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Association of Coronal Mass Ejections and Type II Radio Bursts with Impulsive Solar Energetic Particle Events

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Abstract. We report the association of impulsive solar energetic particle (SEP) events with coronal mass ejections (CMEs) and metric type II radio bursts. We identified 38 impulsive SEP events using the WIND/EPACT instrument and their CME association was investigated using white light data from SOHO/LASCO. We found that (1) at least ~ 28–39 % of impulsive SEP events were associated with CMEs, (2) only 8–13 % were associated with metric type II radio bursts. The statistical properties of the associated CMEs were investigated and compared with those of general CMEs and CMEs associated with large gradual SEP events. The CMEs associated with impulsive SEP events were significantly slower (median speed of 613 km s^{-1}) and narrower (49 deg) than those of CMEs associated with large gradual SEP events (1336 km s^{-1}, 360 deg), but faster than the general CMEs (408 km s^{-1}).

1. Introduction

Solar energetic particle (SEP) events are classified into two classes, impulsive and gradual, on the basis of their abundance, duration, and associated soft X-ray flares (see, e.g. Reames 1999). The gradual SEP events are more intense and longer in duration events and are associated with fast coronal mass ejections (CMEs) (Kahler 2001; Gopalswamy et al. 2002). It is understood that shock waves driven by fast CMEs accelerate these particles. The impulsive SEPs, known as ^{3}He-rich (Z-rich) events, are typically short-lived and are small compared to the large gradual SEPs. The impulsive SEPs are well associated with type III radio bursts. It is thought that the impulsive SEPs are accelerated during flares. Kahler et al. (1985) investigated the occurrence rates of Solwind CMEs and metric type II radio bursts for a sample of 66 ^{3}He-Rich periods observed by the ISEE-3 spacecraft from 1979–1982. Using broad ~ 10 hour windows preceding the ^{3}He-rich interval onsets, they found an association rate of 24 % for type II bursts and 13 % for CMEs, both essentially consistent with random chance as determined by a consideration of adjacent times without ^{3}He enhancements. Thus, it is generally accepted that CMEs and coronal shocks do not play an important role in impulsive SEP acceleration.

However, recently, Kahler, Reames, & Sheeley (2001) reported that an impulsive SEP event on 2000 May 1 was associated with a fast narrow CME observed with the Large Angle and Spectrometric Coronagraph (LASCO) (Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO) spacecraft. Kahler et al. (2001) found 12 candidate CMEs associated with impulsive SEPs and reported those CMEs to be relatively narrow and faint. However, Gopalswamy et al. (2003) found a fast (830 km s^{-1}) and wide (113°) CME associated with an impulsive SEP event on 2001 April 14. There was also metric type II. Therefore, the traditional view on impulsive SEP-CME relationship as well as the revised view of Kahler et al. (2001) needs to be revisited. The LASCO has better sensitivity to detect faint CMEs compared to previous instruments and thus provides us a good opportunity to systematically investigate the CME association with impulsive SEPs. In this paper we report the statistical association of CMEs and type II radio bursts for a large number of impulsive SEP events. We also compare the properties of CMEs associated with impulsive SEP events with those of CMEs linked to large gradual SEP events that occurred over the same interval.

2. Data Selection of Impulsive SEP Events

We examined the time profiles of SEP data from the Energetic Particles: Acceleration, Composition, and Transport (EPACT) instrument (von Rosenvinge et al. 1995) on board WIND spacecraft to identify impulsive SEP events as either those with $^{3}He/^{4}He > 1$ or those with $Fe/O > 1$ and $^{3}He/^{4}He > 0.1$, in the 2–3 MeV/amu region. The selected events were required to show clear onsets with velocity dispersion (earliest arrival of the particles with highest velocity) and to have a He intensity exceeding 10^{-3} (cm^{2} sr s MeV/amu)$^{-1}$. We identified 38 events from January 1996 to April 2002 (see Table 1). To identify the SEP injection at the Sun, we used the associated interplanetary type III bursts observed by the WAVES instrument (Bougeret et al. 1995) on board WIND. In all but 7 cases, there was a unique type III radio burst.

3. CME Association of Impulsive SEP Events

We used the online SOHO/LASCO CME catalog (Yashiro et al. 2004)[†] to search for the associated CMEs. We estimated the CME onset times by linear extrapolation from the projected CME trajectory in the sky plane. We assumed that the CME launch occurred from the heliocentric distance of $1R_{\odot}$ (solar limb). The extrapolated CME onset time is close to the onset of associated X-ray flares and type III bursts. We used a 1.5 hr time windows (1 hr before and 0.5 hr after the onset of type III burst) to identify the associated CME. We also required that the CME be consistent with the flare location.

The time of the first appearance of the CME in the LASCO FOV is listed in col. 5 for SEP events with associated CMEs. Two of the 38 impulsive SEP events (#15 and #33) did not have LASCO coverage. Fourteen of the remaining 36 events were associated with LASCO CMEs. In four of the 14 cases, the association was ambiguous because there were two candidate type III bursts

[†]`http://cdaw.gsfc.nasa.gov/CME_list/`

(noted as b in col. 4 of Table 1). Thus 28 % (10/36) – 39 % (14/36) of impulsive SEP events were associated with CMEs if we only used the LASCO catalog. We examined the LASCO movies again to check for very faint CMEs which were not listed in the CME catalog before this study. We found 6 new faint CMEs (noted by * in col. 5). We also found three obscure brightness changes called "coronal anomalies" (see, e.g. St. Cyr et al. 2000), around the expected time (noted as anomaly). The anomaly classification includes the following types of features: deflection of a streamer, material filling a streamer, remnants of previous CMEs, or faint CMEs. If we include the 6 new CMEs and three anomaly events, the association rate significantly increases: 53 % (15/36) – 64 % (23/36).

Since LASCO observes Thomson-scattered photospheric light, it is difficult to see a faint and narrow CMEs ejected toward Earth (they are far away from the sky plane). Thus the association rate is a lower limit and the true association rate could be higher. In order to check this idea, we examined the locations of Hα flares using the on-line Solar Geophysical Data (SGD). When Hα information was not available, we examined the EUV and X-ray observations obtained by Extreme-ultraviolet Imaging Telescope (EIT) on board SOHO and Soft X-ray Telescope (SXT) on board Yohkoh. We identified source locations (see Table 1, col. 11) for 21 of the 38 SEP events. All but 1 event were located in the western hemisphere, consistent with previous studies (see, e.g. Reames 1999). For events with identified source locations, the CME association rate is high: 70 % (14/20) – 80 % (16/20). The CME association rate is 91 % (10/11) for limb events (longitude $>$ 60 deg) vs. only 44 % (4/9) – 67 % (6/9) for disk events.

3.1. Properties of CMEs Associated with Impulsive SEP Events

The speed of the CME on 1997 Sept 17 (Event #5) could not be measured since the CME had a ragged leading edge. We also excluded the 4 coronal anomalies but included the 4 uncertain events (two type III candidates) in our statistics. We compared the characteristics of the CMEs associated with impulsive SEP events with those of (i) 48 CMEs associated with gradual SEP events observed from 1996 to 2001 and (ii) all LASCO CMEs observed from January 1996 to April 2002. For large gradual SEP events we used the CME data published in Gopalswamy et al. (2002).

Figures 1a–1c shows the speed distributions of CMEs associated with impulsive SEP events, large gradual SEP events, and the general population of CMEs. The median and maximum speed of the impulsive-SEP CMEs are 613 $\mathrm{km\,s^{-1}}$ and 1360 $\mathrm{km\,s^{-1}}$. The speeds of impulsive-SEP CMEs are much smaller than those of the large gradual-SEP CMEs, but the median speed of impulsive-SEP CMEs (613 $\mathrm{km\,s^{-1}}$) is greater than the median speed of all CMEs (408 $\mathrm{km\,s^{-1}}$).

Figures 1d–1f shows distributions of angular widths of CMEs associated with impulsive SEP events, large gradual SEP events, and all CMEs. It is clear that the CMEs associated with impulsive SEP events are much narrower than those of large gradual SEP events: 94 % (44/47) of CMEs associated with large gradual SEP events had a width greater than 130° compared to only 5 % (1/20) for impulsive SEPs. The peak of the width distribution of impulsive-SEP CME is 60° compared to 40° for all CMEs. However, their median widths are nearly identical (impulsive, 49°; all, 51°).

Table 1. Activities associated with impulsive SEP events

Event	Date	SEP time	Type III time	CME time
1	1996 May 14	14:00	11:40	
2	1996 May 15	10:00	07:28	
3	1997 Sep 17	20:00	17:28	18:18*
4	1997 Sep 18	03:00	00:00	
5	1997 Sep 18	22:00	19:52	20:20*
6	1998 May 17	08:00	04:44	
7	1999 Feb 20	06:00	04:00	05:30
8	1999 Feb 20	17:00	15:12	15:54
9	1999 Feb 23	02:00	23:50[p]	
10	1999 Mar 11	02:00	00:04	00:54*
11	1999 Mar 21	08:00	05:56	
12	1999 Mar 21	14:00	12:32	
13	1999 Mar 21	19:00	16:52	
14	1999 Mar 22	22:00	19:24	20:26
15	1999 Jun 18	15:00	11:28	No obs.
			14:00[b]	No obs.
16	1999 Aug 7	20:00	17:04	17:26*
17	1999 Aug 26	01:00	22:28[p]	23:06*[p]
18	1999 Dec 26	20:00	16:16	16:54
			16:54[b]	
19	1999 Dec 27	07:00	01:48	02:06
			03:34[b]	
20	2000 May 1	12:00	10:24	10:54
21	2000 Jun 4	09:00	07:00	07:31
22	2000 Aug 12	14:00	12:40	13:31*
23	2000 Aug 22	03:00	00:16	00:30
24	2000 Aug 22	19:00	18:16	18:30
25	2000 Sep 27	08:00	03:12	03:26
			01:40[b]	
26	2000 Dec 22	08:00	06:08	
			04:44[b]	
27	2000 Dec 28	01:00	23:40[p]	
28	2001 Apr 14	18:00	17:15	17:54
29	2001 Sep 8	12:00	10:04	
30	2001 Sep 22	10:00	05:44	Anomaly
31	2001 Dec 22	02:00	22:19[p]	
32	2002 Feb 4	08:00	04:30	Anomaly
			05:24[b]	Anomaly
33	2002 Feb 5	15:00	11:30	No obs.
34	2002 Feb 25	16:00	15:09	Anomaly
35	2002 Feb 26	20:00	17:04	
36	2002 Apr 14	14:00	07:30	07:50
			12:30[b]	
37	2002 Apr 15	00:00	22:24[p]	23:26[p]
38	2002 Apr 15	05:00	02:50	03:26

[p] Previous day
[b] Second type III burst candidates
* New CMEs (see text)

CPA	Width	Speed	Type II	Flare	Location
			N		
			N		
269	46	613	N	C1.2	S26W70
			N	C1.6	
275	44	—	N	C1.6	S25W90
			N	B5.7	S25W03
265	55	293	Y	C8.2	S21W63
268	49	258	Y	C4.2	S17W71
			N	B7.8	
279	34	319	N	C8.7	S17W63
			N		
			N	B7.4	
			N		
263	13	243	N		
			N	C4.4	N24W90
			N	C1.4	
297	7	577	N		
297	5	624	N		
293	62	339	N	C1.7	N21W26
			N	C2.0	N25W30
283	96	753	Y	M1.0	N24W36
			N		
323	54	1360	N	M1.1	N20W54
295	17	597	N		
318	68	434	N	C3.2	N13W50
307	50	931	N	C2.5	N24W85
318	64	819	N	C2.9	N24W90
309	44	816	N	C9.6	N18W56
			N	C5.2	N17W52
			N		S12E19
			N		
			N		
239	>150	830	N	C1.1	S21W62
			N		
			N	C4.9	S09W65
			N		
			N		S13W20
			N	M2.3	S14W22
			N		
			N		
			N		
326	64	762	Y	C9.6	N19W57
			N		
323	27	294	Y	C7.2	N18W74
319	28	656	N	C9.8	N19W79

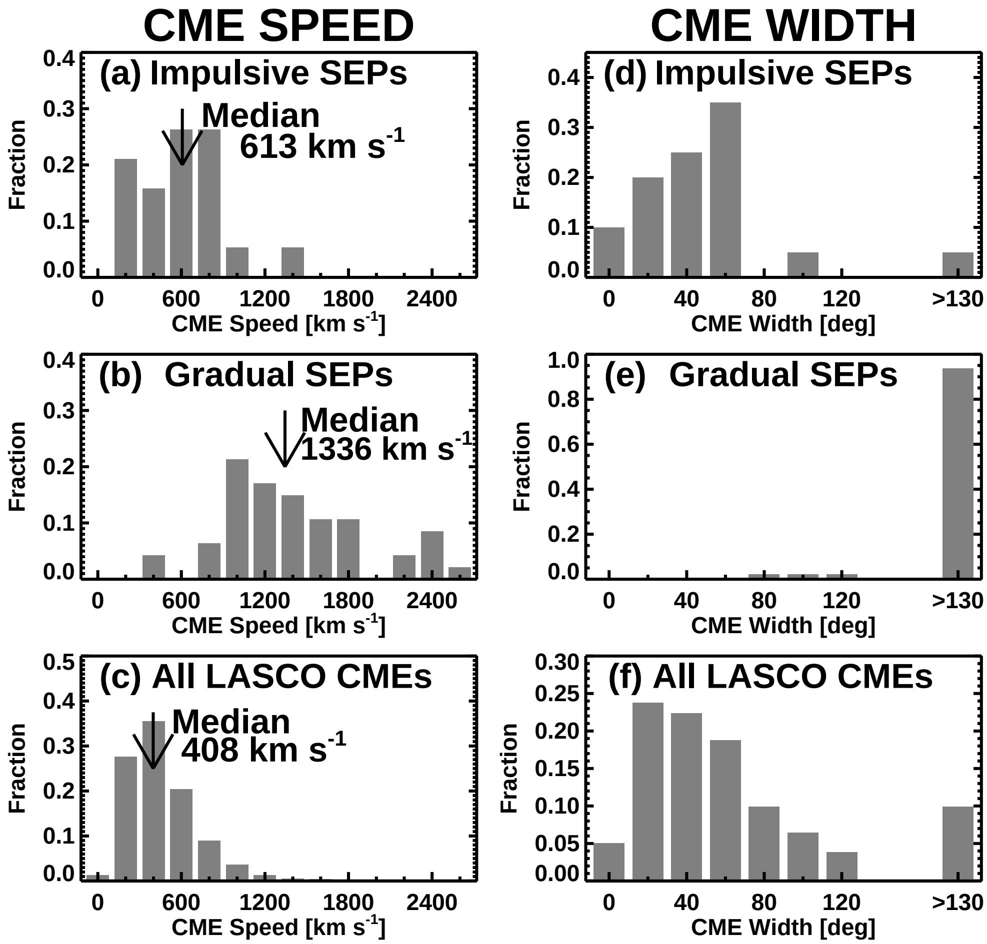

Figure 1. CME speed (a-c) and angular width (d-e) distributions of the three populations of CMEs studied in this paper.

4. Type II Radio Burst Association of Impulsive SEP Events

We also investigated the association of impulsive SEP events with metric type II radio bursts using SGD. This association is given in col. 9 of Table 1. Five of the 38 SEP events were associated with type II bursts although in two of the five cases, the association was ambiguous because there were two candidate type III bursts. Thus only 8 % (3/38) – 13 % (5/38) of impulsive SEP events were associated with metric type II radio bursts. The association rate is much lower than that of large gradual SEP events (71 %) reported by Gopalswamy et al. (2002).

5. Summary and Discussion

We found that the rate of CME association with impulsive SEP events is much larger than previously thought (e.g. Reames 1999). In the familiar table used to describe the two classes of SEP events (Cliver 2000), the percentage of association of impulsive or ^{3}He-rich SEP events with CMEs is usually as zero. As first indicated by the work of Kahler et al. (2001), we have found that the association rate is considerably higher, ranging from 28–39 % to 53–64 %, depending on how broadly one defines CMEs. Moreover, because we would expect a strong visibility effect for the relatively narrow and faint CMEs associated with impulsive SEP events, the rate may be considerably larger since we find that 91 % (10/11) of the limb events in our sample had CME association.

The CMEs associated with impulsive SEP events in our sample have speeds somewhat higher than those of all CMEs (median $\sim 600\ \mathrm{km\,s^{-1}}$ vs. $\sim 400\ \mathrm{km\,s^{-1}}$) but well below those of CMEs associated with large gradual SEP events ($\sim 1300\ \mathrm{km\,s^{-1}}$). The widths of impulsive-SEP CMEs are comparable to those of all CMEs (medians $\sim 50°$), in contrast to the typical large widths of CMEs associated with large gradual SEP events (Gopalswamy et al. 2002). CME width has been found to be an important parameter in deciding whether fast CMEs accelerate particles (Gopalswamy et al. 2001).

There is one important caveat that must be applied, however, to our results. If we assume that every hard X-ray or type III burst represents an impulsive particle acceleration event at the Sun, then it is clear that our sample of 38 events represents only the tip of the iceberg, the largest events in the impulsive SEP distribution. Reames, Meyer, & von Rosenginve (1994) estimates that well-connected impulsive acceleration events occur at the rate of ~ 100 per year vs. ~ 5 per year in our sample. We note that there were 1231 western hemispheric flares listed in SGD for 2001, but only 277 of them were associated with CMEs. Thus since the flare rate greatly exceeds the CME rate, it seems likely that the overall CME association rate may be generally small. Our finding that even the large impulsive events in our sample are poorly associated with type II bursts (8–13 %) is consistent with the view that coronal shocks do not play an important role in impulsive SEP events.

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