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Filament Eruptions Outside of Active Regions as Sources of Large Solar Energetic Particle Events

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Gradual solar energetic ($E > 10$ MeV) particle (SEP) events are produced in shocks driven by fast CMEs, which are nearly always spatially associated with ARs. Several cases of SEP events associated with CMEs originating in large filament eruptions (FEs) from outside ARs have previously been known, but four more such cases from solar cycles 23 and 24 have been described by [1]. The CMEs were fast ($\sim$ 1000 km s^{-1}), appeared as coronagraph halo CMEs, and were associated with interplanetary type II bursts over a wide wavelength range. On the basis of their observed weak post-eruption arcade X-ray flare enhancements, several more candidate large SEP events resulting from eruptions of filaments adjacent to but outside ARs were identified. Thus, large SEP events can arise not only from unobserved ARs behind the disk, but also from non-AR filament eruptions. SEP event forecasting, currently based on observations of front-side solar ARs and X-ray flares, therefore can not predict either kind of SEP event. For the two SEP events with STEREO observations we confirm that despite their good magnetic connections to Earth, the SEP longitudinal distributions are broad. Neither Ulysses SEP observations nor CMEs associated with shocks and type II bursts give any indication that high-latitude polar-crown filament eruptions may have produced SEP events.

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1. Introduction

Large gradual SEP ($E > 10$ MeV) events observed in the interplanetary medium are produced in shocks driven by fast (> 900 km s^{-1}) coronal mass ejections (CMEs) [2, 3, 4]. A major challenge is to forecast the occurrence or peak intensity Ip of a SEP event [5]. This is currently done for about a day in the future on the basis of the magnetic characteristics of ARs, which are assumed to provide the energy sources for the CMEs [6]. Fast CMEs are usually accompanied by AR flares, which can be exploited for immediate SEP forecasting, but only if those ARs lie on the visible solar disk. The accompanying AR flares are usually large, in the M or X range of the GOES soft X-ray scale. The time-intensity profiles of those X-ray flares are more easily and immediately analyzed for SEP forecasting than are the temporal and spatial variations of the white-light CME images, and the X-ray flare source locations can now be rapidly ascertained. Although less directly related to SEP production than are CMEs [7], flare observations continue to be the primary means of the immediate SEP forecasts [8].

In three cases large SEP events have been related to eruptions of filaments lying outside ARs and accompanied by only faint X-ray enhancements from the post-eruptive arcades that follow the filament eruptions (FEs) [9]. These few events are important not only for their elusive nature in the AR and flare-based SEP forecasting schemes, but also for their diagnostic insights into the physics of shock and SEP generation. In a recent work we [1] report four more such FE SEP events from solar cycles 23 and 24 and describe their characteristics in detail using complete data coverage from the Sun to the interplanetary medium. That work relates the FE properties to the associated CMEs and shocks. Here we will summarize and somewhat extend the findings [1] and then discuss the space weather implications of these events.

2. Data Analysis

2.1 SEP Event Selection and Characteristics

[1] selected only large SEP events with a proton intensity in the >10 MeV GOES energy channel $\geq$ 10 pfu (pfu = particle flux unit; 1 pfu = 1 particle cm^{-2} s^{-1} sr^{-1}). In addition, SEPs had to be detected in the >50 MeV channel for a fair comparison with previous events reported by [9]. Table 1 provides an overview of the four events, all of which have been listed in various papers involving statistical properties of SEP events or type II radio bursts [10, 4, 11]. The first two columns give the onset date and the peak intensity (Ip) of the SEP events in the GOES >10 MeV channel. Column 3 gives the best-fit exponent γ to a power-law fit to the SEP energy spectrum at maximum intensity. Column 4 gives the heliographic coordinates of the filament centroid, and column 5 the soft X-ray flare size. Columns 6 and 7 give the speeds of the CME filament/prominences, Vep, and leading edges, Vcme, observed in the LASCO field of view. The wavelength range of the type II burst is given in column 8; this range is a good indicator of where the shock forms and how long it survives [10]. Only one event had a type II burst starting from metric (m) wavelengths (starting frequency was 24 MHz). In all other cases, the type II burst started in the decameter-hectometric (DH) domain (below 13 MHz) as observed by the Radio and Plasma Wave Experiment (WAVES; [12]) on board the Wind spacecraft. In all cases, the radio emission continued down to kilometric (k) wavelengths, indicating that the shocks survived at least to 1 AU.

Table 1: Large SEP Events With Prominence Eruption CMEs

SEP Onset	Ip	γ	Source	X-ray	Vep	Vcme	type II
yyyy/mm/dd	pfu		Location	Imp.	km/s	km/s	m/Dk
2000/09/12	320	4.15	S17W09	M1.0	677	1550	y/Y
2002/05/22	820	4.55	S30W34	C5.0	621	1494	n/Y
2011/11/26	80	4.34	N27W49	C1.2	878	933	n/Y
2013/09/29	180	4.69	N23W25	C1.1	603	1025	n/Y
Additional			*Events*				
2000/04/04	55	4.76	N25W55	C9.7		1188	y/Y
2004/04/11	35	4.01	S14W49	C9.6		1645	n/Y

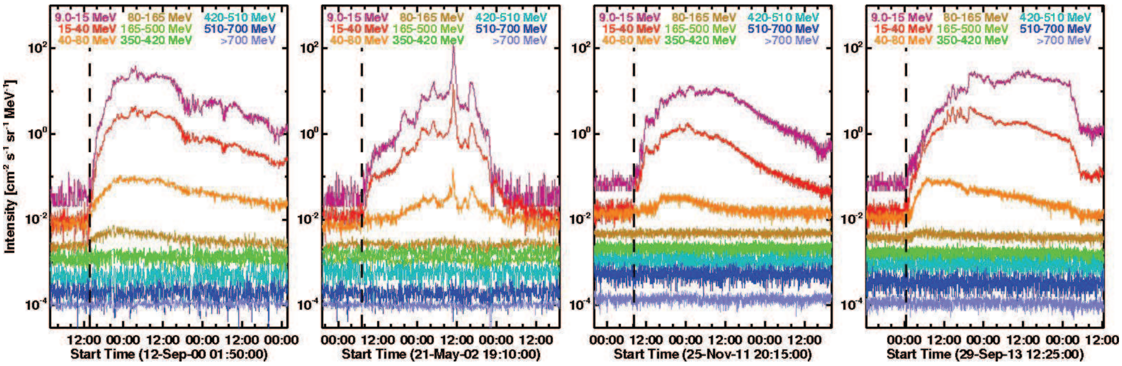

Figure 1: Differential proton intensity profiles of the first four SEP events of Table 1. Figure 2 of [1].

The four SEP events had proton intensity increases extending to 50 MeV, and their profiles in the GOES observations are shown in Figure 1. [1] used proton intensities observed by the Energetic and Relativistic Nuclei and Electron (ERNE; [13]) instrument on board SOHO to derive the power-law spectral index γ, which ranges from 4.15 to 4.69 (Table 1), comparable to the 4.3 value derived for the 1981 December 5 SEP event [14]. These values also lie in the high end of the approximate range of $2 < \gamma < 4.5$ for well-connected $>$ 10 pfu SEP events of the later GOES two-point ($E >$ 10 MeV and $>$ 60 MeV) survey by [15].

2.2 Solar Source Observations

In the pre-eruption phase, the source regions were large-scale bipolar regions with Hα filaments marking the polarity inversion lines of the magnetic structures, as shown in the top panels of Figure 2. The filament eruption was accompanied by a two-ribbon flare in each case, with the ribbons located on either side of the original position of the filament. The photospheric magnetograms of Figure 2 show that the flare ribbons were located on opposite polarity regions, while the filaments were located on the polarity inversion line. The ribbons in the 2011 November 26 event were confined to the stronger magnetic field region, where the pre-eruption filament was very thin. There was another section of the filament that erupted from the southern end, but no ribbons were found around this section. The post-eruption arcades of Figure 2 were also very extended, mostly in the north-south direction. The soft X-ray flares associated with the four SEP events were

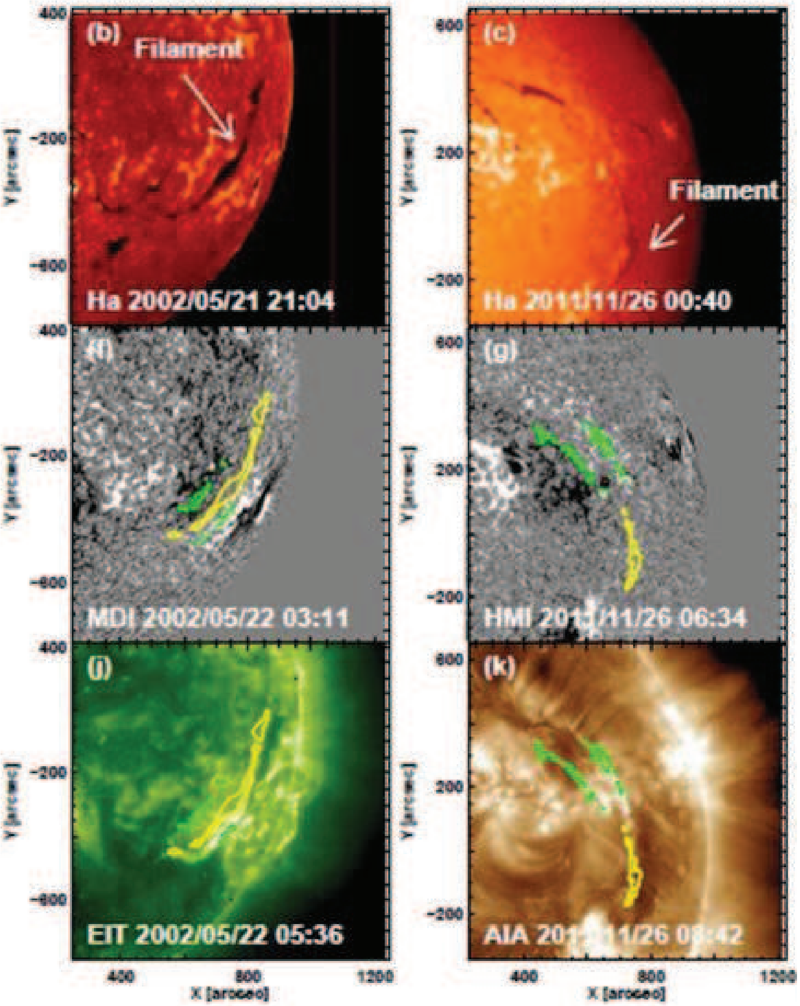

Figure 2: Images of the second and third events of Table 1. The filaments in Hα images (top); flare ribbons (green) and filament locations (yellow) on magnetograms (middle); EUV post-eruption arcades (bottom). From [1].

generally weak, with the flare size ranging from C1.2 to M1.0. The M1.0 flare associated with the 2000 September 12 event was the only one with weak impulsive microwave emission.

The later phases of the erupting filaments were observed as prominences trailing the CME leading edges in the LASCO field of view, shown for the four events in Figure 3 [1]. The four height-time plots showed the well known [16] effect of separations between the CME leading edges and prominences because of their different speeds (Table 1). The CMEs all met the criteria for fast ($\geq$ 900 km s^{-1}) and wide ($\geq 60^\circ$) to drive shocks and accelerate SEPs, but the CME leading edge accelerations were found to be relatively low in comparison with those of large SEP events [17].

In all events, the type II bursts were weak and of narrow band in the DH domain, but intensified around 1 MHz. Shock speeds were deduced from the type II burst drift rates, yielding values comparable to those of the associated CME leading edge speeds, suggesting that the SEP events

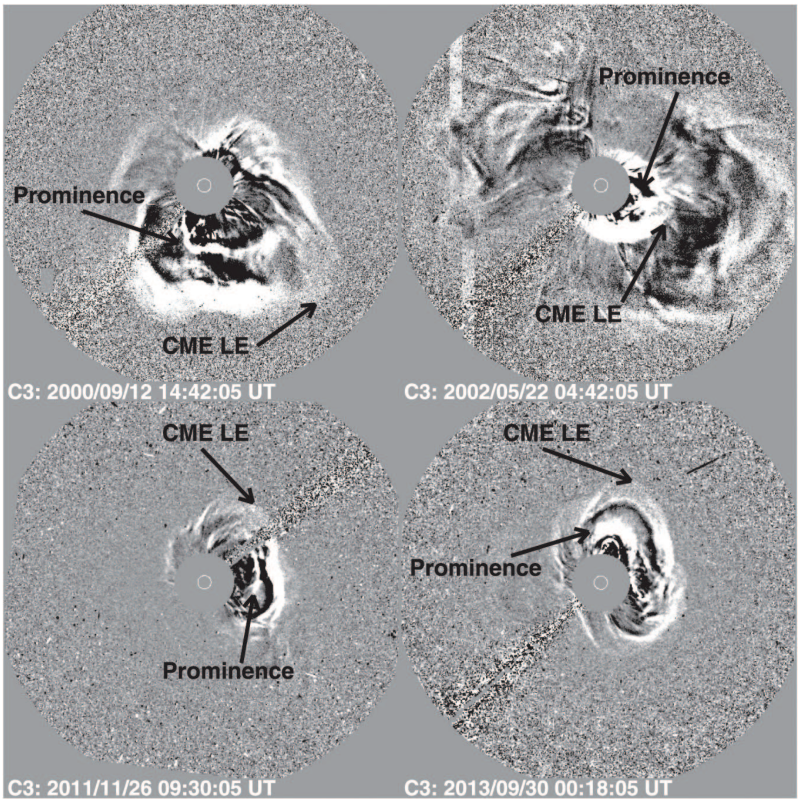

Figure 3: SOHO/LASCO images showing the CMEs and the associated eruptive prominences in four SEP events. All four CMEs became halos in the field of view of the outer coronagraph (C3) of *SOHO*/LASCO. Figure 5 of [1].

were consistent with shock acceleration. The general lack of a metric type II component (Table 1) indicates that the associated shocks formed relatively late. Using previous determinations of shock formation heights [18], [1] established formation heights of $\geq$ 1.92 Rs. All the shocks were relatively strong and survived to the Earth, where they were observed in situ as interplanetary shocks.

2.3 Search for Additional FE SEP Events

[1] used the typical characteristics of FE SEP events to search for additional such candidates among SEP events for which AR sources had been assumed or assigned. They selected large ($>$ 10 pfu) SEP events over cycles 23 and 24 with weak C-class flares and found 5 candidate events. The two best cases of FE events are included at the bottom of Table 1. Examination of Hα, EUV, and magnetogram data showed that a north-south FE and post-eruption arcade occurred $\sim$10° to the east of AR 8933 on 2000 April 4. A circular filament mostly outside AR 0588 was the source region for the 2004 April 11 SEP event and had been studied in detail earlier by [19]. [1] concluded that the 2000 April 4 event was definitely and the 2004 April 11 event likely an FE SEP event. Table 1 shows that they are similar in all characteristics to the first four events, so there now may be 6 additional FE events to add to the earlier list. The remaining questionable cases suggest a

continuum of filament-AR configurations from the more usual filaments embedded in ARs to the clearly non-AR filaments of the first four cases of Table 1.

2.4 SEP Longitudinal Extensions of Two EF Events.

The source longitudes of the 6 EF SEP events of Table 1 are all magnetically well connected to Earth. Including the remaining three candidate SEP events with C-class flares, the 9 EF sources range from W09° to W66°, reminiscent of the limited longitude range of impulsive SEP events [2, 20, 21] and their narrow longitudinal SEP distributions. For events since 2006, STEREO observations can provide spatial distributions of gradual SEP events. We have compared the two latest SEP events of Table 1 with the catalog of STEREO and Earth-based $\sim$ 25 MeV peak proton intensities Ip compiled by [22]. Both events were observed at all three locations, and the maximum Ip was at Earth. The four gradients (two directions and two events) of log Ip versus longitude in degrees ranged from 0.017 to 0.001 deg^{-1}. These gradients are comparable to those on the log plot of Ip versus longitude for 15–40 MeV protons of 35 SEP events observed at STEREO and Earth by [23]. Thus, despite the favorable magnetic source connections of the Table-1 EF SEP events, the longitudinal distributions are most likely comparable to those of more typical SEP events.

2.5 High Latitude SEP Events and Polar Crown Filaments

An extreme example of EFs is that of the high-latitude polar crown filaments, which lie well above the AR zone latitudes. Could polar crown EFs give rise to SEP events? High latitude SEP events were observed on the polar passes of the Ulysses spacecraft, so we examined works dealing with Ulysses SEP events [24, 25, 26] to determine the source regions of those events. In all cases those SEP events could be attributed to CMEs/flares in ARs. The other approach is to ask whether polar crown EFs and CMEs can be associated with type II bursts, indicating that they can drive shocks. Selecting only fast ($>$ 900 km s^{-1}) and wide ($\geq$ 60°) (FW) CMEs from 1996 to 2005, [27] found that solar sources of CMEs both with and without any type II bursts were confined generally to a $\pm$ 40° latitude range. A later survey [28] of CMEs associated with interplanetary shocks detected at Earth revealed a CME source latitude range of $\pm$ 30°. In both studies, there was a pattern of the highest latitudes occurring during the solar cycle rise phase, consistent with the AR latitudes. We conclude that neither the Ulysses SEP observations nor the FW and shock-associated CME studies give any indication that polar crown EFs produce SEP events.

3. Discussion

Most large SEP events are associated with fast and wide CMEs from solar ARs with M or X class flares. However, the SEP events associated with EFs outside of ARs (GMA2015, [1]) are a small but well defined class of events that can be difficult to forecast when the AR X-ray flare is the basic forecasting diagnostic. These SEP events differ primarily in that the CME accelerations are lower, resulting in later shock formation at greater coronal heights. After formation, however, the shocks can be strong and propagate to the Earth. Perhaps the late onset of SEP acceleration is the reason for their characteristically steep energy spectra. The EF SEP events found so far are nearly all magnetically connected to Earth, but they probably have longitudinal intensity peaks similar to AR-associated SEP events. These EF SEP events appear to be confined to AR latitude sources.

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