

Large solar energetic particle events of cycle 23: A global view

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Abstract. We report on a study of all the large solar energetic particle (SEP) events that occurred during the minimum to maximum interval of solar cycle 23. The main results are: 1. The occurrence rate of the SEP events, long-wavelength type II bursts and the fast and wide frontside western hemispheric CMEs is quite similar, consistent with the scenario that CME-driven shocks accelerate both protons and electrons; major flares have a much higher rate. 2. The SEP intensity is better correlated with the CME speed than with the X-ray flare class. 3. CMEs associated with high-intensity SEPs are about 4 times more likely to be preceded by wide CMEs from the same solar source region, suggesting the importance of the preconditioning of the eruption region. We use a specific event to demonstrate that preceding eruption from a nearby source can significantly affect the properties of SEPs and type II radio bursts.

1. Introduction

The leading paradigm for gradual solar energetic particles (SEPs) is that they are accelerated by fast mode MHD shocks driven by coronal mass ejections (CMEs) in the outer corona and in the interplanetary (IP) medium [see, e.g., *Reames*, 1999]. Consistent with this paradigm, SEP intensities and CME speeds are correlated, although it is not uncommon to find SEP intensities over a range of 4 orders of magnitude for a given CME speed. At least part of this scatter may be explained by the observation that higher SEP intensities result when the ambient medium has elevated levels of SEPs [*Kahler*, 2001]. In fact it was noted long ago that very intense SEP events detected at 0.5 AU by the Helios 1 spacecraft were preceded by precursor SEP events [*Van Hollebeke et al.*, 1990; *McDonald et al.*, 1985]. The important implication of this result is that preceding CMEs can provide seed particles to the succeeding CMEs. The occurrence of preceding CMEs along the paths of CME-driven shocks may have much wider implications than just providing seed particles [*Gopalswamy et al.* 2001; 2002a,b].

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In this paper we assess the implications of large-scale CMEs preceding the primary CME on the resulting intensity of SEP events. We also investigate the relation between radio bursts produced by CME-driven shocks, fast and wide CMEs, major solar flares and SEP events as a function of the solar cycle.

2. Data Selection

The starting point of this study is the list of large SEP events collected for the Living with a Star (LWS) coordinated data analysis workshop (CDAW) held recently in Greenbelt, Maryland (<http://cdaw.gsfc.nasa.gov/LWS>). There were in all 52 events with intensity (I) of > 10 MeV protons exceeding 10 particle flux units (pfu). Since we are interested in the associated CMEs, we excluded 5 events that occurred during down times of the Solar and Heliospheric Observatory (SOHO), which detected the CMEs. We do not consider the minor (1 pfu < I < 10 pfu) events, which are comparable in number to the large ones; information on these could be found in *Gopalswamy et al.* [2002a]. We collected the measured properties of the associated CMEs and identified the solar longitude of the associated flares using the on-line Solar Geophysical Data as well as data from other inner coronal imagers such as SOHO's Extreme ultraviolet imaging telescope (EIT) and the soft X-ray telescope (SXT) on board Yohkoh. Using the on-line catalog of SOHO CMEs (http://cdaw.gsfc.nasa.gov/CME_list) we gathered the properties of other CMEs that occurred in the vicinity of the primary CMEs. Type II radio bursts associated with the SEP events were detected by the Radio and Plasma Waves (WAVES) experiment [*Bougeret et al.*, 1995] on board Wind spacecraft and are listed in the web site <http://www-lep.gsfc.nasa.gov/waves/wavesII.html>. Using these data sets we investigate the solar cycle variation of the global properties of the SEP events and study the preconditioning of the eruption regions.

2.1. SEP Occurrence Rate

Figure 1 shows the occurrence rates (per Carrington rotation (CR)) of SEP events, fast and wide frontside western (FWFW) hemispheric CMEs, major solar flares, and the type II bursts in the decameter hectometric (DH) wavelengths. The FWFWM CMEs drive shocks, which in turn accelerate electrons and protons. The DH type II bursts are due to electrons accelerated by CME-driven shocks that just depart from the outer corona. The number of FWFWM CMEs is comparable to that of the major SEP events during our study period [*Gopalswamy et al.*, 2002c]. The occurrence rate of DH type II bursts and FWFWM CMEs is roughly the same, and larger than the rate of large SEP events. The DH type II bursts can occur anywhere on the Sun, while the SEP events preferentially occur on the western hemisphere.

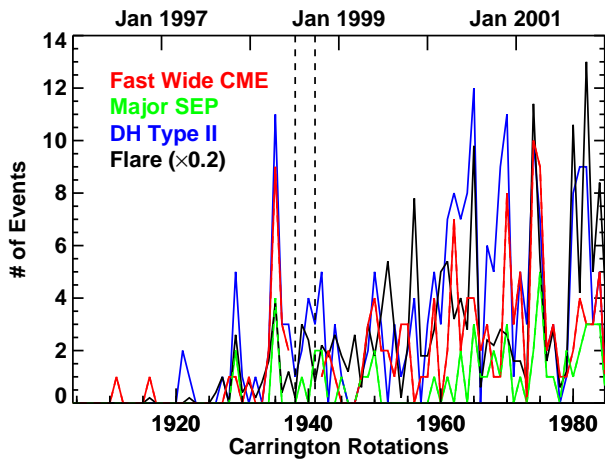


Figure 1. Occurrence rates (per Carrington rotation) of SEPs (red), Fast and Wide Frontside Western (FWFW) CMEs (green), major solar flares (black), and DH type II bursts (blue). No longitude restriction was imposed for flares and DH type II bursts.

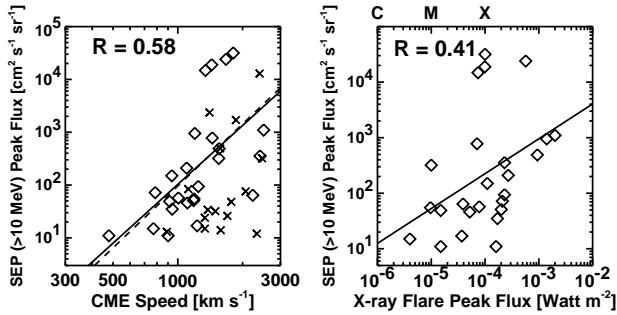


Figure 2. Scatter plot of the SEP intensities of > 10 MeV proton events with CME speeds (left) and X-ray flare size (right). All events are plotted in the left panel, but only the 25 events with $0^\circ < \text{longitude} < 90^\circ$ (diamonds) are included in the correlation. The solid lines are best fits to the diamonds. The correlation coefficients are $r=0.58$ for CME speeds (confidence level 99.9%) and 0.41 for X-ray flux (confidence level 98%). Excluding the outlier CME with a speed of 478 km s^{-1} results in $r=0.54$ (confidence level 99.75%) and the dashed line.

If we include the minor SEP events, and remove the frontside western hemisphere restriction for the FW CMEs, then all the rates are similar. Note that there are two prominent peaks in all the rates: one in April-May 1998 (CR 1935) and the other close to the solar maximum in July-August 2000 (CR 1965). There was also a general paucity of events for several rotations during 1999 when the tilt of the heliospheric current sheet was maximum. The occurrence rate of major (GOES M and X class) solar flares displays an overall similarity to the DH, SEP and FWFWE events as a function of the solar cycle, but differs greatly in details. For example, there were 65 major flares during CR 1982, but there were only 9 DH, 3 SEP and 3 FWFWE events.

2.2. CME speed, Flare Size, and SEP Intensity

One of the basic requirements for shock acceleration is that the CME must be fast enough to drive an MHD shock. The CME speed therefore is of fundamental importance, as

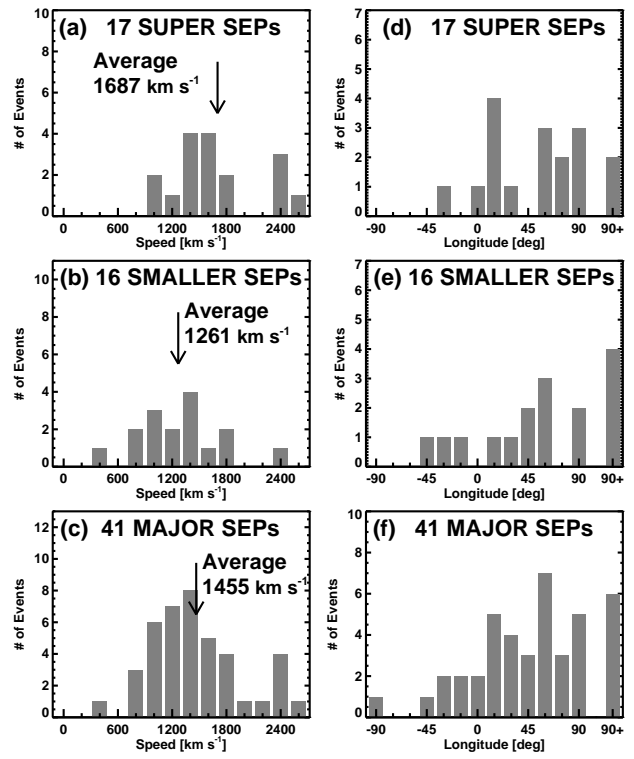


Figure 3. Histograms of speeds (left) and longitudes (right) of high-intensity (SUPER SEPs) and low-intensity (SMALLER SEPs) events compared to all events (MAJOR SEPs).

was demonstrated by the correlation between CME speeds and SEP peak intensities [Reames, 1999; Kahler, 2001]. Since flare observations preceded the CME observations by almost a century, it is inevitable that SEPs have been studied in relation to flares for a long time. Most of the CMEs occur with some level of flare activity especially in soft X-rays. Therefore the three phenomena are closely associated, although the physical relationship is controversial. For the cycle 23 events, the correlation (correlation coefficient $r = 0.58$, see Fig. 2) between the > 10 MeV proton intensity and CME speed turns out to be similar to that obtained in previous studies [Kahler, 2001]. The lowest intensity is 10 pfu (our selection criterion) and the highest intensity was 31,700 pfu (2001 November 4 event at 17:05 UT). Thus we

Table 1. SEP events Preceded by Wide CMEs Within a Day

No.	CME Date/UT	Pre-CME UT	AR	Location	DT (hr)	Flux
1	1997/11/04 06:10	11:11 ^P	8100	S14W33	19.0	72
2	1997/11/06 12:10	04:20	8100	S18W63	16.2	490
3	1998/05/02 14:06	05:31	8210	S15W15	8.6	150
4	1998/05/06 08:29	00:02	8210	S11W65	8.4	210
5	1998/05/09 03:35	13:01 ^P	8210	S11W90	14.6	12
6	2000/06/06 15:54	15:30	9026	N20E18	0.4	84
7	2000/07/14 10:54	20:30 ^P	9077	N22W07	14.4	24000
8	2000/11/08 23:06	?	9213	N10W77	<0.3	14800
9	2000/11/24 15:30	05:30	9236	N22W07	10.0	94
10	2000/11/26 17:06	03:30	9236	N18W38	13.6	940
11	2001/03/29 10:26	19:27 ^P	9393	N20W19	15.0	35
12	2001/04/02 22:06	12:50	9393	N19W72	9.3	1100
13	2001/04/10 05:30	15:54 ^P	9415	S23W09	13.6	355
14	2001/04/12 10:31	13:31 ^P	9415	S19W43	21.0	51
15	2001/04/15 14:06	17:54 ^P	9415	S20W85	20.2	951
16	2001/04/26 12:30	08:30	9433	N17W31	4.0	57
17	2001/09/24 10:30	21:54 ^P	9632	S16E23	12.6	12900
18	2001/10/01 05:30	01:54	9628	S20W90	3.6	2360
19	2001/10/19 16:50	01:27	9661	N15W29	15.4	11

^P Time corresponds to previous day.

[?] Based on EIT eruption at 22:24 UT

are dealing with a range of over three orders of magnitude in SEP intensity from CMEs with speeds ranging from 478 km s⁻¹ to 2505 km s⁻¹. A significant fraction (15%) of the CMEs had speeds exceeding 2000 km s⁻¹, a population not found in previous studies, probably due to the large field of view of LASCO.

We examined the flare size for the 48 events considered in this study. For 6 events, which occurred from behind the limb, the flare might have been occulted by the limb, so it was not possible to determine the X-ray Class. Of the remaining 42 events, 17 were associated with X-class events while 16 were associated with M-class events. There were 8 C-class events. Some of the C-class events were partly occulted so the assigned class may not reflect the actual size of the flare. Two of the C-class events from the western hemisphere were unambiguous. Thus a large majority (79%) of the major SEP events were associated with large (M or X) flares. There is a weak correlation ($r = 0.41$) between the X-ray flare size and SEP intensity (see Fig. 2). The correlation is somewhat poorer than that between the SEP intensity and CME speed (see Fig. 2). This is consistent with the fact that only a small fraction of the major flares is associated with SEP events (see Fig. 1).

3. Preconditioning of the Source Region

It was recently found that most of the SEP-associated CMEs are preceded by other CMEs within a few hours suggesting possible interaction within the field of view of the Large Angle and Spectrometric Coronagraph (LASCO) that observes the CMEs [Gopalswamy *et al.*, 2002a]. Many CME-driven shocks continue to accelerate particles as they propagate into the heliosphere as evidenced by the ‘energetic storm particle’ events, so one has to consider CMEs that preceded the primary CME by more than just a few hours. Large-scale CMEs are likely to produce large changes in the ambient medium above the eruption regions, which we refer to as “preconditioning”. In this paper, we consider the effect of wide (width $\geq 60^\circ$) CMEs that departed from the same source region as the primary CME by about a day earlier. Only the fastest CMEs reach 1 AU within a day, so the normal CMEs are likely to have their leading edge somewhere between the Sun and Earth while being connected to the region of eruption on the Sun.

3.1. Preceding CMEs and SEP Intensity

Out of the 48 SEP events, we have excluded 5 events that had uncertain source location or particle flux and used only 43 in the statistics. We divided the 43 events into 18 low ($I < 50$ pfu) and 25 high ($I \geq 50$ pfu) intensity populations. We searched for all the wide ($\geq 60^\circ$) preceding CMEs that occurred from the same source region as the primary within the preceding 24 hrs. The times of primary and preceding CMEs, NOAA active region and its location at the time of the primary CME, the time separation (DT) between the primary and preceding CMEs, and the proton flux (pfu) are listed in Table 1. When there were more than one preceding CME within 24 hours, we have listed the one closest to the primary CME. For example, the primary CME on 1997 November 4 CME at 06:10 UT (event no. 1) originated from AR 8100 (S14W33). There were two wide CMEs from AR 8100 at 11:11 UT (width = 122° , speed = 352 km s⁻¹) and 05:28 UT (width = 109° , speed = 227 km s⁻¹) on November 3. We have listed the preceding event at 11:11 UT in Table 1. Note that we have not considered narrower ($< 60^\circ$)

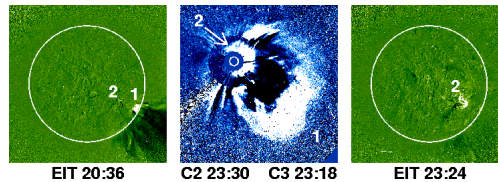


Figure 4. CMEs 1 and 2 observed by SOHO/LASCO as a composite picture using difference images at 23:18 UT (C2) and 23:18 UT (C3) (middle panel) and the source regions from EIT difference images (left and right panels). The white circles represent the optical Sun. CME 2 had occupied the dark region in the middle panel at 22:18 UT.

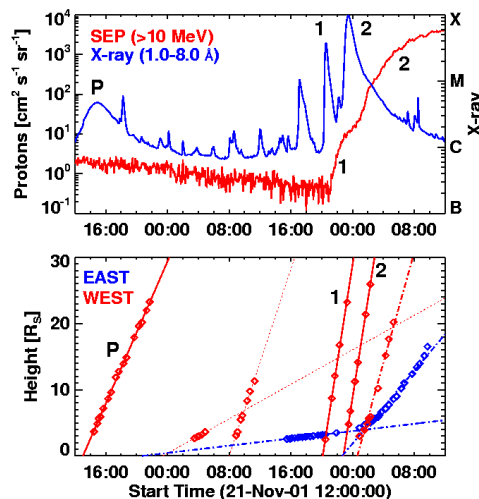


Figure 5. (top) GOES X-ray and proton intensities around the times of the two CMEs (1, 2) on 2001 November 22. The two peaks in the proton intensity and GOES rays corresponding to the CMEs are marked 1 and 2. (bottom) Height-time plots of all the CMEs that occurred above the east and west limb. CMEs 1, 2 and P are discussed in the text.

preceding events. Out of the 19 events in Table 1, there are 16 are high intensity and 3 low-intensity events. Thus, 16/25 (64%) of the high-intensity events and 3/18 (17%) of the low-intensity events were preceded by wide CMEs from the same active region as the primary CME. This suggests preconditioning of the ambient medium overlying the source regions of major SEPs may be a factor in deciding the intensity level reached by the SEPs. If the preceding interval is 36 hours, the fraction of high-intensity events increases to 73%. In order to see if there are differences other than preceding wide CMEs, we have shown the speed and longitude distribution of the highest (> 100 pfu) and lowest (< 50 pfu) intensity events in Fig. 3. The average CME speeds of high- and low-intensity events lie above (1687 km s⁻¹) and below (1261 km s⁻¹) the average (1455 km s⁻¹) speed of all the major SEP events. There is also a significant difference in the longitudes of the high- and low-intensity SEP

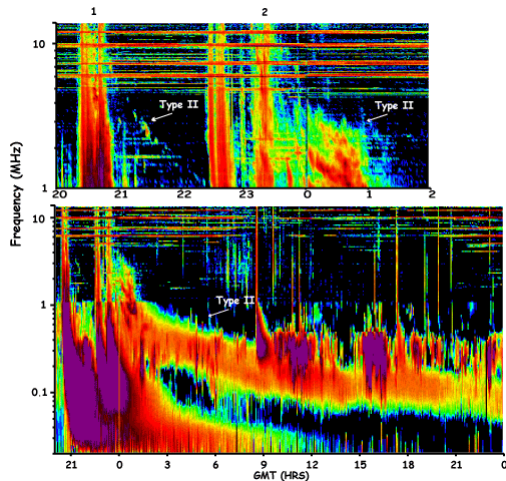


Figure 6. (top) Wind/WAVES dynamic spectrum (1-14 MHz) showing the radio manifestations of the two CMEs (1, 2) of 2001 November 22. An expanded section of the first event is shown on at the top. Type II radio burst (narrow band) from CME1 occurs from 20:30 to 22:30 UT. The second type II starts at 23:00 UT with a huge bandwidth ($\sim 200\%$ at 2 MHz) and continues into the low frequency range (bottom panel) beyond the next day. Broad band enhancement is a typical signature of CME interaction.

populations: a larger fraction of the low-intensity events are poorly connected (eastern longitudes and behind the limb cases).

3.2. Interaction of Nearby Eruptions

Interaction can take place even when the CMEs are from different regions but close enough. This is consistent with the fact SEPs can be observed on field lines more than 90° from the eruption region. Fig. 4 shows an example of two CMEs that lifted off within three hours of each other. CME1 originated from AR 9704 (S25W67) at 20:30 UT and was associated with the M3.8 flare at 20:18 UT. CME2 appeared above the occulting disk at 23:30 UT and originated from AR 9698 (S15W34, associated with the M9.9 flare at 22:32 UT). Thus the two source regions were separated by just 10° in latitude and 33° in longitude. Both were halo CMEs so their true widths are likely to be significantly greater than 60° so interaction between them is expected. The proton intensity shows two peaks (marked 1 and 2 in Fig. 5) corresponding to the two CMEs. There was also a broad enhancement before the two peaks, probably due to the preceding halo CME from AR 9704 and associated with a gradual flare (marked P in Fig. 5). The CME height-time tracks of all the CMEs that preceded the two CMEs illustrate the complexity present in the source region in addition to the interaction between CMEs 1 and 2. Further evidence for CME interaction was found from the Wind/WAVES dynamic spectrum shown in Fig. 6. The radio emission associated with the CMEs consists of the two standard features: a set of complex type III bursts [see, e.g. Reiner *et al.*, 2000] and a type II burst. The two CMEs have almost the same speed (1443 km s^{-1} for CME1 and 1437 km s^{-1} for CME2), yet the type

II bursts are so different. The first type II is close to a normal one with a band width of $\sim 10\%$ [see Gopalswamy, 2000 for a type II burst from a noninteracting CME]. The second type II is extremely broad band ($\sim 200\%$) with a complex structure. The shock of CME1 is propagating through a normal ambient medium while the shock driven by CME2 is propagating through the material of CME1 - a different ambient medium. Since both CMEs are propagating with roughly the same speed, the relative situation must persist for a long time.

3.3. Influence of Background SEP intensity

Kahler [2001] found a weak correlation ($r = 0.28 - 0.36$ for $I > 10 \text{ MeV}$) between the ambient level of SEPs and the peak SEP intensity. For the present events, the correlation was much weaker ($r = 0.15$). Even though the correlation is poor, a large number of events in our sample occurred when the ambient level of SEPs was higher than the instrumental threshold ($\leq 0.1 \text{ pfu}$ for the $> 10 \text{ MeV}$ channel): 37/47 events (79%) had an enhanced background. Of these 37 events, 29 had ambient intensity $> 0.2 \text{ pfu}$. Thus our analysis supports Kahler's suggestion that enhanced ambient SEP intensity may be one of the factors deciding the intensity of SEPs. We must point out that the intensity of the SEPs from preceding CMEs may be significantly higher near the Sun, which may never be observed at 1 AU, as suggested by Van Hollebeke *et al.* [1990] using Helios 1 measurements at a distance of 0.5 AU from the Sun. We have not considered the contribution to the seed particle by preceding flares, which may be relevant from the point of view of SEP composition [Mason *et al.*, 1999].

4. Summary and Conclusions

We have studied the major SEP events of cycle 23 during 1996-2001 using multiwavelength data gathered for the LWS/CDAW held in July 2002. The main results are: 1. The occurrence rates of the SEP events, DH type II bursts and the fast and wide frontside western hemispheric CMEs are quite similar, consistent with the scenario that CME-driven shocks accelerate both protons and electrons. The occurrence rate of major flares, on the other hand, is much higher. DH type II bursts therefore provide an excellent tool for remote sensing SEP-producing CMEs, which constitute only 1-2% of the general population of CMEs. 2. The SEP intensity is slightly better correlated with the CME speed ($r=0.58$) than with the X-ray flare size ($r=0.41$). The correlation between the SEP intensity and the ambient level of SEPs is rather poor. However, a majority of SEP events (79%) occurred when the ambient level of SEPs was higher than the instrumental threshold. 3. CMEs associated with high-intensity SEPs are about 4 times more likely to be preceded by wide CMEs from the same solar source region. Since the magnetic field lines of the preceding CME are still connected to the Sun, they can return accelerated particles back to the succeeding shock for repeated acceleration, essentially modifying the streaming limit. The preceding CMEs may also stretch the field lines overlying the source region, thus temporarily creating a 'quasi-parallel environment' for the shock of the primary CME. 4. Since CMEs tend to exclude SEPs accelerated by their own shocks, neighboring eruptions are more likely to provide seed particles. CME-driven shocks are extended considerably beyond the

confines of the CME itself, which means that eruptions occurring at different locations can influence each other. In summary, a wide range of effects on the observed intensity of SEPs is possible depending on the relative speeds and distances between the primary and preceding CMEs in the interplanetary medium.

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