The Astrophysical Journal, 533:1063–1070, 2000 April 20

# A SEARCH FOR INTERPLANETARY ENERGETIC PARTICLE EVENTS FROM SOLAR POSTERUPTIVE ARCADES

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*Received 1999 March 12; accepted 1999 September 29*

## ABSTRACT

While the $E > 10$ MeV ions observed in gradual solar energetic particle (SEP) events in space are attributed to acceleration at shocks driven by coronal mass ejections (CMEs), it has been suggested that such SEPs may also be produced in the magnetic reconnection of coronal arcades following CMEs. The arcade SEPs could escape the corona along open field lines and provide additional contributions to observed gradual SEP events. We searched for SEP events associated with large, bright solar soft X-ray arcades and intense metric noise storms in the western hemisphere, which should be favorable for the production of arcade SEP events observed at 1 AU. Five arcades/storms were possibly or definitely associated with *IMP-8* 24–28 MeV proton increases, but the latter appear to be shock accelerated. We also found 30 arcades (14 in active regions and 16 outside active regions) with no detectable SEP increases, suggesting that those arcades were not sources of escaping SEPs. This result provides evidence against the possibility of coronal arcade contributions to gradual SEP events.

*Subject headings:* MHD — Sun: corona — Sun: particle emission

## 1. INTRODUCTION

After decades during which $E > 10$ MeV solar energetic particle (SEP) events observed at 1 AU were considered to have solar flares as their sources, it is now widely believed that there are two classes of SEP events (Reames 1995; Cane 1997), only one of them arising in solar flares. The first SEP event class is the impulsive event, marked by durations of hours and distinct relative enhancements of heavy-Z ions (Reames et al. 1994) accelerated in the corona by plasma waves generated by streaming 10–100 keV electrons (Reames 1995) from flares. The other class, known as gradual SEP events for their time scales of days, are closely associated with fast ($v > 400$ km s$^{-1}$) coronal mass ejections (CMEs) that drive coronal and interplanetary shocks (Kahler 1996; Cane 1997). The present paradigm decouples the source of the particles in gradual SEP events (generally the largest events and those receiving the most attention from observers) from the solar flares that are usually associated with the fast CMEs.

The coronal aftermath of a CME is an open magnetic field region with a current sheet separating fields of opposite polarity (e.g., Kahler 1992). Magnetic reconnection is assumed to occur in the current sheet, leading to the formation of a growing coronal arcade of loops visible at lower altitudes in H$\alpha$ and at higher altitudes in soft X-rays (e.g., Schmieder et al. 1996; Harra-Murnion et al. 1998). Because of their long durations, usually greater than 2 hr in full-Sun soft X-ray detectors, they are known as long-decay events (LDEs). A reforming helmet streamer is often seen over the arcade (Kahler & Hundhausen 1992; Hiei, Hundhausen, & Sime 1993; McAllister et al. 1996b). The loop arcade formation with overlying bright, hot features characteristic of energy release in the reconnecting current sheet (RCS) has been modeled in some detail (Tsuneta 1996; Forbes & Acton 1996; Yokoyama & Shibata 1998).

The transient coronal structures following CMEs are often the sites of nonthermal $E \geq 10$ keV electron production as observed in decimetric and metric radio emission (e.g., Klein 1994). Late in solar flares the emission lasting tens of minutes to hours is known as a "storm continuum" or "stationary type IV emission." This phase is sometimes associated with gradual hard ($E \geq 30$ keV) X-ray bursts (Cliver et al. 1986) from an energy source in high ($> 10^4$ km) coronal reconnecting loops (Tsuneta 1996). In addition, radio noise storms lasting hours to days and consisting of broadband continuum with superposed short ($\leq 1$ s) type I bursts are observed in the vicinity of active regions. While these storms are not always associated with flares, their onsets are associated with the rapid coronal changes characteristic of CMEs (Klein 1994; Crosby et al. 1996) and subsequent loop arcades.

Solar $\gamma$-ray line (GRL) flares provide evidence that high-energy ions may also be produced in coronal flares. The facts that many SEP events are not associated with GRL flares and that the correlation between peak SEP intensities and GRL fluences is poor (Cliver et al. 1989) have been taken as evidence for the primary role of shocks in SEP events. Evidence for the production of $E > 300$ MeV ions in flare gradual phases was found in the $\gamma$-ray observations from the *GAMMA* and *CGRO* satellites. Three flares on 1991 June 9, 11, and 15 were found to have $\gamma$-ray time profiles with double exponential decays, the *e*-folding time of the second decay being about 200 minutes (Kanbach et al. 1993; Rank et al. 1997). Gamma-rays up to 1 GeV were observed with a gradually hardening spectrum for at least 8 hr following the June 11 flare (Kanbach et al. 1993). Akimov

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et al. (1996) have argued that the $E > 2$ GeV $\gamma$-ray emission, which lasted more than 2 hr in the June 15 flare, resulted from prolonged proton acceleration through magnetic connection in a coronal vertical current sheet. That current sheet would have formed after the occurrence of a CME inferred from the associated posteruptive H$\alpha$ loop system and LDE. These observations suggest that ions can be accelerated in post-CME current sheets to energies well above tens of MeV.

With this abundant evidence of long-lived particle acceleration assumed to occur in posteruptive arcades, it is not surprising that the following various authors have suggested those arcades as the sources of interplanetary SEP events.

1. Svestka, Martin, & Kopp (1980), noting that nearly all large SEP events were well associated with two-ribbon H$\alpha$ flares, which are part of the magnetically reconnecting loop arcades, envisioned energetic particles escaping upward, perhaps to be further accelerated in the CME-driven shock.
2. Bazilevskaya, Sladkova, & Chertok (1990) and Chertok (1995, 1996) have suggested arcades as the sources of protons in "surplus" SEP events. However, the existence of such events, characterized by intensities of 10 to 30 MeV protons in excess of those expected based on the associated flare characteristics, is doubtful (Cliver, Kahler, & Campbell 1993; Chertok, Bazilevskaya, & Sladkova 1993; Cliver & Kahler 1993).
3. Klein et al. (1996) have suggested that the large noise storm of 1989 October 19, associated with an SEP event and extending over several tens of heliographic degrees, could serve as a secondary source of both electrons and ions for that SEP event.
4. Based on timing and spectral comparisons of the 1991 June 15 solar $\gamma$-ray and terrestrial neutron monitor observations, Kocharov et al. (1994) attributed the source of the associated relativistic SEP event at 1 AU to the coronal $\gamma$-ray source region.
5. Kiplinger (1995) found a nearly one-to-one association between large 10 MeV SEP events and cases of spectral hardening over the flux peak or decay of the associated flare 40–200 keV hard X-ray burst. Without explicitly tying the inferred SEP source regions to posteruptive arcades, he suggested a high coronal source for the SEP events, all of which were likely gradual SEP events.
6. Finally, several studies have invoked a flare-related impulsive, or early SEP component followed by a shock-accelerated component for specific gradual SEP events (Torsti et al. 1996; Cramp et al. 1997; Torsti et al. 1998) or in general (Lin 1994).

The preceding observers have approached the question of SEP sources from different perspectives, but all have argued for a contributing, if not dominant, role for dynamic coronal structures as a source of the SEPs observed in gradual events. These arguments contradict the current paradigm for impulsive and gradual SEP events discussed above.

The idea of acceleration of ions to energies of tens of MeV or higher in coronal reconnecting current sheets (RCS) does not lack a theoretical basis. Martens (1988) calculated that protons accelerated in direct electric fields of coronal RCSs could have typical energies of 200 keV and extend to 20 GeV in power law spectra. However, Litvenenko & Somov (1995) pointed out that the magnetic field transverse to the RCS, $B_\perp$, which acts to restrict the energies of ions, could not be as small as Martens (1988) had assumed. They also noted that there is a transverse electric field pointed toward the RCS, which confines the ions to the region of the electric field parallel to the RCS, enabling the ions to make multiple interactions with that parallel field. They found that the maximum energy $E_{\max}$ scales as $T/\xi_\perp^2$, where $T$ is the plasma temperature of the RCS and $\xi_\perp = B_\perp/B$. They assumed $T = 10^8$ K and a typical value of $\xi_\perp = 3 \times 10^{-3}$ to calculate that $E_{\max} = 2.4$ GeV (see also Kocharov et al. 1994). Taking a more realistic RCS value of $T = 10^7$ K (Tsuneta 1996), we find $E_{\max} = 240$ MeV, still a large value for SEP events. Note that this value does not depend directly on the intensity of $B$. Thus, an RCS in a large weak $\sim 30$ G field outside an active region could accelerate ions to high energies as well as an RCS in an active region field. In fact, the lower collisional energy losses and longer scale size of such a weak magnetic field region could result in even higher ion energies than those of an active region field. Ruffolo (1997) has shown that ion charge states in gradual SEP events require that $nt < 3 \times 10^9$ cm$^{-3}$s, where $n$ is the density of the coronal acceleration and propagation region and $t$ is the time spent in the region. This requirement for ion acceleration favors the lower densities of the high, large arcades over the higher densities of the low active region arcades. As a result of the lower densities and weaker field intensities in high arcades, their radiative signatures due to nuclear collisions of accelerated ions and to bremsstrahlung and cyclotron emission of energetic electrons will be substantially weaker than the signatures of active regions.

## 2. DETECTION OF SEPS FROM CORONAL ARCADES

### 2.1. *Distinguishing Arcade SEPs from Shock SEPs*

In this work we search for evidence of interplanetary SEPs from the RCSs of coronal arcades. An obvious approach to this problem is to seek an example of an energetic solar flare with nonthermal particle signatures in the post- or late-flare phase that can be associated with an interplanetary gradual SEP event. However, all gradual SEP events observed to date appear to be associated with shocks driven by fast CMEs (Kahler 1996), so the problem with looking for SEPs from coronal arcades in those events is that one must detect at 1 AU a separate SEP population produced in the coronal arcade behind the CME shock while the shock itself continues to accelerate and inject SEPs. Intensity-time profiles of the relativistic SEP events at 1 AU accompanying the 1991 June 11 and 15 long-lived solar $\gamma$-ray events (Kocharov et al. 1994) show no obvious signs of two separate SEP populations (Kahler 1996). A drawback for using rise phase variations of SEP intensity profiles as diagnostics for nonshock SEPs is that dynamic variations on those field lines connecting to the quasi-perpendicular part of the CME-driven shock are expected during the early phases of most SEP events (Reames, Kahler, & Ng 1997).

To determine whether there are SEP events that originate in coronal arcades, we make the following basic assumption. If arcades make significant contributions to SEP events associated with CME-driven shocks, then they should also produce significant SEP events when the associated CMEs are too slow to drive shocks. Since only a minority of CMEs are fast enough to drive shocks

(Hundhausen, Burkepile, & Cyr 1994), we should expect that when a large arcade is produced in a coronal region behind any CME, a population of SEPs will escape from the arcade RCS and be observable in interplanetary space.

Because the arcades with the strongest radiative signatures of particle acceleration are invariably associated with CME-driven shocks, our search will necessarily involve arcades either lacking or weak in radiative signatures. However, as we discussed in § 1, high-energy particles may be accelerated in and escape from coronal arcade regions of weak fields and low densities, which are unfavorable for the production of radiative signatures of those particles. Our task, therefore, is to find good examples of coronal arcades for a comparison with interplanetary SEP observations. The occurrence of significant numbers of such arcades well connected to the Earth but without associated SEP events can be taken as supporting, although not definitive, evidence against the concept that arcades are sources of gradual SEP events. It should also be established that those arcades show no obvious differences, other than their radiative signatures, from the arcades associated with SEP events produced in CME-driven shocks.

### 2.2. *Interplanetary Propagation of Arcade SEPs*

A factor not considered by advocates of arcade sources for gradual SEP events is the expected spatial distribution of those SEPs. If SEPs are produced in an arcade RCS, then we should expect that those SEPs are confined to the vicinity of a current sheet as they propagate out of the corona and into interplanetary space. Such a distribution contrasts sharply with the very broad angular extent of shock SEPs. Figure 1*a* shows a confined region of SEP propagation in an ecliptic projection of the coronal field. At 1 AU that population should be centered roughly on magnetic sector boundaries and avoid those fields far from the boundaries, which map back to unipolar solar coronal holes (Neugebauer et al. 1998). Figure 1*b* shows a less favorable situation in which the RCS is surrounded by the closed fields of the CME. Since associated flares generally lie within the angular extents of CMEs (Kahler 1992), this situation may be more likely than that of Figure 1*a*. In this case the only SEPs reaching 1 AU ahead of the shock are those produced in the shock itself. If the interplanetary CME has a very low field variance, as is the case with magnetic clouds (Gosling 1996), then minimal cross-field diffusion of SEPs from the current sheet into the CME will be expected. However, if the interplanetary CME carries the current sheet past the Earth, then the imbedded arcade SEPs should appear at 1 AU at that time.

If we take the suggested arcade SEP spatial distribution of Figure 1*a* seriously, then the simple observational test for an arcade SEP event is whether we find a class of SEP events centered on sector boundaries. Briggs & Armstrong (1984) reported a class of "nonflare" increases of C, N, and O ions at several MeV/nuc with a tendency to occur near sector boundaries, but those events now appear likely to be early examples of impulsive flare SEP events, generally associated with only small solar events (Kahler et al. 1987). Since we know of no other evidence for a class of SEP events concentrated at sector boundaries, we must assume a more relaxed criterion for seeking candidate arcade regions to associate with SEP events. We assume that arcades located in the western hemisphere will be sufficiently well connected to the Earth to produce observable SEP events. Observations of storms of 10 keV electron events following flares show that those electrons are injected over broad cones of tens of degrees and are observed for typically several days (Lin 1985). Even if the escaping SEP distribution is rather narrowly distributed in solar longitude, the arcade lifetimes of one to several days should enhance the probability that such a SEP population from a source near or east of the average W60° connection point will be convected past the Earth during the arcade lifetime.

## 3. DATA ANALYSIS

We use a survey of soft X-ray arcade events observed by the SXT detector on the *Yohkoh* spacecraft over the 18 month period 1993 January 1 to 1994 June 30. The list of 240 X-ray arcade events with a size of $\geq 20°$ in any dimension was compiled by McAllister et al. (1996b). For com-

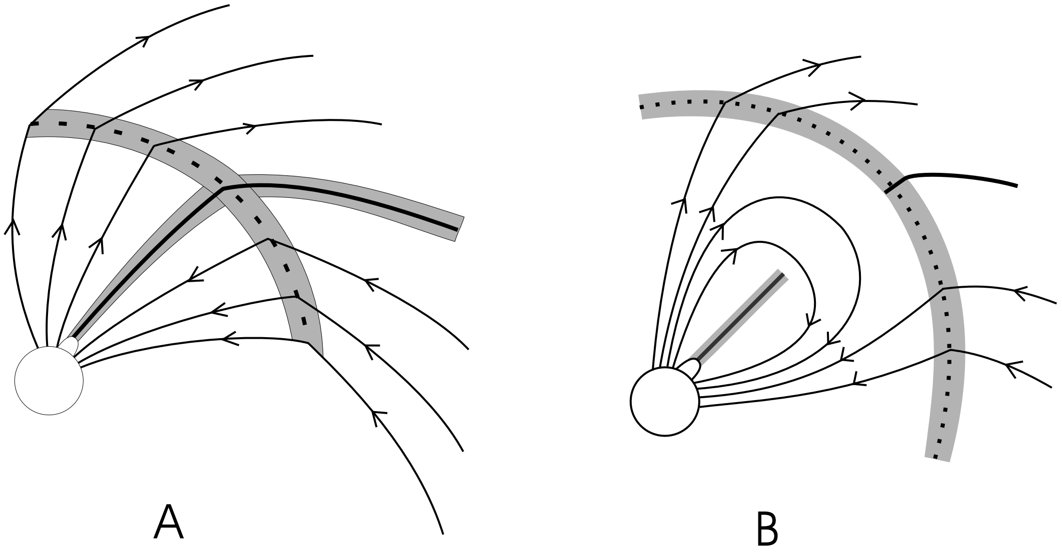

FIG. 1.—*Left:* Schematic of an RCS (*heavy line*), magnetic arcade at base of RCS, and shock (*dotted line*). Arrows indicate polarities of field lines connecting to the Sun, and shaded areas are suggested regions of SEP populations. *Right:* Schematic of an RCS imbedded in closed field lines of a CME. In this case SEPs from the RCS do not extend beyond the CME.

parisons with locations of coronal holes (McAllister et al. 1996b) and streamers (McAllister & Hundhausen 1996), the events were classified in terms of their magnetic neutral line associations as polar (high latitude), midlatitude, or active region. From this list we first selected as the most probable SEP sources the largest and brightest western hemisphere arcades, of which 16 were active region, 10 polar, and 11 midlatitude. The onset times of arcade formation were determined to within about 2 hr.

### 3.1. *Active Region Arcades*

Since, as discussed above, radio noise storms are another good indicator of solar eruptive events, we also used the monthly lists of 164 MHz noise storms from the Nançay radioheliograph (Radioheliograph Group 1993). Centroid positions of noise storms with durations longer than one hour are listed in Coffey (1993) for the period of this study beginning with the first available data in 1993 March. From those lists we selected only storms in the western hemisphere of importance 3 or greater, corresponding to fluxes grater than 20 sfu, and combined them with the list of *Yohkoh* arcades. The first five columns of Table 1 give the date and time of the arcade formation, the flare location from H$\alpha$ reports, the arcade source listing (*Yohkoh* or Nançay), and the size of the associated *GOES* 1–8 Å flare.

For each arcade event of Table 1 we examined the time profiles of 24 to 28 MeV proton intensities from the Goddard Medium Energy Experiment on the *IMP-8* spacecraft. We selected this energy band because intensities of $E < 10$ MeV protons tend to show significant fluctuations not associated with SEP events, and intensities of events at higher energies may not be obvious above the cosmic-ray background. We examined the *IMP-8* particle profiles for at least a 2 day period following the associated X-ray flare to look for any associated intensity increases. Data gaps resulted in the elimination of two of the 16 *Yohkoh* arcade events. The sixth column of Table 1 indicates the result of the search for a SEP event in each case. There were also two SEP events in the study period that were not associated with western hemisphere arcade events. For purposes of comparison, we added those two events to the 19 arcade events of Table 1: 1993 March 6, a Nançay event, but located at E29°; and 1994 February 20 (Weiss et al. 1996), neither a large *Yohkoh* arcade nor an importance 3 Nançay event.

Only three of the 19 western hemisphere *Yohkoh* or Nançay arcade events were definitely associated with SEP events. There were two candidate arcade events for which a SEP event association was uncertain. Thus, 14 of the 19 arcade events did not have associated SEP events. Figure 2 compares the X-ray arcades of two SEP-associated flares with two non-SEP flares. All four images were taken from 4–6 hr after the flare peak. The X-ray arcades showed no significant differences in either size or morphology between the five SEP and the 14 non-SEP associated arcades of Table 1. In Figure 3 the *IMP-8* 24 to 28 MeV proton profiles are shown for the corresponding arcade events of Figure 2.

While size and morphology of X-ray arcades are not significantly different between SEP and non-SEP arcades, the two groups are distinguished by their metric type II burst associations. Metric type II bursts are slow-drift radio signatures of coronal shocks that may or may not be driven by CMEs (Gopalswamy et al. 1998). Of the five certain SEP

TABLE 1

ACTIVE REGION ARCADE EVENTS FROM *YOHKOH* AND NANÇAY OBSERVATORY

| Date | Flare UT | Location | Source[a] | Flare | SEPs | IP Boundary[b] |
|---|---|---|---|---|---|---|
| 1993 | | | | | | |
| Feb 18 ........ | 0300 | N14 W02 | Y | M4 | NO | 19/20 |
| Mar 4 ......... | 1230 | S13 W55 | Y | C8 | 04/1200 | NO |
| Mar 6[c] ........ | 2040 | S04 E29 | N | M7 | 07/0000 | NO |
| Mar 10 ....... | 1230 | S03 W21 | N | C4 | NO | NO |
| Mar 12 ....... | 1800 | S03 W48 | N | M7 | 12/2000 | NO |
| Mar 19 ....... | 0220 | N17 W23 | Y | C5 | NO | 19/20 |
| Mar 21 ....... | 0340 | N16 W47 | Y | M2 | NO | 19/20 |
| Apr 2 ......... | 1900 | N10 W60 | Y | B8 | NO | NO |
| Apr 8 ......... | 0300 | S04 W42 | Y | C5 | <08/1600 | NO |
| Apr 25 ........ | 2200 | S13 W24 | Y | B5 | NO | 24/25 |
| May 9......... | ... | S08 W33 | N | ... | 08 & 09 possible | NO |
| Jun 23 ........ | 1400 | N08 W38 | Y & N | <B5 | 23/2000 possible | 23/24 |
| Jun 29 ........ | 0800 | S10 W03 | Y & N | B6 | NO | 29/30 |
| 26 Jul ......... | 0700 | S05 W80 | Y | B3 | NO | 24/25 |
| Oct 24 ........ | 1400 | N07 W55 | Y | B3 | NO | NO |
| Nov 9 ......... | 1100 | S13 W56 | N | B1.8 | NO | NO |
| Dec 1 ......... | 0600 | N04 W20 | Y | C2 | NO | 29/30 |
| Dec 2 ......... | 0700 | N25 W10 | Y | ... | NO | 02/03 |
| 1994 | | | | | | |
| Jan 8 .......... | ... | N07 W00 | N | ... | NO | 07/08 |
| Feb 20[c,d]...... | 0200 | N09 W02 | ... | M4 | 20/0200 | 21/22 |
| Apr 27 ........ | 0900 | S12 W75 | Y | B1.5 | NO | 28/29 |

[a] Y = *Yohkoh*, N = Nançay Observatory.

[b] Closest dates of magnetic field sector boundary from plots of $\Phi$ angle or from the calculations of Wang & Sheeley 1995.

[c] SEP events added to Table for comparison.

[d] See *Yohkoh* images of this event in Weiss et al. 1996.

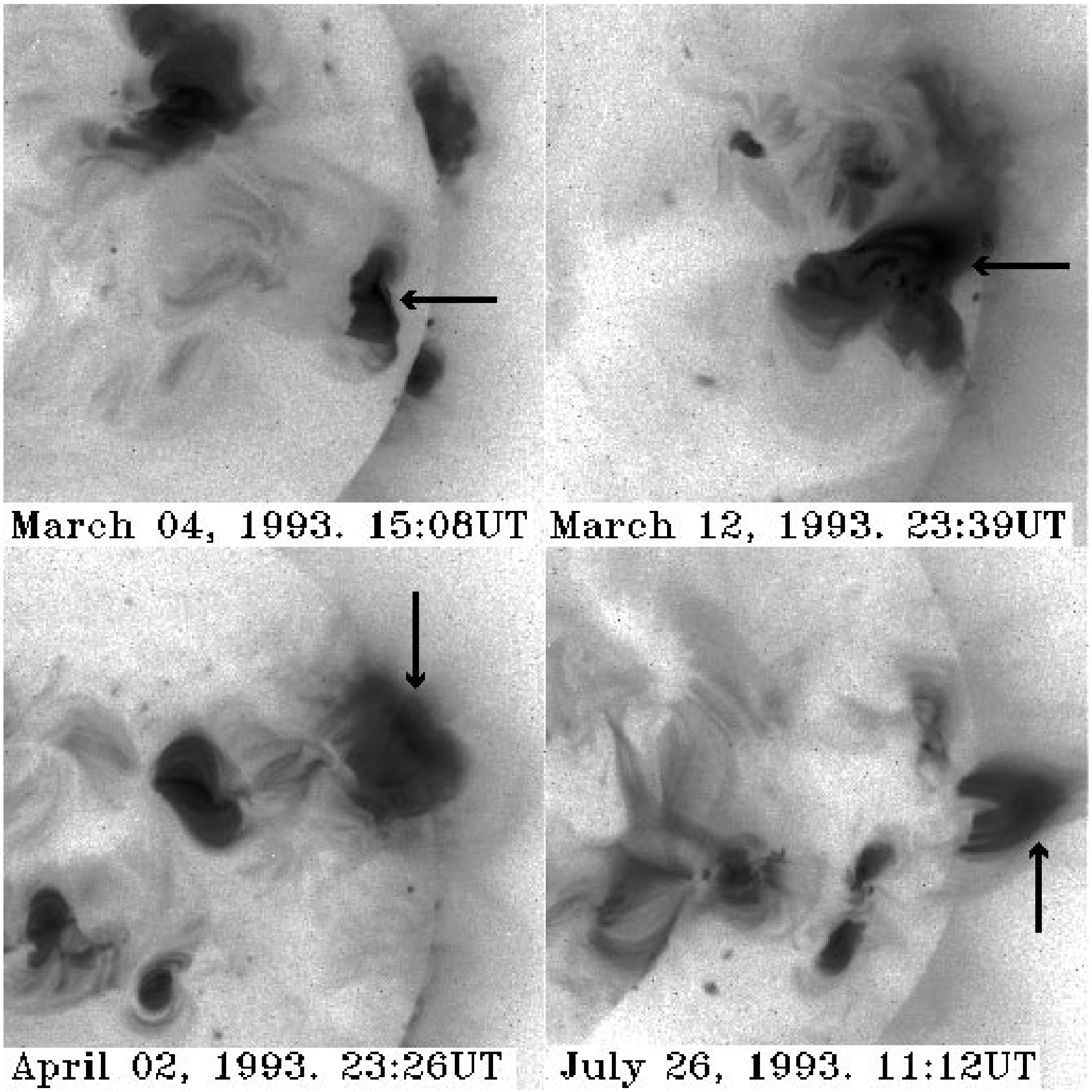

FIG. 2.—*Top: Yohkoh* SXT X-ray arcades of two solar flares associated with SEP events (*left:* 1993 March 4; *right:* 1993 March 12). *Bottom: Yohkoh* X-ray arcades of two solar flares not associated with SEP events (*left:* 1993 April 2; *right:* 1993 July 26). Images are negative, with bright regions dark, and arrows point to the X-ray arcades. North is up.

events of Table 1, all except the 1993 April 8 event were associated with a reported metric type II burst (Coffey 1993). On the contrary, of the 14 certain non-SEP events, only the 1993 February 18 event was associated with a reported metric type II burst (Coffey 1993). The relationship between CMEs and metric type II shock bursts is controversial (Cane 1997; Cliver 1999; Gopalswamy et al. 1999), but the sharp distinction between SEP and non-SEP arcades made by the type II burst associations strongly suggests that shocks rather than coronal arcades are the sources of the gradual SEP events of Table 1.

The SEP events associated with the arcades of 1993 March 6 at E29° and of 1994 February 20 at W02° were also associated with geomagnetic storm sudden commencements (SSC), indicating that interplanetary shocks were present in those events. We assume that those SEP events were produced by the shocks. Supplementing the *IMP-8* SEP data gaps with profiles from the *GOES* energetic particle detectors (Coffey 1993), we find that the SEP events following arcades on 1993 March 4, 1993 March 12 (Figs. 2 and 3), and 1993 April 8 all had fast rise and decay profiles and no observed interplanetary shocks, typical of SEP events associated with flares at ~W50° (Cane, Reames, & von Rosenvinge 1988). The SEP event on 1993 June 23 had a very gradual profile and appeared to be part of corotating interaction region (CIR) event 15 of Richardson, Mazur, & Mason (1998). SEPs in CIR events are produced in interplanetary corotating shocks and are therefore not solar in origin. Thus, only the very small SEP increase on 1993 May 8 remains as a candidate for association with an arcade event.

The last column of Table 1 addresses the location of the nearest sector boundary of the interplanetary field. We determined those locations primarily from the *IMP-8* magnetometer plots of the $\Phi$ angle of the interplanetary magnetic field. When data gaps precluded a determination of the location of the boundary between positive and negative polarities, we used the average daily polarities of photospheric fields extrapolated to 1 AU with a current sheet model by Wang & Sheeley (1995), which showed generally good agreement with the observed sector polarity at 1 AU. To determine whether a sector boundary was present for an

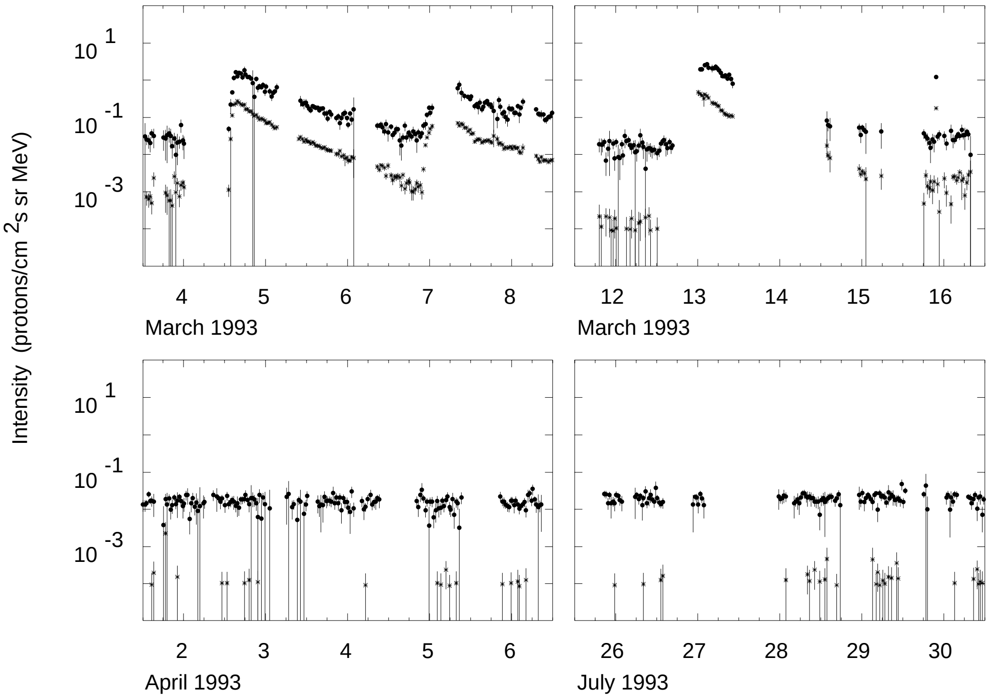

FIG. 3.—*Top: IMP-8* 9 to 23 MeV (*dots*) and 24 to 29 MeV (*crosses*) intensities of the two SEP events associated with the X-ray flares in the top panels of Fig. 2. *Bottom: IMP-8* intensities in the same energy ranges for the two non-SEP X-ray arcades in the bottom panels of Fig. 2. No increases were found for the latter two events.

arcade event, we used an arbitrary criterion of a maximum 3 day separation between the Earth and the sector boundary at the time of the arcade onset. The question here is whether the absence of observed SEPs from RCS events can be attributed to an enhanced distance of the current sheet extension, i.e., the sector boundary, from the Earth at the time of possible injection of SEPs from the RCS. With our 3 day separation criterion, only one of the five SEP events occurred near a sector boundary, but nine of 14 non-SEP events did occur near a sector boundary. Thus the current

TABLE 2

MIDLATITUDE AND POLAR CROWN ARCADE EVENTS FROM *Yohkoh*

| Date | Onset UT | Location | Type[a] | SEPs | IMF Boundary[b] |
|---|---|---|---|---|---|
| 1993 | | | | | |
| Jan 16 ....... | 1200 | S30 W15 | M | NO | 15/16 |
| Jan 26 ....... | 0400 | S40 W10 | M | NO | 26/27 |
| Feb 27 ...... | 1800 | S50 W50 | P | NO | NO |
| Mar 8 ....... | 1900 | S40 W65 | P | NO | NO |
| Mar 21 ...... | 1100 | S60 W23 | P | NO | 19/20 |
| Apr 1 ........ | 1600 | N22 W37 | M | NO | NO |
| Sep 10 ....... | 1200 | N40 W10 | M | NO | NO |
| Sep 16 ....... | 1000 | S12 W47 | M | NO | NO |
| Sep 19 ....... | 1400 | S15 W12 | M | NO | 21/22 |
| Oct 4 ........ | 2000 | S35 W60 | P | NO | NO |
| Oct 21 ....... | 0500 | S17 W14 | M | NO | NO |
| Nov 30 ...... | 0900 | S60 W30 | P | NO | 29/30 |
| Dec 15 ...... | 0800 | S15 W35 | M | 15/1200 possible | NO |
| 1994 | | | | | |
| Feb 1[d] ....... | 1000 | S50 W50 | P | NO | NO |
| Mar 2 ....... | 1900 | S37 W30 | M | NO | 4/5 |
| Apr 14[c] ...... | 0230 | S37 E25 | P | 14/1000 | 16/17 |
| Jun 13 ....... | 2200 | S45 W65 | P | NO | NO |
| Jun 16 ....... | 1800 | N22 W53 | M | NO | NO |

[a] M is midlatitude, P is polar crown.

[b] Closest dates of magnetic field sector boundary from plots of Φ angle or from the calculations of Wang & Sheeley 1995.

[c] SEP event added to Table for comparison.

[d] See *Yohkoh* X-ray images of this event in Weiss et al. 1996.

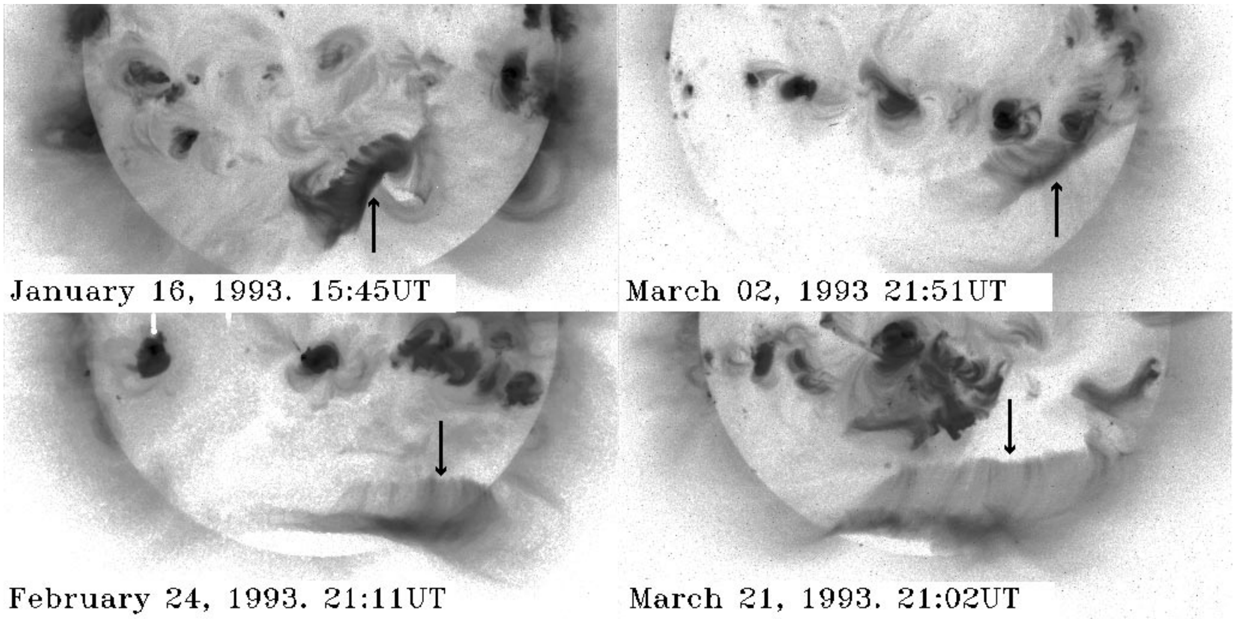

FIG. 4.—*Top: Yohkoh* SXT midlatitude X-ray arcades. *Bottom: Yohkoh* SXT polar crown events. The events are taken from Table 2. Images are negative, with bright regions dark, and vertical arrows point to the X-ray arcades. North is up. No *IMP-8* SEP increases were found for these events.

sheet was more favorably located for those arcades without observed SEPs than it was for the arcades and flares with observed SEPs.

### 3.2. *Polar and Midlatitude Arcades*

Table 2 gives the polar and midlatitude arcades from the *Yohkoh* data. Since these arcades are all outside active regions, there were no matching Nançay Observatory noise storms. The arcade location in the third column was estimated from the *Yohkoh* images, and the fourth column gives the type of arcade. One midlatitude and three polar arcades were eliminated from Table 2 because of significant data gaps in the *IMP-8* energetic particle data. We have added one eastern hemisphere polar X-ray arcade, on 1994 April 14, to Table 2 because that event was associated with an observed SEP event. That SEP event has been associated with shock acceleration in two studies (McAllister et al. 1996a; Kahler et al. 1998). One other arcade of Table 2, on 1993 December 15, is associated with a very small *IMP-8* SEP increase on that day. None of the remaining 16 arcades of Table 2 is associated with a detectable *IMP-8* SEP event. Figure 4 shows two examples of midlatitude arcades and two of polar arcades. As in Figure 2, each midlatitude or polar X-ray arcade is again characterized by growing high coronal loops.

Again considering the role of the proximity to the interplanetary sector boundary, we see that the one SEP event of Table 2 was near a boundary, but only 5 of the 16 arcades without SEPs were near sector boundaries.

## 4. DISCUSSION

Our search for interplanetary $E > 20$ MeV SEP events from well connected coronal arcades has been unsuccessful. We have taken as candidate sources large, bright X-ray arcades or intense metric noise storm regions that are known to be sources of energetic particles in the corona and suspected to be sources of interplanetary SEPs. Several of the candidate sources in this period can be associated with SEP events, but those SEP intensity profiles appear to be consistent with the usual CME shock-driven profiles (Cane et al. 1988). There were 30 solar arcade events, 14 in active regions and 16 at midlatitudes and polar latitudes, that have no observed associated proton increases. These 30 solar arcades are presumed to result from CMEs, so if they were capable of contributing to SEP events, then we suggest that they should also have produced detectable interplanetary SEP increases.

The X-ray sizes and morphologies of the several arcades associated with SEP events are generally similar to those of the 30 arcades without SEP events. Therefore, the arcades without associated SEP events, shown in the bottom of Figure 2 and in Figure 4, should be at least as favorable for SEP production as the arcades of the top of Figure 2, which one might consider as sources of the associated SEP events.

Nearly half the arcade events (14 of 30) were located within 3 days of a sector boundary at the Earth, suggesting a favorable location if we further assume that SEPs from arcade RCSs propagate earthward only in the vicinity of current sheets. However, without specific SEP injection and propagation criteria to allow us to contrast the spatial and temporal distributions of possible arcade SEP contributions with those of the broad and long duration shock contribution, we do not have a clear criterion for testing the hypothesis of arcade SEP contributions.

This negative result for 30 cases is evidence against post-CME arcades as general sources of interplanetary SEP events. This result is not definitive, since one may argue that only occasionally, such as on 11 and 15 June 1991 (Kocharov et al. 1994), do the arcade RCSs provide SEPs of sufficient intensities and at favorable coronal locations for the escape and detection of SEPs at Earth. As we discussed in § 2, those arcades invariably occur in association with fast CMEs and shock-accelerated SEP events, which greatly complicates the identification of a separate arcade SEP population. However, those occasional arcades are capable of producing relativistic ions in the low corona over periods of hours, so we should expect that there are many more arcades capable of producing the much less energetic 20 MeV protons we have surveyed in this study. We have found no examples. If 20 MeV protons are accelerated in the RCSs of arcades, it appears that either they are directed sunward along open field lines or else trapped on newly formed closed field lines. Although our unsuccessful search provides evidence against coronal arcade sources for SEP events, we must recognize that the question of arcade or other coronal structures as contributors to SEP events is not conclusively settled.

The *Yohkoh* X-ray telescope is a project supported by the Institute of Space and Astronautical Sciences of Japan and by NASA. We thank the referee for very helpful comments and suggestions.

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