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Multi-spacecraft observations of decay phases of SEP events

S. Dalla

Blackett Laboratory, Imperial College, London, UK

Abstract. A multi-spacecraft analysis of the decay phase of 26 SEP events is presented, based upon Helios 1 and 2 and IMP8 data. The Helios spacecraft were magnetically connected to the far side of the Sun for part of their lifetime, and detected SEP events at large longitudinal separation from the location of the associated flares. In this study, 26 SEP events are considered, 19 of which observed by three spacecraft and 7 by two. For each event, the total event duration at 1 electron and 2 proton energies is measured. A plot of event duration versus the longitudinal distance $\Delta\phi$ between the associated flare location and the footpoint of the magnetic field line through the spacecraft reveals asymmetries in the detection and duration of SEP events. First, SEP events associated with flares far to the east of the spacecraft footpoint are 5 times more likely than events associated with flares far to the west. Second, the event duration shows a tendency to decrease as the location of the associated flare changes from east to west. We show that the first asymmetry is not a result of the trajectory of the spacecraft.

INTRODUCTION

Gradual SEP events have typically durations of a few days at Earth orbit. After reaching their peak, particle intensities generally show a long duration, quasi exponential decay.

For many years the decay phase of SEP events was interpreted as resulting from particle scattering by the turbulence of the interplanetary (IP) magnetic field. Particle intensity profiles were fitted by means of scattering models and values of the IP diffusion coefficient were derived from the fit. Once the CME shock acceleration paradigm for gradual SEP events became established, however, decay phase energetic particles were attributed to continuous acceleration by the CME shock [1]. By continuous acceleration it is meant that particles are still being accelerated by the shock as it travels through IP space, many days after the flare and CME took place on the Sun. There are two problems with this model: the first is that the fractionation patterns observed in gradual SEP events are not those typical of the solar wind [2] and the second is that their decay phases appear very similar at spacecraft widely separated in longitude [3]. If shock acceleration produces very different profiles at different longitudes during the onset phase, how can it give rise to nearly equal intensities in the decay phase? To explain the latter observation the concept of magnetic bottle was introduced: particles accelerated by the shock are also trapped by it [4]. Consequently, after the shock has passed by, a spacecraft starts detecting the magnetically trapped particles, a spatially nearly uniform population. An explanation along similar lines had been put forward earlier to explain the observation of nearly zero gradients in particle intensities within the inner heliosphere: these would result from trapping by magnetic barriers created by earlier solar events, resulting in particle reservoirs [5].

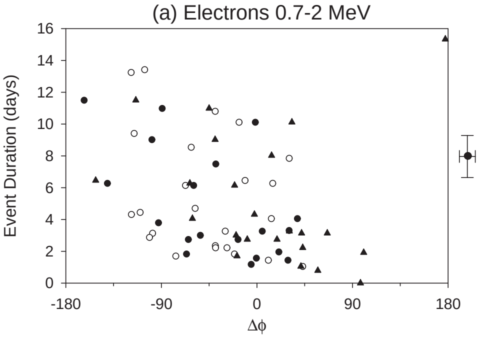
In this paper we investigate decay phases of SEP events using data from the Helios spacecraft. We measure the duration of 26 events at several energies and spacecraft, and plot it versus the angle between the location of the associated flare and the footpoint of the IP field line through the observing spacecraft. This reveals asymmetries in the detection and duration of SEP events.

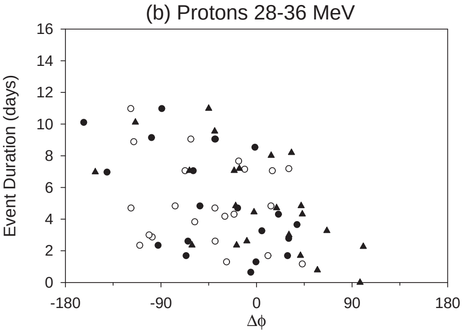
DATA ANALYSIS

The Helios 1 and 2 spacecraft (from hereon H1 and H2) were launched in 1974 and 1976 respectively. They orbited the Sun in highly eccentric trajectories, at radial distances between 0.3 and 1 AU. For part of their lifetime the spacecraft were magnetically connected to the back of the Sun, providing in a few cases measurements of SEPs at large longitudinal separation from the sites of the associated flares, as seen from Earth.

The starting point for our study was the list of 77 Helios SEP events compiled by Kallenrode et al. [6] (from hereon K92) using data from the Cosmic Ray Particles experiment. K92 selected the events were by requiring an increase in intensity of a factor 20 above background in the 0.3–0.8 MeV electron channel, and features of velocity dispersion in the onset. A flare association was also required. Of the 77 events, 52 were classified as gradual and 25 as impulsive.

In this study we considered Helios energetic particle data for the 52 gradual events in the K92 list. Data from


(a) Electrons 0.7-2 MeV


(b) Protons 28-36 MeV

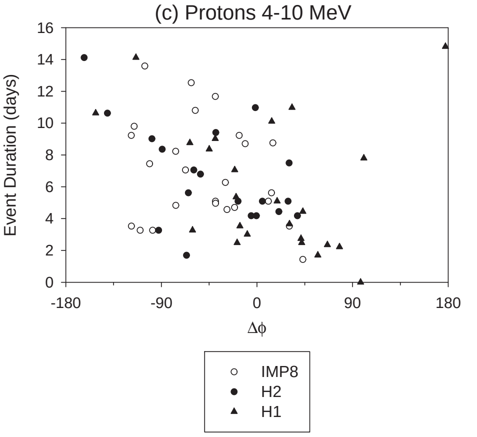

(c) Protons 4-10 MeV

FIGURE 1. Duration of SEP events versus $\Delta\phi = \phi_{\text{flare}} - \phi_{\text{footpt}}$. Filled triangles = H1, filled circles = H2 and empty circles = IMP8. Positive values of $\Delta\phi$ mean that the flare is western (with respect to the spacecraft connection point), negative values that it is eastern. An estimate of the maximum error bar associated to a data point is shown to the right of panel (a).

H1 and H2 were complemented with IMP8 data from the GME and CRNC instruments [7, 8]. A multi-spacecraft plot of intensity profiles was produced for each event. For protons, two energy ranges were considered: low energies (Helios 4–13 MeV; IMP8/GME 4–6 MeV) and high energies (Helios 27–37 MeV; IMP8/GME 29–35 MeV). For electrons, one energy range was considered (Helios 0.8–2 MeV; IMP8/CRNC 0.7–2 MeV). After looking at the plots of the 52 events, a subset was excluded from further analysis. These were events with no flux in the selected channels, or those for which the event duration was an ambiguous quantity. For example, events with decay phase interrupted by the start of a new event were not considered. The final list for analysis comprised 26 SEP events. Of these, 19 were observed by three spacecraft (H1, H2 and IMP8) and 7 by two (H1 and IMP8).

The duration of the SEP event in the three energy channels was measured. Here the event duration is defined as the time between the onset of the SEP event and the time when intensity goes back to the pre-event level. The longitude with respect to Central Meridian of the flare associated with an event, as given in K92, is indicated as ϕ_{flare}. All but one of the 26 SEP events considered are reported by K92 to have a confident flare association. From spacecraft trajectory data, the longitude ϕ_{footpt} with respect to Central Meridian of the coronal footpoint of the nominal IP magnetic field line through the spacecraft was calculated, by using the Parker model and the actual measured solar wind speed. For the very few events for which solar wind speed measurements were not available, a speed of 430 km/s is assumed. The longitudinal separation $\Delta\phi$ between the flare location and position of magnetic footpoint is defined as $\Delta\phi = \phi_{\text{flare}} - \phi_{\text{footpt}}$. Positive values of $\Delta\phi$ indicate western flares and negative values eastern ones, where these terms are intended with respect to spacecraft footpoint rather than Central Meridian. The degree symbol in angles will be omitted from now on.

When we plotted the event duration versus $\Delta\phi$, for the electron and two proton channels, we obtained the plots shown in Figure 1. All three plots display asymmetry in the parameter $\Delta\phi$, in two ways. First, there appear to be many more SEP events in the far left of each plot than in the far right. We will refer to this in the following as the detection asymmetry. Second, the plots show a trend for the event duration to be a decreasing function of $\Delta\phi$. We will call this second asymmetry the duration asymmetry.

DISCUSSION

Detection asymmetry

The first thought that crosses one's mind when presented with the detection asymmetry is that it might result from the particular trajectories of the observing spacecraft. The value of $\Delta\phi$ for each point in Figure 1 is the result of where the flare took place on the visible disk and where the spacecraft magnetic footpoint was located (depending on the position of the spacecraft and the solar wind speed). The footpoints of H1 and H2 spanned the

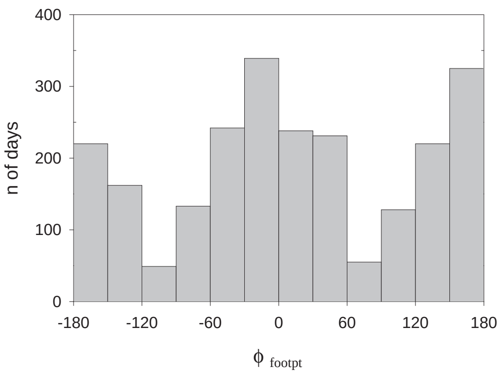


FIGURE 2. Histogram of the number of days spent by the H1 and H2 footpoints in 30° longitude bins. Central Meridian is at 0.

entire interval of longitudes [-180,+180]. Consequently for SEP events observed by H1 and H2 any value of $\Delta\phi$ could in principle occur. For IMP8, ϕ_{footpt} takes values in the range between 30 and 70. Taking a representative value of $\phi^{IMP}_{\text{footpt}} \approx 55$, we get that $\Delta\phi$ for SEP events observed by IMP8 could only be in the range [-145,+35], i.e. IMP8 (and any other near Earth spacecraft) cannot span the far western range. We excluded IMP8 data points from Figure 1 and found that the detection asymmetry was still present: there are only 2 H1 or H2 particle events with $\Delta\phi$ in the range [+90,+180], while there are 11 events in [-180,-90] (the data point with zero duration at $\Delta\phi = 100$ corresponds to an event for which SEPs were detected at other spacecraft but not at H1).

It should be noted that the detection asymmetry was already visible in Figure 4 of K92, where the authors commented that they did not think it had a physical reason, but rather was related to the fact that data transmission from H1 and H2 was poor at times when the spacecraft footpoint was in the eastern hemisphere. This will be commented upon below. It should be pointed out that Figure 4 of K92 contains a different set of data points from our Figure 1, because in K92 for each event only data from the spacecraft closest to the flare were included. The data points of Figure 1 correspond to a subset of the K92 events, where however for each event data from another one or two spacecraft further away from the flare were added. Even with this addition the lack of SEP events associated with far western flares is still present.

To verify whether there is a bias in the Helios dataset towards observing far eastern SEP events rather than far western ones, we estimated the fraction of total observing time spent by the footpoint of H1 and H2 in several longitude bins. We calculated ϕ_{footpt} for the spacecraft from daily averaged trajectory data. To exclude solar minimum times, we restricted the time interval of the analysis to times when the smoothed monthly sunspot number was greater than 60. Furthermore, we excluded data gaps of duration $>$20 days in energetic particle data. The gaps were identified by yearly plots of the 0.3-0.8 MeV electron channel, which was used in K92 to select the events for study. The data gaps were mostly in H1 data, 50% of the days with no data being in 1983. SEP events at times of smaller data gaps appear to have been included in the K92 analysis.

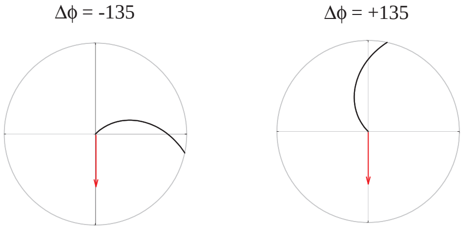


FIGURE 3. Diagram showing the geometry for the cases: $\Delta\phi$=-135 and $\Delta\phi$=+135. The arrow indicates the position of the nose of the shock with respect to the spacecraft footpoint.

Figure 2 shows a histogram of the number of days spent by the spacecraft connection point ϕ_{footpt} in 30 degree longitude bins at times of high solar activity. Would this distribution of ϕ_{footpt} give rise to a smaller probability for SEP events associated with far western flares? To have $\Delta\phi$ in [+90,+180], one would need a flare located to the west of the spacecraft footpoint, at longitudinal distance greater than 90. Now, flares are seen from the Earth only in the interval [-90,+90], where we recall that 0 represents Central Meridian. From Figure 2 we can see that while the Helios connection point did not spend a long time in the longitude bin [-180,-90], it did spend a considerable fraction of the total time in [+90,+180], making eastern flares during this time good candidates for a $\Delta\phi$ in [+90,+180]. This shows that far western SEP events would not require the footpoint to be in the eastern hemisphere as stated by K92, and that poor data transmission cannot be the reason for the detection asymmetry.

We conclude that there is no evidence from trajectory consideration that the Helios spacecraft would be less likely to detect an SEP event with $\Delta\phi$ in the far western regions. It cannot completely be ruled out that a particular pattern of spatial distribution of flares on the solar disk might have resulted in the low number of far western events observed. All indications are however that the detection asymmetry is the result of a physical process.

According to the current paradigm for gradual events, SEPs originate from direct connection of the spacecraft to a CME shock front. The lack of detection of far western events can be explained by this model as resulting from the curvature of the interplanetary magnetic field lines. This can be seen in Figure 3 which shows the location of footpoint and magnetic field line to 1 AU for the cases $\Delta\phi$=-135 and $\Delta\phi$=+135. The latter case would require a shock of wider longitudinal extent than the former one, and is therefore less likely.

It should be noted however, that while the geometry for the $\Delta\phi$=+135 case appears unfavourable for detection of SEPs by the spacecraft at times when the shock is within 1 AU, eventually a connection between shock and spacecraft will be established. Enhancements starting several days after the flare would be expected from this model, but are not seen. The detection asymmetry therefore supports the idea that most of the acceleration in SEP events takes place very close to the Sun.

Duration asymmetry

The panels in Figure 1 suggest a trend for the duration of SEP events to decrease with the angle $\Delta\phi$. The longest duration events are associated with far eastern flares, with the point on the top right corner of the plots being very close to 180 and compatible with a definition of far eastern. Very few events of short duration are seen in the far eastern region of the plot, and there are no long duration events west of $\Delta\phi$=45 (apart from a single data point in panel (c)).

It is also true that there is a lot of scattering in the plots, with event durations at a fixed value of $\Delta\phi$ spanning a very wide range. On the other hand, the lack of events in the far western region of the plot (detection asymmetry) seems to be the obvious continuation of the average event duration going to zero as one moves from east to west.

The duration asymmetry is suggestive of corotation playing a very important role in the decay phase of SEP events. Therefore if the long duration of SEP events were due to a magnetic bottle effect, this would have to still be effective at times when the shock has travelled several AU into interplanetary space.

As far the interplanetary scattering model of SEP decays is concerned, it follows from Figure 1 that fitting SEP profiles with scattering models would give a larger scattering coefficient for eastern flares than for western ones, an unphysical result.

CONCLUSIONS

The main results of the analysis are as follows:

1. Based on Helios data, a spacecraft is 5 times more likely to detect SEP events from flares far to the East of its magnetic footpoint, than from flares far to the West (detection asymmetry). Only 2 far western SEP events were detected by the Helios spacecraft. These observations can be explained by the CME shock acceleration mechanism, when the curvature of the IP magnetic field lines is taken into account. They would however require a large number of shocks of very wide longitudinal extent, which are not observed at 1 AU [7].
2. The Helios data show a possible trend for the total duration of a particle event to decrease as the location of the associated flare changes from eastern to western longitudes with respect to the magnetic footpoint of the detecting spacecraft, within the range of values of $\Delta\phi$ in [-180,+90].

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