

X-ray coronal changes during halo CMEs

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Abstract. Using the *Yohkoh* soft X-ray images, we examine the coronal structures associated with "halo" coronal mass ejections (CMEs). These may correspond to events near solar disk center. Starting with a list of eleven confirmed halo CMEs over the time range from December 1996 through May 1997, we find seven with surface features identifiable in soft X-rays, with GOES classifications ranging from A1 to M1.3. These have a characteristic pattern of sigmoid \rightarrow arcade development. In each of these events, the pre-flare structure disrupted during the flare, leaving the appearance of compact transient coronal holes. The four remaining events had weak or indistinguishable signatures in the X-ray images. For the events for which we could see well-defined coronal changes, we confirm our previous result that the estimated mass loss inferred from the soft X-ray dimming is a small fraction of typical CME masses [Sterling & Hudson 1997].

1. Introduction

Halo CMEs originating on the visible hemisphere represent ejections directed towards the Earth, and thus may have the severest terrestrial consequences [Howard *et al.* 1982]. They occur far from the plane of the sky, so a coronagraph does not represent the optimum tool with which to study them. Because such CMEs result from ejecta directed either towards the Earth or away, the solar behavior near disk center can in prin-

ciple provide a guide as to which hemisphere launched the ejection. The new full-disk coronal instruments on *Yohkoh* and SOHO have an obvious role to play in characterizing the solar antecedents of such events, and this paper represents a first survey of the soft X-ray images from *Yohkoh* [Tsuneta *et al.* 1991] for this purpose.

Our general understanding of the relationships between flares or other low-coronal phenomena and CMEs is undergoing a rapid evolution. The LASCO coronagraphs on SOHO can now monitor continuously and sensitively for CME occurrence. Hudson & Webb [1997] have recently summarized our current state of knowledge, pointing out a variety of signatures for mass loss revealed by the X-ray images. These signatures often take the form of X-ray dimming related to the formation of voids in the visible corona [Hansen *et al.* 1974] and to "transient coronal holes" as noted from the soft X-ray observations from Skylab [Rust 1983].

The sample of LASCO halo events studied here shows (in *Yohkoh* SXT) a clear and expected pattern, which we call a sigmoid \rightarrow arcade development. In this pattern an S-shaped active region structure flares and transforms itself into a set of bright loops during the launching of the CME. Many authors have noted this pattern previously [Kahler 1977; Sakurai *et al.* 1992; Rust & Kumar 1996], and it represents one of the basic motivations for the standard reconnection model of eruptive flares. Our survey of this sample of events therefore gives us a chance to confirm that this pattern does indeed underlie the launches of halo CMEs, and to learn more about it.

2. Data

The list of eleven halo CMEs studied here appears in Table 1. Here "halo" or "partial halo" means a range of position angle exceeding 130°. The three April 27 events might be considered as a single event, even though the CME observations spread out over many hours. Figure 1 shows the SXT full-frame image times for six of these events, along with GOES time profiles

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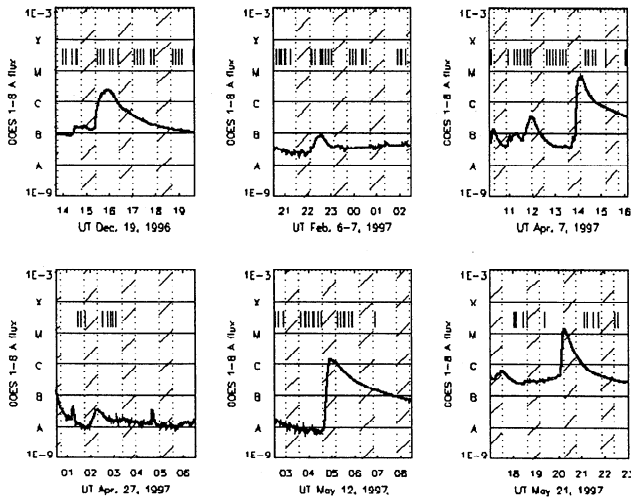


Figure 1. GOES light curves (1-8 Å) of six halo CME counterparts. The vertical tick marks show the times of (*Yohkoh* SXT) long exposures, and the hashed regions show *Yohkoh* orbit night intervals. There were only limited data for the first April 27, 1997 event (#7). In each of the other cases the plot extends plus two hours and minus four hours from the time of the initial LASCO image.

in 1-8 Å X-rays. This spectral band, the soft channel of GOES, responds to higher energies than SXT and furthermore comes from a full-Sun measurement. GOES therefore cannot easily detect large-scale arcade events happening outside active regions, which tend to be fainter, slower, and cooler than the flare-associated events. In some cases SXT will have partial-frame images available for a given event, but these do not show the global morphology so well; the field of view is too small and the short exposure times make it difficult to see faint coronal features.

From the eleven events in the list, we find six and possibly a seventh to be associated with flares. The seven X-ray bursts range in GOES magnitude from A1 to M1, three orders of magnitude in scale of energy release. Since half of the halo CMEs must on average originate on the invisible hemisphere, this rate of identification with features on the visible hemisphere seems reasonable. The Jan. 6, 1997 event (#2 in Table 1) represents the weakest X-ray event in our list. We knew from the heliospheric and Earth-based observation that

it actually occurred on the visible hemisphere, and for this reason we investigated such a subtle event; otherwise it would surely have escaped notice [Webb *et al.* 1997].

3. Image Morphology

We have examined the *Yohkoh* SXT movie around each of the LASCO times reported in Table 1. For each associated event discovered in this way we have also studied the images in greater detail, using the *Yohkoh* software to make standard corrections for dark current, stray light, image motion, and solar rotation. These comparisons consisted of plotting time series of selected image areas and of making difference images from before and after the event. Because of data gaps we could not always study the associated event itself, but could usually make a representative difference image (except for #7 because of poor data coverage). We describe the typical (four) and exceptional (three) events separately below. The latter each show some features of the typical events. The four unidentified events may have originated from behind the limb, although there is some evidence to the contrary.

3.1. The four “typical” events

Figure 2 shows difference images comparing the main flare brightening (positive) with the preflare active-region structure (negative), identified by date. This compact format allows the reader to compare the geometry of the pre-event and post-event structures directly. The events shown have similar characteristics to the original event (#5) for which we carried out this analysis *Sterling & Hudson* [1997]. The general pattern matches that described by [Moore & Labonte 1979], in which outlying “elbows” of the active region expand and form the ejection; see also the magnetostatic modeling of such structures by *Antiochos et al.* [1994]. In this pattern the larger loops of an active region extend outwards in two directions, curling around in the characteristic sigmoid pattern. The bright post-flare arcade develops in the saddle-shaped region between these outlying fields. *Plunkett et al.* [1997] and *Thompson et al.* [1997] discuss events #10 and #5, respectively, in this issue.

3.2. January 6, 1997 (event #2)

This geophysically important event had only weak counterparts in the low corona, which included filament

Table 1. Halo CME events

No.	Date	LASCO		Associated Surface Activity			
		UT	Flare	Max	Position	Radio	Dimming
1	Dec. 19, 1996	17:40	1F C2.3 LDE	15:56	S14W10	No	Yes
2	Jan. 6, 1997	17:34	?? A1? LDE?	14:00	S24W01	No	Yes?
3	Feb. 7, 1997	00:30	?? A9 LDE	23:00 (6)	Large	No	Yes?
4	Mar. 24, 1997	07:37	-	-	-	No	No
5	Apr. 7, 1997	14:07	3N C7 LDE	11:59	S30E19	II, IV	Yes
6	Apr. 16, 1997	~06:00	-	-	-	I	No
7	Apr. 27, 1997	00:31	sF B7 LDE?	23:51 (26)	S17W37	No	-
8	Apr. 27, 1997	10:26	-	-	-	I	No
9	Apr. 27, 1997	15:27	-	-	-	No	No
10	May 12, 1997	06:30	1N C1.3 LDE	04:55	N12W08	I, II, III, IV	Yes
11	May 21, 1997	21:00	sF M1.3 LDE	20:03	N05W11	II, III, IV	Yes

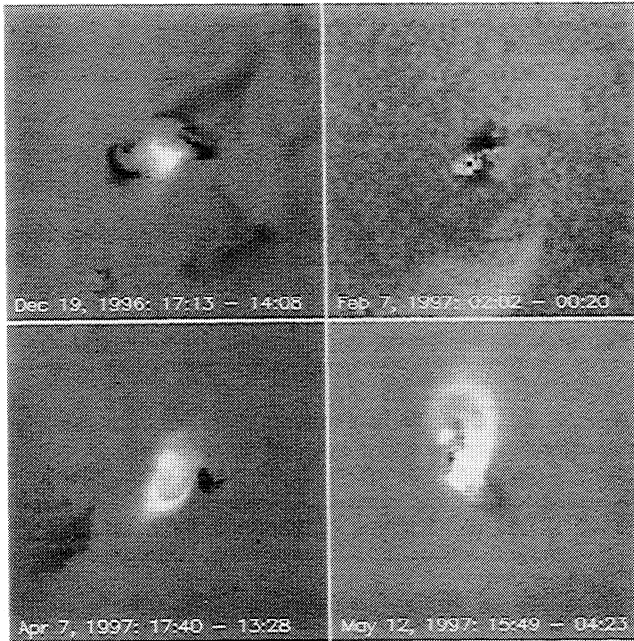


Figure 2. Four difference images of the typical events in our sample (list members #1, #3, #5, and #10), showing the dimmed regions (dark) and the flare loops (bright). We interpret the dimming as the “transient coronal hole” type. The panel on upper right (Feb. 7, 1997) shows the arcade developing to the SE of the active region. The image scales have been altered to make the dimmer preflare structures visible.

activity and an extremely feeble GOES event at about the A1 level [Webb *et al.* 1997]. A data gap from 13:38 UT to 14:43 UT prevented *Yohkoh* from observing ejection from this event directly. A difference image (Figure 3 of Webb *et al.* [1997]) from these times shows a pattern of dimming similar to that of the four “normal” events (#1, #5, #10, and #11), so we conclude that this event probably fits the type but represents the weakest signature of any event in the list. We identify this as a long-duration event (LDE) based upon the duration of the GOES-8 and GOES-9 time profiles, but it is a marginal case.

3.3. February 7, 1997 (event #3)

Event #3 appears to belong partly to a different class, in that an extensive soft X-ray arcade formed [Gopalswamy *et al.* 1997]. It is remarkable in that the associated active region underwent a dimming evolution, as in the pattern of the four events listed above. The arcade extended over a large fraction of the southern solar hemisphere and thus resembled one of the huge polar crown arcade events (*e.g.* Alexander *et al.* [1994], McAllister *et al.* [1996]) observed by *Yohkoh*.

3.4. May 21, 1997 (event #11)

The remaining flare, the M1.3 event of May 21, 1997, has a somewhat different appearance. For this event, the GOES soft X-ray flux had an e-folding decay time (1-8Å channel) of about 20 minutes, clearly placing it outside the category of LDE flares. Event #11 indeed

shows a clear sigmoid preflare structure, but the post-flare configuration is dominated by a single, extremely bright, untwisted loop, whose plane lies near the line of sight.

4. Conclusions

We see low-coronal counterpart features in seven out of the 11 list members, hence possibly for all of the events originating on the Earth-facing solar hemisphere. Even with the great sensitivity of *Yohkoh* SXT, however, some halo CME events, and hence CMEs in general, may occur without strong soft X-ray counterparts. This claim had often been made before on the basis of the GOES data, but without images one could not have been sure. SXT has detected many spectacular arcade events without noticeable GOES signatures. The January 6, 1997, event (#2) now makes it clear that the main coronal counterpart of such an ejection can take place in a volume too large (and hence too faint) or too cool (less than about 1.5×10^6 K) for SXT to detect.

The range of flare energies for surface events related to LASCO halo CMEs from this sample approaches three orders of magnitude, including the A1 event (#2) and using GOES peak flux as a measure of total energy, and could be greater still if one of the four undetected events did in fact occur on the Earth-facing side of the Sun. The before-and-after image comparisons show a clear tendency for mass disappearance, as discussed for April 7, 1997 (#5) by [Sterling & Hudson 1997]. The masses inferred from the disappearance of the preflare bright material amount to only a fraction of “typical” CME mass estimates. To place these results into quantitative perspective, we would need to have mass or energy estimates for the CMEs. This is a difficult analysis task and beyond the scope of this paper. Hundhausen [1997] points out that the correlation between GOES peak flux and CME energy is quite weak, but the inclusion of disk locations of the events improves it [Burkepile 1997]. We believe that it is premature to draw any firm conclusions about energetics or causality.

The active-region evolves from a more-sheared X-ray (sigmoid) to less-sheared (arcade) one [Kahler 1977]. This implies the disappearance of pre-flare structures, as shown in Figure 1. We do not know if this behavior is typical of all flares, or just the ejective ones, but a further study could clarify this important point. The arcade footpoints may not match those of the preflare sigmoid structure, implying the occurrence of plasma heating on field lines not visible prior to the eruption.

The dimming signature, while generally present in our events, is not obvious in some of them (#2, #3). The fact that we have detected it in these weak events strengthens the case that dimming may eventually provide a reliable means of detecting the initiation of a CME. The dimmings found here consist mainly of two symmetrical regions at diagonal positions relative to the postflare arcade [Sterling & Hudson 1997]. We now interpret these dimmings as the aftermath of double-lobed loop ejection in the Moore & Labonte [1979] pattern, and speculate that the larger transient coronal holes Hudson & Webb [1997] detected in the FexII channel of SOHO EIT [Thompson *et al.* 1997] correspond to still larger magnetic loops also rooted in the active region.

These larger loops would be too cool (less than about 1.5×10^6 K) to detect with SXT prior to the eruption. In this interpretation the "transient coronal holes," and the footpoints of the erupted flux rope, connect to the active region itself rather than to the adjacent photosphere. This pattern differs (perhaps only in scale) from that detected during two magnetic cloud events recently reported [Smith *et al.* 1997; Manoharan *et al.* 1997] from comparisons of *Yohkoh* and heliospheric observations, in which the dimmings are remote from the flare activity and on a large scale.

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