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The Influence of Coronal Mass Ejection Characteristics on the Spread of Solar Energetic Particles

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A study of 41 large, multi-spacecraft solar energetic particle (SEP) events observed by ACE and STEREO revealed large variability in the longitudinal spread of SEPs. By examining the longitudinal widths determined using observations of H, He, O, and Fe it was found that the widths exhibited no systematic charge-to-mass (Q/M) dependence. However, a dependence on energy was identified with higher energies (10 MeV/n) exhibiting narrower distributions than lower energies (0.3 MeV/n). Here we investigate the influence of the characteristics of the associated coronal mass ejection (CME) on the widths of the SEP longitudinal spread. In particular, we examine the speed, mass, kinetic energy, and acceleration of the relevant CMEs and the distributions of H, He, O, and Fe at 0.3, 1 and 10 MeV/n. A weak correlation between the SEP longitudinal spreads at 10 MeV/n and CME speed is found for events observed by three-spacecraft; a similar correlation with kinetic energy may be related. The observed correlation with CME acceleration is largely due to one event with narrow width and large deceleration. A comparison of properties for CMEs associated with two- and three-spacecraft events reveals significant differences. The three-spacecraft events have CMEs that, on average, are 50% faster and more massive, have three times the kinetic energy, but decelerate at a rate almost six times those of the two-spacecraft events.

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1. Introduction

For large solar energetic particle (SEP) events, there is a general understanding of the acceleration process at propagating shocks driven by fast and wide coronal mass ejections (CMEs) and the particles' subsequent transport through the interplanetary medium (see, e.g., [1,2]). However, often the details remain elusive as there are rarely measurements of the specific conditions at the acceleration site (e.g., the shock orientation and strength and the level of local turbulence) and of the state of the inner heliosphere which the particles travel through. In situ measurements of the SEP event characteristics are substantial and detailed in energy, time, and species however, primarily confined to ~1 AU. Although the CME-driven shock can be imaged with coronagraphs [3], these observations are limited to within a few solar radii of the Sun and provide no information regarding the orientation of the magnetic field, a critical parameter for diffusive shock acceleration [4].

In 2006, the Solar Terrestrial Relations Observatory (STEREO) was launched to provide simultaneous observations from multiple longitudinal vantage points at ~1 AU. This allows SEP event characteristics to be examined as a function of longitude, while also providing improved imaging of CMEs and associated flares; in particular, from February 2011 to September 2014 it was possible to view the entirety of the solar surface, not just the hemisphere facing Earth. Multiple views of CMEs also allows three-dimensional reconstruction/modeling, yielding better values of their speeds and widths.

Cohen et al. [5] took advantage of the similarity between the SEP instrumentation onboard the STEREO spacecraft (the Suprathermal Ion Telescope [6] and the Low Energy Telescope [7]) and that on the ACE spacecraft (the Ultra-Low Energy Isotope Spectrometer [8] and the Solar Isotope Spectrometer [9]) to make multi-spacecraft observations of H, He, O, Fe at 0.3, 1, and 10 MeV/n for 41 large SEP events. They investigated the spread in longitude of SEPs as a function of energy and species and found no systematic dependence on species but decreasing widths with increasing energy.

Although the work examined the effects of the passage of unrelated interplanetary coronal mass ejections on the particle spread, the authors did not examine the influence of the characteristics of the associated CME on the observed widths. Here we utilize the work of Cohen et al. to perform that study. In particular, we examine the widths of H, He, O, and Fe at 0.3, 1, and 10 MeV/n measured for events observed by both STEREOs and ACE as a function of the CME's speed, mass, kinetic energy and acceleration. Further we compare the CME characteristics for the three-spacecraft events to those of the events observed by only two spacecraft.

2. Coronal Mass Ejection Characteristics

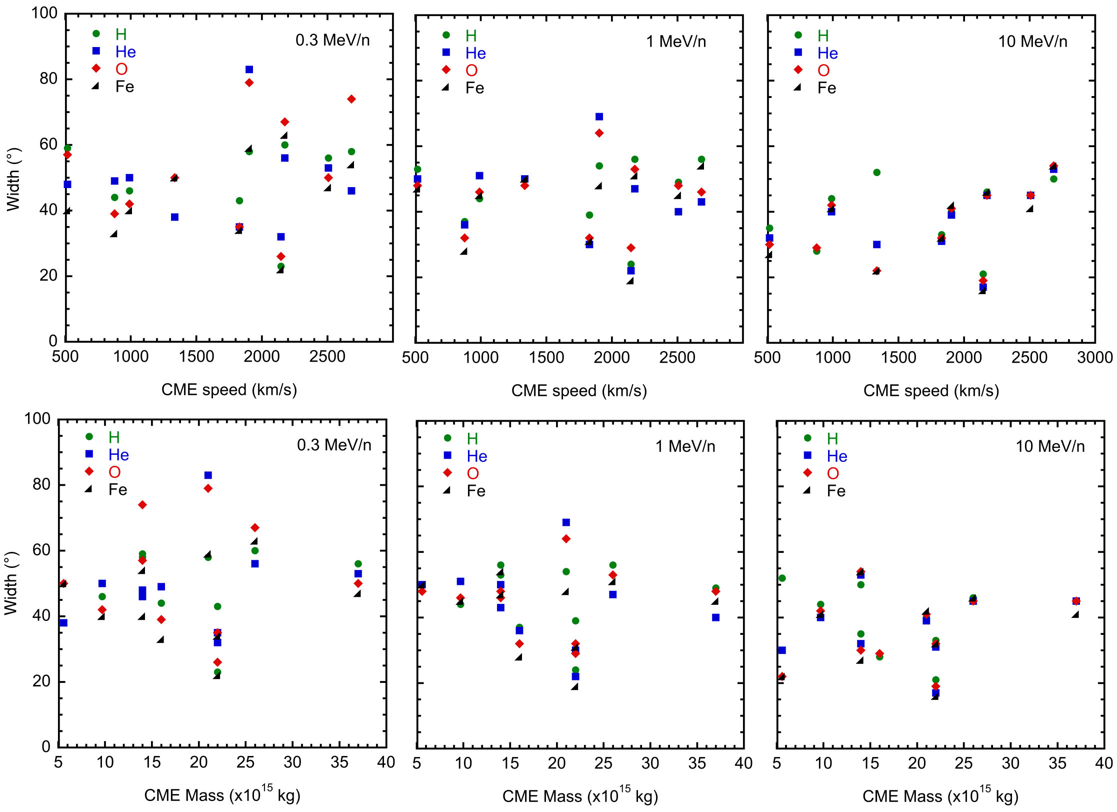
Ideally, the CME parameters would be determined through a three-dimensional fitting of the SOHO/LASCO and STEREO/SECCHI coronagraph observations for each event. We have left this large task for future work and at present have examined the values routinely made available via two catalogs: the LASCO CME catalog [10] and the CACTus catalog [11]. While the CACTus catalog includes both STEREO/COR2 and SOHO/LASCO observations, it is an automated catalog and does not provide masses, kinetic energies or accelerations. Thus, for this study, we have only used the LASCO catalog. It should be noted, however, that the mass and kinetic energy values given in the catalog are generally considered preliminary and may be subject to change in the future. Additionally, for most of the events in the Cohen et al. study (and all of the three-spacecraft events), the LASCO catalog identifies the CME as a 'halo' CME and thus reports its width as 360°. Thus, we have not used this parameter in our study. Finally, in some events LASCO observations are subject to projection effects due to the travel direction of the CME; these have not been corrected for.

3. Three-Spacecraft Events

Plots of the calculated widths for the identified three-spacecraft events of Cohen et al. are plotted versus the CME parameters in Figure 1. There is substantial scatter in the results, but there is a suggestion of an increase in width with increasing speed for at least 10 MeV/n; any correlation is less apparent for 0.3 and 1 MeV/n. The same could be said for the kinetic energy correlations, while the mass plots show no clear correlation at any energy.

In contrast to the other parameters, the plots versus CME acceleration appear to exhibit positive correlations at all energies. However, this is largely driven by two events which have the largest and smallest accelerations: 27 January 2012 and 25 February 2014, respectively (the latter actually having significant deceleration). The remaining events do not appear to be well organized by the CME's acceleration.

Although the plots in Figure 1 have been grouped by energy, there is no evidence of a species dependence in any of the correlations (or lack thereof). This is consistent with the results of Cohen et al. who did not find a species dependence to the calculated widths.



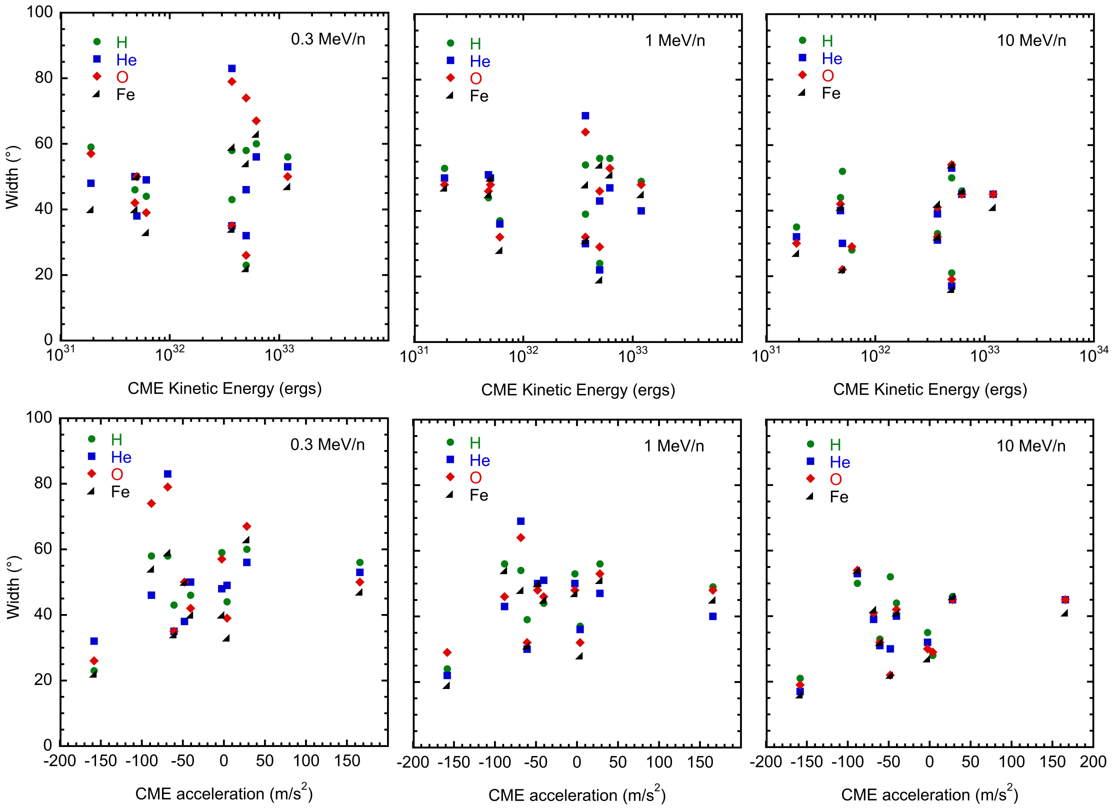


Figure 1. Plots of the calculated widths of three-spacecraft events from Cohen et al. [5] versus CME parameters from [10]. The left column plots are widths of 0.3 MeV/n ions, the center column is for 1 MeV/n ions and the right column is 10 MeV/n. The first row is as a function of CME speed, the second versus CME mass, the third versus CME kinetic energy and the last row is a function of CME acceleration. In each plot the colored symbols identify the species, H, He, O and Fe.

4. Comparison with Two-Spacecraft Events

Calculations of the widths of individual events that were observed by only two spacecraft is not possible, as the Gaussian form used by Cohen et al. requires three measurements to calculate the three parameters. Cohen et al. attempted to fit the aggregate of the two-spacecraft event measurements, but concluded that the results were likely skewed to higher widths due to the large variability in the position of the distribution centers observed in the three-spacecraft events. Thus, here we instead compare the distribution of the CME parameters for the two-spacecraft events to those of the three-spacecraft events (Figure 2), although there are significantly more of the former. It should be noted that we were unable to find the appropriate CME in the LASCO catalog for one of the two-spacecraft events. This was a back-side event, so it may be understandably not well measured by LASCO. Thus there are only 29 two-spacecraft events presented here, in contrast to the 30 listed in Cohen et al.

In all cases there appears to be a clear difference in the distributions of the CMEs associated with the three-spacecraft events compared to those of the two-spacecraft events. The three-spacecraft event CMEs are generally faster, more massive, more energetic, and exhibit stronger deceleration. Table 1 gives the mean values of each parameter for the two groups; the CMEs connected to the three-spacecraft events are, on average, 50% faster and more massive, have three times the kinetic energy, but decelerate at a rate almost six times that of the two-spacecraft event CMEs.

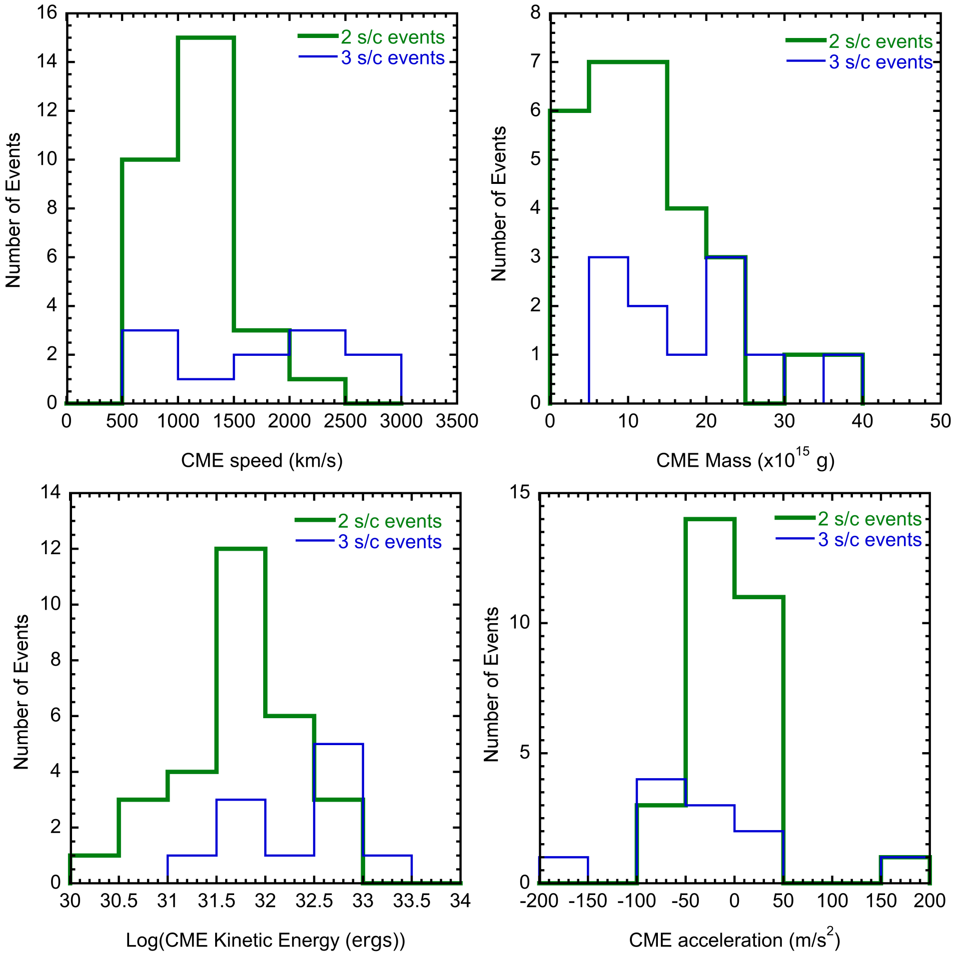


Figure 2. Histograms of CME parameters for the group of CMEs associated with two-spacecraft (thick green line) and three-spacecraft (blue line) SEP events. Note the CME mass is normalized by 10^{15} and the kinetic energy is plotted as the log of the value.

CME Parameter	*Mean of 2 s/c Events*	*Mean of 3 s/c Events*
Speed	1160 km/s	1740 km/s
Mass	1.2 x 10^{16} kg	1.8 x 10^{16} kg
Kinetic Energy	1.1 x 10^{32} ergs	3.5 x 10^{32} ergs
Acceleration	-5.6 m/s^2	-30.1 m/s^2

Table 1. A comparison of mean values of CME characteristics for those CMEs associated with two-spacecraft SEP events and those associated with three-spacecraft SEP events.

5. Discussion and Summary

One might expect that faster or more massive/energetic CMEs would result in wider SEP distributions due to their ability to drive a strong shock that has a larger region of its front capable of accelerating SEPs. However, at best there is a weak correlation in the 10 MeV/n widths with speed. As the CME kinetic energy is a function of the mass and speed, and there is no evidence of a correlation with mass, it is reasonable to assume that any correlation seen in the kinetic energy plots is primarily reflecting the speed dependence. That the correlation with speed is less evident in the lower energy widths may be due to the larger scatter in the individual species widths. However, any one individual species also does not show a correlation between width and speed at 0.3 or 1 MeV/n. The possible correlations at 10 MeV/n are reduced by the anomalously narrow event (~20°) which is associated with a fast (>2000 km/s) and energetic (~5 x 10^{32} ergs) CME. This event, on 25 February 2014, was noted by Cohen et al. and is discussed further below.

It is possible that once a CME exceeds a particular speed threshold, a wide event will be generated whose ultimate width is dependent on additional factors such as variations in the state of the interplanetary medium. If so, correlation with speed above this threshold would be less evident. This is perhaps reflected in the comparisons of the histograms in Figure 2 comparing the properties of CMEs associated with two- and three-spacecraft SEP events, if it is assumed that the two-spacecraft events are generally narrower than three-spacecraft events (stemming from the logic that if a two-spacecraft event had been wider it would have been observed by three spacecraft; which may not be accurate for all the events examined here). The CMEs generating three-spacecraft events are, on average, faster and more massive (and therefore having more kinetic energy) than those of two-spacecraft events. Similar differences are evident in the distributions, for example 5 of the 11 (45%) three-spacecraft events have speeds ≥2000 km/s, while only 1 of the 29 (3%) two-spacecraft events is this fast.

The plots involving the CME acceleration suggest a correlation at all energies; however, this is largely a result of two events with extreme values of acceleration and deceleration. In fact, even the event with the large acceleration (27 January 2012) exhibits widths similar to those of events with more modest acceleration, leaving the 25 February 2014 event as the primary culprit. The events with more mid-range acceleration do not show a clear correlation. The difference in the distributions for the two- and three-spacecraft events may be related to the difference in the speed distributions as it has been found that faster CMEs often exhibit stronger deceleration [12], possibly due to the drag force that increases with speed as suggested by Gopalswamy et al. [13] or due to the shock sweeping up more material as postulated by Sheeley et al. [14].

The 25 February 2014 event has a significantly narrower SEP width (~20°) than the other three-spacecraft events, yet it has a >2000 km/s CME which experiences extreme deceleration. This combination skews the impression of a correlation (or lack there of) in many of the plots in Figure 1. Without this event the correlation between 10 MeV/n width and speed would appear stronger, while the correlation with acceleration (at all energies) would essentially vanish. This event was noted by Cohen et al. to be particularly sensitive to the determination of the spacecraft footpoints due to the fact that although STEREO-A and -B were relatively close together, they measured substantially different fluences. In fact, Klassen et al. [15] found it impossible to fit the 55-65 keV electron observations to a Gaussian distribution (centered at the flare location) for this event. At higher energies, 0.7-3 MeV, they found a fairly nominal width of 47°, similar to the 52° found by Lario et al. [16] using peak intensities of 71-112 keV electrons.

For this work we have utilized the speed, masses, kinetic energies, and accelerations given in the SOHO/LASCO catalog, which, depending on the source longitude, may be more or less subject to projection effects. In the future it may be possible to combine the LASCO and STEREO/SECCHI coronagraph observations with modeling techniques to determine more accurate values (as has been done, for example, by Rouillard et al. [17] and by Lario et al. [16]). It remains to be seen if this yields better or worse correlations with the widths of the SEP distributions.

Acknowledgements

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