Do Interacting Coronal Mass Ejections Play a Role in Solar Energetic Particle Events?

S. W. Kahler
Air Force Research Laboratory, Space Vehicles Directorate, 3550 Aberdeen Ave., Kirtland AFB, NM 87117, USA
stephen.kahler@kirtland.af.mil
and

A. Vourlidas
Space Sciences Division, Naval Research Laboratory, Washington, DC 20375, USA

ABSTRACT

Gradual solar energetic ($E > 10$ MeV) particle (SEP) events are produced in shocks driven by fast and wide coronal mass ejections (CMEs). With a set of western hemisphere 20-MeV SEP events we test the possibility that SEP peak intensities, Ip, are enhanced by interactions of their associated CMEs with preceding CMEs (preCMEs) launched during the previous 12 hours. Among SEP events with no, 1, or 2 or more (2+) preCMEs we find enhanced Ip for the groups with preCMEs, but no differences in TO+TR, the time from CME launch to SEP onset and the time from onset to SEP half-peak Ip. Neither the timings of the preCMEs relative to their associated CMEs nor the preCME widths W_{pre}, speeds V_{pre}, or numbers correlate with the SEP Ip values. The 20-MeV Ip of all the preCME groups correlate with the 2-MeV proton background intensities, consistent with a general correlation with possible seed particle populations. Furthermore, the fraction of CMEs with preCMEs also increases with the 2-MeV proton background intensities. This implies that the higher SEP Ip values with preCMEs may not be due primarily to CME interactions, such as the "twin-CME" scenario, but are explained by a general increase of both background seed particles and more frequent CMEs during times of higher solar activity. This explanation is not supported by our analysis of 2-MeV proton backgrounds in two earlier preCME studies of SEP events, so the relevance of CME interactions for larger SEP event intensities remains unclear.

Subject headings: acceleration of particles—Sun: flares—Sun: particle emission—Sun: coronal mass ejections (CMEs)

1. INTRODUCTION

1.1. SEP Events and CMEs

The production of large solar energetic ($E > 10$ MeV) particle (SEP) events is associated with interplanetary shocks driven by fast ($V \gtrsim 900$ km s^{-1}) and wide ($W > 60°$) coronal mass ejections (CMEs) (Kahler & Reames 2003, Gopalswamy et al. 2008, Li et al. 2012a, Reames 2013). The logs of the SEP event peak intensities Ip correlate with both V and W (Cane et al. 2010, Miteva et al. 2013) of the associated CMEs, but the high degree of scatter in these plots indicates the importance of other factors in the SEP acceleration process. The shock seed population, very likely consisting of ambient suprathermal (Mewaldt et al. 2012) or enhanced SEP (Kahler 2001, Cliver 2006) particles, is one such factor.

1.2. CME-CME Interactions

An enhanced SEP peak intensity Ip may also result from the interaction of a fast primary CME with a preceding CME (preCME). This possibility was first explored by Gopalswamy et al. (2002) using a set of $E > 10$ MeV proton events observed with the GOES satellite and associated with fast CMEs. They first selected 43 major (Ip ≥ 10 pfu (1 particle cm^{-2} s^{-1} sr^{-1})) and 39 minor (1 pfu $\leq$ Ip < 10 pfu) SEP events and looked for CMEs preceding the SEP-associated CMEs. For a presumed interaction of the CME pairs some spatial overlap of the CME angular widths and an intersection within ~ 30 R$\odot$ of the extended height-time trajectories of the CME leading edges was required. In more than 80% of both the major and minor SEP events there was a CME interaction, at an average ~ 21 R$\odot$ height with a slower preCME that departed an average ~ 7 hours earlier. In their inverse study starting with 52 fast and wide (F/W) CMEs there were 10 CMEs with no SEP events, of which only 2 had full ($> 30°$ overlap) interactions. Gopalswamy et al. (2002) concluded that in addition to speed, width, and location, interaction with preCMEs was a powerful discriminator for predicting SEP events.

Richardson et al. (2003) rejected their conclusion, primarily on the basis of the meager statistics of the 10 F/W CMEs with no SEP events, which were consistent with a chance association. The later reclassification by Gopalswamy et al. (2003a) first, of non-interacting SEP CMEs to interacting, on the basis of interactions with streamers or preceding halo CMEs, and second, of interacting non-SEP CMEs to non-interacting, because the preCMEs were narrow or faded early, was also an element of the Richardson et al. (2003) indictment. A further objection was that SEP injections begin when heights of CME leading edges are < 10 R$\odot$, well below the ~ 20 R$\odot$ interaction heights. While ruling out the CME interaction scenario of Gopalswamy et al. (2002, 2003a), they allowed the possibility that preCMEs may somehow modify the source plasma or interplanetary fields to enhance SEP events at 1 AU.

In accord with this idea, Gopalswamy et al. (2003b, 2004) introduced the term "preconditioning" to describe the effect of a preCME on SEP production and limited their preCME selection criteria to (1) wide ($W > 60°$), (2) ≤ 1 day earlier, and (3) from the same source region as the primary CME. Gopalswamy et al. (2004, hereafter Gopalswamy04) selected for study 57 large (≥ 10 pfu) GOES $E > 10$ MeV SEP events, of which 23 had preCMEs (P), 20 were not preceded (NP), and 14 were relegated to an other (O) category. The clear distinction between the P and NP groups and the change of focus from CME interaction to CME preconditioning answered the earlier Richardson et al. (2003) critique. The significant result of their comparison of the P and NP events was that the P events trended higher than the NP events in plots of log Ip versus log V. While the median CME speeds, widths, masses, kinetic energies, and type II burst associations of the two groups were similar, the median peak intensities Ip were a factor of 7 different (210 versus 29 pfu). There appeared minimal overlap between the two groups, suggesting that preCMEs were somehow associated with enhanced Ip.

The Gopalswamy04 result was supported by a comparison of 15 SEP-rich and 16 SEP-poor F/W CMEs by Kahler & Vourlidas (2005). They looked for broad ($W > 40°$), spatially overlapping CMEs during the preceding 12 and 24 hour periods and found that SEP-rich CMEs had about 3 times more such preCMEs than the SEP-poor CMEs. Recently, Gopalswamy (2012) extended the comparison of SEP events with P and NP CMEs to all of solar cycle 23. His median SEP intensities were 317 and 35 pfu for the P and NP CMEs, a ratio similar to that of the earlier study.

1.3. The Twin-CME Scenario

A role for interacting CMEs in SEP production was invoked by Li & Zank (2005), who assumed that the preCME drove a shock that left a turbulent downstream wake where enhanced SEP production occurred at the primary CME shock. In this case the enhanced turbulence resulted in a decreased diffusion coefficient and higher maximum particle momentum of the SEPs produced at the shock of the trailing primary CME. Concerned that the primary CME shock would encounter only the preCME driver and not the turbulent downstream of its shock, Li & Mewaldt (2009) proposed an "offset CME scenario". This involved a faster primary CME magnetically reconnecting with the slower preCME in such a way that the primary CME shock could access the preceding driver material in the turbulent wake of the preceding shock. They considered that at least 11 of the 16 GLE events of solar cycle 23 had preCMEs within 24 hours, but the typical overtaking times for those CME pairs were several hours.

A more nuanced "twin-CME" scenario involving magnetic reconnection between coronal open field and the closed fields of the preCME was discussed by Li et al. (2012b). The role of the preCME is to provide both a seed population of pre-accelerated particles, in particular material with enhanced heavy-element abundances, and enhanced turbulence from the preceding shock, shown schematically in Figure 1. As long as the preCME can drive a shock, and the subsequent Alfvén wave turbulence has not decayed away (estimated at 9 hours), conditions are suitable for the twin-CME scenario. Therefore, contrary to the Gopalswamy04 requirements, the twin-CME scenario requires a preCME with: any width W_{pre}, $V_{pre} > 300$ km s^{-1} (minimal speed for shock generation), a launch up to 9 hours before, and a centerline position angle (PA) within the span of the primary CME. Li et al. (2012b) validated those preCME requirements for the 14 of 16 ground level events (GLEs) of cycle 23 with usable data from the *SOHO*/LASCO coronagraph.

To extend the twin-CME observational validation beyond GLEs, Ding et al. (2013, hereafter Ding13) selected large GOES (> 10 pfu) western hemisphere SEP events from 1997 to 2009. For their control sample they used western hemisphere F/W CMEs not associated with large SEP events. With the same preCME requirements as in Li et al. (2012b) and eliminating events from behind the west limb, they compiled four groups of events: 43 twin-CME SEP events (group I), 16 single-CME SEP events (group II), 30 twin-CMEs without SEP events (group III), and 39 single-CMEs without SEP events (group IV). These numbers alone support the twin-CME scenario for SEP events: most twin-CMEs (43 of 71) lead to SEP events and most single-CMEs (39 of 55) do not.

Their analytical approach is laudable, but several of their conclusions require comment. Ding et al. (2013) report no good correlation between SEP Ip (groups I and II) and either flare X-ray size (FC) or CME V. From their Table 1 we calculate correlation coefficients of log Ip versus log FC and log V. Those values are CC = 0.44 and CC = 0.47, respectively. Both are significant at the 99.9% confidence level (Bevington & Robinson 2003). For group I events alone, the CCs are 0.35 and 0.41, respectively, modest, but significant at the 98% confidence level. For group II, CCs are 0.78 and 0.68, respectively. These correlations are comparable to those of the P (preceding) and NP (non-preceding) speed plots and much higher than those of the flare plots of Figures 11 and 16 of Gopalswamy04. Ding13 dismiss CME width as an indicator of large SEP events, but again, the group I log Ip correlates with W at CC = 0.39, significant at the 98% confidence level, with or without the halo events. These CC values of the two studies are compared in our Table 1.

Despite our disagreements with these aspects of the Ding13 analysis, the strongest argument for the twin-CME scenario comes from a comparison of the median Ip and V for their groups I and II. The primary CME speeds are very similar (their Figure 8), but the median log Ip values of 2.51 (324 pfu) and 1.54 (35 pfu) are nearly an order of magnitude different. This difference was also apparent in Figure 11 of Gopalswamy04. These two observational studies therefore agree on the importance of preceding CMEs for SEP production, but their concepts of the role and the resulting selection criteria for the preceding CMEs are quite different

We believe that a further test of the twin-CME scenario would be useful. In particular, an extension of the SEP events to a range of Ip sizes beyond those of the > 10 pfu GOES events would test the concept for smaller events. Are the narrow ($W < 60°$) preCMEs important, as Li et al. (2012b) and Ding13 argue, or not, as implied by Gopalswamy04? Are SEP event time scales impacted by the occurrence of preCMEs? We use a table of 96 western hemisphere SEP events compiled by Kahler & Vourlidas (2013) for another study to address these questions.

2. DATA ANALYSIS

2.1. Event Selection and Criteria

For this work we use the 20-MeV proton events observed with the EPACT/*Wind* detector over solar cycle 23 compiled by Kahler & Vourlidas (2013) in their study of associated CME dynamics. There were 96 SEP events with sources > W40° for which not only the CME properties could be calculated from *SOHO*/LASCO observations, but also 2-MeV proton event profiles were observable above background. Here we sort those SEP events by their associations with preCMEs to look for possible effects of preCMEs on SEP event properties.

As discussed above, Gopalswamy04 and Ding13 differed considerably in their selection criteria for the preCMEs. Their preCME onset times were 24 and 9 hours, respectively, before the primary CME. Assuming the CME-preCME interactions to occur at low ($\lesssim$ 20 R$\odot$) altitudes, we use here a limit of 12 hours. While Gopalswamy04 limited their preCMEs to $W_{pre} > 60°$ and from the same region, we are guided by the twin-CME model of Li et al. (2012b) and require first that the central position angle PA of the preCME lie in the western hemisphere and within the angular span of the primary CME.

Ding13 assumed that a preCME of any W_{pre} and $V_{pre} > 300$ km s^{-1} would produce a shock and accelerate particles in the corona. However, contrary to wider CMEs, narrow ($W < 20°$) CMEs appear to be mass flows in vertical flux tubes (Yashiro et al. 2003), which could be expected from interchange reconnection of open and closed magnetic fields (Gopalswamy et al. 2006). The different speed distribution and skew toward deceleration (Mittal et al. 2009) suggest an acceleration mechanism for narrow CMEs different from that of normal CMEs (Yashiro et al. 2003).

If narrow CMEs produce shocks, they should be bow shocks (Kahler & Gopalswamy 2009) with thin sheaths (Siscoe & Odstrcil 2008) and angular extents only several times the CME widths (Corona-Romero & Gonzalez-Esparza 2013), not the broad piston-driven shocks with thick sheaths typically associated with observed type II bursts and SEP events (Kahler & Reames 2003, Gopalswamy et al. 2008). Furthermore, it is not clear that a confined turbulent region downstream of a narrow CME would provide an adequate volume for shock acceleration to produce a gradual SEP event extending over tens of degrees. In view of these doubts about shocks from narrow CMEs, we add the selection requirements that $W_{pre} > 10°$ and $V_{pre} > 300$ km s^{-1} for the preceding CMEs.

The question of spatial interactions of preCMEs and primary CMEs is complicated in longitude by the projection of the observations on the plane of the sky and in latitude by the apparent large projected values of W of the primary CMEs, many of which are full halo events. Ding13 required the PA of a preCME to be within the angular span of the primary CME, but many of those primary CMEs were 360° halos, so no real requirement was imposed in those cases. The preCMEs in their tables 2 and 4 are almost always in the west or halo. We note that Cane et al. (2010) gave CME widths W based on early low-altitude observations but did not give corresponding PAs. We further limited our selection to those preCMEs with central PAs within 90° of the primary CMEs (δPA < 90°).

2.2. CME Catalogs and Selections

For each of the 96 SEP events of the Kahler & Vourlidas (2013) study we first selected the corresponding CME launch times and timescales from Table 1 of Kahler (2013). We then searched the CDAW LASCO CME catalog for any preCMEs with estimated launch times, based on the 1 R$\odot$ linear extrapolations from the CDAW height-time plots, of up to δT < 12 hours before that of the primary CMEs. All preCMEs with $V_{pre} > 300$ km s^{-1}, $W_{pre} > 10°$, $180° < PA_{pre} < 360°$, and δPA < 90° were selected. Besides its catalog listing, each preCME is characterized by its parameters W_{pre}; V_{pre}; PA_{pre}; δPA; and δT, the time between preCME and primary CME launches.

We also examined the on-line CACTus catalog (Robbrecht et al. 2009, Yashiro et al. 2008), which begins in May 1997, for matching listings of CDAW preCMEs and for additional qualifying preCMEs. We used the same CACTus selection criteria as with the CDAW catalog except to use the highest speed detected within the preCME, which we take as the equivalent of the CDAW leading edge speed. We made no selections from the CACTus listings of "flows", defined as suspicious detections. We considered, but did not use, the SEEDS (Olmedo et al. 2008) and ARTEMIS (Boursier et al. 2009) catalogs of LASCO CMEs, which are based only on LASCO C2 observations. The CME detection rates of the CACTus, SEEDS, and ARTEMIS catalogs were found to be in good agreement (Boursier et al. 2009), at least during the important rising and maximum phases of the solar cycle 23. The advantage of the CACTus over the CDAW catalog is the larger number of detected narrow ($W < 30°$) CMEs, particularly at solar maximum (Yashiro et al. 2008).

The two catalogs yielded a total of 121 preCMEs, of which δPA $> 60°$ for only 15, and the median width of those 15 preCMEs is $W_{pre} = 60°$. With the large W of the primary CMEs, we expect few cases of spatially non-interacting CMEs in the analysis. In 58 cases we found matches between the two catalogs of preCMEs, allowing for reasonable differences in their listed properties. However, the 24 CACTus preCMEs with no match in the CDAW catalog and the 39 CDAW preCMEs without corresponding CACTus preCMEs were not reassuring that the use of each catalog alone would give similar results.

Proceeding from now on with only the CDAW preCMEs, we found 34 SEP events with no preCMEs, 40 with one (1), and 22 with two or more (2+). These three groups form the basis of our statistical comparisons. We recall that preCMEs not meeting the criteria above are excluded from the listings. Thus, any preCME too slow, narrow, or early, or with $0° \leq PA_{pre} \leq 180°$ or δPA $\geq 90°$, which may have some effect on the primary CME and its associated shock and SEP event, is excluded from the analysis. Further, Ding et al. (2013) selected only a single preCME for each primary CME, contrary to our selection of all candidates with δT < 12 hr.

2.3. Comparison of PreCME Numbers With SEP Event Peak Intensities and Time Scales

The basic goal of this work is to determine statistically whether preCMEs have an effect on the SEP events produced by the primary CMEs, and if so, what is that effect? We first compare the logs of peak intensity Ip, onset times TO, and rise times TR of the SEP events of the three groups of primary CMEs. For better statistics we also combine the 1 and 2+ groups into a single group of 62 total 1+ preCMEs. Because of the large ranges of the SEP parameters indicated by their standard deviations, we use the median values of those parameters of the four groups, shown in Table 2.

We first find that for the no preCME group log Ip is ~ 1.5 smaller than for the 1 preCME or the 1+ preCME group. This appears to validate the basic idea that preCMEs are associated with larger SEP events. From Table 2 we see that the median log Ip declines somewhat for the 2+ preCME group, so Ip depends only on whether there are any preCMEs but not the number of preCMEs. The log-log plot of Ip versus CME V for the no and 1+ preCME groups of events, shown in Figure 2, reveals considerable overlap, but for log Ip > -0.5 there is a strong preponderance (30 of 33) of the 1+ preCME events. Furthermore, while for all 96 events the correlation coefficient CC = 0.56, it is higher for the 1+ group (CC = 0.60) than for the no preCME group (CC = 0.38). The CCs for CME W, excluding the 360°CMEs, are similarly higher, as shown in Table 1.

We have to be careful in this comparison that the primary CME speeds and widths are comparable for the two groups. The median log V of the 1+ preCME group is higher by 0.09 (i.e., V about 23% higher), and the median W about 37° wider, but there is a considerable spread in the distributions of these values, as shown in Table 2. The slightly larger primary CME speeds and widths of the 1+ preCME group are therefore not sufficient to account for the disparity of the two preCME populations of Figure 2. We find no significant differences between the groups for either TO or TR or for the more robust parameter of TO+TR (Kahler 2013) shown in Figure 3. Again there is a considerable spread in those variables, for which the standard deviations are roughly equal to the medians themselves. This results from distributions of TO and TR that are skewed with small numbers of events with large values. We conclude that Ip values of the preCME groups are enhanced significantly by a factor of ~ 30 over those of the no preCME group, and that the somewhat higher values of V and W of the 1+ preCME group do not account for the difference. On the other hand, there are no real differences in the SEP timescales between the two groups.

2.4. PreCME Speeds and Widths

As reported above, we have 40 events with 1 preCME and 22 events with 2+ preCMEs. For the latter events we use the fastest and widest preCME in our statistical comparisons. We first look for a dependence of Ip on the preCME V_{pre} for 61 events since one event speed is indeterminate. We find that log Ip is not correlated with log V_{pre} (CC = 0.03), but log Ip correlates weakly with the preCME W_{pre} at CC = 0.28, at about a 97% significance level for 62 events. The W_{pre} CC = 0.55 for the 22 2+ events but only 0.13 for the 40 1 preCME events. Figure 4 shows the plots for those two groups, in which the considerable amount of scatter is obvious. Using the correlation coefficients as a rough guide, the suggestion is that the widths, rather than the speeds, may be the more important characteristic of the preCMEs.

2.5. The Time Intervals of PreCMEs

The preCMEs of this study are those with inferred launch times up to 12 hours before the launch times of the primary CMEs. What happens if we restrict the preCME launch time interval to δT = 6 hours? If the enhanced log Ip values of the full 12-hour 1+ preCME group are diminished, it would suggest that preCMEs in the 6 to 12 hour preceding interval are the main drivers of enhanced Ip.

We now divide the 62 preCME event groups into 32 events with preCMEs occurring only 6 to 12 hours before the CME and 30 events with preCMEs $<$ 6 hours before the primary CME. The fortuitous division of the groups into nearly equal numbers of events allows us to distinguish whether the timing of the preCMEs is an important factor. Table 3 gives the median values of the SEP event parameters for the three preCME groups. The distributions of log Ip and TO+TR are shown in Figures 5 and 6. No statistical difference between the 0 to 6 hr and 6 to 12 hr groups is seen in the logs of Ip (Figure 5). There is a slight indication in Figure 6 that TO+TR is only somewhat longer in the 6 to 12 hr group than the others, although the median preCME δT of that group is 8.6 hours, compared to 3.3 hours for the 0 to 3 hr group. We conclude that the timing of the preCMEs, at least within the 12-hour intervals of this study, is not relevant for the subsequent SEP events.

2.6. The Background 2-MeV SEP Intensities

We have established that CMEs with preCMEs in the preceding 12 hours before launch are associated statistically with larger 20-MeV Ip SEP events than are those CMEs without preCMEs. Furthermore, the numbers, timings, and speeds of the preCMEs are not factors in the SEP Ip intensities, although the preCME widths W are slightly correlated with log Ip. There is only a weak tendency for TO+TR to increase with earlier (6 to 12 hours) and more (2+) preCMEs. The cause of the increased 20-MeV Ip for cases of preCMEs is not established in these correlations, although if the twin-CME scenario is in effect, we should expect, contrary to our results, that the earlier 0-6 hour preCME group would have higher Ip on the basis of CME interchange interactions in the low corona rather than at the higher altitudes where field lines of the preCMEs begin to resemble those of the solar wind.

In studies of large and GLE SEP events Kahler (2001) and Cliver (2006) suggested that the presence of enhanced intensities of $E > 10$ MeV background SEPs that can act as seed particles for CME-driven shocks is also a factor in the resulting values of Ip. We determined the values of the background 2-MeV proton intensities in the EPACT just before each of the SEP event onsets. The median values of those 2-MeV backgrounds are presented in Table 2 for the 1 and 2+ preCME groups and in Table 3 for the 0-6 and 6-12 hour preCME groups. There is a broad scatter of values, but in both cases the median backgrounds of the preCME groups exceed those of the no preCME groups. A log-log plot of Ip versus the 2-MeV background is shown for the no and 1+ preCME groups of events in Figure 7. For all 96 SEP events log Ip correlates with log 2-MeV background at CC = 0.55, similar to the plot of log V at CC = 0.56 for all events of Figure 2. Some of the correlation must arise from an observational bias against observing small SEP events with large backgrounds, resulting in the lack of events in the lower right corner of the Figure 7 plot.

The results in Figure 7 and Tables 2 and 3 suggest an alternative to the twin-CME concept, that the preCMEs are generating a population of low-energy SEPs that can serve as seed particles for the shock of the primary CME (Li et al. 2013). On the other hand, there may simply be a tendency for continued SEP production and increased CME occurrence during periods of high solar activity in which the high SEP backgrounds are not attributable to the preCMEs. The statistical approach can not make this distinction, so we look for changes in SEP backgrounds during the 12-hour periods preceding all 62 SEP events with preCMEs. We use both the 2 and 20 MeV EPACT plots and the SEP event list of Kahler (2013) to look for cases in which the preCME was associated with a 2 or 20-MeV SEP event and find only three such cases. On 2000 August 12 a preCME launch occurred at 0938 UT, before the primary CME launch of 1403 UT. Although the preCME met the criterion for spatial overlap, it occurred behind the west limb, while the primary CME was associated with a flare at W46°, so the spatial interaction of the two CMEs may have been minimal. In the second case the preCME was launched on 2001 April 2 at 1100 UT and the primary CME at 2143 UT, both from the same active region. However, the preCME would have reached $\sim$ 50 R$\odot$ at the time of the CME launch, so CME interaction was again unlikely. Two fast ($V > 2000\,\mathrm{km\,s^{-1}}$) CMEs occurred at 0905 and 1720 UT on 2003 November 2, likely from different active regions in our third case. The first CME was the preCME of the second, and produced a much smaller SEP event than the second, primary CME. Only this last case seems consistent with a SEP seed production by the preCME for the primary CME.

In all other cases in which the primary CME occurred in an environment of high background of 2-MeV protons (Figure 7) the high background was due to SEP events associated with fast CMEs that occurred from 16 hours to 10 days before the primary CME. Therefore, assuming that the 2-MeV proton intensities at 1 AU are indicative of an enhanced seed population near the Sun, we rule out the scenario in which the enhanced SEP intensities from primary CMEs with preCMEs are due to seed particle production by those preCMEs (Li et al. 2013).

2.7. Background SEP Intensities and PreCMEs

In the absence of any cause and effect between the 2-MeV SEP background and the occurrence of preCMEs, the two phenomena must both arise from the general increase in solar activity. Therefore, if the enhanced seed population, as measured by background 2-MeV protons, is an important reason for SEP events with enhanced Ip, we also expect to find the primary CMEs statistically associated with more preCMEs in those events. However, the increased number of preCMEs is then only a reflection of the overall enhanced CME activity and does not indicate a direct role in SEP production by the primary CMEs. The question here is whether the coincidence of enhanced 2-MeV backgrounds with more preCMEs can explain the twin-CME scenario.

The bottom panel of Figure 8 shows that the numbers of no preCME events decline with increasing 2-MeV backgrounds, while the numbers of the 1+ preCME group peak at intermediate levels and exceed those of the no preCME group at high 2-MeV backgrounds. In Tables 2 and 3 we noted that the median log Ip for the 1+ preCME events exceeded that for the no preCME group by $\sim$ 1.5. The median log 2-MeV background of the 1+ preCME group is larger by $\sim$ 0.7 than that of the no preCME group (Table 2), suggesting that the higher backgrounds might account for approximately half the difference in log Ip between the no and 1+ preCME groups. The least-squares fits of the two groups shown in Figure 7 are a better way to assess the difference, and there we find very similar slopes (0.53 and 0.56 for the no and 1+ preCMEs) and a separation in log 20-MeV Ip of only 0.4. This direct comparison of the two groups is not strictly valid because there are good correlations of log Ip with both log V and W (Table 1), and medians of both parameters are larger for the 1+ than for the no preCME group (Table 2). Those factors should produce some separation between the two groups, as observed. In view of the large scatter of the events of Figure 7, we suggest that perhaps all of the twin-CME effect is due to the enhanced backgrounds of the twin CMEs.

2.8. Background SEP Intensities in Other PreCME Studies

Do we find a similar increase of low-energy background SEPs for SEP events with preCMEs in the two principal studies supporting the twin-CME scenario? As discussed in Section 2.1, the preCME selection criteria of Gopalswamy04 and of Ding13 differed from each other and from ours, but all are consistent with larger SEP events for twin-CMEs. If increased numbers of preCMEs are a signature of enhanced solar activity, along with background SEP intensities, then we should find similar effects in the SEP event tables of those works. Table 1 of Gopalswamy04 lists 23 P (with preceding CMEs) and 20 NP (no preceding CMEs) SEP events. Table 1 (43 events) and Table 3 (28 events) of Ding13 give a total of 71 twin-CMEs and their Table 1 (16 events) and Table 5 (39 events) give a total of 55 single CMEs. A major difference here is that Gopalswamy04 considered only CMEs with SEP events, as we do here, while Ding13 also included for comparison fast and wide CMEs without major SEP events. The inclusion of the latter CMEs is useful for our purpose of comparing the SEP backgrounds of single and twin-CMEs.

We have determined the 2-MeV SEP background for the 43 SEP events of Gopalswamy04 and the 126 CMEs of the Ding13 study using the 2-hour averaged 1.8 to 3.3-MeV proton intensities from the Energetic and Relativistic Nuclei and Electron experiment (ERNE, Torsti et al. 1995) on the SOHO spacecraft. For each of the primary CMEs we select the time interval fully preceding the first observed CME time reported in the LASCO CDAW catalog. Figure 9 compares the binned P and NP distributions of Gopalswamy04 and the distributions of all the single and twin-CMEs of Ding13. In both comparisons there are weak trends for the preCME groups to be more likely to occur during the higher 2-MeV backgrounds, consistent with our SEP events in Figure 8. Table 4 compares the median 2-MeV backgrounds for CMEs with and without preCMEs, and in each case the median backgrounds are higher for the CMEs with preCMEs by factors of ~ 2 to 8. The highest ratio occurs between the groups of twin and single CMEs without SEPs, shown in the last two lines of the Table.

Figure 10 shows the logs of the $E > 10$ MeV Ip versus the logs of the 2-MeV proton backgrounds for both studies, and here there is a significant difference from our results of Figures 7 and 8. The Figure 10 plots show no dependence of either the single (NP) or twin (P) CME events on the logs of the backgrounds. Ding13 did consider a role for background intensities, using for their backgrounds the 0.64 to 1.28 MeV proton intensities from the *ACE*/ULEIS experiment, taken over 24-hr periods on days preceding the primary CMEs. Their Figure 4 is qualitatively very similar to the bottom panel of our Figure 10, and they used their result to rule out any background effect in their finding of enhanced SEP intensities for the twin CMEs. They and Li et al. (2013) pointed out that the weak trend of Ip versus background for the single CMEs was consistent with a requirement for a background seed population for those SEP events. The median values of the logs of Ip and of the 2-MeV backgrounds of those plots are given in Table 4. In each case the difference in the logs of Ip are considerably greater than those of the 2-MeV backgrounds, suggesting that the effect of backgrounds is only a secondary factor in the twin-CME scenario.

3. DISCUSSION

The goal of this work is to understand the role of preCMEs in the production of SEP events by fast and wide CMEs. Earlier work had shown statistically that the occurrence of preCMEs within a given preceding interval δT before the fast CMEs was associated with larger peak intensities Ip. However, the role played by the preCMEs was unclear, although some interaction between preCME and primary CME was assumed that was favorable for the enhanced SEP production. The first part of this work was to validate the statistical results obtained earlier by Gopalswamy04, Kahler & Vourlidas (2005), Gopalswamy (2012) and Ding13. Our preCME selection criteria differed somewhat from theirs, but the results of Tables 2 and 3 and Figures 2 and 5 make clear the difference between CMEs with and without preCMEs for 20-MeV Ip. On the other hand, we find no difference between the two groups for the SEP event timescales TO and TR, although a considerable scatter exists in those parameters.

If preCMEs undergo some interaction with their subsequent CMEs, then one can look for preCME characteristics that enhance that interaction. Accordingly we divided the CME events by the numbers and the times before occurrence of their associated preCMEs. In neither case, indicated in Tables 2 and 3, could we see that the preCME numbers or times had any significance for the resulting values of Ip. We also sought indications in the widths and speeds of the preCMEs that could point to the preCME roles in SEP production, but this also yielded no significant differences either for the SEP event timescales, TO+TR in particular, or for Ip.

We found that the 20-MeV proton Ip increases with the 2-MeV proton background intensities, similar to results found earlier for backgrounds of various suprathermal or energetic particles. If the Ip values increase with both the background SEP intensities and the occurrence of preCMEs, then one has to consider whether the preCME occurrence must also scale with the background SEP intensities. This is indeed the case for our events, as we found in Figures 7 and 8, suggesting that large SEP events are more likely to occur during times of high solar activity in which earlier SEP events are likely to provide a long-lived population of low (2-MeV) energy particles. If enhanced solar activity also means that CMEs are more frequent during any given time period of that high activity, then we expect that any fast and wide CME producing a SEP event will more likely be associated with preCMEs, accounting for at least part of the twin-CME scenario.

A scenario suggested by Ding13 and Li et al. (2013) is that the effect of the preCME is to produce a seed particle population which is then accelerated to SEP energies by the primary CME shock. Li et al. (2013) contrast the independence of the twin-CME Ip on the 1-day prior 1-MeV proton backgrounds with the weak dependence of the single-CME Ip on those backgrounds, evident in Figure 4 of Ding13. Their interpretation is that single CMEs need a pre-existing seed population for SEP production, but the twin CMEs may act on seed particles newly produced by the recent preCME and would be independent of the backgrounds measured before the occurrence of the preCMEs. The Ding13 analysis used for backgrounds the 1-MeV proton intensities from the 1-day periods preceding the CMEs, but we used 2-MeV proton data from 2-hour intervals preceding the CME onsets to get the result of Figure 10, very similar to Figure 4 of Ding13. If SEP production of the twin CMEs is dependent on seed populations recently produced by preCMEs, then a dependence of Ip on backgrounds would be expected, contrary to the result shown in Figure 10. We also examined a number of cases of high 2-MeV backgrounds and find that in general the backgrounds were enhanced well before the 12-hour preCME interval. These results, based on the 2-MeV proton backgrounds, rule out the suggested scenario of preCME production of enhanced seed populations.

We analyzed the data of two previous preCME studies to test whether the statistical association of the enhanced SEP event intensities with preCMEs is in fact due to a correlation of both those phenomena with increased solar activity. While finding slight trends for more preCMEs with increasing 2-MeV backgrounds (Figure 9), there is no indication (Figure 10) in the Gopalswamy04 or the Ding13 work of any dependence of the $E > 10$ MeV Ip on the 2-MeV proton backgrounds.

We suggest several reasons for this disparity with the previous studies. First, the dynamic range of the GOES $E > 10$ MeV proton events of the two earlier studies was limited to events with Ip > 10 pfu, which corresponds to log 20-MeV Ip ~ -0.7, well above the median value of –1.43 for the 96 events of our study. Thus, most SEP events of our study are smaller than those of the previous two studies. In addition, the reported GOES SEP event Ip of those studies sometimes occurred during shock passages, while ours were taken at the first peaks, before shock passage. Second, the solar source longitudes are also different: all longitudes in Gopalswamy04; western hemisphere in Ding13, and $>$ W40° in our study. The magnetic connection is therefore best for the SEP events of the current study, and the measurement of the local 2-MeV background may be more relevant for our better connected solar events than for the events of the previous studies. It is also not clear that the 2-MeV proton background at 1 AU is a good proxy for the near-Sun shock seed population accelerated to $E > 10$ MeV.

A third difference among the three studies is the criteria for the preCME selections, reflecting the authors' ideas for the CME interaction physics. Gopalswamy04 assumed that a CME would interact only with a preCME from the same active region and allowed a generous δT of 24 hours for the fast CME and its shock to interact with an assumed slower preCME, which had to have $W_{pre} > 60°$ but no minimum V_{pre}. Ding13, considering their twin-CME scenario of CMEs adjacent, but not one above the other, used a tighter δT $<$ 9 hours, no limitation on W_{pre}, but $V_{pre} > 300$ km/s, and a generous criterion for δPA. Our criteria of δT $<$ 12 hrs and $W > 10°$ were much closer to those of Ding13, but with differences described in Section 2.2. Thus, the three basic differences among these studies undermine the validity of the comparisons carried out in Section 2.8.

Any role for preCMEs in the production of SEP events remains unproven. In this study we attempted to identify some characteristic of preCMEs that could point to a possible mechanism, but we find that δT, W_{pre}, and numbers of preCMEs do not appear as significant factors. The physical interaction of preCMEs with CMEs would best be observed from several directions, as the STEREO coronagraphs provide. Multiple observations could show the temporal and spatial interactions between preCMEs and primary CMEs that can not be discerned by imposing arbitrary δT, W_{pre} and PA overlap limits. In addition, the observation of resulting SEP events from several locations may also offer clues to the nature of the interaction, if any.

We and Ding13 used 1-2 MeV proton background intensities to look for an effect due to shock seed particles. This has the obvious limitations that we use 1-AU, rather than near-coronal observations, and that suprathermal particles in the 10-100 keV/nucleon range might be much more appropriate as seed populations (Mewaldt et al. 2012). It is, however, surprising that our correlation of Ip with 2-MeV background is so different from the negative results of the other studies shown in Figure 10.

Separate from the possible effect of preCMEs on SEP event Ip is the question of whether the presence of preCMEs will somehow alter the SEP event timescales. We might expect that the preCMEs could alter the magnetic geometry and, possibly through reconnection, the magnetic toplogy of the interplanetary fields through which the SEPs propagate to Earth. Figure 6 shows that within the broad scatter of values of TO+TR we do not find any obvious difference between timescales of SEP events with and without preCMEs. The occurrence and locations of long-lived features such as streamers and coronal holes may have a bigger role in the large range of TO+TR than any preCMEs.

4. SUMMARY

The association of preCMEs with enhanced values of Ip in SEP events has been noted for over a decade and has been the source of several models of interactions between the preCMEs and primary CMEs that could lead to enhanced SEP production. We have carried this association further by looking for properties of the preCMEs that could be important in the production of SEPs. Our results were negative in that we found no role for the numbers, the timing, the widths, or the speeds of the preCMEs that could suggest how the preCMEs might interact with the primary CMEs to produce SEPs. We also found no trends in the SEP event timescales with preCME properties. The association of preCMEs with enhanced SEP Ip is as robust as the underlying cause is elusive.

We found that both SEP event intensities Ip and the occurrence rates of preCMEs increase with the 2-MeV proton background intensities. This provides an alternative explanation for the twin-CME model, that the 2-MeV particles serve as seed populations for the higher ($\sim$ 20 MeV) energy SEP Ip intensities and that the CME rates and the background 2-MeV SEP intensities scale together as manifestations of solar activity levels. In this scenario the preCMEs are signatures of, but not physically coupled with, SEP Ip intensities. The association of larger SEP events with higher 2-MeV backgrounds was not found, however, in our analysis of two earlier twin-CME studies, so the importance of the background effect remains unclear, and the mechanism for enhanced SEP event Ip resulting from CME interactions, if it exists, is still undefined.

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Table 1: CCs[a] between the SEP Event and CME Parameters.

Correlation	Ding13	Gopalswamy04[b]	This Study
		Log Ip versus Flare Size	
All	0.44 (57)	0.35 (54)	NA
Group I or P	0.35 (41)	0.12 (22)	NA
Group II or NP	0.78 (16)	–0.16 (18)	NA
		Log Ip versus Log V	
All	0.47 (59)	0.45 (57)	0.56 (96)
Group I or P	0.41 (43)	0.43 (23)	0.60 (62)
Group II or NP	0.68 (16)	0.58 (20)	0.38 (34)
		Log Ip versus W	
All[c]	0.21 (46)	NA	0.45 (58)
Group I	0.39 (35)	NA	0.54 (36)
Group II	0.03 (11)	NA	0.26 (22)

[a]Correlation Coefficients (number of events).
[b]Numbers for all CMEs, including behind the limb.
[c]Excludes 360° CMEs.

Table 2: SEP Event Median Parameters for the Different PreCME Groups.

SEP/CME Parameter	No preCME	1 preCME	2+ preCMEs	1+ preCMEs
Numbers of events	34	40	22	62
Log Ip	–2.00 ± 1.10	–0.46 ± 1.30	–1.26 ± 1.50	–0.52 ± 1.37
TO (hrs)	2.0 ± 1.8	1.7 ± 1.3	1.8 ± 2.4	1.8 ± 1.8
TR (hrs)	1.5 ± 2.1	2.0 ± 3.0	3.0 ± 3.0	2.5 ± 3.0
TO+TR (hrs)	4.1 ± 2.7	4.2 ± 3.5	5.6 ± 4.2	4.3 ± 3.8
Log 2-MeV H Bkgd	–0.90 ± 1.21	–0.34 ± 1.17	–0.10 ± 1.17	–0.19 ± 1.16
Log CME V (km/s)	3.04 ± 0.20	3.11± 0.21	3.15 ± 0.21	3.15 ± 0.21
CME W (degr)	173 ± 116	212 ± 116	209 ± 120	210 ± 114

Table 3: SEP Event Median Parameters for the 6-Hour PreCME Groups.

SEP/CME Parameter	No PreCME	0-6 hr PreCMEs	6-12 hr PreCMEs
Numbers of events	34	30	32
Log Ip	–2.00 ± 1.10	–0.52 ± 1.38	–0.50 ± 1.38
TO (hrs)	2.0 ± 1.8	1.6 ± 2.1	2.0 ± 1.5
TR (hrs)	1.5 ± 2.1	2.3 ± 3.1	2.5± 3.0
TO+TR (hrs)	4.1 ± 2.7	3.6 ± 4.4	4.8 ± 3.3
Log 2-MeV H Bkgd	–0.90 ± 1.21	–0.50 ± 1.24	–0.16 ± 1.08
Log CME V (km/s)	3.04 ± 0.20	3.15± 0.19	3.10 ± 0.23
CME W (deg)	173 ± 116	188 ± 125	247 ± 114

Table 4: Event Medians by CME Types.

SEP/CME Group	Events	2-MeV Bkgd[a]	Ip[b]
Gopalswamy04			
P (preceding) events	23	2.57	210
NP (no preceding) events	20	0.63	28
Ding13			
Twin-CMEs with SEPs	42	8.0	320
Single CMEs with SEPs	16	3.9	35
Twin-CMEs without SEPs	28	3.3	NA
Single CMEs without SEPs	39	0.36	NA

[a]1.8-3.3 MeV proton intensities p (cm^2 s sr MeV)$^{-1}$.

[b]In proton flux units (pfu) for $E > 10$ MeV.

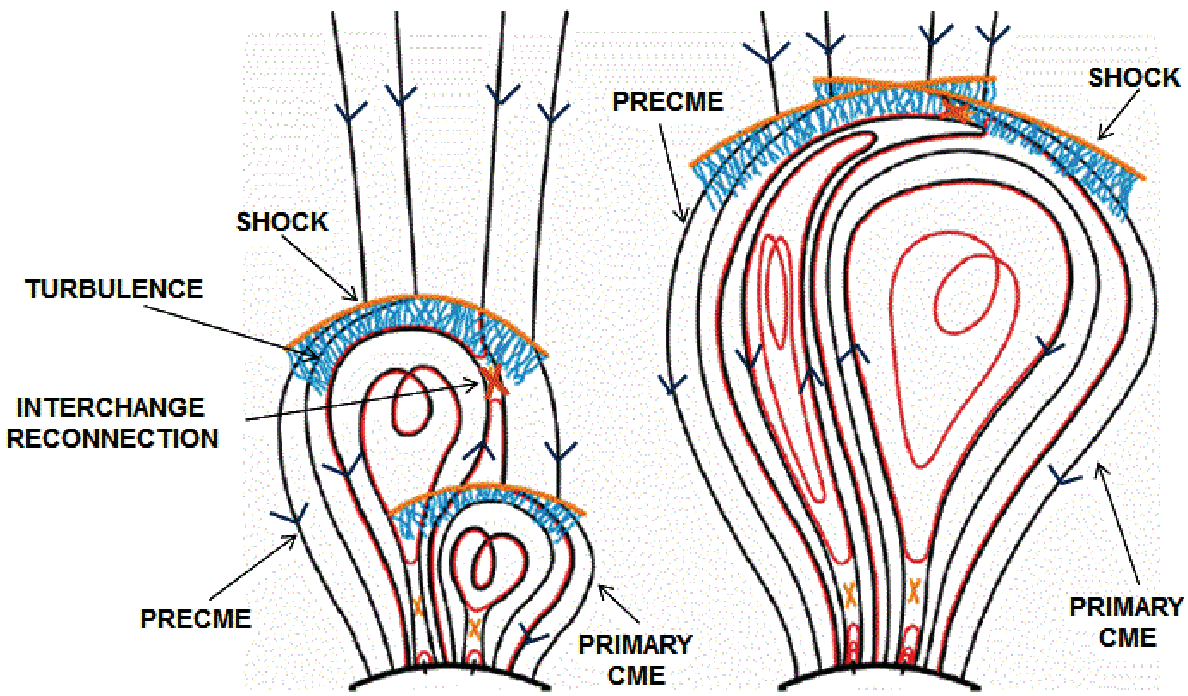

Fig. 1.— Schematic showing magnetic field lines of the twin-CME scenario. Left: The first eruption is the preCME, which drives a shock ahead of a turbulent region shown in blue. The primary CME occurs later in a spatially adjacent region. A magnetic interchange reconnection region allows material to flow from the closed loop into the turbulent region of the preCME, where it gains energy and then is accelerated to MeV energies by the shock of the primary CME. Right: The more developed phase of the preCME-CME interaction, where the primary CME shock has crossed the reconnection region. Adapted from Li et al. (2012).

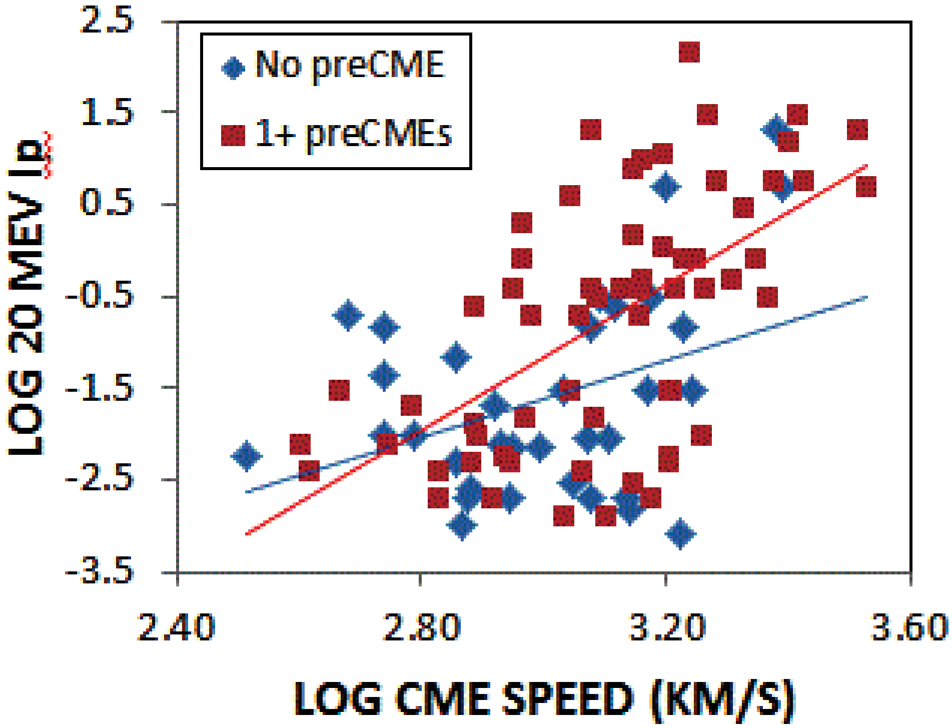

Fig. 2.— Log-log plot of 20 MeV Ip versus the primary CME speeds for two groups of preCME SEP events based on number of associated preCMEs. The lower blue (upper red) diagonal line is the least-squares best fit line to the no (1+) preCME group. The 1+ preCME group dominates the most intense (log Ip > –0.5) SEP events.

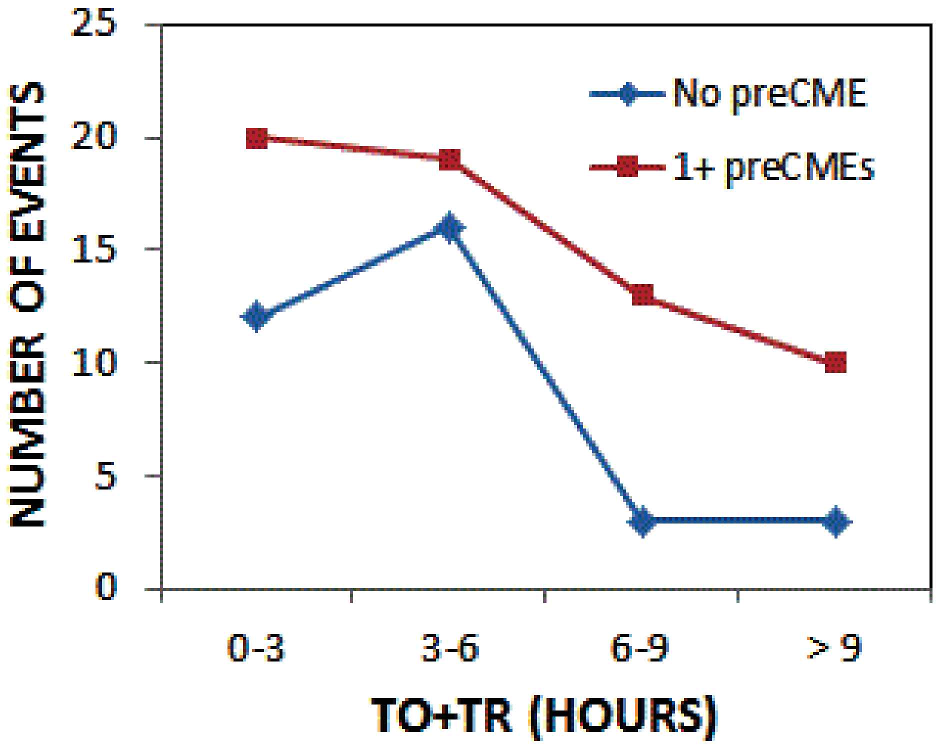

Fig. 3.— Histogram of numbers of preCME events in 3-hour time bins of TO+TR for the no and 1+ preCME groups.

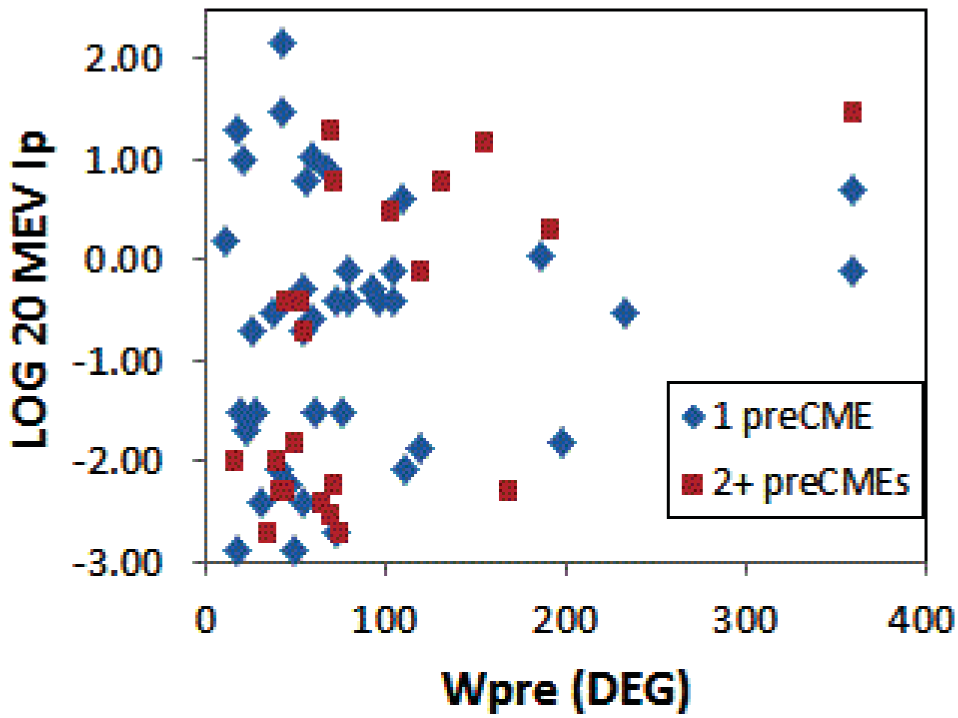

Fig. 4.— Comparison of the SEP Ip with the preCME W_{pre} for the two preCME groups based on preCME numbers. There is a weak correlation between log Ip and W_{pre} only for the 2+ preCME group.

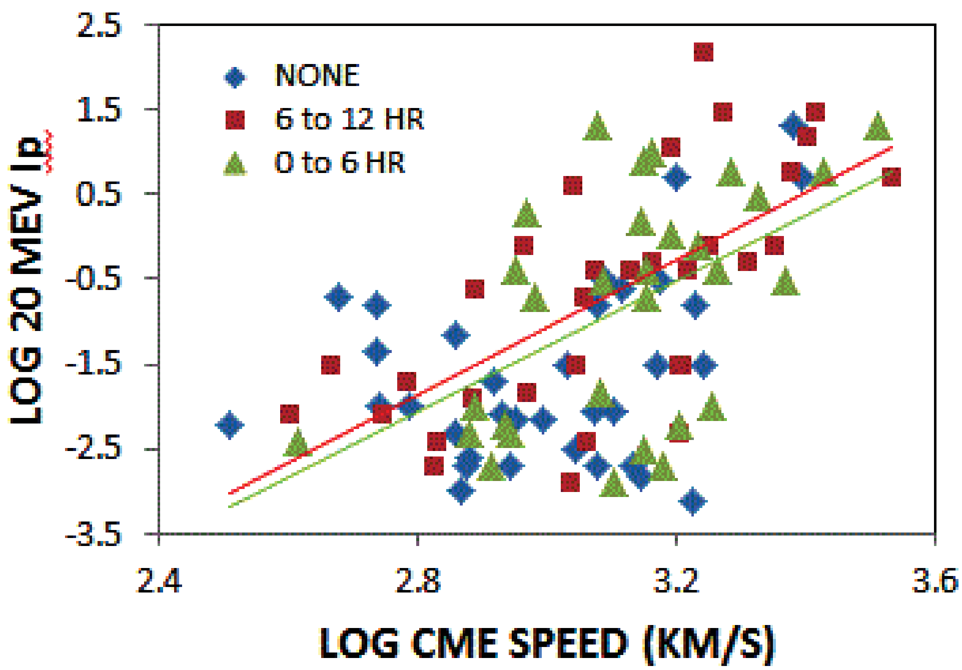

Fig. 5.— Plot of log Ip versus log CME speed V for the three preCME groups based on timing of the preCMEs. The least squares best fit lines are shown for the 0-6 and 6-12 hr groups.

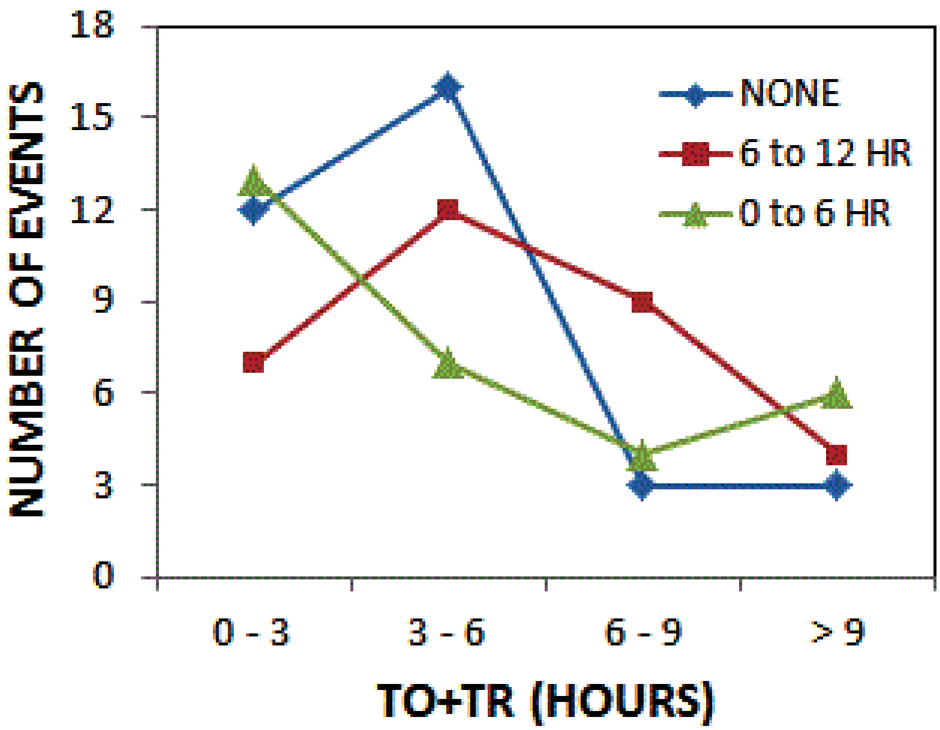

Fig. 6.— Histogram of numbers of preCME events in 3-hour time bins of TO+TR for the none, 6-12 hour, and 0-6 hour preCME groups.

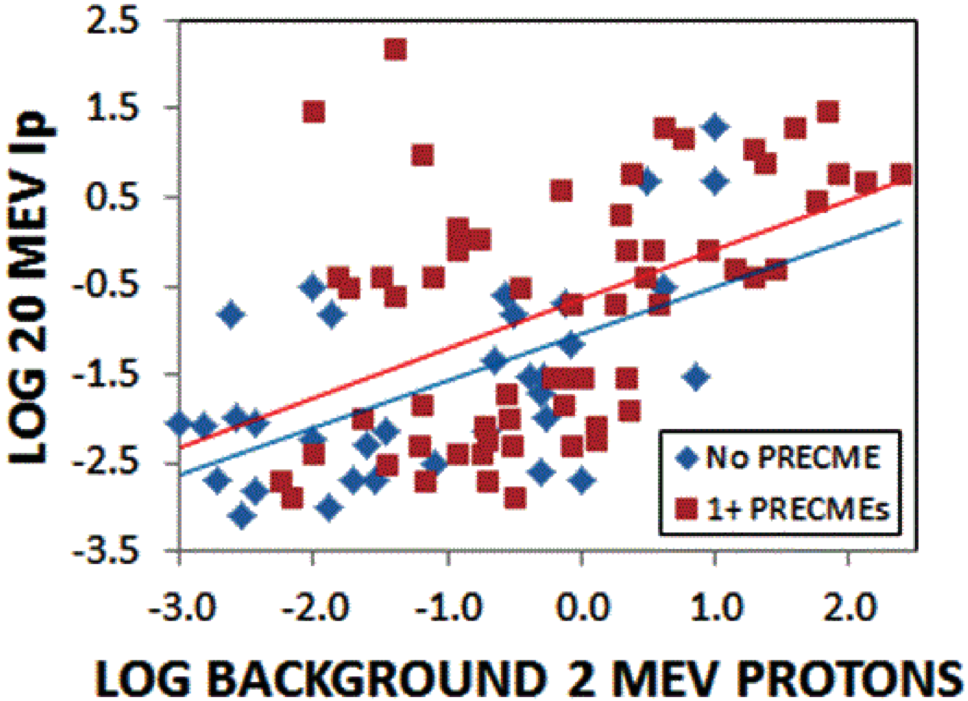

Fig. 7.— Log-log plot of 20-MeV Ip versus the EPACT 2-MeV proton background intensities for the no and 1+ preCME groups. Diagonal lines are the least-squares best fits for each preCME group. The 1+ preCME group is characterized by larger median CME V and W values, which may explain the difference between the fits.

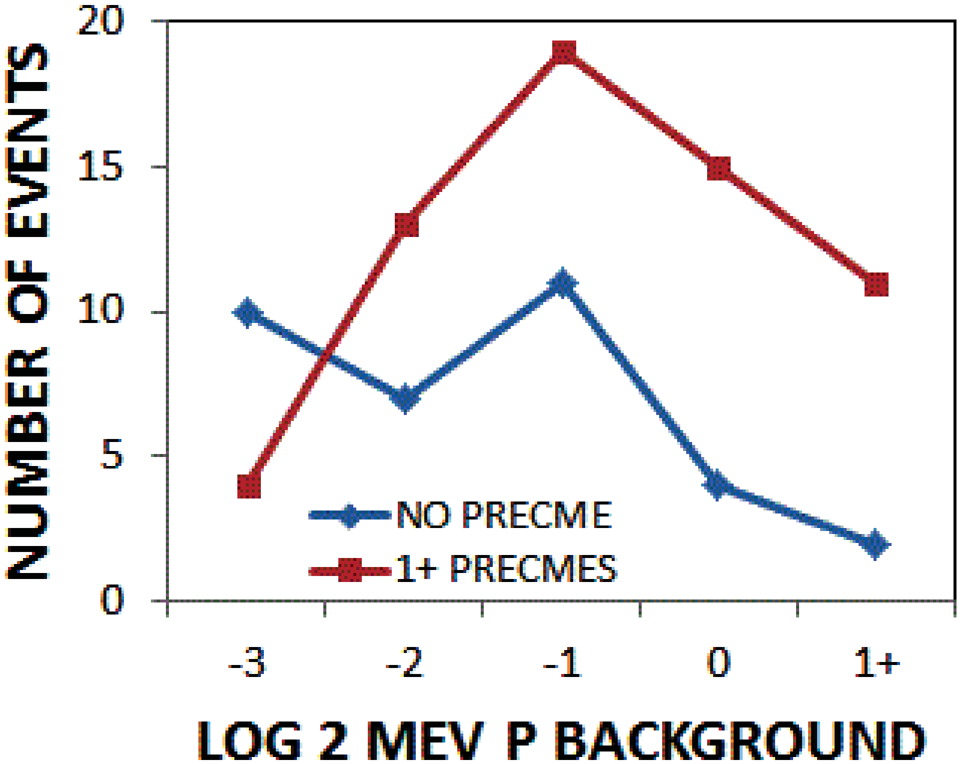

Fig. 8.— The plot of Figure 7 is reduced to a histogram of the numbers of the two preCME groups in bins of logs of ERNE 2-MeV proton background intensities.

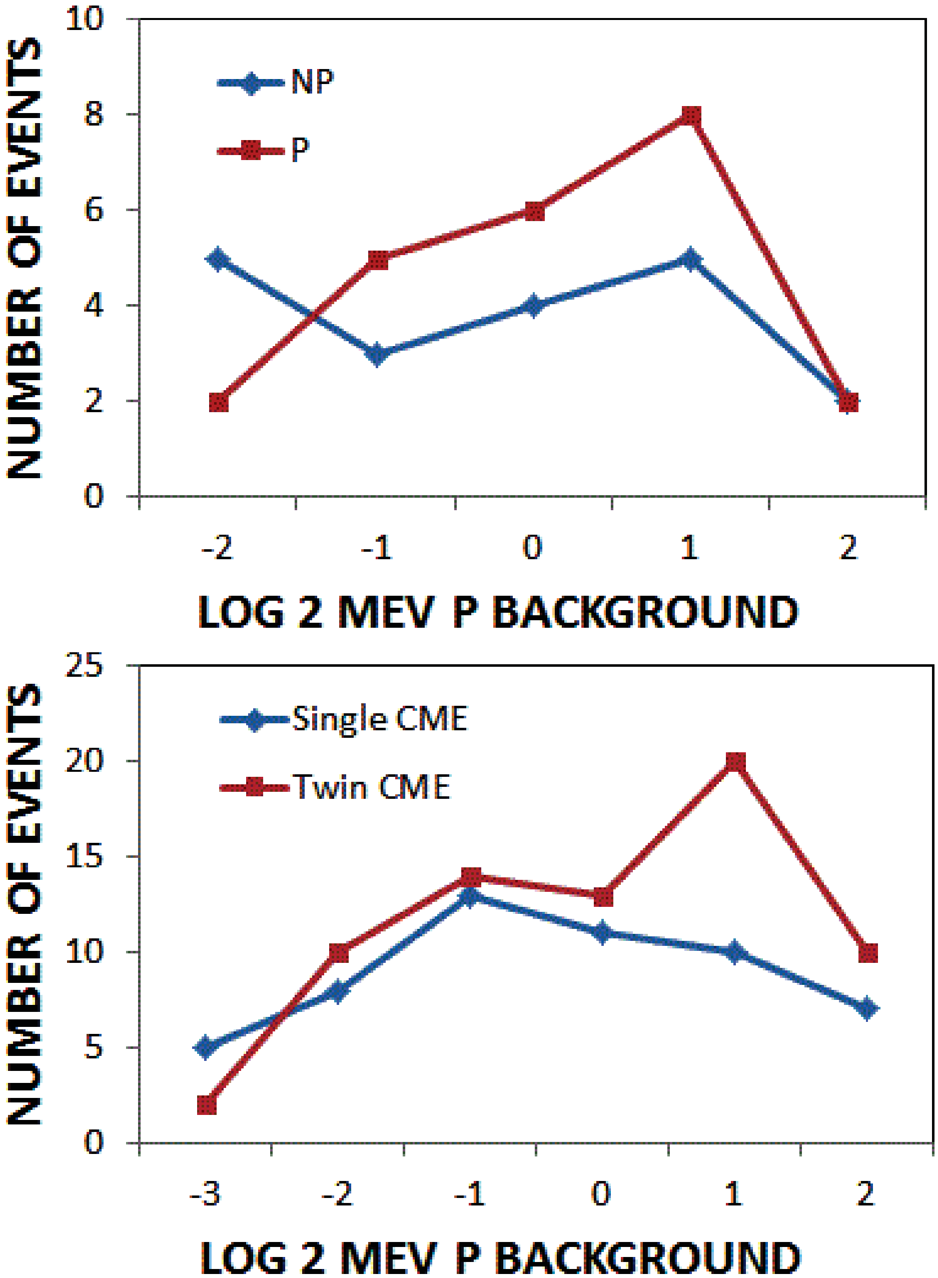

Fig. 9.— Top: Numbers of SEP events in bins of the logs of the 2-MeV background intensities for the NP and P CMEs of Gopalswamy04. Bottom: Same for the single and twin CMEs of Ding13. In both plots the diamonds represent the no-preCME cases.

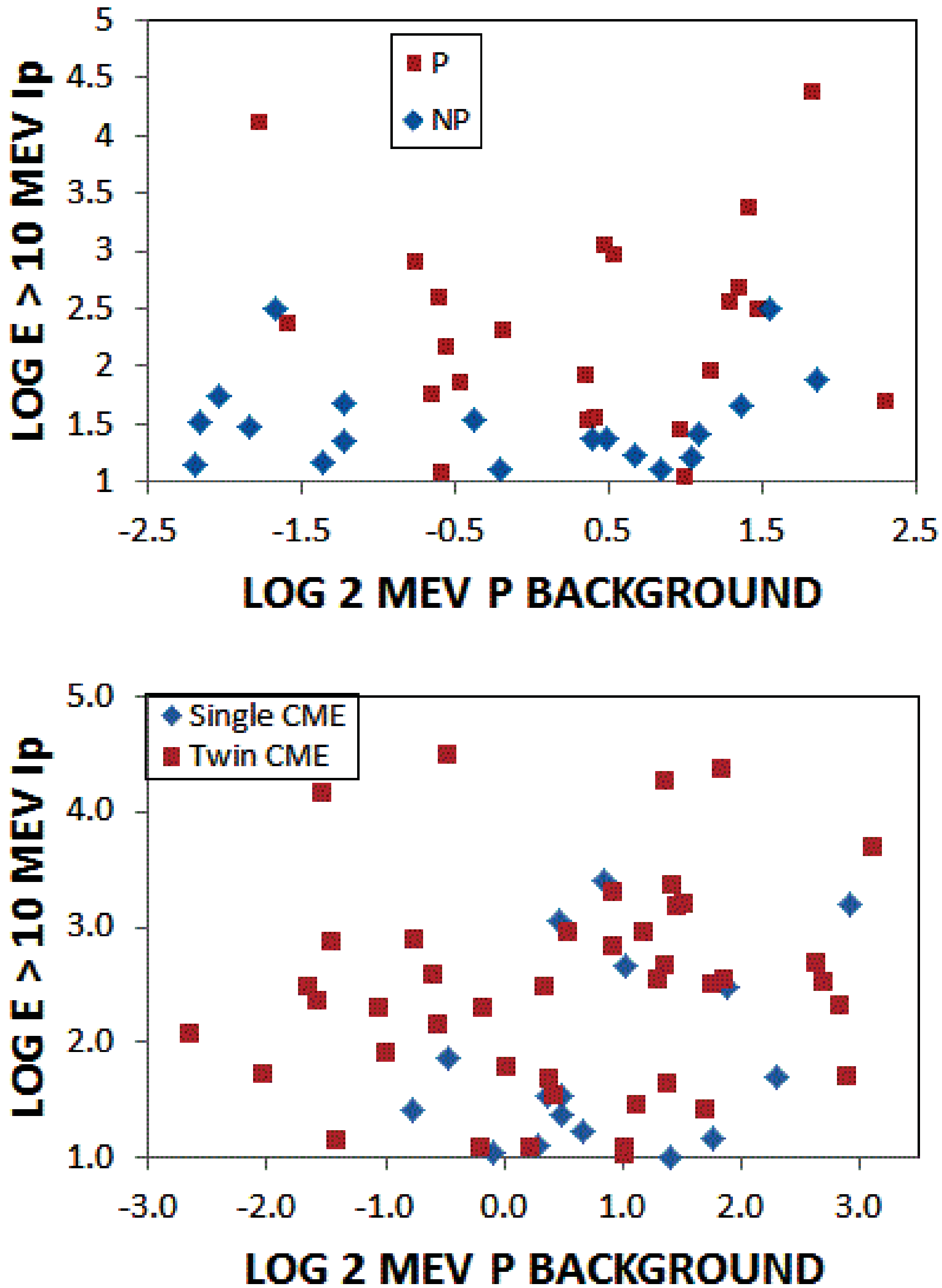

Fig. 10.— Top: Logs of $E > 10$ MeV events versus logs of 2-MeV backgrounds for the NP and P CMEs of Gopalswamy04. Bottom: Same for the single and twin-CMEs of Ding13. In neither case is there a correlation between log Ip and log 2-MeV background.