Role of latitude of source region in Solar Energetic Particle events

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Abstract. Solar Energetic Particle (SEP) measurements from the Ulysses spacecraft have shown that the latitudinal separation between the parent solar flare and the nominal footpoint of the detecting spacecraft is an important parameter in ordering characteristics of the observed time-intensity profiles during SEP events. In this study, we consider data from the GOES and Wind spacecraft over one solar cycle, to address the question of whether the same trend can be observed from in-ecliptic SEP measurements at 1 AU. Because of the inclination of the ecliptic plane with respect to the heliographic equatorial plane, the latitudinal separation between the location of the parent flare associated to an SEP event and the footpoint of a near-Earth detecting spacecraft can vary in latitude between 0 and about 40 degrees. By analyzing a sample of 477 well connected solar events (with source region in W20–W80) and characterized by a magnitude of the associated flare $>$ C8.0, we derive a probability P of observing an SEP event as a function of the latitudinal separation. We find that the P is largest for latitudinal separations between 4° and 12°. Outside this range, including separations smaller than 4° and in the interval [12°, 28°], P remains approximately constant.

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INTRODUCTION

During solar flares and Coronal Mass Ejections (CMEs), ions and electrons are accelerated, often up to near-relativistic energies. Some of these particles can escape the solar atmosphere and travel through interplanetary space to the Earth. They are collectively referred to as Solar Energetic Particles (SEPs).

It is well known that the location of the source of SEP acceleration at the Sun is an important factor in determining whether or not a particle event will be observed at a given location in the heliosphere, as well as the characteristics of the time intensity profiles observed.

Up to the present time, most studies have focused on the role of the heliographic longitude of the source, by analyzing SEP data from near-Earth spacecraft (e.g. [1, 2]). Among important results of these studies, it was shown that the time to maximum intensity of an SEP event has a strong dependence on the heliographic longitude separation, $\Delta\phi$, between the source region and the footpoint at the Sun of the magnetic field line that connects to the detecting spacecraft [1]. The time to maximum is shortest when the source region is near W45, the location on the Sun to which, on average, Earth is directly connected via the interplanetary magnetic field (IMF) (i.e. giving $\Delta\phi \sim 0$). Sample intensity profiles for a variety of eastern and western events were later analyzed [2] and the role of interplanetary shocks in determining the particle time intensity profiles was recognized.

It is also well known that the so-called impulsive SEP events can only be observed when the source region is in the 'well connected' longitudinal range, found to be approximately between W20 and W90. This makes the probability of an SEP event at Earth much larger for source longitudes in the well connected region than for easter longitudes (see e.g. [3]). Detection probabilities appear roughly constant with longitude within the well connected range, spanning some $\sim 70^\circ$.

The role of the latitude of the source region in determining the characteristics of the SEP time-intensity profiles has been only partially addressed so far, by means of Ulysses data. Analysis of SEP time-intensity profiles during 9 large SEP events observed by Ulysses at very high heliolatitudes showed that the latitudinal separation between the spacecraft footpoint and the source region plays an important role. For the Ulysses events, this parameter orders characteristics such as the delay between the start time of the GOES SXR flare and the inferred SEP release time at the Sun (also referred to as delay in onset) and the time to maximum, better than the total separation angle (including both longitude and latitude) between flare and spacecraft footpoint [4, 5].

In this paper, we study the probability of SEP detection as a function of the heliographic latitudinal separa-

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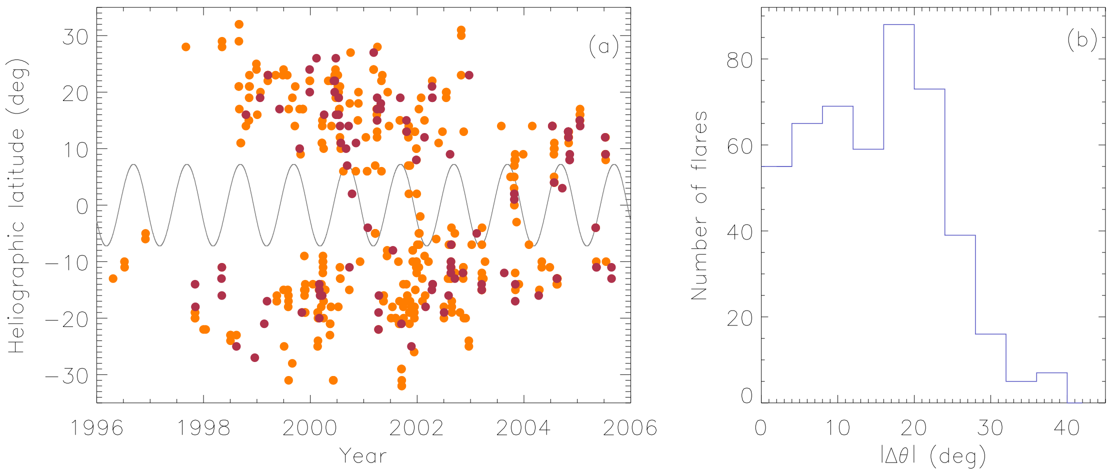

FIGURE 1. (a) Latitudinal position of the flares selected for this study versus time (dark circles: flares with SEPs, light circles: flares without SEPs). The solid line shows the latitude of a near-Earth spacecraft. (b) Histogram of the latitudinal separation $|\Delta\theta|$ between flare and spacecraft footpoint, for all the flares in (a).

tion, $\Delta\theta$, between the source region and the footpoint of the magnetic field line to the spacecraft. We use the timing and location of large flares as a proxy for strong solar activity capable of accelerating particles. In most cases the activity will include both a flare and a CME. In this initial study, we neglect the fact that the configuration of the magnetic fields near the Sun may be more complex than predicted by a simple Parker spiral model, as has been shown by work including potential field reconstruction near the source region (e.g. [6, 7]), and we hope to be able to address this in future.

DATA ANALYSIS

Flare sample

We begin by building a sample of solar flares, that we will use as proxies for solar activity with capability to accelerate particles.

Using the NOAA GOES Soft X-Ray flare list, we select flares satisfying two criteria: (1) that they are well connected in terms of their longitudinal location, so that the role of latitude can be established, and (2) that their magnitude is above a set value, to maximize the likelihood of association with CMEs. We define the range W20 to W80 as 'well connected' and choose C8.0 (i.e. soft X-ray peak intensity $> 8.0 \times 10^{-6}$ W m^{-2}) as the lower threshold flare magnitude for inclusion in the sample. We consider the time range from November 1996 to April 2006, covering approximately 1 solar cycle. We also require that positional information (heliographic longitude and latitude) is available for each flare. The total number of flares that meet the selection criteria is 534.

Figure 1a shows the heliolatitude of the selected solar flares (diamonds) together with the variation of Earth's heliolatitude (solid line) over the time range under consideration. It can be seen that the heliolatitude of the selected solar flares is within $\pm 35°$ of the solar equator, while the Earth's heliographic latitude varies over its orbit within $\pm 7.2°$ due to the inclination of the ecliptic plane with respect to the solar equatorial plane.

If we assume that the latitude of an IMF line does not vary between the Sun and Earth, as would be expected for purely radial solar wind flow, we can define the absolute heliolatitudinal separation between a given flare and the spacecraft footpoint as $|\Delta\theta| = |\theta_{\rm Earth} - \theta_{\rm flare}|$, where $\theta_{\rm Earth}$ is the Earth's heliolatitude at the time of the start of the flare and $\theta_{\rm flare}$ is the heliolatitude of the flare as given in the GOES catalog. Information about Earth's location at the time of each flare was obtained via NSSDC's HelioWeb.

Figure 1b shows the distribution of values of $|\Delta\theta|$ for the flares in our sample. It is apparent that the sample includes a greater number of solar flares with $|\Delta\theta| < 30°$ and that the statistics are low for higher $|\Delta\theta|$ values.

SEP data and association to flares

The next step in our analysis consists of verifying whether or not an SEP event was observed by near-Earth spacecraft following each flare in our sample.

We consider SEP data from the *Wind*/3DP instrument

TABLE 1. Flare-SEP event associations for $|\Delta\theta| \in [0°, 28°)$. Flares are located in W20-W80 and have magnitude >C8.0.

$\lvert\Delta\theta\rvert$ (°)	Number of flares	Number of SEP events	No SEP event
2	54	8	46
6	65	20	45
10	67	23	44
14	63	11	52
18	87	18	69
22	72	14	58
26	41	10	31

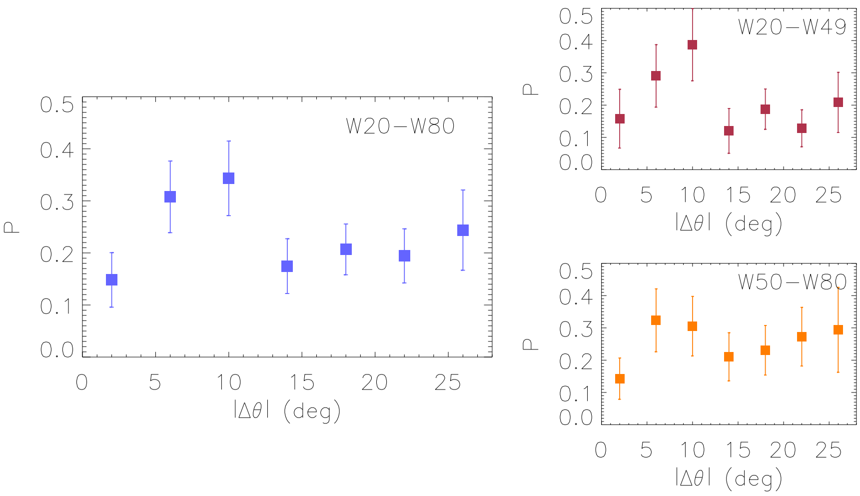

FIGURE 2. Probability of detection of an SEP event versus latitudinal separation $|\Delta\theta|$. The large panel shows data for the entire longitudinal range considered (W20-W80), while the small panels show the ranges W20-W49 and W50-W80 separately.

[8] and from the GOES Energetic Particle Sensor (EPS). Data from several of the GOES monitors were combined to obtain a single time series covering the period from 1996 to 2006. Because of a 2-month gap in GOES data in 2003, we discarded flares that happened within the gap, reducing our flare number to 496. For *Wind*/3DP, we considered the 20–48 keV electron channel and for GOES the 40–80 MeV proton channel. We note that, under scatter-free propagation conditions, 20–48 keV electrons take ~28 minutes to propagate from Sun to Earth, while 40–80 MeV protons take ~24 minutes.

For each of the flares in our sample, we visually inspected the electron and proton data plotted over a time range of 5 days following the flare start time. In addition to the flares that satisfied the selection criteria, we plotted also the times of all other flares with magnitude greater than C8.0, to make the association as accurate as possible. We added an "SEP event" label to each flare, equal to 1 if a particle event was detected in association with the solar flare in either the electron or the proton channel (or both), and equal to 0 if not. We also assigned an index of confidence for the flare-SEP event association between 1 and 3, i.e. $C = 1$ for a clear association (with SEP onset within 24 hours of the soft X-ray flare onset); $C = 2$ for a reasonably confident association and $C = 3$ if the association was not so confident. We excluded from the sample those flares whose association with SEP events had a confidence classification of $C = 3$, leaving a total number of flares for further analysis of 477.

We find that of the 477 solar flares in our sample, 367 were not associated with an SEP event observed by Wind or GOES, giving an average probability of an SEP event being detected of 23%.

Latitudinal dependence of probability of SEP event detection

We group our flares into $|\Delta\theta|$ bins of 4° width, to evaluate whether the latitudinal separation between spacecraft footpoint and the flare location influences the probability of SEP event detection.

Table 1 shows the associations of the flares in our sample to SEP events for each of the bins. We excluded

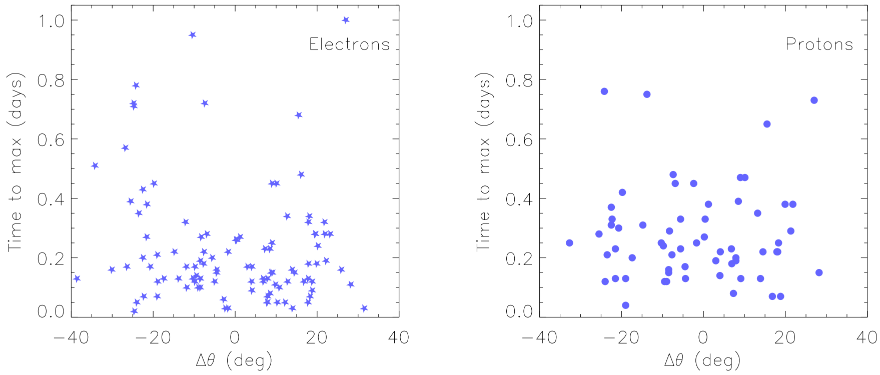

FIGURE 3. Time to maximum for electrons (Wind/3DP, 20–48 keV electrons) and protons (GOES/EPS, 40–80 MeV protons) plotted versus $|\Delta\theta|$.

data with $|\Delta\theta|>28^\circ$ since the statistics are too low. The table columns give, for each $|\Delta\theta|$ bin, the value of $|\Delta\theta|$ for the midpoint of each bin, the total number of flares (N^i), the number of flares that did give rise to an SEP event (N_1^i) and the number of flares that did not give rise to an SEP event (N_0^i).

From the data displayed in Table 1, we can calculate a probability that a flare in the *i*-th $|\Delta\theta|$ bin will give rise to an SEP event at the spacecraft as $P^i = N_1^i/N^i$. The corresponding error can be calculated assuming Poisson statistics as $\sigma_{Pi} = P^i/(N_1^i)^{1/2} = (N_1^i)^{1/2}/N^i$.

Figure 2 shows the probability of SEP detection plotted against $|\Delta\theta|$. It can be seen that the probability of observing an SEP event is much larger for latitudinal separations in the bins centered at 6° and 10° and it decreases significantly outside this range. Interestingly, the probability of detection for the smallest latitudinal separation is only about half that of the 6° bin.

Time to peak intensity

For those events for which SEPs were detected, we measured the time between the flare onset and the peak intensity (in the following referred as time to maximum), for the electron and proton channels considered. Figure 3 shows plots of time to maximum versus $\Delta\theta$. The protons do not show any dependence on latitudinal separation, while a possible small trend is observed in the electron data.

CONCLUSIONS

Our results show that the probability of an SEP event being detected is largest if the source region and the spacecraft footpoint are separated in latitude by an angle between 4° and 12°. When the spacecraft is nominally very well connected in latitude $|\Delta\theta|<4^\circ$, the probability of an SEP event is lower than for $|\Delta\theta|$ values in the interval [4°, 12°].

At the largest value of latitudinal separation that we are able to resolve in this study, $|\Delta\theta|$=26°, the probability of an SEP event is still as large as for $|\Delta\theta|$=14° and 2°.

We find that, in the range of $|\Delta\theta|$ that can be probed by near-Earth spacecraft, the time to maximum does not display a clear trend with latitudinal separation.

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