A Search for Interplanetary Energetic Particle Events from Solar Post-Eruptive Arcades

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Abstract

E $>$ 10 MeV ions observed in gradual solar energetic particle (SEP) events are attributed to acceleration at shocks driven by coronal mass ejections (CMEs), but it has been suggested that such SEPs may also result from acceleration in the magnetic reconnection of coronal arcades following CMEs. The arcade SEPs could escape the corona along open field lines, but those components of SEP events would be difficult to distinguish from shock SEPs. We examine large solar soft X-ray arcades and metric noise storms in the western hemisphere which should be favorable for the production of arcade SEP events observed at 1 AU. Besides 5 arcades possibly associated with 24 $<$ E $<$ 28 MeV SEP events, we also find 14 arcades in active regions and 16 outside active regions with no detectable SEP increases. This negative result for the 30 arcades is evidence that arcades are not sources of escaping SEPs.

1 Introduction

Gradual solar energetic particle (SEP) events observed at 1 AU are characterized by time scales of days and associations with fast (v $>$ 400 km/s) coronal mass ejections (CMEs) which drive coronal and interplanetary shocks (Cane, 1997). The shocks are assumed to accelerate ambient coronal ions to energies sometimes as high as E $>$ 1 GeV (Reames, Kahler & Ng, 1997). 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 Hα and at higher altitudes in soft X-rays (e.g., Harra-Murnion et al., 1998).

These 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). Besides the solar flare emission known as “storm continuum” or “stationary type IV bursts”, radio noise storms lasting hours to days are observed in the vicinity of active regions. Their onsets are associated with the rapid coronal changes characteristic of CMEs (Klein, 1994) and subsequent loop arcades.

Evidence for the production of E $>$ 300 MeV ions in flare gradual phases was found in the γ-ray observations from the GAMMA and CGRO satellites (Kanbach et al., 1993). Akimov et al. (1996) have argued that the E $>$ 2 GeV γ-ray emission, which lasted more than 2 hours in the 15 June 1991 flare, resulted from prolonged proton acceleration through magnetic connection in a coronal vertical current sheet. These observations suggest that ions can be accelerated in post-CME current sheets to energies well above tens of MeV.

Bazilevskaya et al. (1990) and Chertok (1995) have suggested arcades as the sources of protons, and Klein et al. (1996) identified a large noise storm as a secondary source of both ions and electrons in a 1989 SEP event. From a timing and spectral comparison of the 15 June 1991 solar γ-ray and terrestrial neutron monitor observations, Kocharov et al. (1994) attributed the source of the relativistic SEP event at 1 AU to the coronal γ-ray source region. Several studies have invoked a flare-related impulsive component followed by a shock-accelerated component for specific gradual SEP events (Torsti et al., 1996; Cramp et al., 1997) or in general (Lin, 1994). All these observers have argued for a contributing role for dynamic coronal structures as a source of the SEPs observed in gradual events.

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. Litvenenko & Somov (1995) noted that an electric field pointed toward the RCS 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. The maximum energy E_{max} scales as $T/\xi_{\perp}^2$ where T is the plasma temperature of the RCS and $\xi_{\perp}$ = $B_{\perp}/B$. For their assumed values of T = 10^8 K and $\xi_{\perp}$ = 3 $\times$ 10^{-3}, E_{max} = 2.4 GeV. This value does not depend directly on the intensity of B, so an RCS in a large weak field of $\sim$ 30 G outside an active region could accelerate ions to energies as high as those in an RCS in an active region field. The requirement that $nt < 3 \times 10^9\ cm^{-3}s$, where n is the density and t is the time spent in the coronal acceleration and propagation region (Ruffolo, 1997), favors the high, large arcades over the denser active region arcades as acceleration sites.

2 Detection of SEPs

Since all gradual SEP events observed to date appear to be associated with fast CMEs (Kahler, 1996), the unambiguous detection of a separate SEP population from a coronal arcade RCS behind the CME is difficult. To determine whether SEPs originate in coronal arcades, we assume that if arcades make supplementary contributions to SEP events produced in CME-driven shocks, then arcades should also produce significant SEP events when the associated CMEs are too slow to drive shocks. Thus, 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. The occurrence of significant numbers of such arcades well connected to the Earth but without associated SEP events can be taken as supporting evidence against the concept that arcades are sources of gradual SEP events.

We assume that arcades located in the western hemisphere will be sufficiently well connected to Earth to produce observable SEP events. 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 to 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 from 1 January 1993 to 30 June 1994. From a list of 240 X-ray arcade events with a size of $\geq 20^{\circ}$ in any dimension we selected the largest and brightest western hemisphere arcades, of which 15 were classified active region and 17 polar or mid-latitude. The onset times of arcade formation were determined to within about 2 hours. Since radio noise storms are another good indicator of solar active region eruptive events, we also used the monthly lists of 164 MHz noise storms from the Nancay radioheliograph (Radioheliograph Group, 1993) to select storms in the western hemisphere of importance 3 or greater, corresponding to fluxes $>$ 20 sfu.

For each arcade or storm event we examined the time profiles of 24 to 28 MeV proton intensities from the Goddard Medium Energy Experiment on IMP 8 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 Yohkoh arcade events. For purposes of comparison, we added two SEP events to the 19 active region arcade and storm events: 6 March 1993, a Nancay event at E29°; and 20 February 1994, neither a Yohkoh arcade nor an importance 3 Nancay event.

Only 3 of the 19 western hemisphere Yohkoh or Nancay 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 active region arcade events did not have associated SEP events. Figure 1 compares the X-ray arcades of two SEP-associated flares with two non-SEP flares. All four images were taken from 4 to 9 hrs after the flare peak. The X-ray arcades showed no significant differences in either size or morphology between the 5 SEP and the 14 non-SEP associated arcades.

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. Four of the 5 certain SEP events were associated with reported metric type II bursts (Solar-Geophysical Data, 1993). On the contrary, only one of the 14 certain non-SEP events was associated with a reported metric type II burst. This 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.

The SEP events associated with the arcades of 6 March 1993 at E29° and of 20 February 1994 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 (Solar-Geophysical Data, 1993), we find that the SEP events following arcades on 4 March 1993, 12 March 1993, and 8 April 1993 (Figure 1) all had fast rise and decay profiles and no observed interplanetary shocks, typical of SEP events associated with flares at $\sim$ W50° (Cane et al., 1988). A SEP event on 23 June 1993 had a very gradual profile and appeared to be part of corotating interaction region (CIR) event of Richardson et al. (1998) and therefore not solar in origin. Thus, only a very small SEP increase on 8 May 1993 remains as a candidate for association with an arcade event.

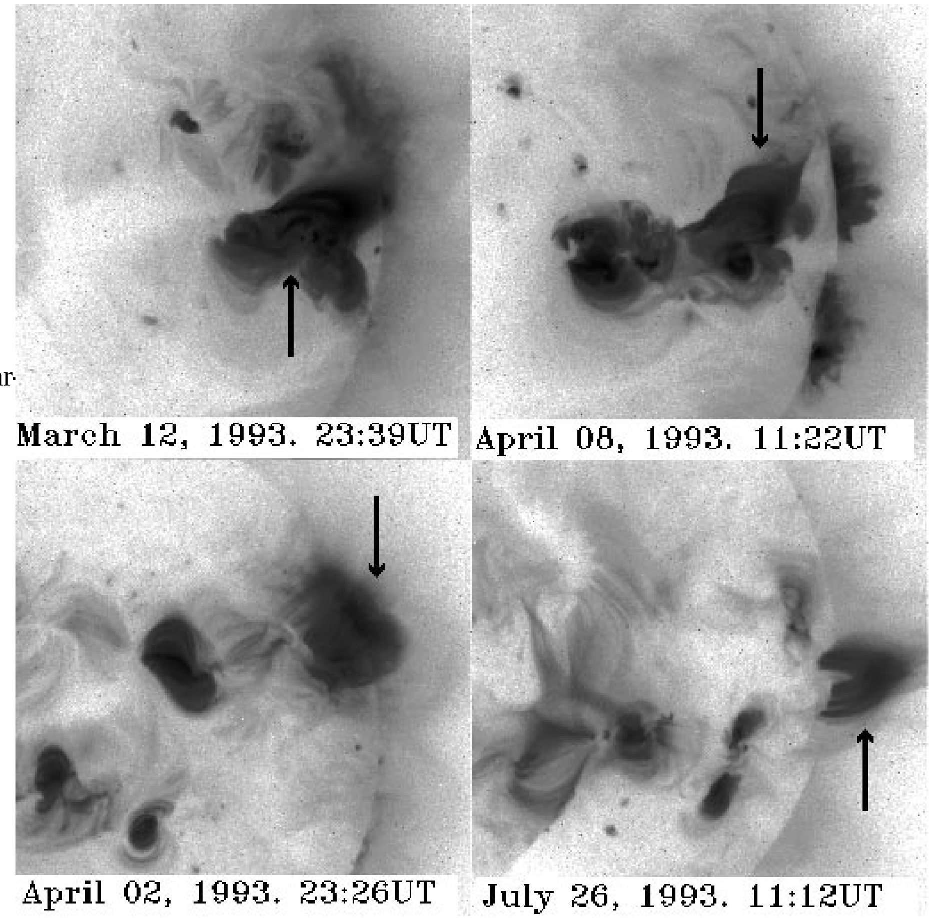

Figure 1: Top: Yohkoh SXT X-ray arcades of two solar flares associated with SEP events (left: 12 March 1993; right: 8 April 1993). Bottom: Yohkoh X-ray arcades of two solar flares not associated with SEP events (left: 2 April 1993; right: 26 July 1993). Images are negative, with bright X-ray regions dark, and vertical arrows point to the X-ray arcades. North is up.

The 17 polar and mid-latitude arcades from the Yohkoh survey are all outside active regions. Each of those arcades is again characterized by growing high coronal loops. One arcade, on 15 December 1993, may be associated with a very small IMP-8 SEP increase on that day. None of the remaining 16 arcades is associated with a detectable IMP-8 SEP event.

4 Discussion

We have addressed the question of contributions to gradual interplanetary SEP events from X-ray arcades or metric noise storm regions that are known to be sources of energetic particles in the corona and suspected to be sources of interplanetary SEPs. We have picked solar events in the western hemisphere which should be reasonably close to a good magnetic connection to the Earth. 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 shock-driven profiles (Cane et al., 1988). More important are the remaining 30 solar events, 14 from active region arcades and 16 from midlatitude and polar crown arcades, that have no observed associated SEP event. These solar arcade events are presumed to result from CMEs, so if they could have made some contribution to the SEP events as the arcades shown in the top panels of Figure 1 might have done, then we suggest that those arcades should also have produced detectable interplanetary SEP events when they were favorably located on the disk.

This negative result for 30 cases is evidence against post-CME arcades as general sources of interplanetary SEP events, but it is not conclusive, since one may argue that only occasionally do the arcade RCSs provide SEPs of sufficient intensities and at favorable coronal locations for the escape and detection of SEPs at Earth. 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.

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