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CORONAL MASS EJECTIONS ASSOCIATED WITH IMPULSIVE SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

An impulsive solar energetic particle (SEP) event observed on the *Wind* spacecraft on 2000 May 1 was associated with an impulsive solar active region M1 X-ray flare. The timing and position of a fast ($v = 960$ km s^{-1}), narrow CME observed in the LASCO coronagraph on *SOHO* make clear the connection between the CME and the flare and SEP event. Impulsive SEP events have long been associated with impulsive flares, but only gradual SEP events have thus far been found to be associated with CMEs. A comparison of impulsive SEP events with CME observations from the Solwind and LASCO coronagraphs revealed further good cases of narrow (10°–40°) CMEs associated with impulsive SEP events. A recent model of impulsive flares includes jets or plasmoids that are ejected upward from magnetic reconnection sites over active regions and might therefore be expected to appear in exceptional cases as faint and narrow CMEs in coronagraphs. We suggest that this model allows us to understand better SEP production and propagation in impulsive flares.

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

1. INTRODUCTION

Observations of solar energetic ($E \gtrsim 1$ MeV nucleon^{-1}) particle (SEP) events observed at 1 AU have established the existence of two general classes of SEP events. Reames (1999) has reviewed the properties of these two SEP event classes in detail. The more intense and longer duration events, known as gradual SEP events, are now understood to be produced in coronal and interplanetary shocks driven by fast ($v \gtrsim 700$ km s^{-1}) coronal mass ejections (CMEs; Kahler 2001).

The second class, known as impulsive SEP events, was initially discovered because of their high ^{3}He/^{4}He abundance ratios, which exceed the coronal values by several orders of magnitude. The SEPs of these events ("impulsive SEPs"), which are more generally characterized by large enhancements of high-Z elemental abundances and are known as Z-rich events, are now understood to be accelerated in impulsive solar flares and released into narrow angular ($\theta \lesssim 30°$) regions of interplanetary space (Reames 1999). Using the precise onset timings of the associated energetic ($E \gtrsim 5$ keV) electron events, good associations of the impulsive SEP events were found with solar kilometric (Reames et al. 1988) and metric (Kahler et al. 1987) type III fast-drift radio bursts. The flare acceleration of the impulsive SEPs has been modeled by stochastic ion interactions with electromagnetic hydrogen cyclotron waves (Roth & Temerin 1997) and cascading Alfvén and fast-mode waves (Miller 2000) generated in the flare impulsive phase.

A major distinction between the two classes of SEP events is that gradual SEP events are essentially always accompanied by CMEs, while the impulsive SEP events have no known CME associations (Reames 1999). The observational basis for the latter property is a statistical comparison of 1.1–1.6 MeV nucleon^{-1}, ^{3}He-rich SEP events with metric type II bursts and CMEs by Kahler et al. (1985). Because of their low intensities and long Sun-Earth propagation times, the onsets of the SEP events of that study were known only to within 5 hr. Using 10 hr windows to search for associated CMEs observed with the NRL Solwind coronagraph on the *P78-1* spacecraft, Kahler et al. (1985) found six CME associations for 45 ^{3}He-rich SEP events with Solwind observations. The control periods of 10 hr windows exactly 1 day before each SEP event onset period yielded a total of 14 CMEs, very close to the average CME rate calculated for the 1979–1982 period (Howard et al. 1985). Thus, Kahler et al. (1985) concluded that there was no evidence for an enhanced rate of CME occurrence during the injection times of the ^{3}He-rich events.

We report here the first observation of a CME clearly associated with an impulsive SEP event. The event on 2000 May 1 has already been reported by Reames (2000a) as an Fe-rich impulsive event. In § 2, we discuss the observations of the SEP event and the associated CME. The results of a search for further such events are presented. The implications for SEP acceleration and injection in impulsive flares are discussed in § 3.

2. OBSERVATIONS

2.1. *The 2000 May 1 Event*

Figure 1 shows time profiles of the 2000 May 1 SEP event from the Energetic Particles: Acceleration, Composition, and Transport (EPACT) experiment (von Rosenvinge et al. 1995) on board the *Wind* spacecraft. The event is immediately identified as an impulsive SEP event not only from its high (>1) Fe/O and low (~10) H/He ratios (Reames 1999), but also by its short duration of ~1 day. The relative abundances of the $Z \geq 34$ elements have been discussed by Reames (2000a). The event is unusual in that a distinct intensity increase can also be seen up to an energy of 20 MeV in H. A clear timing dispersion between the profiles of

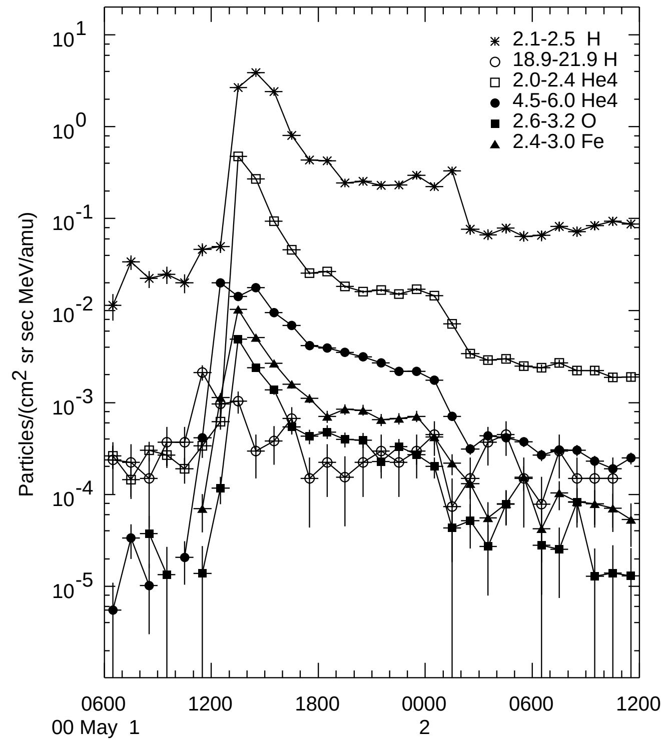

FIG. 1.—EPACT hourly averages of the intensities of various elemental species for the SEP event associated with the impulsive flare ejection of 2000 May 1. Energy ranges are given in MeV nucleon^{-1}.

the 2.3 and 20 MeV H indicates that an impulsive injection occurred $\lesssim$1100 UT.

The top panel of Figure 2 shows the *GOES 10* X-ray flux profiles on May 1. A very impulsive M1.1-class flare with an onset at 1016 UT and maximum at 1027 UT is the largest event on that day. The bottom panel of Figure 2 shows a height-time profile of gray-scale images of coronal white-light brightness profiles generated from the Large Angle Spectroscopic Coronagraph (LASCO; Brueckner et al. 1995) on the *SOHO* spacecraft. The height-time profile consists of sequences of subtracted images from the C2 and C3 coronagraphs along a fixed radial direction at $\phi = 312°$, using the technique discussed by Sheeley et al. (1999). The fields of view of the C2 and C3 coronagraphs are 2–6 $R_\odot$ and 4–30 $R_\odot$, respectively. In the subtraction technique, the location of new material in an image is shown as white, while material in the preceding image is black. The figure shows a fast, bright CME with a projected onset at ~1000 UT and a speed of 960 km s^{-1}.

Subtracted C2 and C3 images of the CME are shown in the bottom panels of Figure 3. The narrow (~20°) width of the CME places it in the lower end of the statistical distribution of CME widths (St. Cyr et al. 2000). The top panels of Figure 3 show a direct and a subtracted image in the 195 Å band from the Extreme-Ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) on the *SOHO* spacecraft. A compact brightening in Active Region 8971 at approximately N20 W54 with a maximum in the 1024 UT image clearly corresponds to the M1 flare in Figure 2. No Hα flare was reported for this event.

The timing and spatial relationships of Figures 1–3 make it very probable that the May 1 impulsive SEP event is associated with the compact flare and narrow CME observed in the EIT and LASCO images, respectively. This flare was confined to the active region and was associated with a 950 sfu burst at the peak frequency of 8800 MHz and with groups of metric and kilometric type III radio bursts. No type II radio bursts were reported. As discussed in § 1, the impulsive SEP event follows the accepted paradigm (Reames 1999) in its association with the impulsive solar flare, but not in its association with the CME.

2.2. *Survey of Solwind CMEs*

The association of a CME with the impulsive May 1 flare and SEP event suggests that other such cases must have occurred in the past. After the statistical survey of ^{3}He-rich SEP events and Solwind CMEs of Kahler et al. (1985), a list of flare associations for ^{3}He-rich SEP events was published by Reames et al. (1988). A second list of Fe-rich SEP events with associated $E > 200$ keV electron onsets determined to ± 15 minutes, but without flare associations, followed (Reames, Cane, & von Rosenvinge 1990). Many of the events in both lists occurred during the 1979–1985 period of observations by the Solwind coronagraph, so we have compared those candidate SEP events with the times of Solwind CMEs. To avoid a bias in making the associations, we used only the CMEs in the publicly available list at the LASCO web site.[1]

We found 11 cases in which the CME was judged to be associated with a listed impulsive SEP event, based on a CME onset time of less than 2 hr before the associated electron event onset time and on a west-limb CME location. However, three of those cases may have been gradual SEP events incorrectly identified as impulsive events. All three events had peak $E > 10$ MeV proton intensities ≥ 1 cm^{-2} s^{-1} sr^{-1} (Bazilevskaya et al. 1990) and were associated with CMEs with angular widths $\geq 40°$ and speeds ≥ 600 km s^{-1}. Those three events may therefore have been gradual SEP events large enough to result in temporal variations of Fe/C due to transport processes (Ng, Reames, & Tylka 1999; Reames, Ng, & Tylka 2000). Of the eight remaining candidate impulsive SEP events, six had identified flares with longitudes from W18 to W80. The eight associated CMEs had speeds of 240 km s^{-1} $< v <$ 660 km s^{-1} and angular widths of 10°–30°. Two of the associated Solwind CMEs are shown in Figure 4.

2.3. *Survey of LASCO CMEs*

We have also surveyed data from the EPACT instrument to compile a list of impulsive ~1 MeV nucleon^{-1} SEP events based on high ^{3}He/^{4}He and Fe/O ratios. Some of these events can be associated with 20–400 keV electron events observed on the Plasma and Energetic Particles (3DP) instrument on the *Wind* spacecraft (Lin et al. 1995; R. P. Lin 2001, private communication). The SEP solar injection times for those events were determined to ± 30 minutes and were then compared to the web-based LASCO CME list for associated events. As with the Solwind events, we work only with existing CME listings to avoid any bias from new searches for faint events. In the LASCO CME list compiled by St. Cyr and Plunkett,[2] we identified 12 candidate associations, including the 2000 May 1 event, based on a requirement for the first CME observation to be $\lesssim$2 hr before the electron injection time. The CMEs for four of

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[1] Available at http://lasco-www.nrl.navy.mil/solwind.html.

[2] Available at http://lasco-www.nrl.navy.mil/cmelist.html.

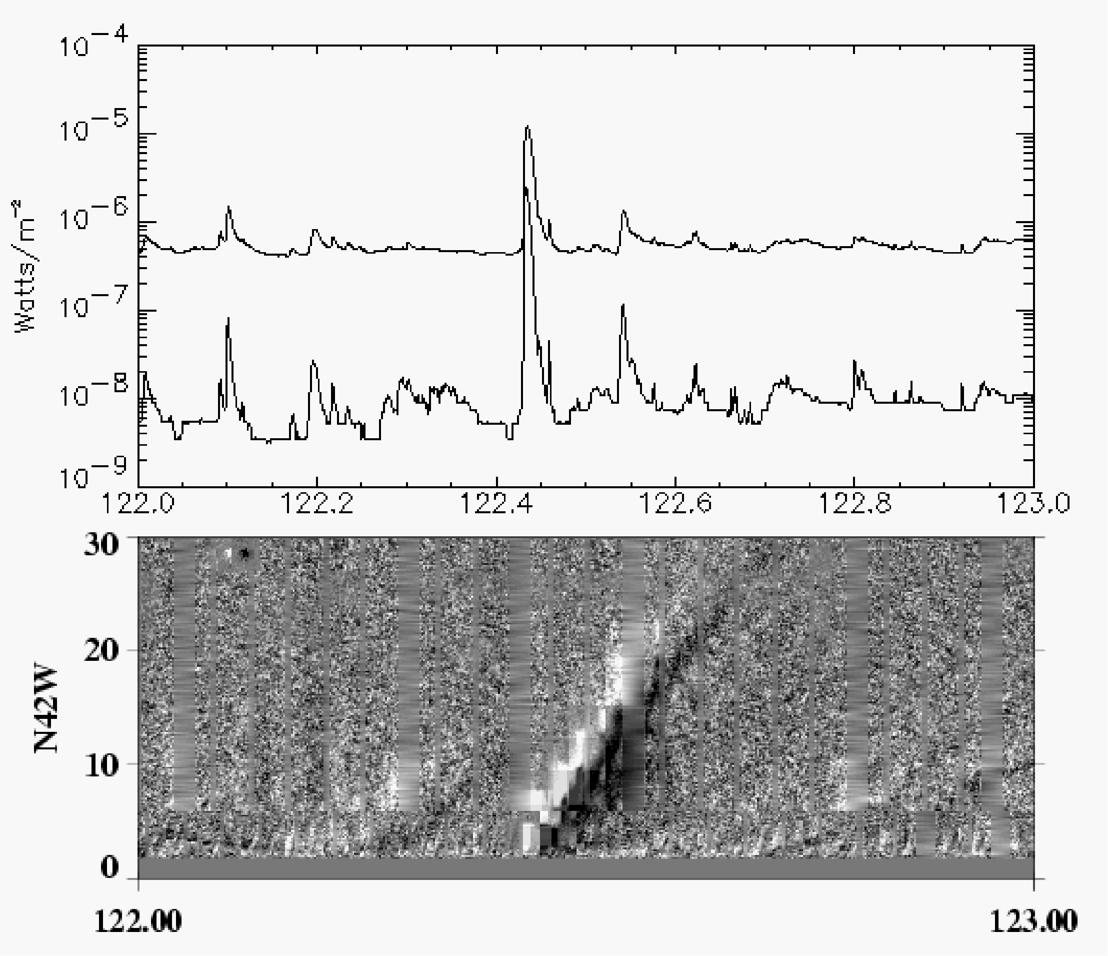

FIG. 2.—*Top*: *GOES 10* 1–8 Å (*top trace*) and 0.5–4 Å (*bottom trace*) X-ray flux profiles on 2000 May 1. The M-class flare at ∼1030 UT is associated with the CME and impulsive SEP event. *Bottom*: Gray-scale images of C2 and C3 coronal brightness height-time profiles along a fixed radial direction at $\phi = 312°$. The C2 and C3 coronagraphs view heights of 2–6 and 4–30 $R_\odot$, respectively.

those cases are shown in Figure 5. Those CMEs are relatively narrow and faint.

3. DISCUSSION

The May 1 impulsive flare seems to be an extremely energetic case in which an associated ejectum was so bright that it was easily visible in the LASCO coronagraph. Besides an intense X-ray burst, the flare was characterized by interplanetary SEPs with proton energies extending to 20 MeV and by an intense microwave burst with a peak at 8800 MHz. We believe that we have also found several other cases of impulsive flare ejecta in the Solwind and LASCO CME images. However, we find that very few of the impulsive SEP events can be associated with CMEs, perhaps because the ejecta are too faint to be detected or to warrant selection as CMEs in coronagraph observations. The best chance for seeing such events would probably occur when very energetic impulsive flares occur near the solar limb. Conversely, we expect that only a few impulsive flares will be favorably located to produce SEP events observable at 1 AU (Reames 1999).

While the association of CMEs with impulsive ^{3}He-rich or Fe-rich SEP events seems contrary to the current understanding of impulsive SEP production at the Sun, there are at least two reasons why this association might have been expected. First, the lack of CME association with impulsive flares and SEP events was not firmly established, and second, there has been increasing evidence that impulsive flares produce faint coronal ejecta. Many bright, jetlike CMEs observed in the LASCO coronagraph seem to be associated with impulsive flares. We now summarize the work that has led us to this view and consider some of the implications of this new association of CMEs with impulsive SEP events.

3.1. *CME Associations with Impulsive SEP Events*

Cane, McGuire, & von Rosenvinge (1986) used $E > 3$ MeV electron events observed at 1 AU to define two classes of SEP events based on the durations of their associated 1–8 Å solar flares. Their impulsive events were associated with flare durations of less than 1 hr and their long-duration events with flare durations of more than 1 hr. Their basic result was that the impulsive SEP events were associated with high electron-proton intensity ratios (e/p), strong type III radio bursts, and good magnetic connection to the Earth. The long-duration SEP events were associated with low e/p, coronal and interplanetary shocks, and flare locations anywhere on the solar disk. These two flare-based SEP event classes were also in agreement with Švestka's (1986) division of all flares into two classes: dynamic flares and confined flares. A key basis of that view was the discovery by Pallavicini, Serio, & Vaiana (1977) that the spa-

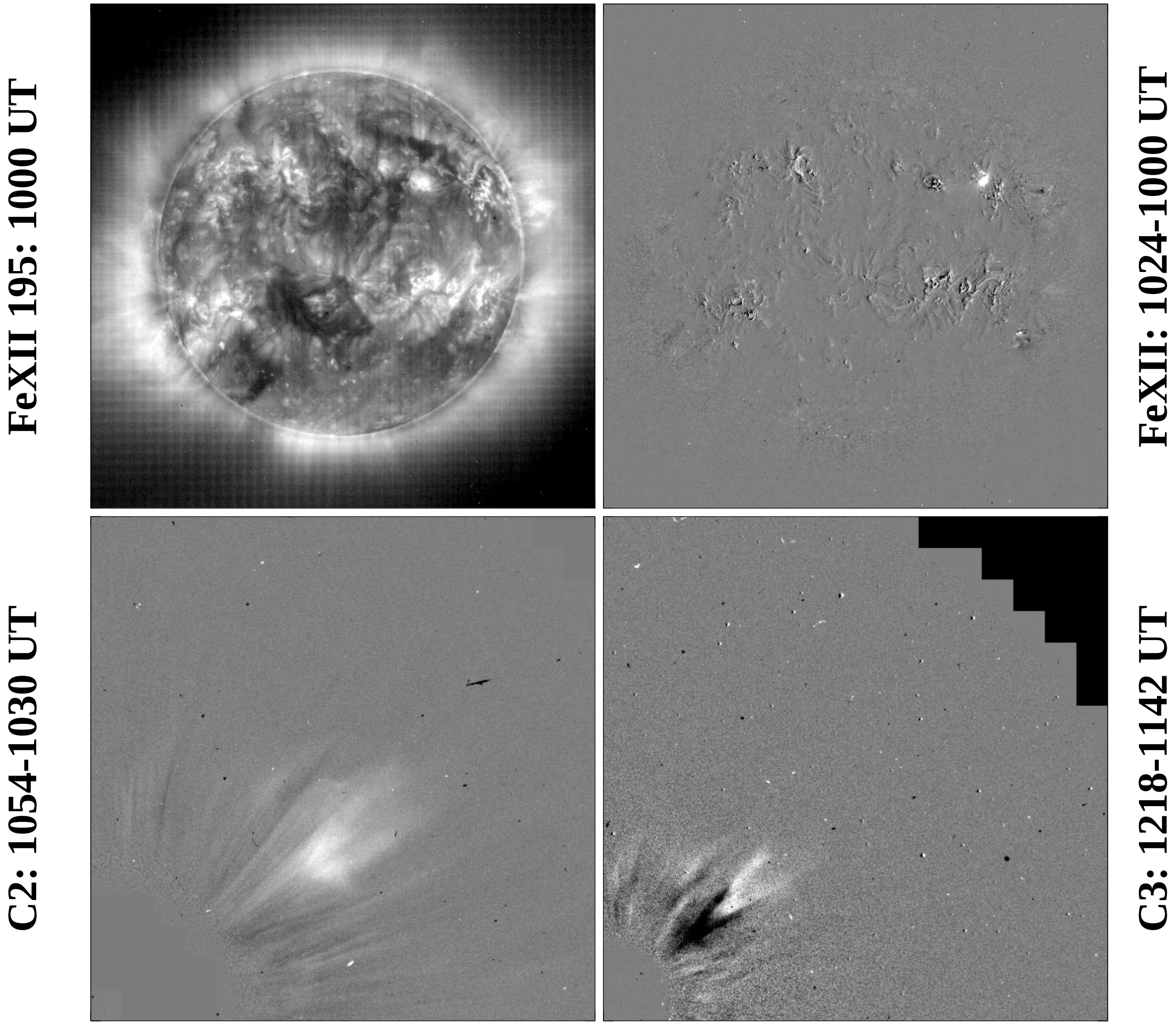

FIG. 3.—2000 May 1. *Top left*: Direct EIT 195 Å image showing the solar disk before the flare. *Top right*: Subtracted EIT 195 Å image showing the impulsive flare as a small white feature in the northwest quadrant of the disk. *Bottom*: subtracted C2 (*left*) and C3 (*right*) images of the northwest quadrant of the corona showing the CME. The C2 and C3 coronagraphs view heights of 2–6 and 4–30 $R_{\odot}$, respectively.

tially resolved flare X-ray observations on *Skylab* revealed two classes of flares, of which the more compact and shorter duration class were found not to be associated with CMEs.

Several of the SEP events defined as impulsive in the Cane et al. (1986) study were associated with observed CMEs and interplanetary shocks, but the relationship between the high–e/p events of their study and ^{3}He-rich or Fe-rich impulsive SEP events was also undefined. The picture was further confused by the subsequent discovery of large initial temporal variations of elemental abundances in gradual SEP events (Reames et al. 2000). On the other hand, the study of Kahler et al. (1985) was limited to ^{3}He-rich SEP events and found no statistical evidence for CME associations with those events, but, as discussed in § 1, specific flare associations were not used in that study. Thus, it had become clear that CMEs were not normally associated with impulsive SEP events, and no cases of clear CME associations with ^{3}He-rich or Fe-rich SEP events were found. However, this did not preclude the possibility that future cases might be found.

3.2. *Observations and Modeling of Flare Coronal Ejecta*

The basic view that the impulsive flares had no coronal ejecta changed when Masuda et al. (1994) found a hard X-ray source overlying a compact soft X-ray flare in the *Yohkoh* soft X-ray telescope (SXT) observations. As reviewed by Shibata (1999a, 1999b), that discovery, along with the possibility that the energy source of the hard X-ray emission was magnetic reconnection thought to occur in long-duration event (LDE) flares, led to a successful search for soft X-ray ejections from compact limb flares (Shibata et al. 1995). Ejecta were found for all eight X-ray flares at least M2 in size, and the range of velocities of the faint ejections was 50–400 km s^{-1}. In their view the ejecta from compact flares were plasmoids formed in the reconnection region over the flare and threaded by twisted field lines connected

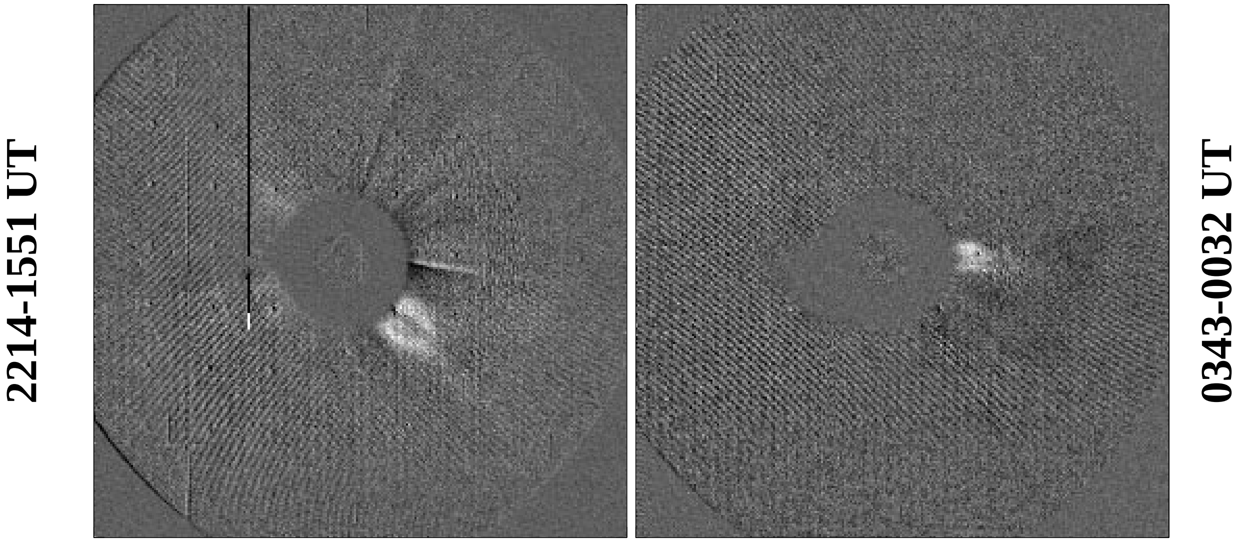

FIG. 4.—*Solwind* subtracted images of CMEs associated with two impulsive SEP events. The times of the image pairs are given at the sides of the images. The narrow widths seem to be characteristic of such events. The inner and outer limits of the Solwind field of view are 2.5 and 10 $R_\odot$, respectively, and north is up. *Left*: CME of 1981 July 28. That CME, with an estimated speed of 240 km s^{-1}, was associated with an impulsive M3 1B flare at S09 W18 and an Fe-rich SEP event. *Right*: CME of 1984 April 7. That CME, with an estimated speed of 580 km s^{-1}, was associated with an impulsive M2.9 1B flare at S10 W80 and an Fe-rich SEP event.

to the photosphere, as shown in Figure 6. Ohyama & Shibata (1998) discussed a case of an impulsive SXT flare with an ejected plasmoid penetrated by or connected to the top of a large-scale faint loop, matching the cartoon of Figure 6. In a recent work, Ohyama & Shibata (2000) surveyed SXT limb flares and found that 36–40 of the 57 flares with good observations during the flare impulsive phases were associated with X-ray plasma ejections.

Shibata (1999a, 1999b) has proposed a model of magnetic reconnection that unifies the flare plasmoid model with the earlier model of Yokoyama & Shibata (1995, 1996) for observed hot X-ray jets and adjacent cool Hα surges as products of magnetic reconnection between emerging magnetic flux and overlying magnetic field lines. Shimojo & Shibata (2000) have measured the physical properties of 16 X-ray jets from small flares and interpreted them in terms of Figure 7, in which the jets are driven along open field lines by evaporation flows produced by magnetic reconnection. An alternative driver for jets is the release of the magnetic tension of reconnected field lines (Yokoyama & Shibata 1995, 1996). The basic difference between the flare plasmoids and the smaller scale jets is that the latter are the results of plasmoids that have already reconnected with ambient fields to transfer their plasma into open flux tubes.

Some X-ray jets are associated with type III radio bursts (Shibata, Yokoyama, & Shimojo 1996). Raulin et al. (1996) discussed two cases of *Yohkoh* SXT and metric observations, showing that the type III burst electrons from active regions propagated along the enhanced density region of the X-ray jets. They associated both the electron acceleration and the jet production with magnetic reconnection. The presence of type III bursts indicates the rapid upward propagation of keV electrons, which is possible only along open field lines. If we assume the geometry of a dipolar active region with an overlying current sheet, then Figure 6 may provide an appropriate context for understanding the upward and downward propagation of impulsive SEPs. However, for rapid escape from the reconnection region the SEPs must have access to open field lines around the plasmoid. The lack of a closed field plasmoid therefore makes the scenario of Figure 7 attractive. Slow ejecta would result from evaporation flows as shown, but ejecta with speeds around the Alfvén speed would result from forces of magnetic tension.

Detailed modeling of the electric field at the X-point in the reconnection model by Magara, Shibata, & Yokoyama (1997) shows a peak in the electric fields during the impulsive phase, at the time of type III burst production by energetic kilovolt electrons. Consideration of the effects of the nonzero magnetic field components in the current sheet by Litvenenko (2000) shows that the electric fields in the flare reconnection regions can preferentially accelerate electrons to energies of several MeV and may explain the acceleration regions for electron-rich flares (Rieger, Gan, & Marschhäuser 1998). His scenario for electron acceleration in current sheets over flare loops is similar to that of Aschwanden et al. (1996). If we further assume that the stochastic acceleration of ions by wave-particle interactions (Miller 2000; Roth & Temerin 1997) occurs in the reconnection region, then the magnetic connection of that region both to the flare footpoints and to interplanetary space explains why the elemental abundances of Fe-rich SEP events are similar to those of the flare γ-ray events (Murphy et al. 1991; Reames 2000b).

3.3. *Implications for Impulsive SEP Source Regions and CMEs*

We note that the observational and theoretical work connecting plasmoid ejections with impulsive solar flares has dealt with X-ray ejecta, rather than the white-light CMEs we discussed in § 2. The masses of the ejecta from impulsive flares are expected to be small and difficult to observe in either X-ray or white-light image data. For example, the estimated mass of the ejected X-ray plasmoid and entwined loop of the 1992 October 5 flare was only $\sim 3 \times 10^{13}$ g (Ohyama & Shibata 1998), a value below the general range

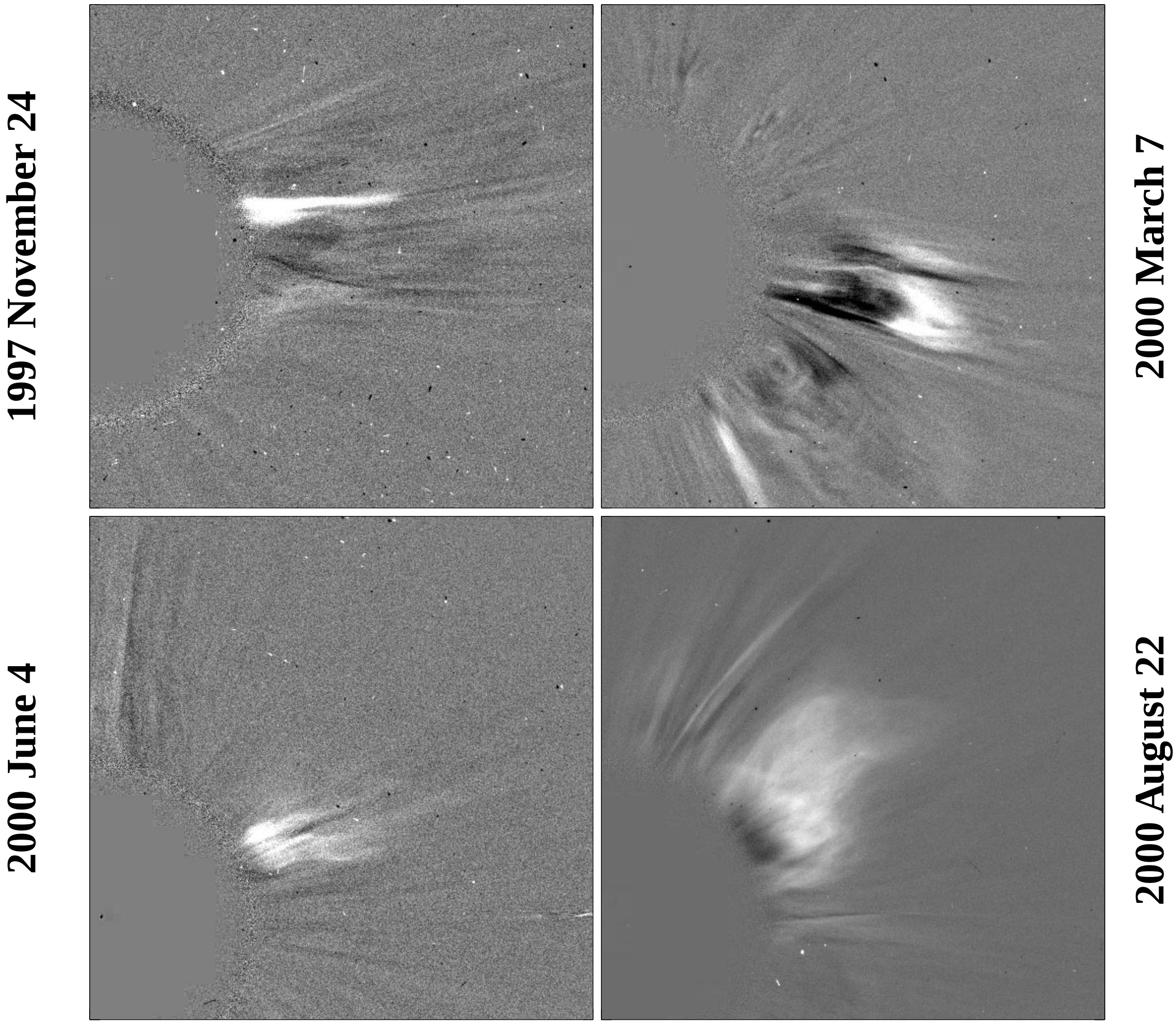

FIG. 5.—LASCO C2 subtracted images of west-limb CMEs associated with four impulsive SEP events. The inner field of view is 1.5 $R_\odot$, and north is up. *Top left*: CME of 1997 November 24 (1337–1247 UT). That CME was associated with a B6 subflare at N21 W58. *Top right*: CME of 2000 March 7 (1354–1331 UT). That CME was associated with a subflare at S12 W71. *Bottom left*: CME of 2000 June 4 (0754–0731 UT). That CME was probably associated with a C1.5 flare, but no reported Hα flare. *Bottom right*: CME of 2000 August 22 (0054–0006 UT). That CME was probably associated with a C2.5 flare, but no reported Hα flare.

of 10^{14}–10^{16} g measured for typical CMEs (Hundhausen, Stanger, & Serbicki 1994). Nitta & Akiyama (1999) surveyed 17 X-ray limb flares with significant signals above 14 keV and found SXT X-ray ejecta for nine flares and LASCO CMEs for 12 flares. However, some of these seemed to be large ($>$M1) eruptive flares with broad ($>40°$) CMEs. Nitta & Akiyama (1999) also found that smaller flares were less likely to have detectable X-ray ejecta, as did Ohyama & Shibata (2000) with their larger data set. Thus, the white-light masses for impulsive flares can be expected to be very faint or invisible, even when viewed at the solar limb.

An important question about the narrow CMEs associated with impulsive flares is whether they can be regarded as a CME population physically distinct from the brighter and larger CMEs. That question was addressed by Kahler, Sheeley, & Liggett (1989), who found first that impulsive, $\geq$M1 solar flares were associated with rather narrow (5°–40°) CMEs. They then used a larger flare group to compare all X-ray flare durations with associated CME widths and found a general correlation of $0.4 < r < 0.65$, depending on the flare duration criteria. That result favored a continuum, rather than two classes, of flares or CMEs. The size distributions of both X-ray flare intensities (Crosby, Aschwanden, & Dennis 1993) and CME widths (Hundhausen 1993; St. Cyr et al. 2000) also show no evidence of bimodal distributions.

These observations favor the view of Shibata (1999a) that a single model of magnetic reconnection can explain both the impulsive and eruptive flares. The major differences between the two kinds of flares would appear to be that the ejecta of eruptive flares (prominences or filaments) are spatially large and massive, extend well beyond the confines of the associated active region, leave behind reconnecting coronal arcades, may be accelerated over an extended coronal height by a gradual energy release, and retain their magnetic flux rope topology far into interplanetary space. The ejecta of impulsive flares would be small, of low mass, originate directly over the associated active region, leave

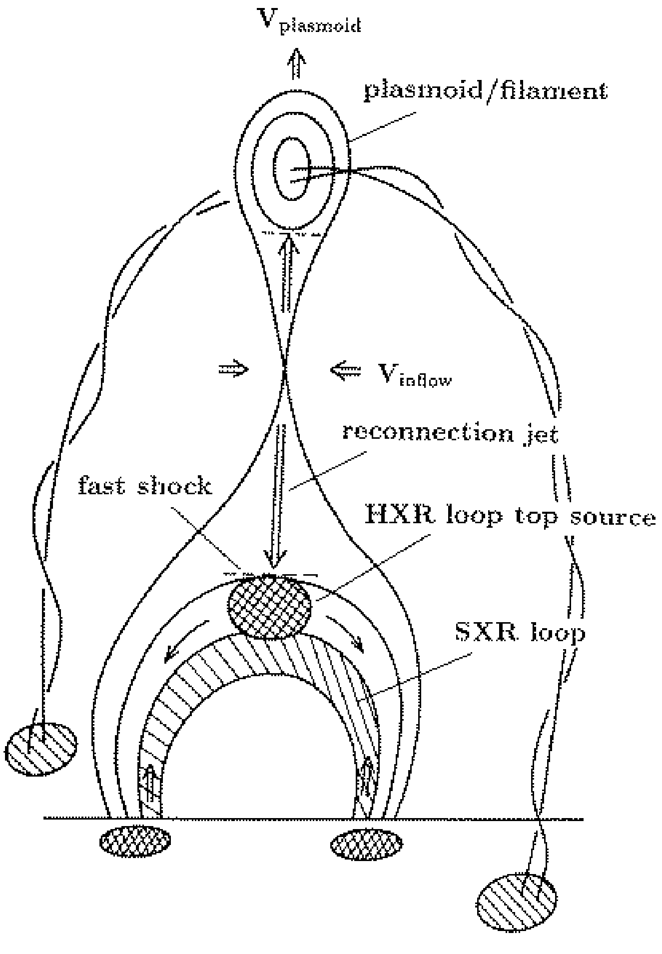

FIG. 6.—Reconnection plasmoid model from Shibata et al. (1995) for compact loop flares. In impulsive flares, the ejecta is a relatively small plasmoid. In the eruptive flares the ejecta is a filament or prominence.

little or no reconnecting coronal arcades, travel at uniform or decelerating speeds in the corona because of the early impulsive energy release, and attain an open field topology because of reconnection in overlying ambient coronal fields.

Observational support for some of those differences was found by Kahler et al. (1989). Using flare Hα images, they found that 16 of 22 impulsive flares and all four LDE flares in their sample had filament eruptions, while all five LDE flares, but only two of 27 impulsive flares, had postflare loops. They further found that impulsive flares with observed CMEs were much more energetic, as judged by radio, X-ray, γ-ray, and Hα indices, than impulsive flares without observed CMEs. If we assume that relatively larger and longer duration energy releases are needed to propel ejecta massive enough to be observable in the high corona, then we can understand why the CME associations increase with X-ray flare durations (Sheeley et al. 1983) and the observed X-ray plasmoid associations increase with flare intensities (Ohyama & Shibata 2000). In this context, the 2000 May 1 flare is considered an extremely energetic impulsive flare associated with an unusually high impulsive SEP production and ejected mass. The difference between impulsive and eruptive flares, however, now becomes a matter of degree and not of kind, contrary to the view espoused by Švestka (1986).

The spatial coincidence of the type III radio bursts with SXT X-ray jets (Raulin et al. 1996) suggests that the impulsive flare ejecta provide a coronal/interplanetary spatial signature of the impulsive SEP coronal injection region. The cones of injection of impulsive SEPs into space are $\lesssim 30°$ wide (Reames 1999), matching the angular widths of the CMEs that we and Kahler et al. (1989) find associated with the impulsive flares. The injection of impulsive SEPs onto a limited range of magnetic field lines over the active region is also suggested by the sharp spatial intensity variations of $\lesssim 1$ MeV nucleon^{-1} ions from impulsive solar flares

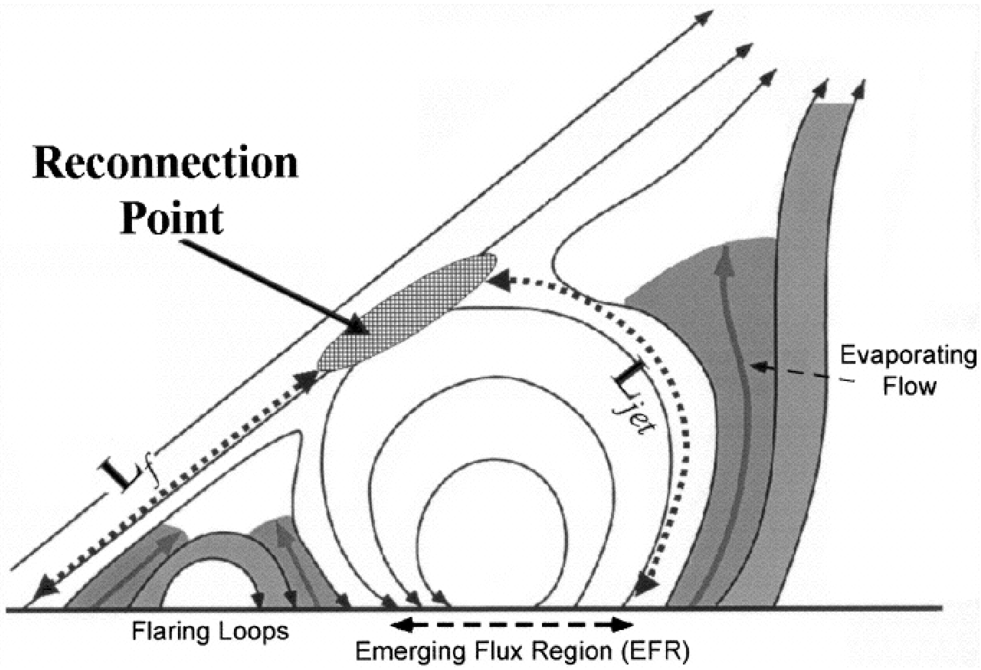

FIG. 7.—Reconnection jet model from Shimojo & Shibata (2000), based on magnetic reconnection and a jet. $L_{\rm jet}$ and L_f are the distances from the reconnection region to the flare and associated jet.

(Mazur et al. 2000). Thus, in contrast to the SEPs of gradual events, whose spatial injection profiles at coronal/interplanetary shocks remain invisible to us, we can expect to see in white-light images at least the spatial outline of the impulsive SEP injection regions.

The type III burst electrons may also tell us something about the magnetic topology of the CMEs from impulsive flares. In situ measurements of energetic solar electrons and ions have been used to diagnose the topologies of magnetic fields at 1 AU (Kahler 1997). If it can be established that the type III burst electrons are accelerated after the initial ejection of the plasmoid, as modeled by Magara et al. (1997), and that the electrons propagate through, rather than around, the plasmoid, as seemed to be the case with the type III electron events discussed by Raulin et al. (1996), then their rapid propagation through the plasmoid would suggest that the plasmoid magnetic fields have already reconnected with the ambient fields to provide an open path for the electrons.

4. SUMMARY

One of the defining features of impulsive flares has been the lack of coronal ejecta. The 2000 May 1 impulsive flare, with its associated CME and impulsive SEP event, has forced us to revise that basic view. We find that previous work with impulsive SEP events was not definitive in precluding such associations. The recent observations and modeling of X-ray flare plasmoids by Shibata and Yokoyama and their colleagues provide an appealing framework for a new understanding of SEP acceleration at magnetic reconnection regions in solar flares and propagation of the SEPs both into the active region flare and into interplanetary space.

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