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EUV and Coronagraphic Observations of Coronal Mass Ejections

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Abstract. The Large Angle Spectrometric Coronagraph (LASCO) and Extreme-ultraviolet Imaging Telescope (EIT) onboard Solar and Heliospheric Observatory (SOHO) provide us with unprecedented multi-wavelength observations helping us to understand different dynamic phenomena on the Sun and in the corona. In this paper we discuss the association between post-eruptive arcades (PEAs) detected by EIT and white-light coronal mass ejections (CMEs) detected by LASCO/C2 telescope.

Key words. Sun—corona: coronal mass ejections—post-eruptive arcades—filaments—prominence.

1. Introduction

When inspecting the Sun we basically observe two different kinds of mass loss: the steady solar wind outflow and the sporadic ejection of large plasma structures which are called coronal mass ejections (CMEs). A CME is defined as an observable change in the solar coronal structure that:

- occurs over a time-scale of several minutes to hours, and
- involves the appearance and outward motion of a new discrete, bright white-light feature in the field-of-view (FOV) of a coronagraph (Hundhausen *et al.* 1984; Schwenn 1996).

CMEs propagate in the corona with speeds ranging from 50–2500 km s^{-1} (e.g., Gopalswamy *et al.* 2003b) and are very important for space weather when they approach Earth (e.g., Webb 2004). When CMEs hit the Earth, they can produce strong geomagnetic storms interrupting satellite communication and sometimes also causing electrical power blackouts. Despite these tangible effects, the basic physical mechanism of CME initiation and their evolution is not well understood.

In order to study the initiation mechanism of CMEs, it is mandatory to precisely pin-point their source regions in the low corona and photosphere. This topic has been at the forefront of solar physics research in recent decades. Unfortunately CMEs which originate near the disk center, for which the source regions are better observed, appear

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unstructured, covering the occulter either partially or fully as they propagate parallel to the line-of-sight (LOS). Consequently they are called halos (Howard *et al.* 1982). Moreover these CMEs are often difficult to observe because of the dependence of the intensity of the Thomson scattered light on the viewing angle (Thompson *et al.* 1998; Plunkett *et al.* 1998).

After its launch in December 1995, SOHO (Solar and Heliospheric Observatory) has provided us with the observations of dynamical processes in the solar atmosphere from 1.0 to 30 $R_\odot$ helping us study the source regions of CMEs and their evolution in the corona. Previous statistical studies showed that erupting prominences/disappearing filaments and X-ray flares (mainly long-duration: life time more than 6 hours), were found to be strongly correlated with CMEs (Sheeley 1983). Dimming regions observed in the low corona at soft X-ray and EUV wavelengths imply that the region has been evacuated and have often been found to be associated with CMEs (Biesecker *et al.* 2002 and references therein). Most of the time, dimming regions provide information about the complete base of the CME source region (Thompson *et al.* 2000).

One of the most conspicuous signatures of CMEs in the low corona is the development of arcades of bright loops on the solar disk after the CME eruption (Kahler 1977-Skylab; Hudson & Webb 1997-Yohkoh; Zarro *et al.* 1999-X-ray and EIT; Tripathi *et al.* 2004-EIT).

In this paper we present a study of the association between EUV post-eruptive arcades (PEAs) observed by the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière *et al.* 1995) at 195 Å and white-light CMEs observed by the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner *et al.* 1995) C2 aboard SOHO.

2. Observations

The EUV post-eruptive arcades (PEAs) were identified based on observations made by EIT aboard SOHO. EIT observes the Sun in four different wavelengths, namely 171 Å (Fe IX, X; 1.3×10^6 K), 195 Å (Fe XII; 1.6×10^6 K), 284 Å (Fe XV; 2.0×10^6 K) and 304 Å (He II; 8.0×10^4 K). EIT obtains one image in every 12 minutes at 195 Å which is ideal to observe the active regions and closed field regions of the quiet Sun (Moses *et al.* 1997).

The PEAs were identified using daily EIT mpeg-movies taken by EIT from 1997–2002 based on the following criteria (Tripathi 2005):

- Appearance of localized transient brightenings of large-scale loop systems ($\approx 5^\circ$) over a period of several hours.
- The large-scale loop systems which were selected had to be clearly discernible with respect to the ambient corona and observable over their full spatial extents so that their extreme end points could be located.

By definition, the criteria exclude almost all the limb events because for most of the PEAs forming at the limb the two extreme end-points cannot be uniquely defined and therefore, do not satisfy the criteria. These criteria also exclude the events which were formed after the eruption of polar-crown filaments being at higher latitude making it difficult to identify the two extreme end-points of the PEAs.

Figure 1 shows an example of a PEA identified by EIT at 195 Å on 25 January 1998 in the north-east quadrant of the solar disk. For this event the two extreme end-points

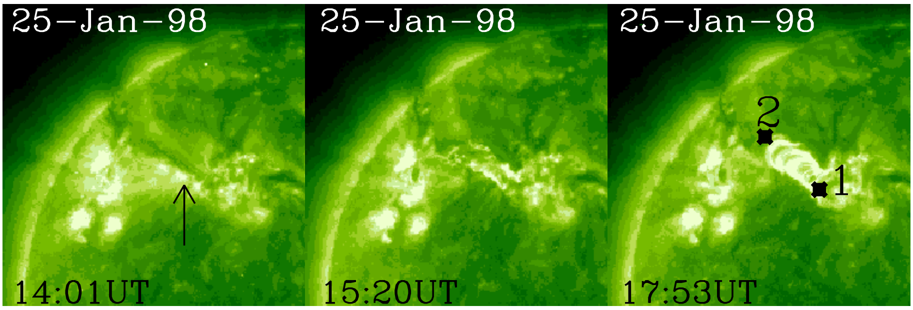

Figure 1. Images taken by EIT at 195 Å on 25 January 1998. The first two images show the eruption of a prominence (marked with an arrow in the left panel) and the consequent post-eruptive arcade. The right panel shows the post-eruptive arcade at times of its maximum evolution (emission). Point '1' and '2' represent the two extreme end-points of the post-eruptive arcade. In the images north points upwards and west towards the right.

of the PEA were uniquely located and are marked as '1' and '2' in the right panel of Fig. 1. The PEA was formed after an eruption of a prominence which is marked by an arrow in the left panel of the figure. This event has been studied in detail by Lara *et al.* (2000a, b); Gopalswamy (1999) and Gopalswamy *et al.* (1999).

Based on the above criteria, Tripathi *et al.* (2004) short-listed 236 EUV PEA events in the time period of 1997–2002. These events are tabulated and are accessible at *http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/422/337*. The table includes life-time, length, source region among other related characteristics.

Figure 2 shows the yearly variations of the total number of PEAs (blue colored bars) based on the EIT 195 Å daily mpeg-movies together with the variations of yearly averaged sunspot numbers (red colored bars). The number of identified PEAs could have been biased in early 1997 due to telemetry restriction (Subramanian & Dere 2001) and from June to December 1998 during the SOHO recovery phase after temporal disability during June–October 1998. As can be seen from Fig. 2, the total number of identified PEAs increased in the rising phase of solar activity from 1997–2000 and decreased after solar maximum in the years 2001 and 2002. Figure 2 shows a strong correlation of PEA frequency with sunspot numbers.

3. EUV post-eruptive arcades and white-light coronal mass ejections

The prime goal of this paper is to study the association of EUV PEAS observed by EIT at 195 Å with white-light CMEs detected by LASCO/C2 coronagraph. For studying the association of EUV PEAs with white-light CMEs there are basically two criteria which have to be taken into account: the spatial and temporal correlations. The spatial correlation of PEAs with CMEs was investigated by comparing the CME's position angle (PA) as provided in the CME catalogue (Yashiro *et al.* 2002; *http://cdaw.gsfc.nasa.gov/CME_list*) with the location of the related PEAs on the solar disk. The PA is measured positive in the counter-clockwise direction, starting with zero degrees at the solar north. Ideally the associated PEA should lie on the same line as the radial line passing from the disk center to the center of the leading edge of the CME. However, this is always not the case and the spatial correlation alone does not always ensure that a particular CME was indeed associated with a given PEA.

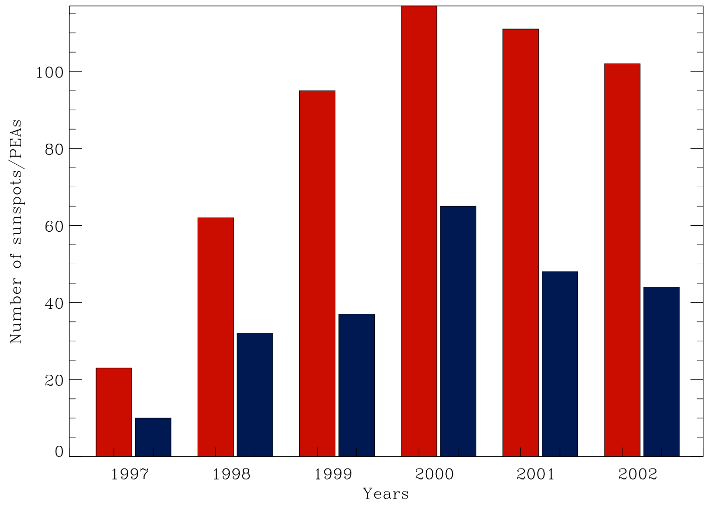

Figure 2. Averaged sunspot number (red colored bars) and total number of identified EUV post-eruptive arcades at 195 Å (blue colored bars) from 1997–2002.

Therefore, in order to support the relationships of a given PEA with CME detected by LASCO/C2, the temporal correlation of both phenomenon was further investigated by comparing the observation time of the PEA with height-time diagrams of the CME taken from the CME catalogue. The height-time diagram of the CME includes observation taken from both the LASCO/C2 (FOV 2-6 $R_{\odot}$) and C3 (4-30 $R_{\odot}$) telescopes. The height-time diagrams were produced by measuring the evolution of the leading edge of the CME under the assumption that CME is evolving radially with respect to the solar limb. From the backward extrapolation of the height-time diagrams the approximated CME onset time were inferred and were compared with the approximated onset time of PEAs in EIT images.

The CME detected by LASCO/C2, associated with the PEA observed by EIT on 25 January 1998 (see Fig. 1) is displayed in Fig. 3. The CME was first detected at 15:26 UT in the LASCO/C2 field-of-view. The CME seen in LASCO/C2 was preceded by a filament eruption seen by EIT at 195 Å marked by an arrow in the left panel of Fig. 1. The estimated onset time of the CME was 14:58 UT based on the backward extrapolation of the height-time diagram. The onset time of the CME is in good agreement with the onset time of the prominence eruption observed by EIT at 195 Å. The determinations of onset times from the simple extrapolations can be misleading, e.g., for those CMEs that were either accelerated or decelerated in the phase of the evolution. This can also happen in cases with Halo CMEs. The onset time of the PEA in EIT 195 Å was estimated to be about 15:02 UT. The estimated onset time for the CME and PEA is labeled in Fig. 4. This onset time of the CME is not consistent with the one reported by Gopalswamy *et al.* (1999) based on the multi-wavelength observations. This discrepancy is due to the linear backward extrapolation of the height-time diagram.

A systematic investigation was performed by Tripathi *et al.* (2004) to study the association of the entire set of PEAs identified by EIT at 195 Å with white-light CMEs detected by LASCO/C2 based on the two criteria described above.

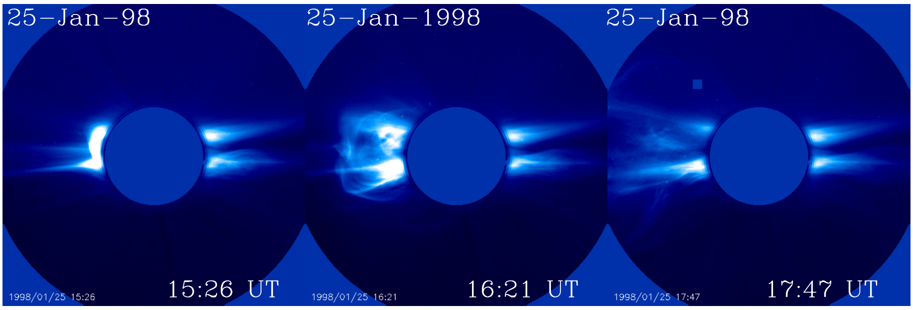

Figure 3. SOHO/LASCO/C2 white-light images showing the coronal mass ejection at the east limb associated with the post-eruptive arcade shown in Fig. 1.

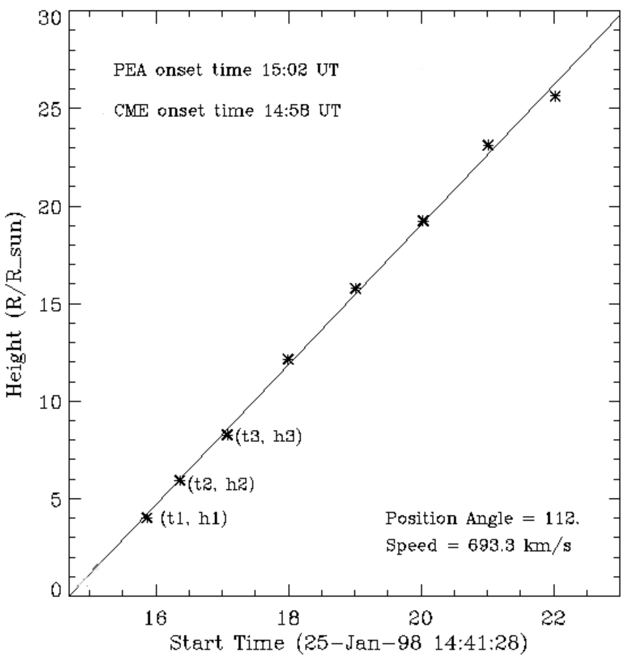

Figure 4. Height-time diagram for the leading edge of the CME observed on 25 January 1998 as provided by LASCO/C2 and C3 observations. h1 is the height measured at time t1, h2 is measured at t2 and so on. Approximate timings of CME (triangle) and PEA (solid dot) onset is marked in the figure.

Figure 5 shows the distribution of all identified PEAs in heliographic longitude presented in bins of 10 degrees. Due to selection criteria of the events, as expected the population of identified PEAs peaks near the central meridian region where PEA events can be observed over their full spatial extent. Based on this study it was found that 92% of all the identified EUV PEAs were associated with white-light CMEs. The dashed portion of the bars represent those PEA events (other 8%) with no CMEs detected with LASCO/C2. However, from Fig. 5 it is clear that all of these events were

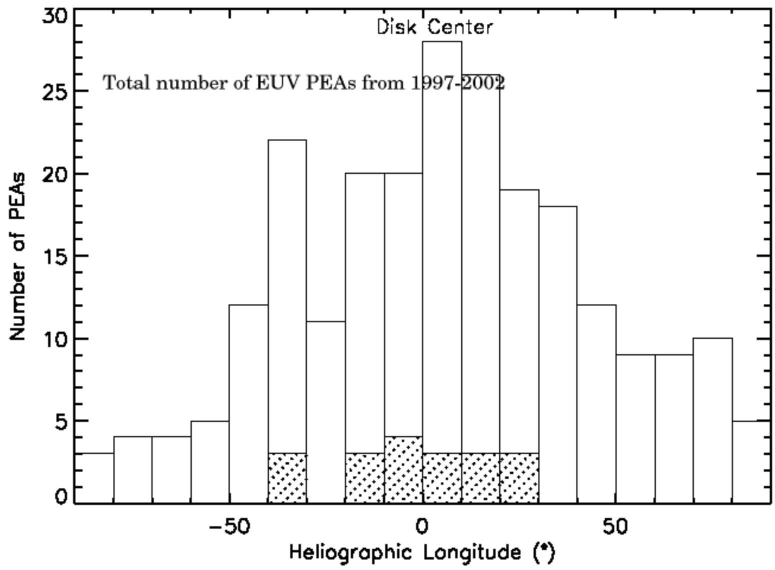

Figure 5. Distribution of PEAs in heliographic longitude in bins of 10 degrees as identified in EIT 195 Å images from 1997–2002. The portions of the bars presented as the spotted areas represent those PEAs for which no white-light CME had been detected by LASCO/C2 (adopted from Tripathi *et al.* (2004)).

located very near to the central meridian (in the range of $\pm 40^\circ$). The CMEs coming from the disk center are hardest to detect because of the dependence of the viewing angle on the Thomson scattered light (Thompson *et al.* 1998; Plunkett *et al.* 1998). Therefore, it seems plausible to assume that the absence of CME for some PEA events is just an observational bias and we conclude that all the PEAs observed by EIT at 195 Å are associated with white-light CMEs.

Moreover, for 8% PEA events which were not associated with white-light CMEs, a comparison was made with erupting prominences and disappearing filaments based on ground-based $H\alpha$ observations. Erupting prominences and disappearing filaments are believed to be one of the clearest signatures of CMEs on the solar disk (e.g., Gopalswamy *et al.* 2003a). Taking this into account, the association between the EUV PEAs and white-light CMEs increases to 98%. Therefore, we can conclude that each PEA observed at EUV wavelength (195 Å) has an associated white-light CME and so PEAs can be considered as reliable disk tracers of CMEs on the solar disk even without simultaneous coronagraphic observations.

4. Summary and conclusions

Based on the observations made by EIT at 195 Å and LASCO/C2 coronagraph it was found that all the EUV PEAs were associated with a white-light CME. Therefore, EUV PEAs can be considered as a reliable disk tracer for the CMEs. Moreover EUV PEAs can provide information about CMEs even without simultaneous coronagraph observations. These EUV PEAs serve as footprints of CME source regions.

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