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Decay phases in gradual and impulsive solar energetic particle events

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Abstract. We have studied the decay phases of energetic particle (SEP) events associated and non-associated to coronal mass ejections (CMEs) and interplanetary (IP) shocks using multispacecraft observations in the end of 1970s and 1980s. Here several examples of successive SEP events observed simultaneously at widely spaced s/c are presented. It is pointed out that often during long time intervals (up to one month) the decays of >4 MeV proton and >0.3 MeV electron intensities are very similar over a wide range of angles between the observer and proposed source (up to 60° and more). The spatial and temporal invariance of the particle intensities during the late phase of large proton events associated to the fastest CMEs and CME-driven shocks is valid not only in a wide angular regions but at different distances from the Sun from 0.3 to 1 AU.

1 Introduction

The study of SEP events is mainly based on the examination of intensity-time profiles for particles with given energies. Up to now many investigations have been directed to the rising parts of events and especially to the peak fluxes (c.f. Kahler et al., 1987; Kallenrode et al., 1992). As far as proton events are concerned, it is known that energetic particle intensity is positively correlated with CME speed (Kahler, 1996). The search for other coronal/interplanetary factors responsible for the energetic proton intensities in gradual SEP events was less successful, moreover, opposite conclusions on the significance of some parameters (for example, ambient SEP intensity) have been obtained (Kallenrode and Wibberenz, 1992; Kahler et al., 1999a).

As for the decay phase of SEP events attention was mostly paid to times at/or around shock passage through the observation point and to the reactions of energetic protons on the shock. Slow and long lasting intensity increase, "classical" energetic storm particles, shock-spikes, Forbush-decreases, etc. were distinguished and basically explained (e.g., Cane et al., 1988; Kallenrode and Wibberenz, 1992). The declining phase as a whole was considered to a smaller extent. Meanwhile, during the late phase of events when the influence of the sources at and near the Sun becomes negligible, the effects and peculiarities of particle acceleration, propagation and losses in IP space become more pronounced. The phenonenon of spatial and temporal invariance in particle energy spectra is namely proper to the decay phase of events (Reames et al., 1996, 1997).

We considered SEP events observed simultaneously by the Helios 1, Helios 2 and IMP s/c in the distance range of 0.3 to 1 AU. Most of events have been described earlier (Cane et al., 1988; Daibog et al., 2000; Kahler et al., 1999b; Kallenrode, 1993, 1996; Kallenrode et al., 1992, 1993; Reames et al., 1996, 1997). Solar wind and IMF parameters, as well as data about flares and CMEs, were taken from the NSSDC website. CME observations by the SOLWIND coronagraph began only in March 1979 (Sheeley et al., 1985), so for the part of events we could use only data on interplanetary shocks from Volkmer and Neubauer (1985). However, fast CMEs and transient IP shocks are well correlated according to Sheeley et al. (1985) and others.

2 SEP observations

2.1 Decay times

Looking at the successive events it can be seen that during rather long time intervals (two weeks to month) the characteristic decay times of particle intensities, τ are very similar. Periods with small τ can be followed by periods with large ones. As an example, Fig.1 shows the intensity-time profiles of energetic electrons and protons according to measurements at Helios 1 and 2 s/c from February 16 to March 18, 1979, when the two s/c were at radial distance

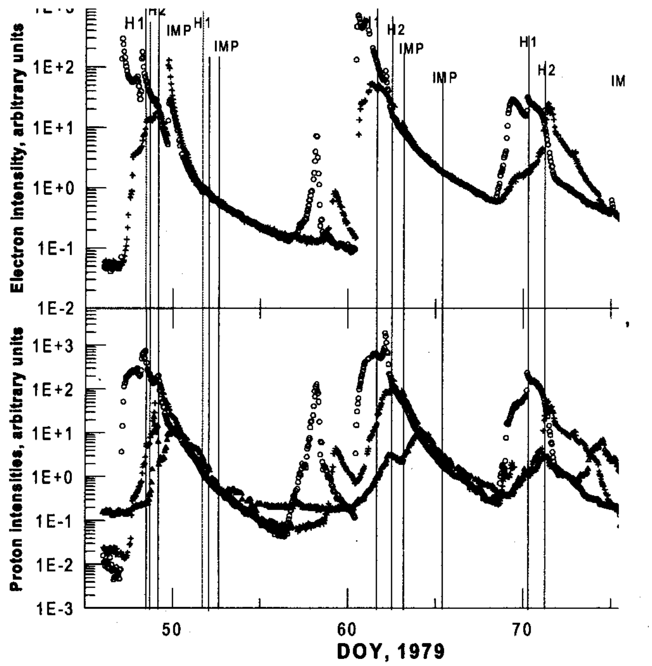

Fig. 1. Intensity time profiles during February-March 1979. Upper panel: 0.3-0.8 MeV electrons, lower panel: 4-13 MeV protons (Helios 1, 2) and >4 MeV protons (IMP). Circles – Helios 1, crosses - Helios 2, triangles - IMP. Vertical lines, marked by H1, H2 and IMP show times of shock arrivals to the observation points.

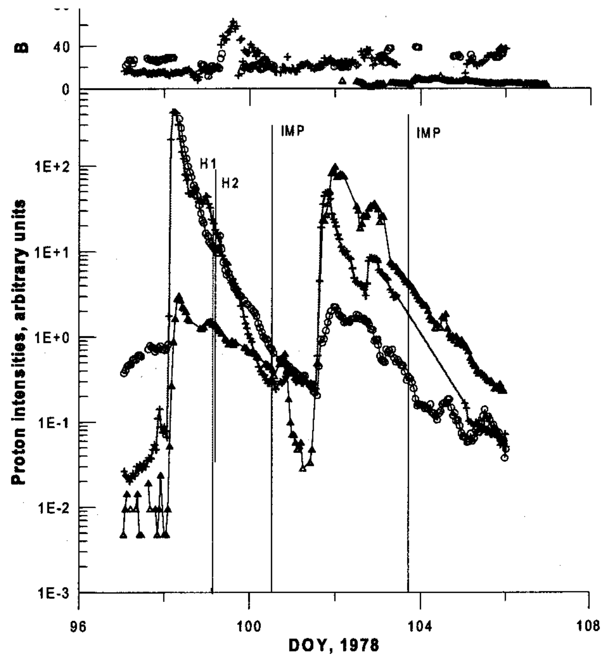

Fig. 2. Intensity time profiles of the April 8 and April 11, 1978 events. Upper panel: interplanetary magnetic field, lower panel: 4-13 MeV protons (Helios 1, 2) and >4 MeV protons (IMP). Circles – Helios 1, crosses - Helios 2, triangles - IMP.

$r \approx 0.9$ AU and heliolongitudes λ of 67E and 27E, correspondingly. Two very large events occurred on February 16 (47 DOY) and March 1 (DOY 60). They were also observed at IMP and discussed in literature (e.g., Reames et al., 1996) and >4 MeV proton intensity-time profile observed on IMP is presented in the figure as well. Both events were associated with fast shocks. In both cases the intensity decay rates are very close at late phases of events far past shock crossings. Here we can add that there was one more very complicated event on March 9 with a similar decline in the late phase. Moreover, there was a less energetic event on February 26 (57 DOY) with the same decline in proton channels. Thus we may conclude that a period during which τ was ~40-50 hrs lasted for a month.

SEP events with τ of about tens of hours were observed many times. For example, in July 1982 two large events were observed (12 and 22 July) in which τ were of 30-40 hrs. The 12 and 22 July events were caused by flare/CME associations and high-speed (>1000 km/s) CME-driven shocks. Other shocks observed during this period had smaller transit speeds and exerted weak influence on the SEP intensity. In this case a rate of SEP intensity decay was practically the same during a month. These events occurred at the late phase of June 5 event, which was characterized by extremely slow particle intensity decrease with $\tau \geq 60$ hrs. One more example of an event with quasiconstant decline which lasts more than two weeks is the 23 Sep. 1978 event when τ was ~30 hrs.

Examples of faster, but very similar SEP intensity declines are the series of small events between May 26 and June 10, 1980 observed onboard the Helios 1 s/c. At this time s/c was at $r \approx 0.3$ AU and flied over the longitude range, $\Delta\lambda$ of 90°. During this time 6 SEP events occurred but there were no fast (>600 km/s) shocks. The magnitude of τ was about 7-10 hrs during this time. The analogous result can be seen from SOHO observations in July 1996 when SEP events had a τ of about 15-20 hrs.

It is possible to conclude that the near constant value of τ late in SEP intensity decays, when particle sources at or near the Sun already stopped to act, may mean stability of conditions in interplanetary medium. In the "old diffusive language" we might speak about constancy of mean free paths throughout the whole period. The modern language of exclusive shock acceleration would formulate this as a similarity of particle holding between strong magnetic field near the Sun and the shock front and particle acceleration in interplanetary space.

2.2 Invariant spectra

Reames et al. (1996, 1997) found that in the major proton events particle intensities were nearly identical over longitude intervals of up to 160° and that the proton intensities at all energies of 1-100 MeV declined with the same τ (phenomenon of spatial and temporal invariance in the SEP energy spectra). It was suggested that the particles originated from large "quasi-trapping" regions between converging magnetic field lines near the Sun and moving shells of strong scattering downstream from the travelling shocks 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. 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. It is necessary to note that the causes of these delays and advances are different. Delay is the time necessary for corotation of magnetic field lines together with the Sun after crossing the shock until the s/c becomes to intersect the region where shock is quasi-parallel. In a case of advance the s/c is connected to this region from the onset of SEP event and corresponding time is that of waiting the shock arrival to the observer. This is valid in all the events considered below.

According to Helios 1, 2 and IMP data there were a few tens of events when intensity profiles at different points of interplanetary medium in wide angular range and at different distances from the Sun coincide during the decay phase. After subtracting the background from the February 16 and March 1, 1979 events, intensities at all three s/c, spread over 70-80 degs coincide till the very end of events.

In the absence of diffusive scattering particle intensities in the region of invariant spectra have to be identical all the way from the Sun. We considered events observed by Helios 1 and 2 at distances 0.3-0.6 AU and possibly near the Sun-Earth line. We found that, in spite of the low number of events there were those in which Helios intensities became nearly equal to those observed at IMP after the shock crossing the respective s/c.

Fig. 2 demonstrates the intensity-time profiles of 4-13 MeV (Helios) and >4 MeV (IMP) protons in the 8 Apr 1978 event after the N19W11 flare at 01:09 UT. Helios 1 and 2 were at about of 0.5 AU from the Sun and heliolongitudes E39 and E09, respectively. Helios 1 and 2 intensities became equal after shock arrival. Just after the shock arrival at IMP, the >4 MeV proton intensity becomes close to those measured by Helios 1 but for a short time only because later on the more or less smooth intensity decline is distorted and the intensity decreases abruptly in the manner similar to that on Helios 2. The abrupt intensity decrease is connected with a plasma structure (plasma data indicate a time shift of about 1.25 day between Helios 2 and IMP). The event of 11 April 1978 did not permit to judge what we could see at IMP after plasma structure mentioned above passing away. Before the shock arrival the decay rate of the proton intensity at IMP is far less than in the case of Helios 1 and 2. It can be explained by a contribution of protons accelerated by IP shock during its travel to the Earth. One can see that the proton intensities at Helios 1 and 2 for the last 15 hrs before the next, 11 April event onset are close to that at IMP before the shock arrival. This event, related to the N22W56 flare at 13:42 UT, was discussed by Valdes-Galicia et al. (1987) in detail and the authors successfully described it in the frame of a diffusive-convection model. We can note that in the absence of shocks at Helios the intensities do not equalize, although their declines are very close and similar to 8 April event. One more flare event was observed on April 12, corresponding to the second maximum in the Helios 2 and IMP profiles.

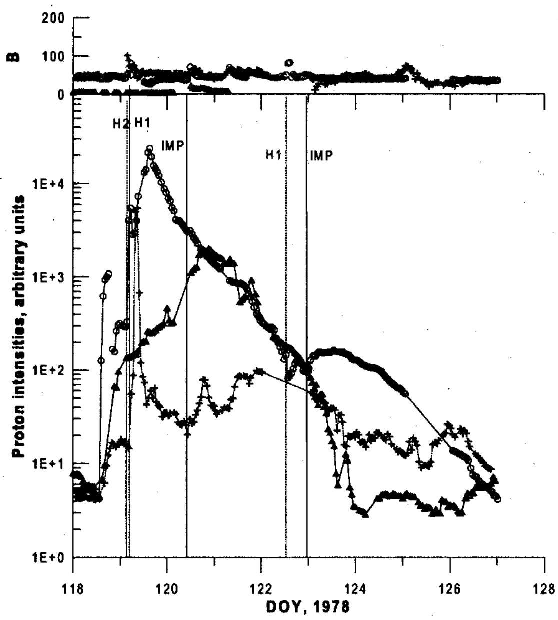

Fig. 3. The same as Fig. 2 for the April 28, 1978 event.

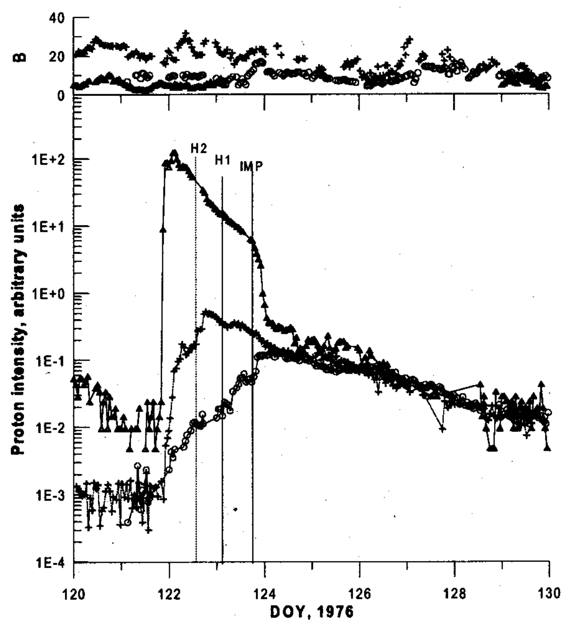

Fig. 4. The same as Fig. 2 for the April 30, 1976 event.

We should like to mention that nearly the same situation took place during the 23 and 28 March 1976 events. For the 23 March event Helios 2 was at 0.57 AU and nearly at the same heliolongitude as IMP. Proton intensities at both s/c equalized after shock crossing. Helios 1 was located at 0.3 AU and separated only by 10 degs with Helios 2 but the particle intensity-time profiles from Helios 1 and 2 are totally different (this event will not be discussed here). Following next, the 28 March event was discussed by Kunow et al. (1980) as a typical pattern of coronal diffusion.

Fig. 3 displays the April 28, 1978 event after the flare N22E38 at 13:04 UT. Both Helios s/c were at 0.3 AU and at W38.5 (Helios 1) and W67.5 (Helios 2). Again, after the arrival of the shock the intensity of >4 MeV protons at Helios 1 is very close to that measured by IMP. Helios 2 was too far west from the nose of the shock and only a very short enhancement was observed. This indicates a non-efficient interplanetary shock acceleration in this event at distances more than 0.3 AU at large angular distances at the west shock flank, as well as about absence of effective scattering of accelerated particles.

In the April 30, 1976 small event after a flare at S08W46, 20:47 UT the relative positions of the flare and the s/c were similar to those in Sep 23, 1978 event, when at the distance >0.7 AU proton intensities were similar over longitude interval of 160 degs. On 30 April 1976 Helios 1 and 2 were at 0.65 AU and 0.42 AU, respectively, and at longitudes about W160. This event is presented in Fig. 4 and one can see that the >4 MeV proton intensities at all three s/c become very close at the time after shock arrival to IMP. We marked also apparent shocks at Helios 1 and 2 calculated according to IMP shock transit speed 910 km/s.

The angular distance between the magnetic foot points of the Helios 1 and 2 s/c were only 10 deg but it took about 3 days before intensities became equal. According to SW and IMF data from the westward s/c just at about the time of apparent shock crossing has suddenly encountered the same population of accelerated particles as the eastward one had been observing for the previous time. This is obviously connected with a structure leaving the Sun with the speed of about 400 km/s. It may also indicate the change of particle propagation conditions just at about 0.5 AU.

3 Conclusions

The analysis of the SEP time profiles shows that

i) often during long time intervals (two weeks to one month) the intensity decays of >4 MeV protons and of >0.3 MeV electrons at different distances from the Sun are very similar over a wide range of angles between the observer and proposed source (up to 60° and more);

ii) the effect of spatial invariance in flare-shock associated events is valid not only in wide angular regions but at different distances from the Sun from 0.3 to 1 AU as well.

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