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Coronal Dimmings and Energetic CMEs in April-May 1998

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Abstract. We have analyzed the coronal dimmings for seven fast (> 600 km/s) coronal mass ejections (CMEs) occurring between 23 April and 9 May which were associated with flares from NOAA active region (AR) 8210. Each of these CMEs had at least one group of interplanetary radio bursts associated with them. These dimming regions were identified by their strong depletion in coronal EUV emission within a half hour of the estimated time of CME lift-off. They included areas which were as dark as quiescent coronal holes as well as other regions with weaker brightness depletions. While the location of the active region and the associated flare did not correspond well with the coronagraph observations, we found that the extended dimming areas in these events generally mapped out the apparent "footprint" of the CME as observed by white-light coronagraph. We briefly discuss the implications of these results on models of CME topology.

1. Introduction

The series of solar eruptions associated with NOAA active region (AR) 8210 during its disk passage in late April / early May in 1998 comprise a sequence of recurring energetic (massive, fast) CMEs early in Solar Cycle 23. The seven major CMEs observed between 23 April and 9 May were associated with M- and X-Class soft X-ray flares, interplanetary shocks at Earth, intense geomagnetic storms, and the onset of the 11-year cosmic ray modulation cycle [*Gopalswamy et al* 2000]. We analyze data from the EUV Imaging Telescope [EIT; *Delaboudinière et al* 1995] and the Large Angle Spectroscopic Coronagraph [LASCO; *Brueckner et al* 1995] from the Solar and Heliospheric Observatory (SOHO) spacecraft to investigate the source regions of these energetic CMEs.

We focus on the coronal dimming regions which have been identified in EIT data as regions of decreased brightness in the vicinity of the flares associated with CMEs [*Thompson et al* 1998]. Such brightness depletions were discovered in Skylab soft X-ray images by *Rust* [1983, and references therein] who referred to them as "transient coronal holes." Subsequently, *Hudson et al* [1996], *Sterling and Hudson* [1997], and *Hudson and Webb* [1997] reported such depletions in Yohkoh SXT data and referred to them as coronal "dimmings." A comparison of Yohkoh SXT data and EIT observations for the 7 April 1997 event [*Zarro et al* 1999] established that the dimmings resulted from a decrease of coronal density, consistent with Rust's original interpretation [c.f. *Hudson et al* 1996]. The "double dimmings" such as those observed in the well-studied event of 7 April [*Sterling and Hudson* 1997; *Zarro et al* 1999; *Thompson et al* 1999], in which darkened areas appear in the concavities of sigmoid-like structures [*Canfield et al* 1999], readily lend themselves to a flux rope interpretation [*e g Sterling and Hudson* 1997; *Titov and Démoulin* 1999, and references therein]. In such a picture, the indents in a sheared (S-shaped) neutral line represent the opposite ends of a flux rope. Upon eruption of the flux rope, the nascent dimming regions are "opened" to the solar wind and become dark as mass escapes.

Despite the potential significance of the dimming signature as a diagnostic of CME origin, no comprehensive study has yet been undertaken of the relationship of the dimming events to CMEs. Such a project presented itself naturally to the "Arcades and Dimmings" subgroup at the International Solar Terrestrial Physics (ISTP) Workshop On the Global Picture of Eruptive Solar Events. Of the 29 interplanetary radio events which were the focus of the workshop, we chose to focus on the seven major CMEs (which corresponded to ten separate interplanetary radio events) associated with the disk passage of AR 8210. These CMEs, despite originating in the same active region, display great variation which allows us to compare and contrast the eruptions. Six of these CMEs had speeds > 1000 km/s. Evidence of "EIT Wave" transients [*e g Thompson et al* 1999] and/or coronal bright arcs [*Delannée and Aulanier* 2000] were also observed in each of the seven eruptions.

2. Observations and Analysis

During the disk passage of AR 8210, SOHO EIT images at 195 Å were taken at an average cadence of 17 minutes. Most of the images were full-resolution (2.6 arcsec per pixel), with some periods at half-resolution. The 195 Å bandpass is dominated by Fe XII emission lines at 192.3, 193.5 and 195.1 Å which corresponds to a temperature of 1.5 MK at typical coronal densities.

The dimming regions for the seven CMEs we considered were defined by examining EIT data over a range of several hours surrounding the eruption. In most cases, the full extent of coronal dimming was not apparent in a single image. Areas exhibited different degrees of decreased emission and different areas could commence dimming at different times. Generally, the maximum spatial extent of the dimming was reached within ~ 30 minutes after the soft X-ray flare peak. What appeared to be either EIT wave transients [*Thompson et

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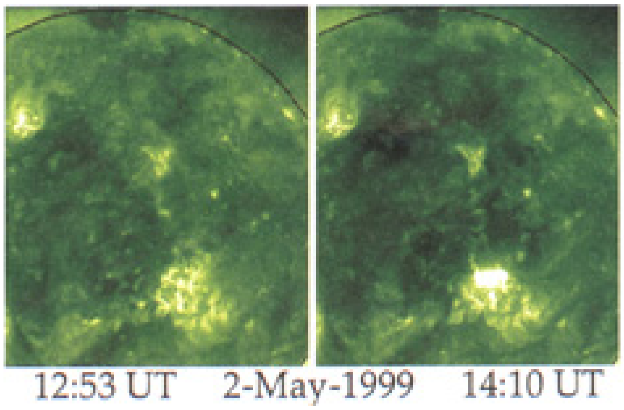

Figure 1. *SOHO*/EIT Fe XII 195 Å images recorded before (12:53 UT) and after (14:10 UT) the eruption on 2 May 1998.

al 1999] or coronal bright arcs [*Delannée and Aulanier* 2000] characteristically appeared outside the expansion of the dimming region from the flare site, and the waves typically first appeared in the same image in which the dimming increase was first observed. Unfortunately, the 17-minute cadence made it difficult to determine the exact correspondence between these two phenomena.

Figure 1 shows non-differenced EIT data for the 2 May 1998 eruption at 12:53 and 14:10 UT, the latter image exhibiting a patchy decrease in emission over a large portion of the visible disk. Over half of the solar disk is shown in the images, with the entire northern limb of the Sun visible in the upper portion of the images. The EIT 195 Å data best exhibits a decrease in emission in the low ($< 1.2\ R_{\odot}$) corona, in areas that previously had been strongly emitting in EUV. Regions that were weakly emitting relative to the background emission level would not be readily identifiable if they experienced a decrease in emission, which must be considered when comparing the soft X-ray data. The dimming or disappearance of transequatorial loops in the 6 May and 9 May eruptions were easily observed in the SXT data. Each of the seven eruptions in our study exhibited strong dimming at 195 Å near the flaring region, but they were also accompanied by other areas which dimmed to a lesser extent.

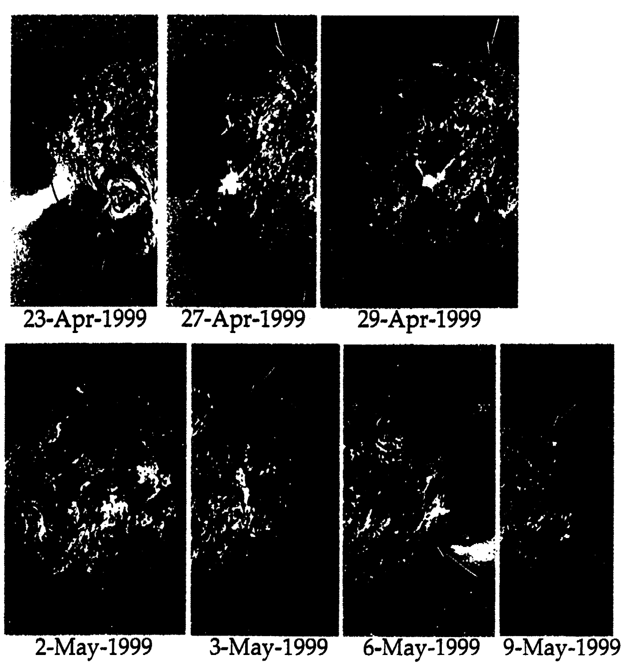

Figure 2. *SOHO*/EIT "percentage-difference" images in Fe XII 195 Å for each of the events listed in Table 1.

Figure 2 shows the dimming regions for the seven eruptions in the form of "percentage-difference" images. A percentage-difference image represents the percentage change in emission between a reference image and a post-eruption image. The solar limb is outlined in black in each of the images. Data on the seven events, including the times of the reference images and the post-eruption images are given in Table 1 (t_{base} and t_{dim}). The advantage of percentage-difference images is that a weakly emitting region showing a fractional change in emission can be identified in an image simultaneous with a brighter region. Each of the images are scaled from a 20 % decrease in emission (black) to a 20 % increase in emission (white). The gray regions represent areas which exhibited little or no fractional change in emission.

For two of the seven events, 23 April and 27 April, motions in the corona and/or dimmings were apparent about a half hour before the main phase of the flare began. The early dimming in the 27 April event has been discussed in detail by *Gopalswamy et al* [1999]. The 23 April eruption also shows a similar sequence of events, with the dimming to one side of the CME commencing before the flare, while the second dimming progresses with the flare.

We examined the LASCO C2 coronagraph data to identify the white light counterparts of the EIT dimmings shown in Figure 2. The LASCO C2 coronagraph

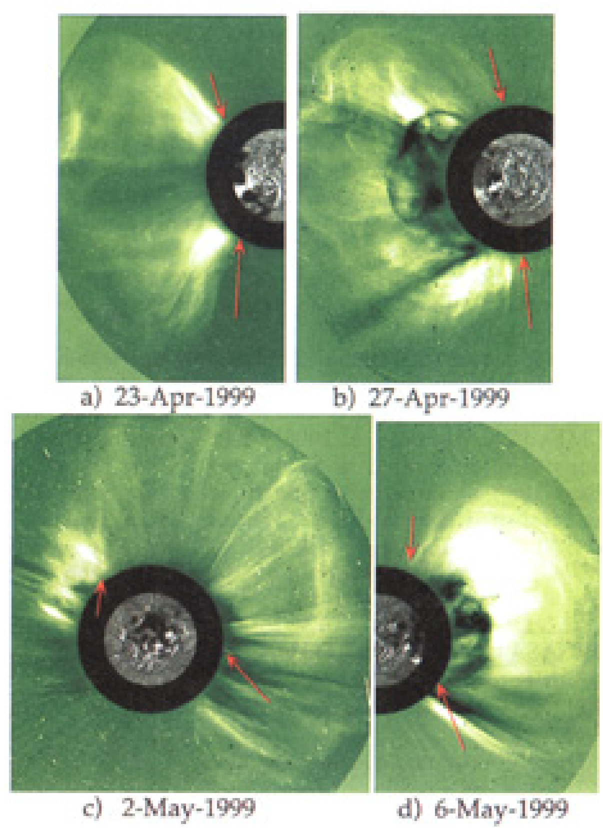

Figure 3. EIT percentage-difference images from Figure 2 combined with *SOHO* LASCO C2 data for the same eruption.

Table 1. Summary of Events Studied

Flare				Dimming		CME				
Date	t_{GOES}	Flux[a]	Location	t_{base}	t_{dim}	t_0[b]	t_1[c]	v km/s[d]	Θ	Θ_{LASCO}[d]
04/23	05:57	X1.3	S16E90	05:33	06:01	05:27	06:27	1390	103	360
04/27	09:20	X1.1	S16E50	08:06	09:50	08:56	09:56	1631	169	360
04/29	16:37	M7.0	S16E23	15:51	17:03	16:59	17:27	1016	158	360
05/02	13:42	X1.1	S15W15	12:53	14:10	14:06	15:13	1044	115	360
05/03	21:29	M1.5	S15W34	21:09	22:06	22:02	22:27	639	59	240
05/06	08:09	X2.8	S11W65	07:58	08:38	08:05	09:02	1053	93	185
05/09	03:40	M7.8	S11W90	03:11	04:02	03:36	04:10	1726	75	143

[a]Mm.n and Xm.n stand for peak X-ray fluxes of m.n$\times 10^{-5}$ W/m^2 and m.n$\times 10^{-5}$ W/m^2, respectively, as measured in the 1–8 Å channel of the GOES detector.

[b]Time of the LASCO C2 image in which the CME is first recognized.

[c]Time of the LASCO C2 image in which the angular extent of the CME (Θ) is measured.

[d]From the LASCO CME list compiled by *O.C. St. Cyr and S.P. Plunkett* [1999].

(2.0 - 6.0 field of view) records the white light brightness of coronal structures and eruptions at an image cadence that typically ranged from 25 to 90 minutes in April and May of 1998. As with the EIT data, the LASCO images were examined in different ways to determine the extents of the CMEs. Running-difference movies were used to highlight the transient features, and standard images were examined to determine the morphology of the eruption without differencing artifacts. For six of the seven events, the angle over which the white light CME ranged (projected radially back to the solar surface) is indicated by the solid arrows in Figure 2. The arrows are omitted for the 2 May 1998 eruption because the CME brightening extended over a large range. This eruption is a good example of a "halo" CME, typical of eruptions which occur near the solar disk center. The corresponding depletion in emission also extended over a great deal of the solar disk.

The time of the first appearance of the CME in the LASCO C2 data is given in Table 1 along with the time (t_1) for which we determined the latitudinal extent (Θ) of the CME. In general, the CME appeared in the LASCO C2 field of view within a half hour (before or after) of the peak SXR flux. The cadence of the EIT and LASCO images prevented us from precisely determining the timing of the dimming onset relative to the appearance of the white light CME. However, the EIT dimming commenced within a half hour of the initial appearance of the CME in LASCO C2 in every event.

Examples illustrating our technique of measuring the CME width are shown with arrows in Figure 3(a-d) for four of the events in Table 1. In these composite images, the inner image is the EIT image shown in Figure 2. In Figure 3a, the outer image is the raw (undifferenced) C2 data for the time given in Table 1, while in Figure 3(b-d), the outer image is a subtraction from an earlier image. Of particular interest are the bright and dark streamers in the lower right corner of the outer subtracted image in Figure 3(d). The dark "streamer" results from the displacement of the bright streamer away from the CME in the time between the two images. It is a signature of a deflection/compression event [*St. Cyr and Hundhausen* 1988] and helps us to distinguish between the "true" extent of a coronal mass ejection and other dynamically transient features. From the last two columns of the table, it can be seen that our measured angular span is in all cases smaller than that listed on the LASCO CME list shown in the last column of the table. Four of the seven events are listed as full (360°) halos; according to our determination, none of the seven CMEs had angular spans >170°. For example, the 2 May 1999 CME angular extent represents the primary loop-shaped feature; including adjacent brightenings results in a measured extent greater than >170°.

A comparison of the outlined dimming regions with the arrows marking the angular extent of the CMEs in Figure 2 (and the EIT dimmings in Figure 1 and coronagraph images in Figure 3) suggests that the EIT dimmings mark the source regions of the CMEs. Even for the 27 April event [*Gopalswamy et al* 1999] for which the angle subtended by the dimming regions is much smaller than the angular span of the CME (Figure 2), the composite in Figure 3(b) indicates that the CME observed in LASCO C2 is centered about the EIT dimming and exhibits a reasonable correspondence with the off-limb dimming.

3. Discussion and Conclusions

Typical CME angular extents are much larger than the 20-30° longitudinal span of major active regions. The average CME span is ~45° [*Hundhausen* 1993]; for CMEs associated with kilometric Type II bursts, such as the events considered here, the median span is ~ 90° [*Cane et al* 1987]. Until now, no chromospheric or coronal feature of comparable angular size with the CME has been identified as a signature of the source region for energetic (massive, fast) CMEs associated with active region flares. We submit that the EIT dimming regions which appear to crudely map the "footprint" of the major CMEs associated with AR 8210 in April and May 1998 represent such a diagnostic.

In all 7 events in our study, the dimming regions extend well away flare site in AR 8210, and appear to correspond to the white light extent of the CME better than the flare location. For the last five events in the sequence, occurring between 27 April and 9 May, the principal northward expansion of the dimming regions corresponds to the observed location of the CME relative to the active region. The first two events, which exhibited either a launch which preceded the flare as described by *Gopalswamy et al* [1999] or consisted of a closely-spaced sequence of two eruptions, display an angular extent far to the south of the flaring active region. In these two events, the white light extent of the CME also extended far south of the active region. Thus, the first two white light events appear to be centered about the flaring region, while the following five exhibit a flare at one "leg," as observed by *Harrison et al* [1990].

Because of the low image cadence in EUV and white light, it is sometimes not possible to declare whether one phenomenon led or preceded another. However, the timing of the different aspects of the eruption were fairly close - the peak soft X-ray flux generally occurred within a half hour of the first observation of the CME in the LASCO C2 data, and the dimming in the EIT images commenced within a half hour of the appearance of the CME in LASCO C2.

Some caveats apply. The workshop events are biased toward the most energetic eruptions. Assuming at least a rough correlation between the CME mass and the extent of the dimming [*e g Gopalswamy and Hanaoka* 1998], such eruptions appear to be those most likely to exhibit brightness depletions in EIT. However, many eruptions exhibit little or no decrease in EUV emission. Thus, while the white light extent of a coronal mass ejection appears to be demarcated by the EUV emission depletions in the case of energetic eruptions, this conclusion may not extended to "typical" CMEs. We have conducted a detailed analysis for only 7 of the 29 workshop events with EIT and LASCO coverage. A preliminary examination of the remaining events supports our conclusion and the full results will be reported elsewhere.

What are the implications of the extended dimmings for CME topological models? If twin transient coronal holes, centered on the flare neutral line, represent the ends of a flux rope, then to what do the extended dimmings in the last five events in the April/May 1998 sequence correspond? The eruptions earlier in the cycle such as that of 7 April 1997 may provide insight. In that case the source active region on the Sun was less magnetically complex (was more bipolar), and there were few other active regions on the Sun at that time. The associated double dimmings were well-defined and remained relatively close to the active region. Between 23 April and 9 May 1998, however, the magnetic structure of the surface of the Sun was more complex, as there were multiple active regions with non-bipolar structure. In particular, after 30 April active region 8214 ($\sim$ N26 latitude), which lagged $\sim 40°$ behind AR 8210 in longitude evolved rapidly (Figure 2). The coronal depletions for the last five events in Table 1 all extended north and east towards this active region.

A similar north-and-south active region geometry held for a shorter sequence of three major CMEs in early November that has been studied in detail by *Delannée and Aulanier* [2000, and references therein]. They showed that transequatorial loops (observed in EIT) which linked the principal flaring region and magnetic regions on the opposite side of the equator faded from visibility or disappeared in conjunction with the CMEs and were replaced by dimming regions. Thus the underlying magnetic geometry of CMEs at solar maximum - when active regions characteristically appear on both sides of the equator - is likely more complicated than those earlier in the cycle, *e g*, for April 1997, and can involve connections between widespread magnetic regions.

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