Coronal and Interplanetary Environment of Large Solar Energetic Particle Events

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Abstract

We studied the properties of coronal mass ejections (CMEs) associated with large solar energetic particle (SEP) events during 1997-2002 and compared them with those of preceding CMEs from the same source region. The primary findings of this study are (1) High-intensity (> 50 protons cm^{-2} s^{-1} sr^{-1}) events are more likely to be preceded by other wide CMEs. (2) The preceding CMEs are faster and wider than average CMEs. (3) The primary CMEs often propagate through the near-Sun interplanetary medium severely disturbed and distorted by the preceding CMEs.

1. Introduction

Shocks driven by energetic coronal mass ejections (CMEs) are thought to be responsible for large solar energetic particle (SEPs) events [6]. Although acceleration of particles by collisionless shocks has been considered for a long time, there is still no widely accepted theory that explains all the observed properties of SEPs. For example, the CME speed and SEP intensity are reasonably correlated, yet the scatter is very large: For a given CME speed, the SEP intensity has been found to vary over four orders of magnitude [3, 4] and there is no satisfactory explanation for this discrepancy. Presence of SEPs in the ambient medium and variations of energy spectra among SEP events are thought to be significant factors that can account for one to two of the 4 orders of magnitude variation in the range of SEP intensities [4]. The source of ambient SEPs could be impulsive flares [5] or preceding CMEs [2]. Preceding CMEs in the near-Sun region can also drastically modify the medium through which CME-driven shocks propagate and hence the characteristics of the shocks themselves. A recent study [3] showed that SEP events of cycle 23 (1997-2001) preceded by wide CMEs within a day were more likely to have higher intensities than those without such preceding CMEs. This paper extends that study to obtain the statistical properties of the preceding CMEs by expanding the data set to the end of 2002.

pp. 3549–3552

Table 1. Properties of Primary and Preceding CMEs

Date/ T2	V2	W2	T1	V1	W1	Loc.	AR	DT	Flux
97/11/04 06:10	785	360	11:11^p	352	122	S14W33	8100	19.0	72
97/11/06 12:10	1556	360	04:20	307	59	S18W63	8100	7.8	490
98/05/02 14:06	938	360	05:31	542	360	S15W15	8210	9.0	150
98/05/06 08:29	1099	190	00:02	786	110	S11W65	8210	8.6	210
98/05/09 03:35	2331	178	13:01^p	432	85	S11W90	8210	14.6	12
00/06/06 15:54	1119	360	15:30	929	90	N20E18	9026	0.3	84
00/07/14 10:54	1674	360	20:30^p	839	62	N22W07	9077	14.7	24000
00/11/24 15:30	1245	360	05:30	994	360	N22W07	9236	10.0	94
01/03/29 10:26	942	360	19:27^p	258	59	N20W19	9393	15.0	35
01/04/02 22:06	2505	244	12:50	731	155	N19W72	9393	9.3	1100
01/04/10 05:30	2411	360	15:54^p	1192	360	S23W09	9415	13.6	355
01/04/12 10:31	1184	360	21:30^p	469	74	S19W43	9415	13.8	51
01/04/15 14:06	1199	167	17:54^p	830	190	S16W71	9415	20.2	951
01/04/26 12:30	1006	360	08:30	740	91	N17W31	9433	4.3	57
01/09/24 10:30	2402	360	21:54^p	633	163	S16E23	9632	13.0	12900
01/10/01 05:30	1405	360	01:54	478	68	S20W90	9628	4.5	2360
01/10/19 16:50	901	360	01:27	558	254	N15W29	9661	15.9	11
02/02/20 06:30	952	360	03:30	813	54	N12W72	9825	3.3	13
02/04/17 08:26	1218	360	11:06^p	496	56	S14W34	9906	21.7	24
02/05/22 03:50	1494	360	00:06	1265	117	S19W56	9948	3.6	820
02/07/15 21:30	1307	111	20:30	1105	360	N19W01	0030	1.2	234
02/08/22 02:06	1013	360	04:06^p	395	70	S07W62	0069	22.6	36
02/08/24 01:27	1878	360	13:27^p	321	103	S02W81	0069	12.3	317
02/11/09 13:31	1793	360	18:30^p	840	62	S12W29	0180	19.2	404

2. Data and Statistics

The starting point of our study is the set of all large SEP events (intensity $\geq$ 10 pfu, with 1 pfu = 1 proton cm^{-2} s^{-1} sr^{-1}) in the > 10 MeV channel of the GOES instrument from 1997 to 2002 that overlapped with the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO) data. Elimination of shock spike and interplanetary (IP) modulation events resulted in 58 SEP events. For each of the 58 events, we identified a unique CME (which we call the primary CME) and compiled its properties such as first-detection time (T2), speed (V2 km/s), width (W2 deg), and the solar source region (AR, NOAA active region). Within one day ahead of the primary CMEs, we looked for wide (width > 60 deg) CMEs originating from the same solar source as the primary CME. For 24 cases, there were preceding CMEs, whose first-detection time (T1, with superscript 'p' indicating that the time corresponds to previous day), speed (V1), width (W1) and heliographic location (Loc.) are listed in Table 1. The last two columns give the preceding time (DT, computed based on surface onsets) and SEP flux (pfu), respectively. T2 and T1 refer to the first appearance in the coronagraph field of view. We excluded 15 events from statistics: 6 had interactions within the occulting disk of the coronagraph, 7 had primary CMEs interacting with streamers, one was completely back-sided, and the solar source could not be identified for one event. The remaining 43 events fell into two groups: 24 with preceding wide CMEs (group 1) and 19 without (group

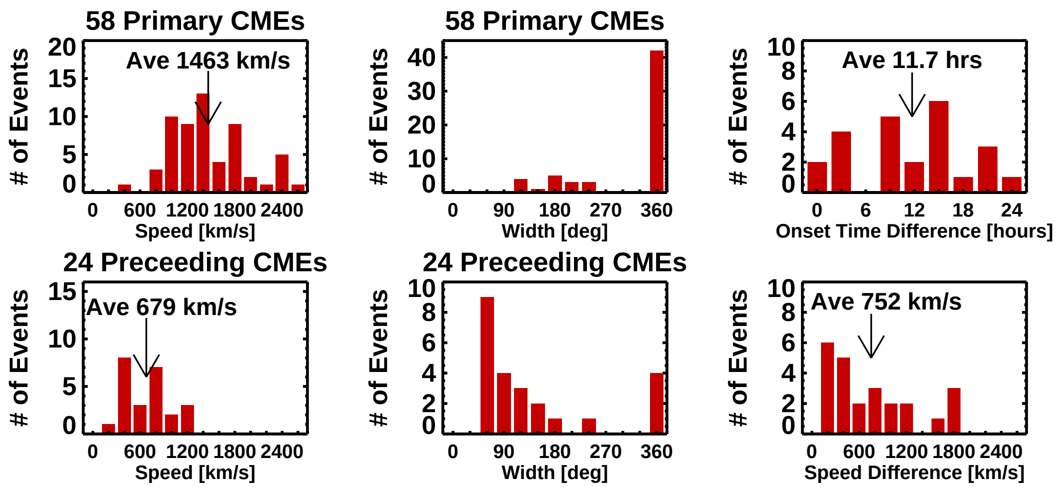

Fig. 1. left: The distributions of speeds of the primary (top) and preceding CMEs (bottom). middle: The distributions of widths of primary (top) and preceding CMEs. right: Onset time difference (top) and approaching speed (bottom). The arrows point to average values of the distribution.

2). From Table 1, we see that the majority (18/24 = 75%) of the group 1 SEP events had flux exceeding 50 pfu. However, only 6 of the 19 (32%) group 2 SEP events had high intensity; the majority (13/19 = 68%) were of low intensity ($<$ 50 pfu). Only three of the 19 group 2 events had flux exceeding 100 pfu, compared to more than half of the group 1 events. Thus, there is a clear tendency that the high-intensity SEP events are more likely to be preceded by wide CMEs from the same solar source within a day.

3. Properties of Preceding CMEs

The speed distributions in Fig. 1 (left) show that the average speed (679 km/s) of the preceding CMEs is smaller than that (1463 km/s) of the primary CMEs. However, the preceding CMEs seem to have an average speed significantly larger than that of the general population of CMEs ($\sim$ 450 km/s). The primary CMEs associated with SEP events are very wide as expected [2]. The majority of the preceding CMEs also seem to have widths well above the lower cutoff (60 deg) used. The preceding CMEs are thus more energetic than average CMEs. These CMEs are likely to accelerate at least a low level of energetic particles, which may serve as seed particles for the shock of the primary CME. The average preceding time (11.7 hrs) and the approaching speed (752 km/s) suggest that the primary CMEs would catch up with the preceding CMEs in the near-Sun IP medium (within about 44 solar radii). It is also important to note that the shock driven by the primary CME is still young and potent around this time and has to propagate through the preceding CME and its aftermath. This means the medium through which the primary CME propagates is highly disturbed and distorted by the preceding CME. The shock becomes weak or strong depending on the magnitude and distribution of the plasma density (n) and magnetic field (B) in the disturbed region because these parameters decide the characteristic speed (Alfven speed Va, since the sound speed is relatively small) of the medium: $dVa/Va = dB/B$ - 1/2 (dn/n). Near the Sun, the density enhancement represented by the preceding CME may be important, which lowers Va and makes the shock strong [1, 2] resulting in higher SEP intensity. Detailed modeling is needed to assess the influence of the disturbed conditions on the transport of SEPs as well as on the shock itself.

4. Discussion and Conclusions

This study finds that: (1) High-intensity (> 50 pfu) SEP events are more likely to be preceded by other wide CMEs. (2) The preceding CMEs are faster and wider than average CMEs. (3) The primary CMEs often propagate through the medium severely disturbed and distorted by preceding CMEs. The selection criteria we used are quite conservative and hence the presence of preceding CMEs must be more common due to the following reasons: (i) There are other narrower CMEs which might interact with the primary, as was shown in [2]. (ii) The requirement that the preceding CME originates from the same active region as that of the primary CME was imposed to make sure that the CMEs interact. Since CMEs are large-scale structures, the coronal volume affected by fast and wide CMEs is generally very large especially at larger heliocentric distances. Therefore, even nearby eruptions can significantly affect particle acceleration and provide seed particles [5]. (iii) There are may events (including the Bastille Day 2000 event) in which two intense eruptions seem to occur close to the Sun and what is seen in the coronagraph field of view is a compound of the two eruptions. In summary, these disturbed conditions need to be incorporated into shock acceleration theories to get a better agreement between theory and observations.
Acknowledgments: Work supported by NASA and NSF/SHINE (ATM 0204588).

5. References

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