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Coronal/Interplanetary Factors Contributing to the Intensities of E $>$ 20 MeV Gradual Solar Energetic Particle Events

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Abstract

Gradual solar energetic particle (SEP) events are produced in coronal and interplanetary shocks driven by fast coronal mass ejections (CMEs). There is a correlation between peak $\sim$ 20 MeV proton intensities of SEP events at 1 AU and the associated CME speeds measured in coronagraph white light images. However, a considerable scatter is found in that correlation, suggesting that factors other than CME speeds play significant roles in the production of SEP events. To search for these additional factors, we use peak 28 to 43 MeV proton intensities of 17 SEP events from IMP-8 and associated west limb CMEs from SMM with a restricted 650 to 850 km/s CME speed range. Despite the narrow CME speed range, the 17 SEP events ranged over more than 4 orders of magnitude. We find that the SEP intensity does not depend on the CME latitude or even whether the CME lies in the ecliptic plane. SEP intensities are also independent of CME location in or out of coronal streamers. There is a weak correlation of SEP intensities with CME angular width and a strong correlation with ambient SEP intensity.

1 Introduction

The acceleration of charged particles to MeV energies in solar events remains a poorly understood topic. Over the last two decades we have understood that solar energetic particles (SEPs) observed at 1 AU arise in two kinds of sources - solar flare impulsive phases and coronal/interplanetary shocks driven by coronal mass ejections (CMEs)(Reames, 1997; 1999). SEP events from shocks are marked by durations of days, a broad range of inferred solar source longitudes, the dominance of protons over electrons, ionization states characteristic of the ambient corona, and the occurrence of fast CMEs.

CMEs are transient expulsions of mass and magnetic fields from the solar corona. An example of a CME is shown in the sequence of images of Figure 1. Several thousand CMEs have been observed by various space-borne white-light coronagraphs, and their properties, such as solar event associations, speeds, angular widths, masses, structures, and apparent solar latitudes, have been determined (Hundhausen, 1993, 1997; Webb, 1998).

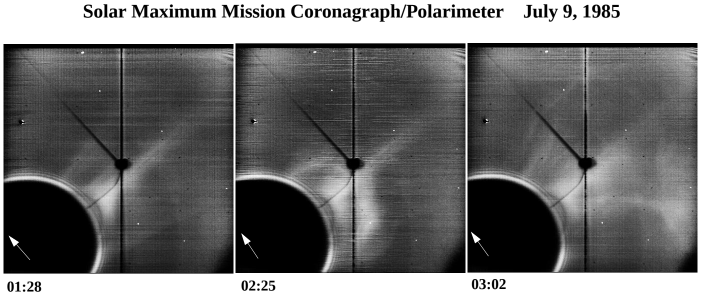

Figure 1: A SEP-associated CME observed on the solar west limb on 9 July 1985. White arrows point to solar north; dark lines are detector artifacts. The occulting disk extends to 1.6 Ro. The pre-CME coronal streamer appears at 0128 UT. The CME appears as a bright loop over a cavity centered near the streamer at 0225 UT. At 0302 UT the loop has moved to the edge of the field of view in the upper right. The speed of the leading edge of the loop was 690 km/s (Burkepile and St. Cyr, 1993).

Studies of CMEs from the Skylab, Solwind, and SMM coronagraphs have shown a close association of SEP events with the fastest (v $\geq$ 400 km/s) CMEs (Kahler, 1996). The higher the speed of an optimally located CME, the higher is the probability of an accompanying gradual SEP event. The basic picture is that when the speed of a CME exceeds the local fast-mode Alfven wave speed, the CME drives a shock at which SEPs are produced. Supporting this idea is the result that fast transient interplanetary shock waves are also well correlated with fast and massive CMEs (Cane et al., 1987). Furthermore, gradual SEP events can occur in the absence of solar flares (Kahler et al., 1998), and Hundhausen (1987) has argued that solar flares are not drivers of CMEs. Thus, the recent study of gradual SEP events has focused on fast CMEs and shocks (Cane, 1997; Reames, 1996; 1997; 1999).

The best correlation between SEP intensity I and CME speed v has been found to be that between log I and log v, but for a given value of v there is still a considerable spread of event intensities I that indicate that factors other than CME speed are important for the production of SEPs. Our goal here is to look for evidence of those other factors. We consider the following:

1. The CME width. A wider CME may drive a spatially broader shock.

2. The displacement of the CME from the ecliptic plane. Let α be the smaller of the two angles between the ecliptic plane and one edge of the CME. A high latitude CME with a small value of α may produce only a weak shock in the ecliptic plane. For a CME lying out of the ecliptic plane α = 0. Note that α refers to the solar equator, but this displacement is $\leq 8^\circ$ from the ecliptic plane.

3. The location of the CME relative to the heliospheric current sheet or to coronal streamers. A CME in a dense, slow solar wind of a streamer may drive a shock stronger than a CME in a tenuous, fast wind regime.

4. CME acceleration. An accelerating CME may produce a shock later than a CME with a constant speed.

5. Ambient SEP intensity. A high background of SEPs may provide seed particles for the shock.

6. Ambient solar wind speed. A slow solar wind speed measured at 1 AU may indicate that the shock near the Sun is also being driven through slow wind and hence is stronger.

7. Mean shock transit speed. The CME speed may not be a good indicator of the shock speed; the mean transit speed inferred from arrival at 1 AU may be better.

Our basic approach here is to consider these various factors for a group of fast CMEs with a fairly narrow range of speeds. This should minimize the effects of the speed variation and allow us to look for other factors important in producing SEPs.

2 Data Analysis

We first looked for $28 < E < 43$ MeV proton SEP events observed with the GSFC particle detector on the IMP-8 spacecraft during the periods of operation of the HAO Coronagraph/polarimeter on the SMM spacecraft in 1980 and from 1984 to 1989. We also considered all fast ($v > 500$ km/s) west limb CMEs with solar flare associations that indicated a west hemisphere connection to Earth and a possible SEP event. This yielded a total of 33 CMEs with plane-of-sky speeds ranging from 346 km/s to 2100 km/s and associated flares located between W20° and W100°. While the expected correlation was found between peak SEP intensity and CME speed, 17 of the CMEs were in the relatively narrow speed range of 650 to 850 km/s with associated SEP intensities extending over more than four orders of magnitude.

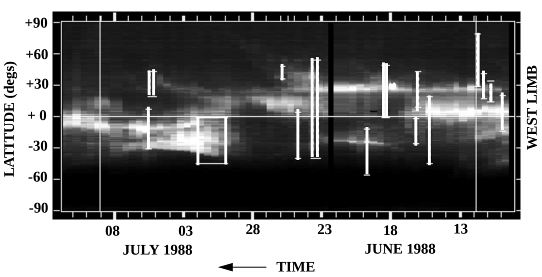

Figure 2: A white light synoptic map of the Sun for one rotation made from coronagraph intensity profiles at a height of 2.8 Ro above the west limb. The bright horizontal streaks are the streamers. Vertical bars show the times (increasing to the left) and latitudes of the CMEs. The CMEs of 15 and 24 June 1988 from the table are shown with other CMEs.

The events are listed in the table in decreasing order of peak 28 to 43 MeV intensities I, in units of counts/cm^{2}s·sr·MeV, to facilitate the search for trends with other variables. The upper limits of some SEP intensities, result from background values and the lower limits from data gaps. The CME full widths and α (defined above), both in units of degrees, are given in the third and fourth columns. In the fifth column we show whether the location of the CME lay in a white light streamer (SR) or on the Stanford source-surface current sheet (CS). We used synoptic maps of coronal brightness generated from the SMM coronagraph images, such as that shown in Figure 2. The CME positions, shown as vertical bars, could be compared with the locations of the streamers. We also compared the

Table 1: SEP EVENT DATES AND PARAMETERS

Date	log I	width	α	streamer	accel.	bkgd	V_{SW}	T_{shock}	flare
18/3/89	>0.4	62	0	–	acc 1.3	2.5	500	NONE	– W75
15/8/89	0.22	95	20	–	2 pt	2.6	620	NONE	X1 W73
7/2/86	-0.06	82	32	SR/CS	1 pt	2.5	480	2.07	M5 W21
9/7/85	-0.09	100	33	CS	2 pt	–	610	2.16	M3 W25
17/3/89	-0.1	33	0	SR/CS	lin 1.3	–	N.A.	1.10	X6 W61
25/3/88	-0.62	54	10	SR	1 pt	–	N.A.	NONE	C3 W90
7/11/87	-1.22	43	0	–	1 pt	–	N.A.	NONE	M1 W100
21/1/85	-1.22	100	50	SR/CS	2 pt	–	N.A.	1.08	X5 W40
4/5/86	>-1.85	70	30	SR/CS	lin 1.2	–	460	NONE	M1 W90
15/6/88	>-2.4	65	21	SR	2 pt	–	460	NONE	C3 W54
19/8/87	<-2.7	86	36	SR/CS	lin 0.3	–	420	4.23	C9 W47
18/1/89	>-2.92	81	12	SR/CS	lin 0.8	–	N.A.	2.05	X1 W67
25/3/80	-3.14	15	0	–	lin 1.2	–	350	NONE	C8 W25
20/2/88	-3.44	65	20	SR/CS	2 pt	–	N.A.	NONE	M1 W71
24/6/88	>-4.	45	6	–	2 pt	–	500	NONE	X4 W52
7/4/80	-4.	81	0	–	lin 1.0	0.5	480	2.00	M9 W75
2/5/85	<-4.	40	20	CS	2 pt	–	N.A.	NONE	M3 W86

CME locations with the published Stanford source surface maps. The sixth column, labeled ”accel.”, indicates that the speed profile of the CME leading edge was fitted with only one or two coronagraph images (1 pt or 2 pt) or that a linear (lin) or accelerating (acc) profile was the better fit to the height-time plot. The one-point fits were done using a CME start time at the onset of the associated X-ray flare. The linear or accelerating preference is followed by the ratio of the final accelerating speed to the linear speed.

The seventh column of the table (”bkgd”) indicates the 20 to 80 MeV background counting rate prior to the SEP event onset. The logs of the background counting rates were < 0 unless otherwise indicated. The eighth column gives the solar wind speed V_{SW} in km/s measured near the time of the peak of the SEP event. The ninth column gives the transit time T_{shock} in days and hours for the shock to reach the Earth, determined primarily from SSCs at the Earth. The last column gives X-ray flare size and longitude.

3 Results

1. The CME width. We find a weak correlation coefficient of r = 0.28 between log I and the CME width. Hundhausen et al. (1994) found a weak correlation of r = 0.21 between the speeds and widths of all SMM CMEs, suggesting that a correlation of log I with width would follow only because of correlations between log I and speed and between speed and width. However, the correlation between speeds and widths for our 17 events is only r = 0.008, suggesting that the CME width may play some role independently of the CME speeds. The width correlation is weak, however, so we are not claiming CME width as a significant factor.

2. The displacement of the CME from the ecliptic plane. The parameter α in the table shows no obvious relationship to log I, somewhat surprising, since some CMEs lie completely out of the ecliptic plane.

3. The location of the CME relative to the heliospheric current sheet or to coronal streamers. More than half of the CMEs occurred in a white light streamer (SR) or on the computed current sheet (CS) location, but we find no correspondence of SEP intensities with those locations. Combining this result with (2) above, we conclude that the location of the CME either in latitude or relative to the current sheet is not an important factor for SEP intensity.

4. CME acceleration. The observing cadence and coronagraph field of view were often inadequate to obtain good speed profiles of the fast CMEs we are considering here. The limited data of the table do not show evidence for a distinction between accelerating versus constant speed profiles.

5. Ambient SEP intensity. The three most intense events of the table all occurred during a high SEP background from previous events. The weak event on 7/4/80 was enhanced by only a factor of 3 to 5 above background. This appears to be the most significant factor for high SEP intensities in this study.

6. Ambient solar wind speed. Only 10 solar wind speeds available but no obvious correlation.

7. Mean shock transit speed. Only 7 transit times determined and no obvious correlation.

4 Discussion

We have examined the properties of SEP events and associated CMEs with speeds in the narrow range of 650 to 850 km/s to look for factors in addition to CME speeds that govern the peak intensities of the SEP events. We had expected that CMEs erupting into the slow solar wind would drive stronger shocks than those erupting into the fast solar wind. Since the solar wind is generally slowest around the streamer belt, we looked for a difference of associated SEP intensities between CMEs in streamers and those out of streamers. We found no difference between the two groups. More surprising is that the CMEs need not occur in the ecliptic plane to be associated with SEP events at Earth. The results here indicate that the latitude and the coronal environment of the CME are not significant factors for SEP production.

The most significant association of the SEP intensities is that with the background intensities of the SEPs prior to the CME. The three largest SEP events of the study were the only ones to occur when the background was substantially enhanced above background. The largest SEP event of this study, on 18 March 1989, was studied in some detail by Kahler (1993), who found that the combined SEP event following two CMEs from different source regions on 17 March and 18 March had an unusually long rise time to maximum through which the $E > 10$ MeV proton spectrum continued to harden. A similar pattern was observed following a pair of CMEs on 12 August 1989, again from separate source regions. The CME of our study on 15 August 1989 occurred in the same region as the first CME on 12 August. Another large CME with undetermined speed occurred in the same region at about 0130 UT on 16 August and was associated with a ground-level neutron monitor event. These episodic events could be simply the result of a sequence of strong shocks driven by fast CMEs, but our results suggest that the ambient SEP level is an important factor either as a seed population for the new CME shock or because of some enhancement resulting from particles interacting with two shocks in space.

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