ENERGETIC PARTICLE ACCELERATION BY CORONAL MASS EJECTIONS

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ABSTRACT

The current paradigm for the source of large, gradual solar energetic particle (SEP) events is that they are accelerated in coronal/interplanetary shocks driven by coronal mass ejections (CMEs). Early studies established that there is a rough correlation between the logs of the CME speed and the logs of the SEP intensities. Here I review two topics challenging the basic paradigm, the recent discovery that CMEs are also associated with impulsive, high-Z rich SEP events and the search for gradual SEP sources other than CME-driven shocks. I then discuss three topics of recent interest dealing with the relationship between the shock or CME properties and the resulting SEP events. These are the roles that CME accelerations, interactions between fast and preceding slow CMEs, and widths of fast CMEs may play in SEP production.

CORRELATIONS OF CME SPEEDS AND SEP PEAK INTENSITIES

The early history of gradual SEP events emphasized their association with solar flares and suggested that SEPs were produced in coronal flares and somehow escaped to interplanetary space from the strong flare-loop magnetic fields of the corona. The discovery of CMEs and their roles in driving interplanetary shocks changed the focus of our understanding of SEP sources (see reviews in Reames (1999) and Kahler (2001a)). One of the enduring signatures of the CME-SEP association is the correlation between the logs of the CME speeds and the logs of the peak SEP intensities for SEPs at tens of MeV energies (Figure 1). We understand this in terms of enhanced SEP production at stronger or faster shocks driven by the fast CMEs (Zank et al., 2000), which exceed the Alfvén and flow speeds of the solar wind. However, the spread of the peak intensities still ranges over several orders of magnitude, indicating that other factors must play important roles in SEP production (Kahler, 2001b). We now must ask what those other factors are and whether there are significant solar contributions to gradual SEPs from sources other than only fast CMEs.

CMES ASSOCIATED WITH IMPULSIVE SEP EVENTS

The basic paradigm of two classes of SEP events (Reames, 1999) associates CMEs with only the gradual SEP events, which are assumed to be produced by shocks driven by sufficiently fast ($v \geq 500$ km s^{-1}) CMEs. The impulsive SEP events are produced in solar impulsive flare events and released into narrow angular ($\theta \leq 30^\circ$) regions of interplanetary space. It was therefore surprising to find an impulsive SEP event on 2000 May 1 that violated the basic paradigm. That SEP event had a relatively short duration and high (> 1) Fe/O and low (~ 10) H/He ratios (Kahler et al., 2001). It was unusually intense for an impulsive SEP event, with a clear increase in 20 MeV protons observed in the Wind/EPACT detector. The SEP event was associated with a compact impulsive X-ray flare at N20 W54 and with a narrow (20°) and fast (960 km s^{-1}) CME observed in the Lasco coronagraph. Kahler et al. (2001) found additional candidates of impulsive SEP events with narrow CMEs by comparing electron onsets of earlier impulsive SEP events with Solwind and Lasco CME listings. Those CMEs were generally narrow and faint and had rather typical CME speeds. A review of the earlier observational evidence by Kahler et al. (1985) against CME associations for impulsive

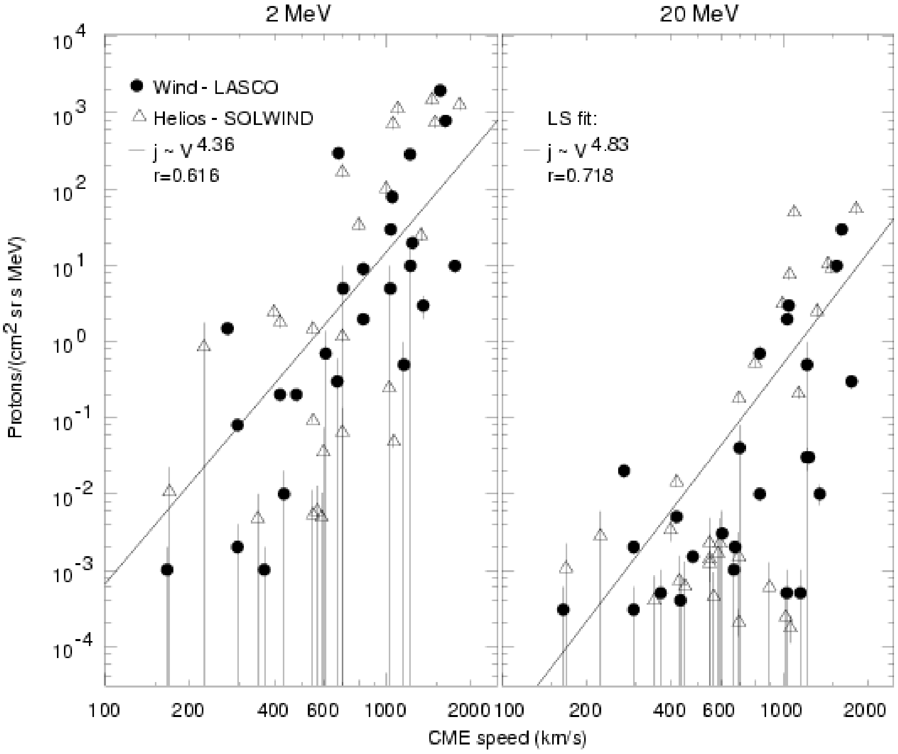

Fig. 1. Proton peak intensities at two different energies versus the associated CME speeds for Wind/Lasco (dots) and Helios/Solwind events (triangles). Diagonal lines are least-squares best fits to the data. From Kahler (2001a).

SEP events showed that their work was based on 10-hour CME-onset windows which showed no statistical increase in CME numbers compared with control periods. The recent work involved good flare associations for the SEP events which could yield precise timing and spatial requirements for CME associations.

The interpretation of the SEP acceleration and transport in those CME-associated events is an interesting challenge for CME models. It is assumed that the impulsive SEPs and accompanying keV electrons escape the corona along open magnetic field lines. CMEs, on the other hand, are presumed to be the eruption of closed field configurations which are generally too slow to drive shocks. Kahler et al. (2001) offered one interpretation of the CMEs in terms of material ejected along open field lines, based on a coronal jet model (Figure 2) of Shimojo and Shibata (2000). There are two significant implications of this interpretation. First, not all CMEs are necessarily closed field configurations, suggesting that there may be two classes of CMEs, one of the classic bipolar closed fields (Low, 2001) and a second of material ejected from a coronal reconnection region through open field regions into space. Second, the CME itself may provide a visible signature of the coronal SEP injection region. Previously, we had only the flare locations and the typical angular extent of $30°$ to $50°$ for impulsive SEPs as guides to the actual injection regions.

Three additional impulsive SEP events have been reported since the discovery of the 2000 May 1 event. St. Cyr et al. (2001) reported a SEP event on 2001 March 10 that was electron rich and associated with a narrow CME. A second event occurred on 2001 April 14 (Tylka et al., 2002). That SEP event was characterized by a high Fe/O ratio throughout the ~ 1 day duration of the event. The associated CME event, however, was not narrow, contrary to our expectations based on the the May 1 and March 10 impulsive SEP events. At this conference Mazur (2002) discussed a recent SEP event on 2002 February 20 that also showed the Z-rich characteristics of an impulsive event. Table 1 shows the relevant CME data for the four impulsive SEP events. In each case I give the Lasco CME speeds and widths reported on the Catholic University web site at http://cdaw.gsfc.nasa.gov/CME_list/. Also included as alternative values are the widths that I measured

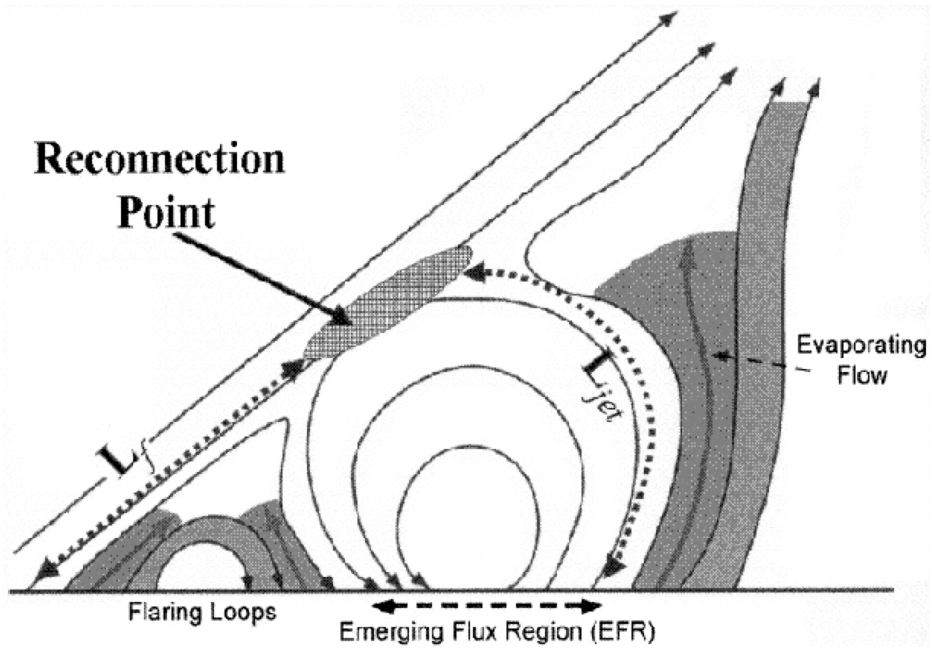

Fig. 2. Reconnection jet model from Shimojo and Shibata (2000), based on magnetic reconnection and a jet. L_{jet} and L_f are the distances from the reconnection region to the flare and associated jet. Kahler et al. (2000) interpreted the source region of the 2000 May 1 impulsive SEP event in terms of this concept, which allows for the escape of both SEPs and coronal plasma along open magnetic field lines.

Table 1. Impulsive SEP Event CMEs

Date	Speed	Width	Flare
2000 May 01	1360 km s^{-1}	54/19°	W54
2001 Mar. 10	819 km s^{-1}	81/29°	W42
2001 Apr. 14	830 km s^{-1}	113/88°	W71
2002 Feb. 20	(990 km s^{-1})	NA/88°	W72

using Lasco C2 subtracted images and the speed that I determined for the February 20 CME. The May 1 and March 10 CMEs are narrow in my measurements, but not so narrow by the web listings. However, there is no doubt that the April 14 and February 20 CMEs are wide by both my and the web values. Note also that both the April 14 and February 20 CMEs occurred relatively close to the solar limb, as indicated by the flare locations, and should be relatively free of projection effects. Thus, we are now confronted with Z-rich SEP events that are associated with a CME that is not only broad, but also sufficiently fast to drive a shock. It is not clear how these SEP events can be fitted into the revised paradigm for impulsive and gradual SEP events discussed above.

ALTERNATIVE SOURCES OF GRADUAL SEP EVENTS

The basic paradigm that gradual SEP events are produced in shocks driven by fast CMEs (e.g., Reames, 1999; Kahler, 2001) has been questioned by several investigators. Klein et al. (1999) examined the SEP and solar radio profiles during two large events in 1989 and argued that acceleration processes in the low and middle corona supply both the particles producing the X-ray, gamma-ray, and radio emission as well as the interplanetary SEPs. In their view the CME shock is not the main accelerator of E $>$ 20 MeV SEPs. Klein and Trottet (2001) emphasized the time-extended particle acceleration that occurs in the corona following the flare impulsive phase. More recently, Kocharov and Torsti (2002) have proposed a three-phase scheme based on their analyses of a number of SEP events with the ERNE particle experiment on the SOHO spacecraft. Phase A is attributed to a high coronal wave generated as a coronal response to the impulse of a CME liftoff (Torsti et al., 2001) and propagating well away from the associated flare/CME site. This phase may be associated with Moreton/EIT waves (Torsti et al., 1999) and produces a hard SEP energy spectrum. Phase B is due to acceleration in the reconfiguration of coronal magnetic fields during or after CME liftoff and after the flare impulsive phase and is characterized by a small injection region. Phase C is the familiar CME-driven shock acceleration. Further alternatives to the classical paradigm are listed by Kahler et al. (2000).

A search for SEPs produced in the magnetic reconnection of coronal arcades following CMEs was carried out by Kahler et al. (2000). They reasoned that while only sufficiently fast CMEs can drive shocks that produce SEPs, there should be many other CMEs that do not drive shocks but are sufficiently large or energetic to leave behind a coronal arcade formed by magnetic reconnection of open field lines with soft X-ray emission and/or a metric noise storm. They examined western hemisphere X-ray arcades in the Yohkoh SXT images (Figure 3) and noise storm sources observed with the Nancay radioheliograph. Five 24-28 MeV SEP events were associated with those arcades/storms, but they all appeared to be shock-associated SEP events. On the other hand, 30 cases of arcades with no detectable SEP events were found, providing evidence against the possibility of coronal-arcade contributions to gradual SEP events.

Although the acceleration of SEPs to GeV energies in magnetic fields of coronal arcades appears to be quite feasible with self-consistent models of reconnecting current sheets (Craig and Litvenenko, 2002; Heerikhuisen et al., 2002), the null result of Kahler et al. (2000) strongly suggests that if they are produced in arcades, the SEPs are not able to escape the corona in significant numbers. Despite their arguments to the contrary, the results also provide evidence against the SEP acceleration phase B as described by Torsti et al. (2001). They relate phase B to coronal field reconfigurations, and speculate that shock waves are involved, but this clearly refers to the location and time when magnetic reconnection in the coronal arcade is most active.

CME DYNAMICS AND SEP EVENTS

Since gradual SEP events are produced in CME-driven shocks, the speeds of CMEs have been seen as the key factor in their association with SEP events (Kahler, 2001a,b). Since the correlation between the logs of CME speeds v and the logs of peak SEP intensities I has so much spread, we look to other CME factors that may contribute to that spread. Here we briefly review three recent developments that bear on this question.

CME Acceleration Profiles

The speed profiles of some CMEs show clear evidence of acceleration. St. Cyr et al. (2000) found that a second-order fit, implying acceleration, was appropriate for 17% of a sample of 640 CMEs observed by Lasco from 1996 to 1998. Kahler et al. (1999) included CME acceleration as a candidate in their study of factors contributing to the spread of log I versus log v but were unable to draw any conclusion about the role of acceleration from their limited data set. Kocharov et al. (2001a,b) took up this challenge with a much larger data set consisting of 542 Lasco CMEs from January 1997 to June 1998 with measured speeds. They selected only CMEs with final speeds of 300 to 800 km s^{-1}, a total of 296 CMEs, and then separated out two groups - one with high accelerations a (A3, or impulsive) and one with low accelerations (A1, or gradual), shown in Figure 4. Their impulsive group consisted of CMEs observed to have constant speeds in the Lasco field of view. They estimated that for the constant-speed, impulsive group $a > 20$ m s^{-2}, with all the acceleration occurring below $\sim$ 2 to 4 Rs, where coronagraph observations began. Their gradual group consisted of CMEs with $a < 10$ m s^{-2}. They compared the SEP event associations of the two CME groups and found that all 19 SEP events of the study were associated with impulsive CMEs. From this they concluded that a high magnitude of the acceleration a is an important factor in the production of SEP events, perhaps because the impulsive CME launch produces coronal shocks which accelerate the first protons seen in interplanetary space.

The Kocharov et al. (2001a,b) study is based on a misconception that most of the acceleration of their

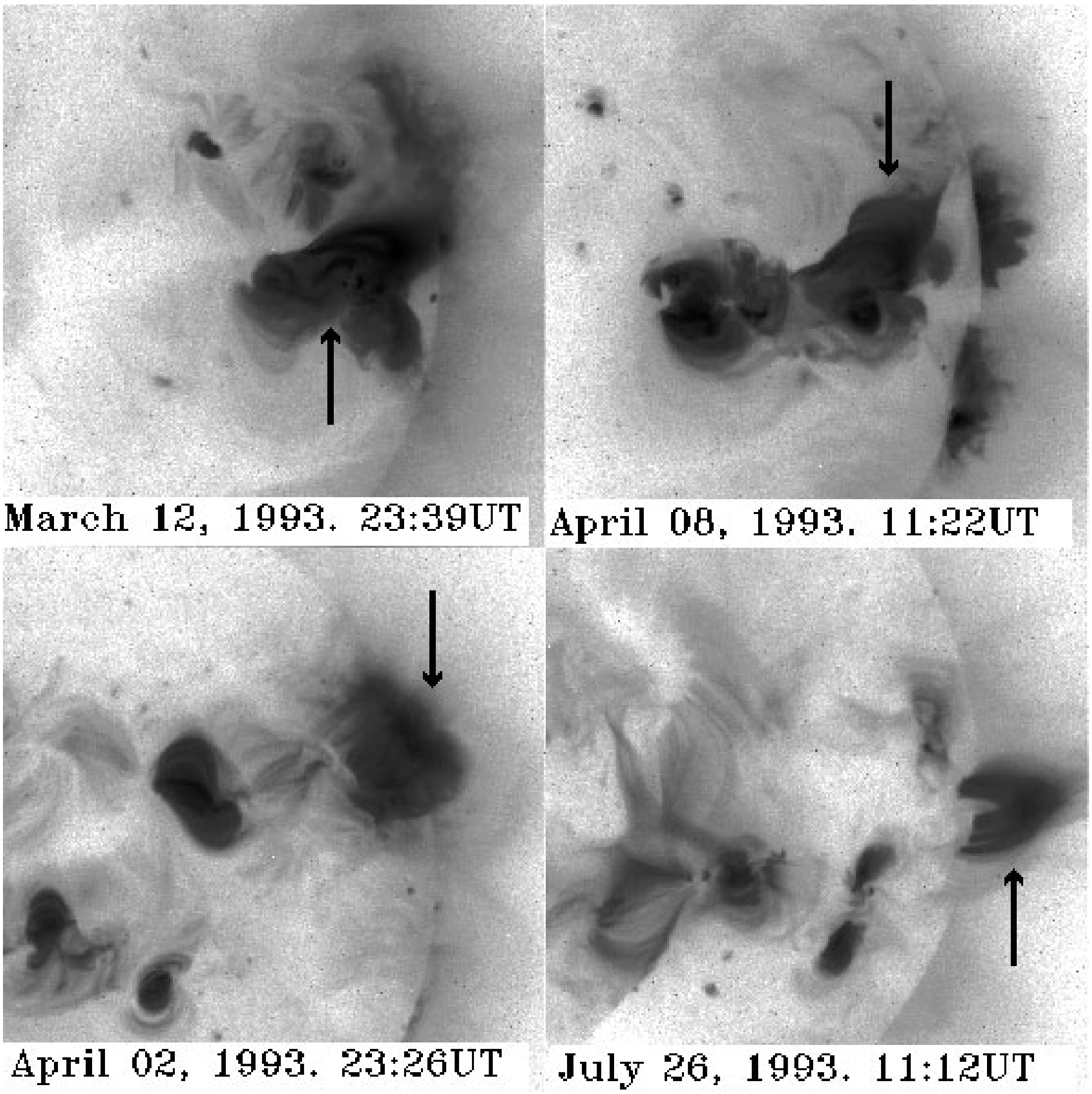

Fig. 3. Top: *Yohkoh* SXT X-ray arcades of two solar flares associated with SEP events of 1993 March 4 (left) and 1993 March 12 (right). Bottom: *Yohkoh* X-ray arcades of two solar flares on 1993 April 2 (left) and 1993 July 26 (right) not associated with SEP events. All four images were taken 4 to 6 hours after the flare peaks. The arcade structures are comparable for the flares with and without SEP events, contrary to what might be expected if the arcades were sources of SEPs. From Kahler et al. (2000).

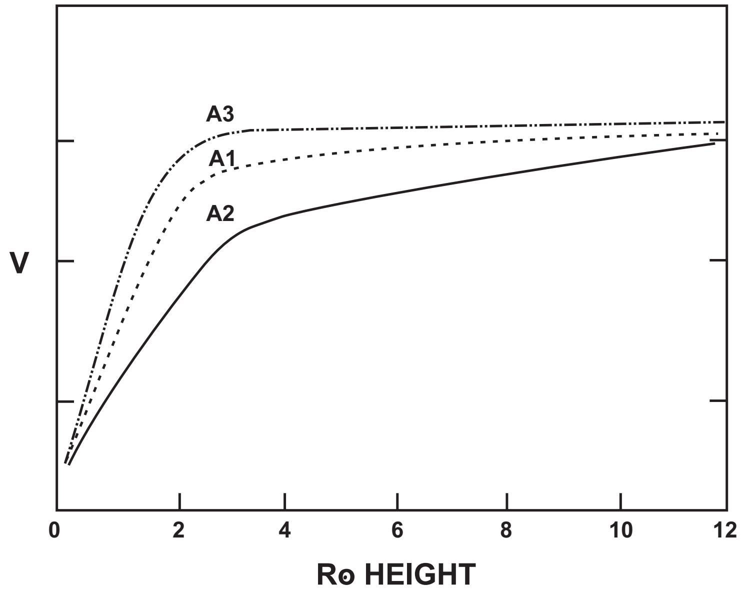

Fig. 4. Schematic speed profiles for the gradual (A1) and impulsive (A3) CMEs of the Kocharov et al. (2001b) study. Most of the acceleration occurs in the low corona for both groups. A2 indicates the speed profiles for those with the largest accelerations in the Lasco field of view.

gradual CMEs must occur in the Lasco field of view. In fact, both the impulsive (their A3) and the gradual (their A1) CMEs of their study must have undergone high accelerations in the low corona, as shown in Figure 4. For a typical gradual CME with a final speed of 500 km s^{-1} and $a = 10$ m s^{-2}, the speed increase over a 3-hr period in the coronagraph field of view is only 108 km s^{-1}, meaning that the initial speed of $\sim$ 400 km s^{-1} must also have been achieved in the low corona. CME accelerations of $\sim$ 50 to 500 m s^{-2} have generally been found in low coronal observations (St. Cyr et al., 1999; Zhang et al., 2001; Neupert et al., 2001). A further problem is that about half of all CME accelerations are negative, with decelerations predominant for faster ($v >$ 400 km s^{-1}) CMEs (Moon et al., 2002). A comparison of the Lasco CME accelerations given at http://cdaw.gsfc.nasa.gov/CME_list/ with those given in the gradual (A1) CME list of Kocharov et al. (2001b) shows at least 9 CMEs with negative accelerations at the web site. Thus, some of their gradual CMEs have undergone even higher low-coronal accelerations than have their impulsive CMEs.

Contrary to Kocharov et al. (2001a,b), their A2 group of CMEs with $a >$ 10 m s^{-2} is not intermediate in acceleration, but an extreme group with the smallest low-coronal acceleration and the highest high-coronal ($\sim$ 3 to 20 Rs) acceleration among their three groups. The important question is how the A2 ($a >$ 10 m s^{-2}) group compares with the A3 ($a = 0$) group, to which Kocharov et al. (2001b) provide details. Their A3 group consisted of 253 CMEs and 19 SEP events, and their A2 group consisted of 20 CMEs and 3 SEP events, showing that CMEs with large high-coronal accelerations can also be associated with SEP events. Although their intermediate (gradual) group with $a <$ 10 m s^{-2} had 43 CMEs and no SEP events, their results do not indicate a significant role for CME accelerations in the production of SEP events. This does not preclude the possible affects of CME accelerations on SEP event spectra or on SEP intensity-time profiles.

Interacting CMEs

The basic paradigm of SEP acceleration in CME-driven shocks assumes that a single fast CME drives the shock through the corona and solar wind. A recent study of Gopalswamy et al. (2002) found that

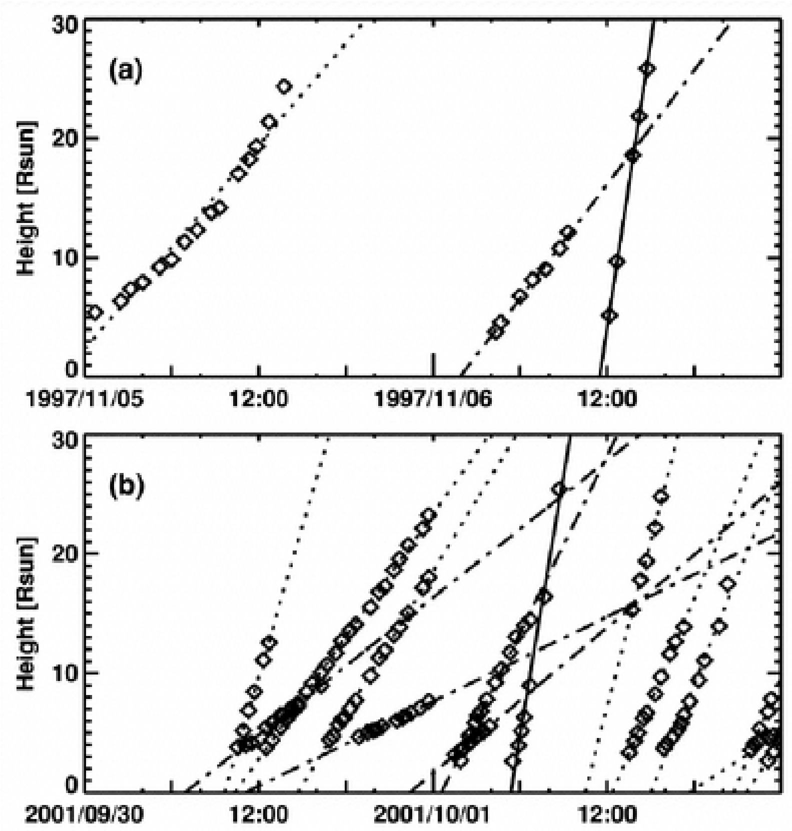

Fig. 5. Height-time plots of Lasco fast CMEs associated with SEP events (solid lines) and the preceding slow CMEs with which they interact (dashed-dotted lines). From Gopalswamy et al. (2002).

fast CMEs associated with large SEP events had very high probabilities of undergoing interactions with preceding slower CMEs (Figure 5). The speeds of the latter CMEs did not appear to be important to this result. The authors found that 22 of 26 major SEP events were associated with CME interactions. Looking at minor SEP events, 13 of 16 were associated with interactions. In a sample of fast ($v > 900$ km s^{-1}) and wide (60°) western CMEs without associated SEP events 6 of 10 were associated with interactions. These statistics do not clearly support a role for CME interactions in SEP production, so the results must be confirmed with further studies.

If the CME interactions are important for SEP events, then several questions are raised with this result. The first is one of timing. Preceding CMEs depart the corona on average 7 hours prior to the primary CME and the leading edges overlap at about 21 Rs. SEP injection appears to begin close to the time of SEP onset (Kahler, 1994), so it might appear that the effect of SEP production precedes the important causal CME interaction. Why is the initial SEP injection so early, and if there is a second, enhanced SEP production in the CME interaction, do we see evidence of that production? Gopalswamy et al. (2002) suggest that the composition of the seed particles will be different inside the preceding CME from that of the normal solar wind, so compositional changes in SEP events should be observable, even though we see no changes in the SEP intensity-time profiles attributable to the CME interactions.

Second, if we suppose that the plasma β of the preceding CME is lower than that of the surrounding solar wind, then the Alfvén speed will be enhanced in the CME, making shocks weaker or less likely to occur, rather than stronger or more likely. A 2.5-d MHD model of a shock overtaking a preceding magnetic cloud was modeled by Vandas et al. (1997). They found that the magnetic field increase and particle density decrease in the preceding cloud resulted in an increase in the Alfvén velocity by an order of magnitude. Furthermore, the penetrating shock wave slowed down and transferred part of its energy to the cloud.

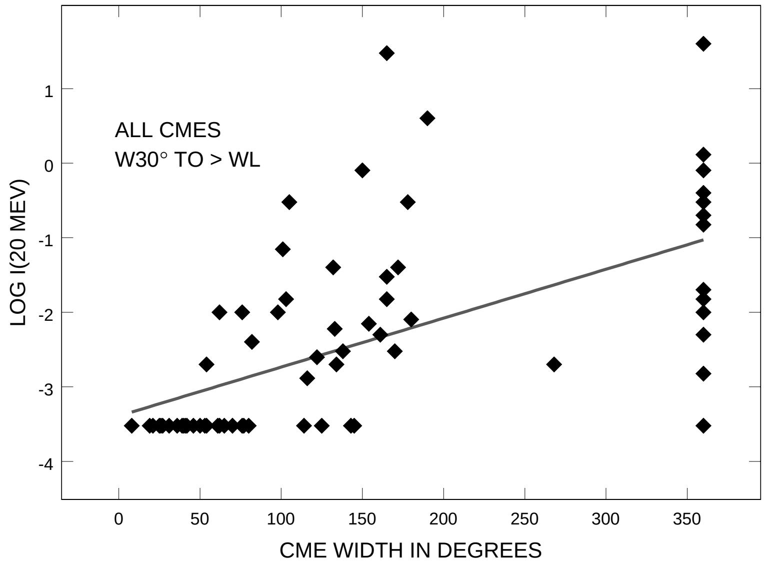

Fig. 6. Plot of log I(20 MeV) versus CME width for the 75 CMEs with solar source associations from W30° to behind the west limb. Of the 23 CMEs with widths less than 60° only one, on 2000 May 1, was associated with a SEP event, which was an impulsive SEP event. The halo events are the points at 360°. The diagonal line is the least-squares best fit to the data. From Kahler & Reames (2002).

Their work suggests that shock acceleration of SEPs would be inhibited, not enhanced, in the region of the preceding CME.

A third problem is that the magnetic topology of CMEs is presumed to be primarily closed, at least early in the CME development, so any SEPs produced in the preceding CME itself would be magnetically trapped in the CME. This suggests that the SEP propagation away from the shock would be diminished, not enhanced at 1 AU. If confirmed, CME interactions could reveal considerable insight into SEP production and propagation, but the questions raised here indicate the need for a clear confirmation of the results of Gopalswamy et al. (2002). Their study reminds us that the shocks driven by fast CMEs propagate into a solar wind of complex transient and long-lived flows which may have important affects on SEP production and propagation.

Widths of Fast CMEs

In a recent study of fast ($v > 900$ km s^{-1}) CMEs and SEP events Kahler and Reames (2003) plotted log I(20 MeV) against the CME widths, as shown in Figure 6. The narrowest CME associated with a SEP event had a width of 54°; that CME was associated with an impulsive Z-rich SEP event on 2000 May 1 (Kahler et al. 2001). If we count the May 1 CME as not associated with a SEP event, then all 23 CMEs narrower than 60° are not SEP-associated. On the other hand, only 2 of the 16 halo (360°) events were not SEP-associated. The lack of an association between the narrow fast CMEs and gradual 20-MeV SEP events suggests an intrinsic limitation of the ability of those narrow CMEs to drive the shocks that accelerate SEPs.

Such a limitation was also suggested in the result of Gopalswamy et al. (2001) that only 6 of 101 CMEs associated with decametric-hectometric (DH) type II radio bursts, attributed to coronal/interplanetary shocks, were narrower than 60°. Further, the average width of 142 fast ($v > 900$ km s^{-1}) CMEs limited to widths $< 200°$ and not associated with DH type II bursts was only 66°. Thus, while we found many fast, narrow CMEs not associated with gradual SEP events, Gopalswamy et al. (2001) also found a large population of fast, narrow CMEs unassociated with DH type II bursts.

It is not clear why the narrow CMEs, despite their high speeds, are apparently unable to produce shocks and SEP events. One possibility is that the speed measured at the leading edge of a narrow CME is characteristic of only a small part of the CME as a whole. A new CME analysis tool has been developed by Berghmans et al. (2002) which uses a Hough transform to convert an $[r, \theta, t]$ coronagraph image data cube into a $[v, \theta, t]$ data cube in which CMEs are represented by a cluster of points. That representation can then be used to find the variations of v across the angular extents of CMEs. The characterization of the calculated CME latitudinal speed profiles may be important for their capability for driving shocks.

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