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# LOW CORONAL SIGNATURES OF LARGE SOLAR ENERGETIC PARTICLE EVENTS

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## ABSTRACT

We report on the low coronal signatures of major solar energetic particle (SEP) events. Because large SEP events are highly associated with both flares and coronal mass ejections, we focused on flare-associated motions in soft X-rays. In a sample of a half-dozen well-observed flares associated with SEP events, we identified two basic types of motions or ejections. For one class of events including those of 2001 November 4 and 1998 April 20, the ejections occur on active region or larger scales. They have an extended "preeruption" phase in which the involved structures slowly rise or expand on timescales of tens of minutes. For the second class of events, including those on 1997 November 6 and 2001 April 15, the large-scale preeruption phase is absent. In these events, ejecta appear explosively at the onset of the flare impulsive phase. The observed differences in ejections appear to correlate with spectral/compositional/charge state characteristics of large SEP events, suggesting that flare ejecta are diagnostic of shock properties/environment.

*Subject headings:* Sun: coronal mass ejections (CMEs) — Sun: flares — Sun: particle emission

## 1. INTRODUCTION

Solar energetic particle (SEP) events, which represent an important aspect of space weather, are still not well understood. Particles in large "gradual" SEP events are generally thought to be accelerated at shocks driven by fast coronal mass ejections (CMEs; see the review of Reames 1999 and references therein). Several studies have tried to correlate the occurrence and peak intensity of SEP events with CME properties such as their speeds (Kahler 2001) and, more recently, their interactions (Gopalswamy et al. 2002).

Before CMEs were discovered, large SEP events were thought to originate in flares. Indeed, most large SEP events are associated with major flares, reflecting the intimate, although not well-understood, relationship between flares and CMEs. Interest in flares as possible contributors to large SEP events, either directly or as a seed population, has been rekindled by recent observations of SEP composition and charge state at high energies (e.g., Cohen et al. 1999; Leske et al. 2001; Tylka et al. 2001; see Cliver 2000). Over the years, there have been several efforts to correlate SEP events with properties of the associated flares, such as metric type II radio bursts (Švestka & Fritzová-Švestková 1974), $\gamma$-ray line fluence (Cliver et al. 1989), progressively hardening hard X-ray spectra (Kiplinger 1995), and low-frequency type III radio emission (Cane, Erickson, & Prestage 2002).

Most of these efforts to correlate flare properties with SEP events have used spatially integrated radio and high-energy data, rather than images of the low corona. The detailed work on H$\alpha$ data for proton flares made in the 1960s (e.g., see Švestka & Simon 1969) has not been carried over into the space age. It seems likely that X-ray images of flares, when they have both adequate spatial and temporal resolution and a field of view wide enough to capture the associated large-scale changes, contain important information on the origin of SEP events. At present, such images are poorly utilized in conjunction with SEP events.

In this Letter, in an attempt to gain insight to the SEP acceleration process, we examine coronal signatures of flares that are associated with intense, gradual SEP events, using data primarily from the *Yohkoh* soft X-ray telescope (SXT). The main focus is on flare-associated motions, which are correlated with CMEs (Nitta & Akiyama 1999). These motions are usually observed for shorter times than the EIT waves, which have been linked at least anecdotally to SEPs (Torsti et al. 1999). We examine SXT data for a sample of six flares that were associated with major proton events with prompt onsets at high (>10 MeV) energies. After describing the data in § 2, we discuss in §§ 3 and 4 outward motions in the early phase of SEP-associated flares. In § 5, we discuss the results in terms of a possible dependence of SEP event characteristics on the origin of the CME.

## 2. OBSERVATIONS

### 2.1. *Events*

We began with the list of major proton events[4] and selected large SEP events during 1997–2001 whose peak flux of greater than 10 MeV protons exceeded 100 particle flux units (PFU; defined as particles $s^{-1}$ $sr^{-1}$ $cm^{-2}$ measured by the *GOES* satellite). There were 22 such events, of which 19 occurred while the *Solar and Heliospheric Observatory* (*SOHO*) was operational. Data from the Large Angle and Spectrometric Coronagraph (LASCO) on *SOHO* show a CME associated with each of them, except for one event (2001 December 30) that appears to be a modulation of a high background flux from an earlier event. From these 18 events, we then selected events that started within 2 hr from the onset of the associated CME.[5] Ten events met this criterion, and six of these were observed by SXT.

The flare, CME, and SEP properties of these six events are summarized in Table 1. To obtain the CME onset time, we extrapolated the first two LASCO measurements of the height of the CME to the projected height of 1.1 $R_\odot$ at the flare location. We added the 2000 November 8 event, which was not observed by SXT but by the *Transition Region and Coronal*

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[4] Compiled and maintained by J. Kunches at the NOAA Space Environment Center. See http://umbra.nascom.nasa.gov/SEP/seps.html.

[5] We used the *GOES* 5 minute proton data and the LASCO CME catalog of the Catholic University of America.

TABLE 1

Flares Associated with SEP Events and Observed by *Yohkoh*/SXT

| | Flare | | | | | | | CME | | | >10 MeV Protons Flux at Two Times[f] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Start[a] | Peak | End[b] | Intensity | Location (deg) | AR[c] | Motion[d] | Onset[e] | Speed[e] ($\mathrm{km\ s^{-1}}$) | Width (deg) | $t_3$ | $t_p$ |
| 1997 Nov 06 ...... | 11:49 | 11:55 | 12:01 | X9.4 | S18 W63 | 8100/760 | E 11:54 | 11:42 | 1717 | 360 | 135 | 490 |
| 1998 Apr 20 ....... | 09:38 | 10:21 | 11:18 | M1.4 | S30 W90 | 8194/60[g] | Q 09:46 | 09:51 | 1543 | 165 | 15 | 1700 |
| 1998 May 06 ...... | 07:58 | 08:09 | 08:20 | X2.7 | S11 W65 | 8210/390 | E 08:05 | 07:56 | 1052 | 190 | 77 | 210 |
| 2000 Nov 08 ...... | 22:42 | 23:28 | 00:05 | M7.4 | N10 W75 | 9213/80 | Q 22:55[h] | 22:37 | 1138 | 170 | 5900 | 14800 |
| 2001 Apr 15 ....... | 13:19 | 13:50 | 13:55 | X14 | S20 W85 | 9415/350 | E 13:47 | 13:38 | 1311 | 167 | 438 | 950 |
| 2001 Sep 24 ....... | 09:32 | 10:38 | 11:09 | X2.6 | S20 E22 | 9632/790 | S 10:10 | 10:14 | 1923 | 360 | 106 | 12900 |
| 2001 Nov 04 ...... | 16:03 | 16:20 | 16:57 | X1.0 | N06 W18 | 9684/550 | S 16:09 | 16:12 | 2071 | 360 | 950 | 31700 |

[a] The first minute, in a sequence of 4 minutes, of steep monotonic increase in 1–8 Å flux (from the NOAA daily prelinary list of solar events).

[b] The time when the flux level decays to a point halfway between the maximum flux and the preflare background level (from the NOAA daily prelinary list of solar events).

[c] NOAA AR number/sunspot area (millionths).

[d] S: Ejection from a sigmoid region (§ 3). Q: Ejection from weak field regions (§ 3). E: Explosive event (§ 4). The time indicates when the motions showed significant acceleration.

[e] Based on the first two LASCO C2/C3 data.

[f] In PFU; $t_3$ is 3 hr after the onset, and $t_p$ is the time of the peak flux.

[g] Sunspot area as of April 17.

[h] Referring to motions seen by *TRACE*, not by SXT.

*Explorer* (*TRACE*), because, together with the 1998 April 20 event, it appears to be representative of a class of large SEP events that do not involve major active regions.

### 2.2. *SXT Observations of Motions in Flares*

Hot (>2.5 MK) plasma ejections or outward motions, typically seen early in flares, are not easily detected in the basic *Yohkoh* SXT non–full-disk images that were taken in the $2'.6 \times 2'.6$ field of view with full-resolution ($2''.46$) pixels. Such images are too small to permit tracking of fast motions. More importantly, the automatic exposure control (AEC) shortens the exposures of these images to avoid saturation, and the faint ejections quickly fall below their dynamic range. Ejections are best observed in half-resolution and quarter-resolution images with accordingly expanded fields of view, where the AEC is either turned off or adjusted to retain faint features. In these images, the central part of the flare is often heavily saturated, producing vertical spikes. Because of the potential importance of flare ejecta and faint motions away from the central flare loop, the cadence of these SXT images was increased in 1997.

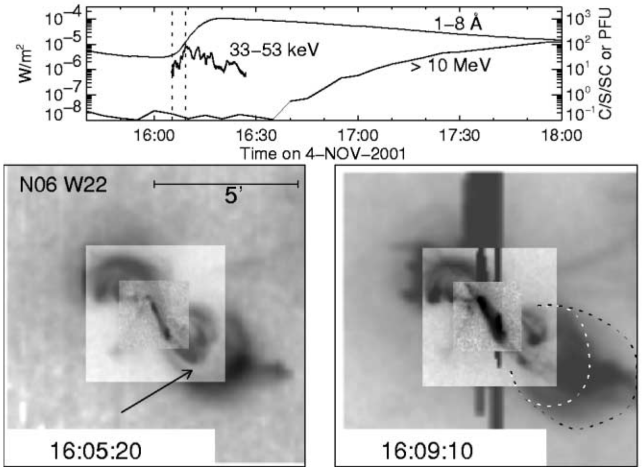

Fig. 1.—*Lower panels*: SXT quarter-resolution images in reverse color of the X1.0 flare of 2001 November 4, with the central part replaced with less saturated half-resolution and full-resolution images. The field of view is $10'.4 \times 10'.4$. The southwestern side of the S-shaped region erupted. The front of the expanding loops is marked by dotted lines (white for 16:05:20 UT and black for 16:09:10 UT) and can be traced until 16:10:30 UT, at which the plane-of-the-sky speed was $\sim 850\ \mathrm{km\ s^{-1}}$. Closer to the central flare loop, another ejection can be seen (*arrow*). The vertical features in the second image represent saturation. The times of these images are indicated in the upper panel, where the light curves in soft and hard X-rays are plotted with the time variation of the *GOES* greater than 10 MeV proton flux.

## 3. OUTWARD MOTIONS IN FLARES ASSOCIATED WITH SEPs: EVENTS WITH GRADUAL MOTIONS OF LARGE-SCALE STRUCTURES

For four of the seven events under consideration, large-scale structures were observed to gradually accelerate on timescales of tens of minutes, with movement beginning either before the flare or near flare onset.

Two such events involved eruptions of a large part of a sigmoidal (Canfield, Hudson, & McKenzie 1999) active region, leaving a rather large (i.e., $\sim 3'$ long) flare loop.[6] Figure 1 shows SXT images for the X1.0 flare on 2001 November 4. In this event, the southwestern side of the region erupted (as marked by dotted lines), following a slow expansion (at a few kilometers per second), which was first seen in the image taken at 15:30 UT. The first few images after satellite night show that the plane-of-the-sky speed was already $75\ \mathrm{km\ s^{-1}}$ at 16:06 UT. It had increased to $850\ \mathrm{km\ s^{-1}}$ when the ejection moved out of the SXT field of view at 16:11 UT. In addition to the outer structure, which was initially $\sim 1.5 \times 10^5$ km away from the flare, another ejection was seen closer to the flare (as indicated by the arrow). It is possible, although not proven, that the two ejections corresponded to the CME front and core. The extrapolation of the LASCO height-time relation for the CME front puts the CME onset time to be at 16:13 UT; this time could be a little earlier, depending on a finite acceleration phase. The CME liftoff is also indicated by motions of large-scale loops in a quiescent region west of the flare, as observed in *TRACE* 171 Å images during 16:08–16:14 UT. The X2.6 flare on 2001 September 24 showed a similar morphology. Its south-

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[6] The X5.7 flare on 2000 July 14, associated with another huge SEP event (Tylka et al. 2001; Smith et al. 2001), is not studied here because SXT missed the critical period. It should in principle be included in this category, however, because it was a sigmoid region and the filament eruption was preceded by a gradual motion, as captured by *TRACE*.

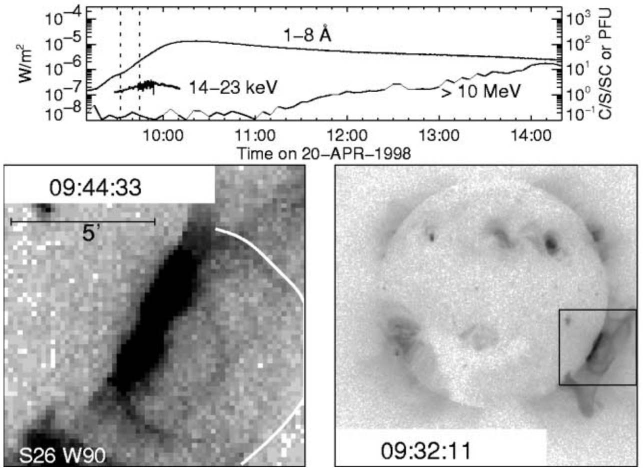

FIG. 2.—SXT images for the M1.4 flare of 1998 April 20. The field of view of the image on the left is indicated in the full-disk image on the right. The white line traces the outer edge of the ejection, which is actually part of a larger scale structure as seen in the full-disk image. The times of these images are shown in the top panel.

eastern part erupted at 10:13 UT, following a gradual expansion that started at 09:53 UT.

Other events of this basic type appear to involve eruptions that were associated with minor sunspot groups (see Table 1) and then only peripherally. An example is the 1998 April 20 event (Fig. 2). SXT images allow us to trace a rising structure, which is marked in the image of 09:44:33 UT, from 09:20 UT (at 1.1 $R_\odot$) to 09:46 UT (at 1.3 $R_\odot$), in which it accelerated from 45 to 450 km s$^{-1}$. Full-disk images (available up to 09:36 UT) show that the rising structure was part of a large-scale eruption from the front and back sides of the Sun (see the image of 09:32:11 UT). While the limb occultation may be partially responsible for the slow rise and decay in soft X-ray flux (peak at M1.4) and the weak hard X-ray emission, this event seems to be a repeat of the large-scale eruption that took place around NOAA Active Region 8194 on April 16. Such an eruption would be different from usual flares in active regions. We note that NOAA AR 8194 (20°–30° behind the west limb at the time of the April 20 event) was the only active region in the southern hemisphere during April 15–20 whose sunspot area had exceeded 100 millionths of the solar disk during disk passage. But it decayed significantly before reaching the west limb and did not produce any flares greater than C1 after April 11.

The 2000 November 8 event (Fig. 3) serves as another example of a large SEP event not involving a major sunspot group. *Yohkoh* missed the presumably most dramatic part of the eruption (no data during 20:08–23:18 UT), but *TRACE* had reasonably good coverage. In *TRACE* 171 Å images, multiply oriented loops (seen in the larger box) were seen to rise at 10–20 km s$^{-1}$ before the data gap of 22:11–22:35 UT. The loops were probably linked to the dark filament seen in absorption against the solar disk (in the smaller box). During 22:49–22:54, the lower part of the loops as marked by the dotted line in the second image was seen to move at ~80 km s$^{-1}$. The rising motion left a faint two-ribbon flare, as circled in white (not visible in the *GOES* light curve). This was at an area outside two minor active regions, to the north of the M7.7 flare (*circled in black*), which originated in AR 9213. The CME was first seen at the height of 3.9 $R_\odot$ at 23:06 UT, so the associated SEP event appears to have originated in the non–active region eruption rather than the M7.7 flare, although the entire complex of minor active regions was probably involved at some level. During the eruption, the nonthermal signature was very weak, as indicated by the 17 GHz time profile.

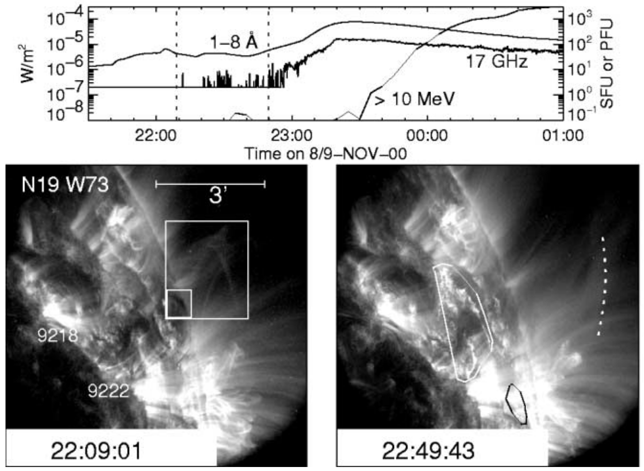

FIG. 3.—*TRACE* 171 Å images taken before the M7.7 flare of 2000 November 8. The larger box in the left image contains multiply oriented loops above the limb, and the smaller box a dark filament. The lower part of the multiply oriented loops is indicated by the dotted line in the right image. The area encircled in white shows two ribbons, and that in black corresponds to the main brightening after 23:10 UT.

## 4. OUTWARD MOTIONS IN FLARES ASSOCIATED WITH SEPs: EXPLOSIVE ACTIVITY

The second basic type of flare-associated motion we identify in large SEP events does not start with gradual motions of large-scale structures. Figure 4 shows SXT images for the 2001 April 15 X14 flare (Tylka et al. 2002). We note the propagation of a faint looplike structure, as marked by dotted lines. This structure became visible suddenly after the onset of the impulsive phase at 13:45 UT. It occurred about the time of the ejection of a bright helical structure in *TRACE* 171 Å images, which are given as insets in the SXT images. The *TRACE* ejection was preceded by a slower rising motion for 8 minutes. The explosive motions in the SXT images, which accelerated

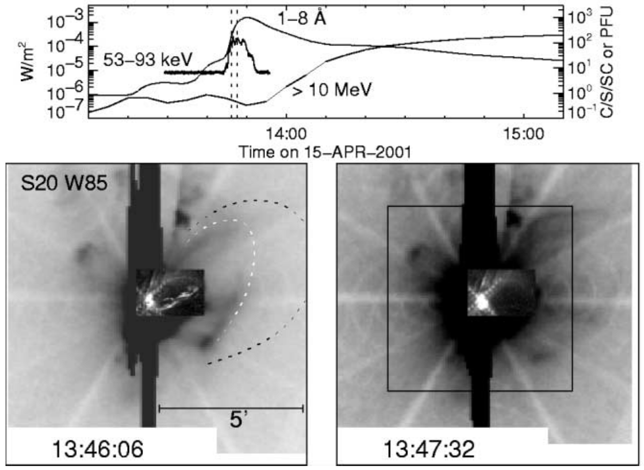

FIG. 4.—SXT overexposed images for the 2001 April 15 X14 flare. Nearly simultaneous (13:46:08 and 13:47:44 UT) *TRACE* 171 Å images (in positive) are inserted as insets. The first one shows a bright ejection. The dotted lines mark the positions of the outer edge of the flare-associated motions in X-rays for the times shown. The box in the second image shows the *TRACE* field of view.

from 600 to 1200 km $s^{-1}$ between 13:46 and 13:49 UT, appeared to be a response to the ejection closer to the flare. Note that the motions seen in SXT images were more extended than the *TRACE* ejection and that the *TRACE* field of view for this event (as indicated by the square box) was too small to follow the fast motions seen by SXT.

There are two other SEP events (1997 November 6 and 1998 May 6), whose associated flares show motions that did not start from the "preeruption" of large-scale structures but appeared suddenly during the impulsive phase. In the 1998 May 6 flare, the initial motions were identified with coronal waves, preceding further ejections (Hudson et al. 2002). In the 1997 November 6 flare, fast (>2000 km $s^{-1}$) but very faint X-ray motions were recognized at the onset of the impulsive phase. A detailed study including LASCO C1 data has shown that the associated CME was explosively accelerated (Zhang et al. 2001). One common characteristic of these three events is that the estimated CME onset time from the first two LASCO images precedes the times the explosive X-ray motions were seen (see Table 1). This suggests that the CME already decelerated close to the Sun.

The differences in flare-associated motions between the events in this section and those in § 3 are reflected in flare timescales, as measured by the decay time from maximum to the half-power point in the *GOES* 1–8 Å light curves. The decay times for the disk events in § 3 were 37, 31, and 37 m. Those for the three events in § 4 were 6, 11, and 5 m.

## 5. DISCUSSION

We have conducted a first study of low coronal signatures in soft X-rays (and EUV) for large SEP events with prompt onsets, by studying motions in the associated flares. These motions may provide an important link between small-scale energy release and large-scale CMEs. For the events discussed in § 3, the motions represent gradual eruptions of large-scale structures. This could occur without the participation of major active regions, which are often used as a basis for predicting SEP events. For the events shown in § 4, explosive motions start locally close to intense impulsive flares.

The two basic types of flare-associated soft X-ray motions (gradual and explosive) that we identify in this small sample of flares associated with major proton events remind one of the distinctions made by early H$\alpha$ observers between filament eruptions and flare sprays (Švestka 1976, p. 223). Later, a similar distinction has been pointed out between disappearing filament- and flare-associated CMEs (MacQueen & Fisher 1983). It is not clear if these two types of motions (whether in X-ray ejecta, H$\alpha$ ejecta, or CMEs) represent fundamentally different physics or simply a difference along a continuum of acceleration timescales (Rust et al. 1980; Cliver & Hudson 2002), ranging from slow acceleration of quiescent filaments to explosive mass acceleration in complex sunspot regions. While the above classification of flare soft X-ray ejecta into two basic categories (or ends of a continuum) has appeal, we note that Hudson et al. (2002) interpreted motions in one of our explosive events as a flare wave.

There is evidence that the two different manifestations of coronal motions may correspond to different SEP characteristics. For the four events of § 3, the energetic particles exhibit the following: energy spectra for oxygen above ~1 MeV nucleon$^{-1}$ that are power laws modulated by an exponential rollover (Ellison & Ramaty 1985); Fe/O above ~1 MeV nucleon$^{-1}$ that decreases with increasing energy, falling to highly suppressed levels relative to the corona and solar wind; and low Fe charge states (~10–14) whenever measurable. On the other hand, for two of the events of § 4: the oxygen spectra above a few MeV nucleon$^{-1}$ are pure power laws without any sign of an exponential rollover; Fe/O increases with energy above a few MeV nucleon$^{-1}$ and reaches values that are enhanced with respect to the corona and solar wind; and the Fe charge states are high (~20). The other event in § 4 (1998 May 6) has similar, but not identical, spectral and compositional characteristics. This correlation between low coronal signatures of solar eruptions and properties of associated major SEP events, which will need to be checked for a larger sample, suggests that these flare-associated motions reflect characteristics of the shock and/or the environment in which it moves.

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