEP events and explained the invariance by particle acceleration on the eastern flanks of CME-driven shocks, where the shock waves are quasi-parallel and change only slowly with time.

The question arises whether energetic electrons show the same spectral invariance as protons. Droge (1995) investigated electron spectra in the 0.2-40 MeV energy range in five SEP events after large solar flares and showed that in each event the maximum spectra observed on the Helios-1 and -2 and ISEE-3 spacecraft were in good agreement despite considerable differences in azimuthal and radial locations of the three spacecraft. Daibog et al.(1999) examined the intensity-time profiles of E $>$ 0.3 MeV electrons during the decay phases of 20 gradual SEP events and found that late in the events, well behind the shocks, electrons have features of invariance similar to those of protons when the shock speed is $\geq$ 700 km/s. The decay times of electron intensities were practically the same as those of protons (the difference was less than 20-30%), and electron intensities at a given time t were nearly the same over wide longitude intervals.

Reames et al.(1997) showed that for SEP events on the eastern flank of the shock, invariant spectra of proton intensities are seen up to a day before shock arrival and continue through the remainder of the event. For SEP events near the nose and on the western flank of the shock invariance begins after shock passage. In the present paper we investigate the onset of electron spectral invariance relative to the time of shock crossing at the observer.

2 SEP Observations

We considered SEP events observed simultaneously by two Helios spacecraft and selected 17 electron enhancements at radial distances in the range of 0.4 to 1.0 AU that show the invariance features during the decay phases. These events are listed in Daibog et al.(1999). Criteria of event selection, as well as the data analysis procedures and results, including an estimate of their accuracy, are described there in detail. Here we note only that we analysed intensity-time profiles of electrons in nominal energy ranges of 0.3-0.8 and 0.8-2.0 MeV and protons with energies of 4-13 MeV and 13-27 MeV. The ratio of counting rates in the two electron energy ranges was taken to be a characteristic of the electron spectrum.

We also required the solar sources of fast shocks. Fast CMEs and transient interplanetary shocks are well correlated (e.g., Sheeley et al.(1985)). Unfortunately observations of CMEs by the SOLWIND coronagraph (Sheeley et al., 1985) began only in March 1979, so for most of the events we had data on interplanetary shocks from Volkmer and Neubauer (1985) but no CME observations. Fortunately, most SEP events considered here were discussed earlier by other authors (Wibberenz et al., 1989; Kallenrode et al., 1992; Kallenrode, 1993; Reames et al., 1996, 1997). Following Reames et al.(1996, 1997), we assumed that CMEs were associated with these flares and directed radially from the flare sites. We understand that the flare is not necessarily centered on the CME and that an error of 10-20° could easily take place in this presumed CME direction.

As an example, the event of 19 December 1979 is shown in Figure 1. This event was considered also by Reames et al.(1996). Unfortunately, lack of magnetic field data prevented detection of a shock at either spacecraft. Reames et al.(1996) marked an apparent shock position according to solar wind data, and we show this position in Figure 1. The angular distances between the magnetic footpoints of the observer and the flare (CME) locations were 13°E and 89°E, respectively, which explains the difference of time behaviour of particle intensities at Helios 1 and 2 during the initial part of the event. In the decay phase of the event the intensities of electrons and protons with the same energies are close in magnitude and decrease with nearly the same rates on both spacecraft. The nearly identical particle intensities after the apparent shock suggest that Helios 2 has suddenly encountered the same population of both accelerated electrons and protons that Helios 1 had been observing for a day and a half. The ratio of the 0.3-0.8 to the 0.8-2.0 MeV electron intensities varied from 27 to 33 dur-

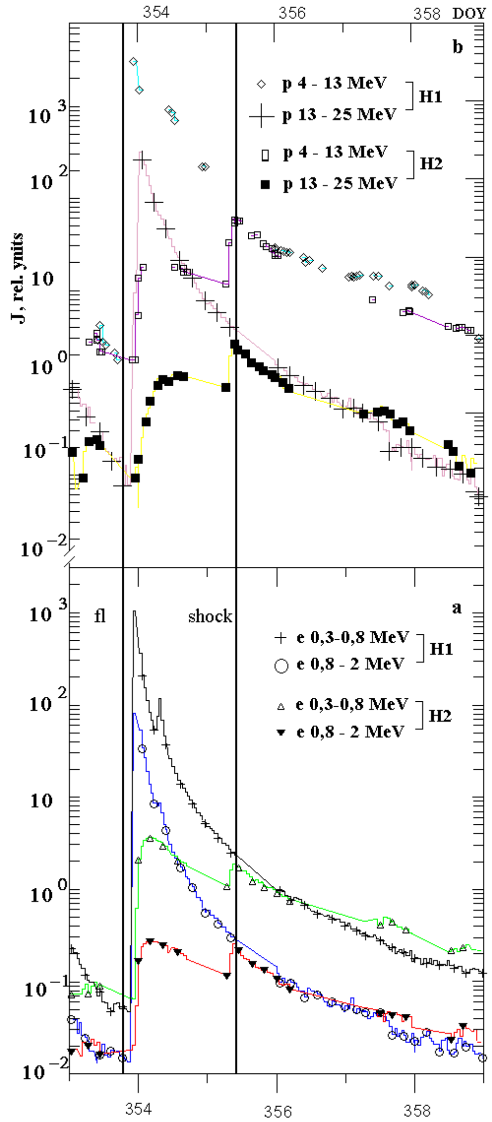

Figure 1: Intensity-time profiles of the 19 December 1979 event observed on the Helios-1 and -2 s/c. a - for electrons, b - for protons. J is the hourly averaged particle count rate. Particle energy ranges are shown in the figure. ”fl” and ”shock” mark the flare and apparent shock arrival times, respectively.

ing this period. Thus, we can say that the electron intensities show spectral invariance. The longitudes of the shock nose (flare heliolongitude) relative to Helios 1 and Helios 2 were W34 and E18, respectively. Although the angular spacing between the spacecraft was not very large, their locations eastward and westward from the flare make it possible to observe a difference in the onsets of spectral invariance at both spacecraft: before the apparent shock arrival at Helios 1 and after it at Helios 2.

It was found in Reames et al.(1997) that the delay (or advance) of the invariance onset times of proton intensities increases with increasing longitudinal separation of the spacecraft from the flare location. For eastern flares this is explained by the time intervals between crossings at the spacecraft of field lines connecting to the shock and field lines connecting to the quasi-parallel shock region on the eastern flank of the shock, while in the case of western flares the spacecraft is connected to this region from the very beginning of the event.

The question now is whether electrons also show this variation of invariance onset times with flare-spacecraft locations. In Figure 2 we present a plot of delay and advance time intervals Δt versus the corresponding longitudinal distances for all events considered. Here the left side of the plot shows the events associated with flares at eastern longitudes relative to the spacecraft, and on the right those with western flares. Positive values of Δt correspond to advances (the invariance precedes the shock), and negative to delays (the invariance follows the shock). All eastern events but one occupy the quadrant with delays, and all western events but one occupy the quadrant with advances. One can see the tendency of increasing time intervals Δt with increasing separation. For additional illustration we marked three events: the 08 April 1978 event (flare longitudes are W49 and W20 for H1 and H2, respectively) is labelled by triangles; the 24 September 1977 event (longitudes are E25 and E48) by circles; and the 19 December 1979 event (longitudes are W34 and E18) by open squares. The large scatter of Δt values is due to the considerable variance of the solar wind and shock speeds and a possible change of shock sizes at different radial distances, etc. The scatter and the poor event statistics do not permit us to obtain a reliable correlation function.

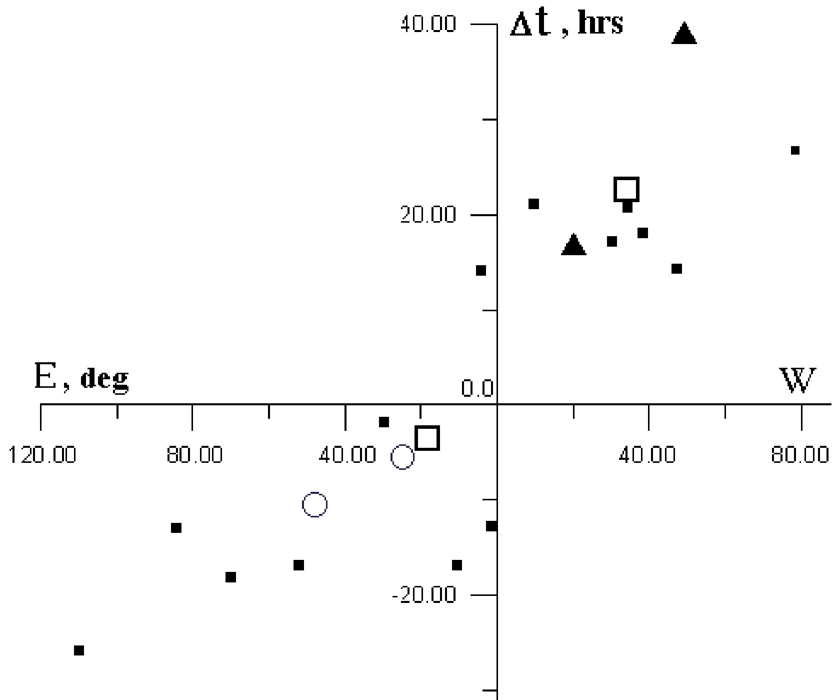

Figure 2: Plot of Δt, the time delay or advance of the electron invariance onset times (in hours) relative to the associated flare longitudes for the spacecraft. The selected events are described in the text.

We determined that the 13 February 1978 and 11 December 1978 events were incorrectly plotted in opposite quadrants of the plot. There were two flares on 11 December 1978: at W50 at 18:33 UT and at E14 at 19:23 UT and two shocks at Helios 2 at 2:47 and 12:47 UT. Following Kallenrode (1993) and Kallenrode et al.(1992), we associated that event with the E14 flare. The invariance onset time is advanced 3 hrs in the first shock and 14 hrs in the second. According to the time of the SSC at the Earth at 01:27 UT on 14 December, we associated the event with the second shock and thus obtained the most unfavorable situation from the point of view of the invariance start. However, if we connect the event with the W50 flare position, the corresponding point on the plot would be improved because its coordinates on the plot would then be W59 and 14 hours. We omitted the 13 February 1978 event on the plot because the spectral invariance began too late to support the idea of an advanced onset and would have considerably enlarged the figure size.

3 Results

We find an indication that the delay or advance of the electron spectral invariance onset time relative to the time of shock arrival at the observation point depends on the location of the observer relative to the shock nose. The magnitude of the delay or advance increases with the longitudinal separation between the spacecraft position and the shock nose longitude. It was shown that the temporal and spectral characteristics of electron and proton intensities in shock-associated events have similar features relative to the shock crossing times at the observer. This is a rather intriguing result because it implies effective shock acceleration in interplanetary space for both protons and energetic electrons. To obtain more definitive results, it is necessary to obtain better statistics of electron events, especially with multispacecraft observations.

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