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Solar Energetic Particle Event Onsets: Far Backside Solar Sources and the East-West Hemispheric Asymmetry

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Prompt onsets and short rise times to peak intensities Ip have been noted in a few solar energetic ($E > 10$ MeV) particle (SEP) events from far behind the west limb. We discuss 15 archival and recent examples of these prompt events, giving their source longitudes, onset and rise times, and associated CME speeds. Their timescales and CME properties are not exceptional in comparison to a larger set of SEP events from behind the west limb. A further statistical comparison of observed timescales of SEP events from behind the west limb with events similarly poorly magnetically connected to the eastern hemisphere shows the longer timescales of the latter group. We interpret this result in terms of a difference between SEP production at parallel shocks on the east flanks of west backside events and at perpendicular shocks on the west flanks of eastern hemisphere events.

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1. Introduction

While it was understood that solar energetic ($E > 10$ MeV) particle (SEP) events could originate from sources behind the solar west limb, the source of an SEP event on 1966 July 16 was inferred from optical and radio observations to lie ∼180° behind the limb [1]. This distant location, in AR 8362, was the source of not only $E > 10$ MeV protons, but also $E > 45$ keV electrons, and raised the question of how far SEPs could propagate across coronal magnetic fields before injection into space. Within a year another SEP event was observed on 1967 January 28 with an inferred source region at W154° [2], this time energetic enough to be a ground level event (GLE) [3, 4]. On the basis of yet another GLE on 1971 September 1, from W140° and accompanied by a type II radio burst, [5] argued that the SEP source must be a shock wave broad enough to generate SEPs over a large longitudinal region. A subsequent GLE from W130° on 1984 February 16 [6] was consistent with that view.

An observed CME, an EIT/EUV wave, and a type II radio burst were sufficient to allow [7] to infer from a helioseismology analysis an ∼180° source location for a large SEP event on 2001 August 16. They argued that the prompt arrival of $E > 400$ MeV protons within ~ 40 minutes of the solar eruption was caused by a shock sweeping around to the front side of the Sun from its distant backside origin. That event was another example of "extreme propagation" (EP) that [8] had considered earlier in a survey of proton and electron events observed on Helios 1/2 and IMP-8. With associated flare maxima as their timing fiducials, they found ∼1 to 3 MeV electron onsets often occurring within 2 hours for longitudinal separations up to ∼150°, establishing EP as a common phenomenon of SEP events.

[8] found frequent differences in the early rise phase profiles of eastern versus western hemisphere electron events as observed at several spacecraft, but they could not establish a pattern distinguishing the two groups. The idea was to find east/west differences in the propagation of Hα Morton waves, now studied as the more easily observed EUV waves (e.g., [9, 10]), or in the efficiency of SEP acceleration at the inferred shock fronts. Here we compare statistically the large numbers of onset and rise times of ∼20 MeV proton events for the far eastern and western longitude ranges compiled by [11]. First, however, we add more recent examples of far backside SEP events to those of earlier studies and then compare their parametrized timescales with those of the large sample of SEP events from ≥ W100°.

2. Data Analysis

2.1 Event Selection and Criteria

We began our selections with three SEP events prior to cycle 23 which we reviewed in Section 1 and list in Table 1. SEP events of cycles 23 and 24 from behind the west limb were examined using different spacecraft data sets, all in the range of 10 to 50 MeV for protons. We selected events for prompt onset intensity profiles, as described in the next section, and arbitrarily required a source location at least 25° behind the west limb to serve as far backside examples of the most extreme cases of longitudinal separation. For cycle 23 we selected, besides the 2001 August 16 event highlighted by [7], a SEP event from [12] and three events from the lists of [13] and [11] for which the source longitudes could be well specified and the timescales were short.

Table 1: SEP Events at Longitudes >115° With Prompt Onsets.

Year	Date	Long.	CME Onset T	SEP Onset T	TO hrs	TR hrs	Vcme km/s	Ip pfu	Type II UT
1966	16 Jul	W172°	20:50	22:30	1.7	4.0	NA	1.1	N
1971	1 Sep	W120°	19:35	21:00	1.4	1.5	NA	300	m19:43
1984	16 Feb	W130°	08:58	09:35	0.6	0.4	NA	660	m09:01
1996	13 Aug	W150°	14:15	17:00	2.7	3.0	620	<0.1	m14:59
2001	18 Apr	W117°	02:12	03:00	0.8	4.0	2465	321	02:55
2001	16 Aug	W180°	15/23:41	01:00	1.3	1.5	1575	493	00:10
2004	3 Sep	W120°	2/23:46	03:00	3.2	0.5	751	<0.2	N
2005	29 Aug	W148°	10:47	13:00	2.2	4.0	1600	1.0	N
2011	21 Mar	W138°	02:12	04:00	1.8	2.6	1341	14	02:30
2011	3 Nov	E152°	22:13	23:30	1.3	1.5	991	3	22:35
2012	26 May	W116°	20:42	23:00	2.3	2.0	1966	14	20:50
2012	8 Sep	W145°	09:26	12:00	2.6	1.5	734	1.0	09:45
2013	21 Apr	W124°	07:13	10:00	2.8	1.5	919	3	N
2013	24 Apr	W175°	21:45	23:00	1.3	4.0	594	0.7	N
2013	28 Dec	W130°	17:15	18:40	1.4	2.3	1118	29	N

For cycle 24 the STEREO mission provides accurate SEP event source longitudes for the catalog of [14] from which the last 7 events of Table 1 were taken. The Ip of those events were generally lower than for the pre-cycle 23 events cited above, owing to the better longitudinal coverage of the STEREO spacecraft. The SEP event of 2011 November 3 was outstanding for the very rapid rises to peak intensities at STEREO A, B, and ACE, despite the wide separation of the three spacecraft [15, 16, 17]. That event was the poorest connected event of Table 1 and its associated CME was the only one observed off the east limb of the Sun.

The appropriate longitudes (Table column 3) and associated CMEs were taken from [12] and the SEP event tables of [13, 11, 18, 14, 19]. The onset times and speeds of the CME leading edges (columns 4 & 8) were taken from the CDAW web site [20] of the LASCO/SOHO instrument. Widths of all but one of the CMEs were full 360° halos. The Ip observed with the GOES instrument are given in proton flux units (pfu, 1 p/cm^2 s sr for $E > 10$ MeV protons) in column 9. The associated decametric-hectometric (DH) type II burst onset times from the Wind/WAVES experiment are given in column 10; earlier periods are the reported metric (m) type II burst times, if observed.

2.2 Defining Prompt SEP Event Timescales

Describing SEP events as prompt has generally meant a relatively short interval from flare impulsive phase or CME launch to the SEP event onset (e.g., [8, 7]). The profiles of the rise phases can also carry information about the early shock acceleration and/or propagation of the SEPs and can show marked differences between observations on opposite sides of the source regions [8]. The times of Ip of SEP events can serve as event timing fiducials, but the profiles around those times can also vary substantially. To obtain perhaps a better measure of SEP event rise phases, [21] adopted

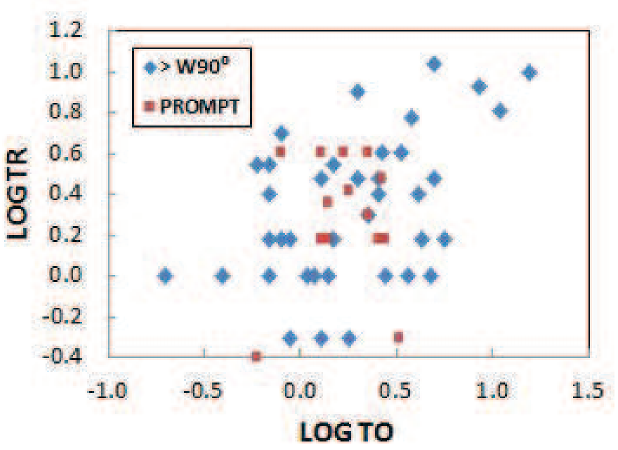

Figure 1: Comparison of log TR versus log TO for the 15 prompt backside events of this study (red squares) and the 38 ≥ W110° SEP events (blue diamonds) of [11]. Units of TO and TR are hours.

as the rise time TR the time from SEP onset to the time of 0.5 of Ip. TO, the time from CME onset to SEP onset at 1 AU, and TR were measured in the E = 20 MeV proton events for 217 SEP events with associated LASCO CMEs [11] from 1996 to 2008. We extended this definition to the more recent SEP events of Table 1.

The prompt SEP events of Table 1 are limited to those with both TO $\leq$ 3.2 and TR $\leq$ 4.0 hrs. TO can be overestimated for events with low signal/background ratios [11], but that problem is mitigated by our selection of the smallest observed TO values here. The uncertainties in TO and TR are generally about 0.5 hours for these events. The first three events of Table 1 had radio or optical emissions that served as solar eruptive event timings to obtain TO.

2.3 Comparing Timescales of Prompt Backside SEP Events with All Backside SEP Events.

To provide a context for the 15 prompt SEP events of Table 1, we compare in Figure 1 their TO and TR values with those of a similar larger group of ≥ W100° (WL) events from the survey of [11]. The prompt events satisfy the conditions: longitude ≥ W115°, TO $\leq$ 3.2 hrs, and TR $\leq$ 4.0 hrs. The larger WL group satisfy only the longitude condition of ≥ 100°, and most of those events may lie only just beyond the limb, but there was not an attempt to define specific event source longitudes. The median longitude of the prompt SEP events is W138°, probably only slightly larger than those of the larger WL group. The four events common to both groups are shown as prompt events. The main result of this comparison is that the backside SEP events considered to be exceptional because of their prompt onsets at Earth are not distinguished from the class of all backside SEP events in terms of their onset times TO and rise times TR.

For the 12 SEP events of Table 1 the median, low and high Vcme are 1055, 594, and 2465 km/s, compared to 1090, 325, and 2036 km/s of the 38 remaining WL SEP events. All but one of the 12 CMEs of Table 1 are full-width 360° halo events, but only 16 of the 38 WL CMEs are full haloes, and widths of 11 of those CMEs are $< 150°$. To summarize this comparison of the prompt far backside SEP event examples, they are exceptional in neither their intensity timescales nor CME speeds, but a full halo may be a requirement to observe a far backside SEP event.

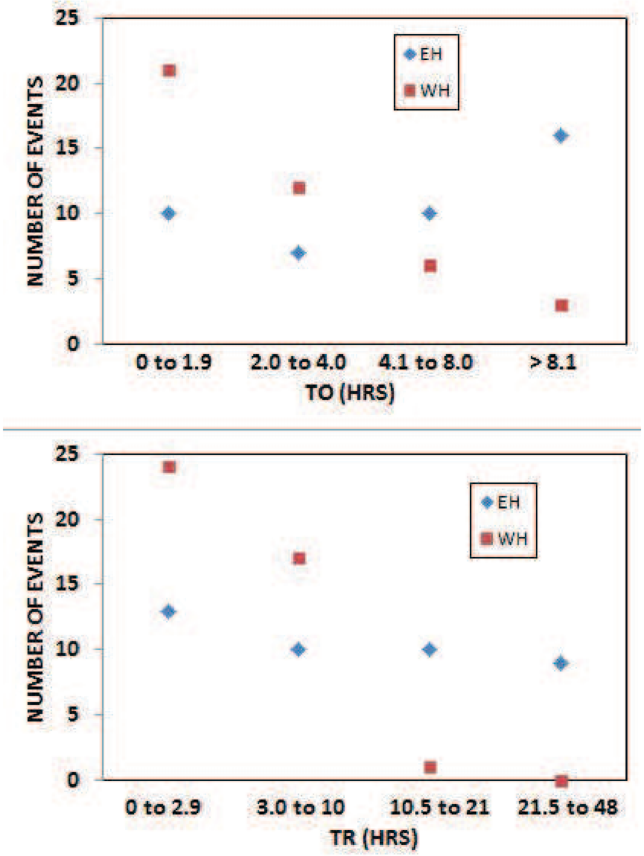

Figure 2: Comparisons of relative numbers of SEP events with timescales TO (top) and TR (bottom) for eastern (E130° - E06°, EH) and western (≥W100°, WH) hemispheres. Event times are taken from Table 1 of [11].

2.4 Backside SEP Events and Eastern Hemisphere (EH) SEP Events

The significant difference in the SEP intensity-time profiles between western and eastern hemisphere (EH) events has long been recognized to result from the role of shocks propagating radially [22] in a spiral interplanetary magnetic field. Most of the shock modulation occurs well after the rise phase of the SEP event, as the shock and/or CME miss or intersect the Earth several days later. If the Sun were not rotating and the interplanetary fields were completely radial, we might expect similar intensity profiles on each side or flank of the CME-driven shock. In particular, we could expect matching values of TO and TR for events equally displaced in longitude from their source CMEs.

We can examine the observed differences of TO and TR between SEP events roughly equally separated from the eastern and western flanks of the associated CMEs. Taking an average longitude connection of W50°, appropriate for a solar wind speed of $\sim$ 450 km s^{-1}, the longitude ranges of $<$ E00°, i.e., eastern hemisphere, and $>$ W100°, would be well matched for such a comparison. These two ranges compare to the longitude groups of E130° to E06°, and $\geq$ W100° of the survey of [11]. Each longitude group contained 42 events, for which TO and TR were plotted against their associated CME speeds in his Figures 1 and 2. In our Figure 2 we compare the number distributions of SEP events versus TO and TR for these EH and WL hemisphere groups. There is a clear asymmetry in that the EH events are broadly distributed across both time bins while the WL events show sharp decreases with longer timescales. The median CME speed of the EH events, 1374 km s^{-1}, exceeds that of the WL events, 1136 km s^{-1} by about half a standard deviation. However, TO is not correlated with Vcme for either group, and TR correlates only weakly, but equally, r = 0.32, with each group (Table 2 of [11]). Thus the somewhat larger Vcme of the EH group is not a factor in the different distributions of Figure 2.

3. Discussion

SEP events originating from far behind the west limb have been regarded as remarkable for their rapid access to Earth, despite their large longitudinal separations. We have shown that when those events are parametrized in terms of TO and TR and compared with a larger sample of backside SEP events (Figure 1), they appear as representative examples, rather than exceptional events. The interpretation of a broad coronal source region of shock production agrees with observations of associated fast CMEs and with the well known coronal waves observed in the EUV imaging instruments [9, 23, 10].

A perhaps more important question here is the reason for the asymmetry in timescales between the EH and WL SEP events. We argued that the two groups profiled in Figure 3 are approximately equally statistically offset from the average optimum magnetic connection of W50°. The symmetry is broken by the solar rotation, but in the $\sim$ 10 hr timescales encompassing nearly all events of Figure 1, that rotation is $< 6°$. The rotation seems therefore unlikely to produce the dramatic hemispheric difference of Figure 2.

If we suppose that the first SEP injections occur in quasi-radial coronal fields, we might expect little or no difference between the onset intensity profiles of the WL and EH events. In the WL (EH) events the SEPs will arise from shocks at the eastern (western) flanks of propagating CMEs and then follow the interplanetary spiral fields out to 1 AU. A more likely situation is that shocks propagating farther from the corona will see asymmetric fields that give rise to quasi-parallel shocks in the east and quasi-perpendicular shocks in the west.

Another approach to SEP production at shocks is that of [24], who surveyed the longitudinal distributions of peak electron and proton SEP intensities at STEREO-A, STEREO-B, and near-Earth spacecraft for 35 selected events. They fitted their longitudinal distributions with Gaussian distributions, which were generally displaced $\sim$15° from the nominally well connected field lines, therefore favoring longitudes closer to central meridian for each observer. [25] interpreted this result in terms of the location of the shock at the time when the peak intensity is observed at a given position at 1 AU. The nose of the shock was taken as the prime region in which SEPs are produced, so that an observer would see the peak intensity Ip of a SEP event near the time when the shock nose crosses his connecting magnetic field line. As the shock moves outward, its nose crosses increasingly western field lines, implying that the times to peak intensity, comparable to our TR, will be longer for observers to the west, who view the source region to the east. This view is in qualitative agreement with Figure 2 showing the larger TR for EH events, and has been argued in the review by [26].

While [26, 25] have emphasized the location of the shock nose, we have considered that for widely separated source regions, it is the dominance of the kind of shock, quasi-parallel or quasi-perpendicular, that determines the SEP TO and TR event timescales and energy spectra.

4. Summary

A dependence of SEP intensity profiles on the CME/shock source longitude is well known. We first examined the cases of EP documented in the literature for prompt SEP events from the far western backside of the Sun and showed that they are consistent in their timescales TO and TR with a larger population of WL SEP events. An extension of the comparison to EH and WL events showed statistically shorter timescales in addition to the previously established harder energy spectra for the WL events.

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