BRIGHT RAY-LIKE FEATURES IN THE AFTERMATH OF CORONAL MASS EJECTIONS: WHITE LIGHT VERSUS ULTRAVIOLET SPECTRA

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ABSTRACT

Current sheets (CSs) are important signatures of magnetic reconnection in the eruption of confined solar magnetic structures. Models of coronal mass ejections (CMEs) involve formation of a CS connecting the erupted flux rope with the post-eruption magnetic loops. CSs have been identified in white light (WL) images of CMEs as narrow rays trailing the outward moving CME core, and in ultraviolet spectra as narrow bright features emitting the $[\text{Fe XVIII}]$ line. In this work, samples of rays detected in WL images or in ultraviolet spectra have been analyzed. Temperatures, widths, and line intensities of the rays have been measured, and their correlation to the CME properties has been studied. The samples show a wide range of temperatures with hot, coronal, and cool rays. In some cases, the UV spectra support the identification of rays as CSs, but they show that some WL rays are cool material from the CME core. In many cases, both hot and cool material are present, but offset from each other along the Ultraviolet Coronagraph Spectrometer slit. We find that about 18% of the WL rays show very hot gas consistent with the CS interpretation, while about 23% show cold gas that we attribute to cool prominence material draining back from the CME core. The remaining events have ordinary coronal temperatures, perhaps because they have relaxed back to a quiescent state.

Key words: Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: UV radiation

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1. INTRODUCTION

The loss of equilibrium in magnetic structures that disrupts coronal structures and ejects confined plasma into interplanetary space requires magnetic reconnection (Forbes 2000; Forbes et al. 2006; Low 2001). Dissipation of magnetic energy and topological reconfiguration of the magnetic field arise in strong current sheets (CSs), regions of large gradient in the tangential component caused by layers of antiparallel field lines. In the standard picture of solar eruptions, a CS connecting the flare loops to the coronal mass ejection (CME) core is where magnetic free energy is converted into thermal and bulk kinetic energies and into beams of energetic particles (Livshits 1996; Lin & Forbes 2000; Forbes et al. 2006). The reconnection must be rapid in order to explain the rapid rise times of flares, and current models stress kinetic effects (Priest & Forbes 2000), turbulence (Lazarian & Vishniac 1999; Emslie et al. 2004) or instabilities related to the tearing mode, and the growth of magnetic islands (Loureiro 2007; Ji & Daughton 2011). To test these theories it is important to measure the physical parameters, such as temperatures, densities, velocities, turbulence, and widths, of the CSs.

Recent observational studies of CSs include coronagraph observations in white light (WL) based on timing and morphology of rays that connect the eruption site to the apparent trailing edge of a CME flux rope (Webb & Cliver 1995; Webb et al. 2003) or based on coincidence of a bright feature with a CS identified from X-rays (Patsourakos & Vourlidas 2011). Vršnak et al. (2009) measured the properties of several such rays as functions of height and time. Song et al. (2012) analyzed the morphology of 11 WL rays that had plasma blobs flowing outward sequentially along the ray. Four of their rays are also included in the sample studied in this paper.

In ultraviolet spectra, CSs were identified as narrow regions of very hot plasma seen with the Ultraviolet Coronagraph Spectrometer (UVCS) between flare loops and CME cores (Ciaravella et al. 2002; Ko et al. 2003; Bemporad et al. 2006; Ciaravella & Raymond 2008; Schettino et al. 2010) or as hot gas with very large line widths above flare loops observed by the Solar Ultraviolet Measurements of Emitted Radiation (SUMER; Innes et al. 2003; Wang et al. 2007). Narrowband EUV images also show hot gas in CSs above the limb, notably the Transition Region and Coronal Explorer images of Innes et al. (2003) and the Solar Dynamics Observatory/Atmospheric Imaging Assembly (AIA) images of Reeves & Golub (2011) and Cheng et al. (2011). CSs have also been identified with X-ray emission above the flare loops (Sui & Holman 2003; Savage et al. 2010; Savage & McKenzie 2011).

In this paper, we attempt to clarify the relationship between the WL and UV manifestations of CSs, both to determine whether the identified features really are CSs and to better constrain their physical properties. We approached the problem from two directions. First, we systematically searched for WL rays that meet criteria for identification as CSs: the requirements of a “disconnection event” morphology and location in wake of a CME led to 157 candidate CSs from among many thousands of radial features in LASCO images. We then examined UVCS data to see whether they contained hot gas. Second, we used the catalog of UVCS observations of CMEs in which CSs or possible CSs were indicated by narrow emission features in the $[\text{Fe XVIII}]$ line. Again, this was a stringent criterion, as fewer than 20 such events have been found among the thousand CMEs in the UVCS CME catalog. We then examined the LASCO data for these events to see whether they corresponded to WL rays that met the CS criteria. The WL-selected rays cover the periods 1996 April through 1998 December to sample solar minimum
and the year 2001 to sample solar maximum. The UV-selected rays were obtained from the period 1996 June through 2005 December.

The paper is organized as follows. In Section 2, the UV and WL instruments used for the analysis are described. WL and UV selection of the rays is presented in Section 3. The analysis and results are in Section 4, and summary and conclusions are in Section 5.

2. UVCS AND LASCO OBSERVATIONS

The study we present in this paper is mainly based on the observations of two instruments aboard the Solar and Heliospheric Observatory (SOHO), LASCO and UVCS. LASCO C2 is a WL coronagraph that continuously observes the solar corona from 2.3 to 6 $R_\odot$ with a cadence of about 20 minutes and a pixel size of 11.4′′ (Brueckner et al. 1995). For those events in which the UVCS slit was located below the LASCO C2 occultor disk we also examined, whenever the data were available, the Mark-III or Mark-IV K-coronometer data from Mauna Loa Solar Observatory (MLSO). The MLSO coronographs are ground-based instruments that produce polarization brightness maps of the solar corona from 1.14 to 2.86 $R_\odot$ in the range 7000–9000 Å with a 3 minute cadence. The typical observing period is from ∼17:00 to ∼02:00 UT each day. The data for some days show misalignment with LASCO images as large as 13′′. In those cases, we adjusted the MLSO images by eye.

Unlike the WL coronagraph with its complete view of the solar corona, the UVCS spectrometer has a field of view defined by its narrow entrance slit 42′ long and up to 82′ wide. The slit can be placed at any solar angle (PA) and at heliocentric heights between 1.5 and 9 $R_\odot$. UVCS has two channels, OVI and Lyα, optimized to detect the Ovi $\lambda\lambda$1032, 1037 doublet and H1 Lyα lines, respectively, but it covers the wavelength range from 945 to 1270 Å in first order and from 473 to 635 Å in second order (see Kohl et al. 1995 for a detailed description). The OVI channel has a redundant path that allows detection of the H1 Lyα line. The spatial pixels are 7′′ and spectral pixels are 0.0993 Å (0.0915 Å for the redundant path) and 0.1437 Å for the OVI and Lyα channels, respectively. The radiometric calibration is discussed by Gardner et al. (2002). The second-order calibration needed for the Si xii lines is uncertain, but we adopt factors of 0.14 and 0.09 lower efficiency for the $\lambda\lambda$521 and 499 lines, respectively. Due to telemetry limitations, UVCS can only observe the full wavelength range using low spatial and spectral resolution. A full range is usually obtained with a 10 × 2 pixel binning in the spatial and spectral ranges, respectively. However, most of the UVCS observations are made with spatial resolution of 3 (21′′) or 6 (42′′) pixels and a reduced spectral range. Observations with high spectral and spatial resolution require masking the detector in order to select the wavelength range of interest with the desired spectral and spatial binning.

The UVCS daily observation schedule includes a synoptic program in which the corona is scanned between 1.5 and 3 $R_\odot$ at eight PAs in about 10 hr, and special observations designed to observe specific objectives, such as streamers, coronal holes, CMEs, etc. The synoptic program has changed over the years, with varying ranges of heliocentric heights observed, spatial and spectral resolutions, and spectral range. Despite this, the spectra always included the Ovi doublet, Si xii $\lambda\lambda$499 or 521, Lyα, Lyβ, and C iii $\lambda$977. During most of 2001, the synoptic scans also included the high temperature line of [Fe xviii] (106.8 K), but in 1996 through 1998 they did not. [Fe xviii] is the key indicator of hot gas because it is only detected by UVCS above 1.5 $R_\odot$ in the wake of CMEs as bright spatially narrow features (Ciaravella et al. 2002; Ko et al. 2003; Bemporad et al. 2006; Ciaravella & Raymond 2008; Schettino et al. 2010) or hot blobs (Raymond et al. 2003).

Streamer studies, especially those devoted to elemental abundances, have a large wavelength coverage, often the full wavelength range. CME watch sequences are designed to have high cadence with typical exposure time of 120 or 200 s. The observations are at a constant height or switch between two heights. Typical observation heights are between 1.6 and 2.3 $R_\odot$, and they cover a broad ionization range from cool lines such as C iii ($\sim$105 K) to hot lines such as [Fe xviii].

3. RAY SELECTION

3.1. White Light Sample

The WL ray-like features we analyzed in this paper were selected from the LASCO C2 observations. A catalog of LASCO CMEs with trailing concave-outward structures and rays has been developed by Webb. A comprehensive paper on the results of analysis of the WL rays is in preparation (D. F. Webb 2013, in preparation).

Early studies found that about 20% of the CMEs showed concave-outward features in Solar Maximum Mission (SMM) and LASCO coronagraph data, and these were identified as magnetic disconnection events (Webb & Cliver 1995; Webb et al. 2003). Webb & Cliver (1995) examined SMM coronagraph data for bright rays in the wakes of CMEs that were coaxial with the CME and had outward-moving U- or V-shaped structures at the top. Recently, Howard et al. (2012) have presented beautiful examples of a few disconnection events seen in STEREO coronagraph data and tracked their evolution into the heliosphere. In Figure 1, the sequence of LASCO wavelet-processed images shows the CME on 2001 August 9 moving outward and the bright ray behind it. During this event the pre-existing streamer has blown out and on August 10 at 02:06 UT the transient ray has started to form. This is an event wherein the ray becomes a new, reformed, streamer. The depletion of Si xii emission as well as Lyα and O vii in the region of the pre-CME streamer supports the LASCO movie interpretation of a ray-reforming streamer.

The selection criteria for the events in the WL catalog are essentially those described by Webb et al. (2003) and summarized above. Events were selected that had a bright, narrow, linear ray following the concave-outward structure and coaxial within a few degrees with the CME volume. We required that such a ray appears within no more than about 12 hr following CME onset. Adequate data coverage was required during this period, ideally for at least a full day starting from just before CME onset to enable the identification of pre-existing structures, especially streamers, and whether a new streamer appeared in the wake of the CME and any ray. Indeed many of the WL rays form after streamer blowout and are associated with the subsequent reformation of the streamer (Webb et al. 2003).

In our sample 29 events (∼40%) are associated with streamer blowout, and in 7 cases the streamer forms afterward. For the events selected, we recorded the time when the ray appeared, its position angle, and duration, along with the parameters of the CME. If Mauna Loa data for the appropriate time period were available, they were examined for the presence or absence of a corresponding ray. The ray-like features analyzed in this paper were selected from the LASCO ray catalog, mainly within
Figure 1. LASCO images of the CME on 2001 August 9. The images show the pre-CME corona (top left) at 19:54 UT and the CME evolution at 21:54, 22:30, and 23:30 UT. The bottom row shows the appearance of the ray at 02:06 UT and the clearly formed ray at 02:54 UT.

(A color version of this figure is available in the online journal.)
the two temporal windows: from 1996 July to 1998 December during solar minimum, and 2001 for solar maximum. A total of 157 rays have been selected from LASCO images, of which 74 occur during the solar minimum period and 83 during the maximum. Once the WL rays were selected, UVCS archival data were examined for the existence of spectra at the appropriate position angle and time. There were cases in which UVCS did not observe any narrow bright feature corresponding to the WL ray. Of the 157 LASCO rays, 60 (~47%) had appropriate UVCS spectra showing bright features that matched the WL rays. Of these, 26 were found during the solar minimum period and 34 during solar maximum. Narrow bright features in the H_i, O_i, Si_xii, and, if possible, Fe_xviii lines were searched for at the position angle of the WL feature. Some misalignment in position angle was tolerated because the features evolve in time and are not always radial, and most of the UVCS observations covered regions below the LASCO occulter height of 2.3 \( R_\odot \). In general, if a UVCS feature was found, it was within about 3° of the LASCO position angle, but we include a few events with larger position angle differences. Most of the rays were detected during the daily synoptic scans, which unfortunately used a narrow spectral range and often did not include [Fe_xviii] line. We chose 2001 for this study because the synoptic sequence did include the [Fe_xviii] line.

### 3.2. UVCS Sample

In the wake of CMEs, UVCS has observed several spatially narrow and bright features in the hot line of [Fe_xviii] that have been interpreted as signatures of the CS associated with CMEs (Ciaravella et al. 2002; Ko et al. 2003; Bemporad et al. 2006; Ciaravella & Raymond 2008). Figure 2 shows the spectrum of the CS associated with the CME on 2003 June 2 at 08:54 UT. The narrow bright feature in [Fe_xviii] appeared after the CME passed the UVCS field of view, and it was well aligned with the prominence core. This feature was also detected in the [Ca_xiv] line in the fourth panel.

UVCS has observed more than a thousand CMEs and a catalog (Giordano et al. 2013), linked to the CDAW catalog of LASCO CMEs (http://cdaw.gsfc.nasa.gov/CME_list/), was constructed by examining the UVCS data for each LASCO CME from the start of regular SOHO operations in 1996 through the end of 2005. For each WL CME, a special purpose computer code selected UVCS data at the position angle of the CME within 4 hr of the event. As part of the catalog, we determined whether there was an indication of a CS, usually by the presence of a narrow feature in [Fe_xviii]. For the present analysis, we examined the spectra of the 18 CSs that showed clear features in [Fe_xviii] and compared them with LASCO data to determine whether a WL ray with CS morphology coincided with the UV feature. The sample includes the six events for which analysis of the CS has been previously published.

### 4. RAY ANALYSIS

In our analysis, we used LASCO WL background-subtracted and wavelet-processed images. The background-subtracted images have been obtained by subtracting the related monthly minimum background from LASCO images and removing the spikes mainly due to the cosmic rays. The wavelet technique is particularly suitable for analysis of data containing discontinuities or sharp spikes and makes it possible to recover weak signals from noise. It uses mathematical functions to decompose data into different frequency components and then study each component with a resolution adapted to its scale. The wavelet-processed images from the LASCO archive are based on a technique developed by Stenborg & Cobelli (2003).

Before presenting our results we will describe the analysis method used for all the rays reported in this work by discussing in detail three events representative of hot, coronal, and cool rays. We define hot as the rays that show [Fe_xviii] emission, coronal as those that are detected in Si_xii and O_vi, and cool rays as those that show emission only in the lines of O_vi and/or Ly\(\alpha\). We note that O_vi emission peaks at a temperature of about 0.3 MK, but that it persists up to about 2 MK due to dielectric recombinatiion of O_vi. Ly\(\alpha\) also peaks at low temperatures, but the combination of large hydrogen abundance and strong illumination by chromospheric Ly\(\alpha\) photons combine to make it the strongest coronal UV line in spite of the \(10^{-6}\) H_i fraction. These lines seen in combination with coronal lines such as

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**Figure 2.** UVCS spectrum observed on 2003 June 2 after a CME. Some of the main lines are marked. The second-order lines of Si_xii, \(\lambda 521\) is the first line on the left of first panel and \(\lambda 499\) is in the second panel.

(A color version of this figure is available in the online journal.)
Figure 3. LASCO C2 images and wavelet-processed of the ray associated with the CME on 2000 September 23 at 21:30. The images show the pre-CME corona (top row) on the 23rd at 20:26 UT, the ray in the wake of the CME (2nd and 3rd rows) on the 24th at 01:27 and 10:26 UT, and the post-ray corona (bottom row) on the 24th on 23:50 UT. The green dashed line indicates the position of the WL ray. The images below the occulter are \([\text{Fe}^{xviii}]\) along the UVCS slit taken on the 23rd at 1.67 \(R_{\odot}\) (from 22:19 to 22:28 UT) and at 1.53 \(R_{\odot}\) (from 22:29 to 22:33 UT). The white dashed line at 2.4 \(R_{\odot}\) marks the area where the LASCO data have been extracted to obtain the intensity distribution for Figure 4.

(A color version of this figure is available in the online journal.)

Si\(^{xii}\) indicate a temperature similar to that of the corona. Bright emission in these lines without corresponding coronal emission lines indicates a temperature below 1 MK. This is often corroborated by very cool lines such as C\(^{iii}\) and by very narrow line widths.

**Hot ray (2000 September 23).** The WL images of the event have been analyzed before, during, and after the CME in order to detect rays with the characteristics described in the previous paragraph. Figure 3 shows a sequence of LASCO and related wavelet-processed images for the event on 2000 September 23. From the movies, images of the pre-CME corona (top row), of the ray in the wake of the CME (2nd and 3rd rows), and of the post-ray corona (bottom row) have been selected. The dashed green line in the images marks the position of the ray, the images below the occulter are the \([\text{Fe}^{xviii}]\) images along UVCS slit obtained at 1.53 and 1.67 \(R_{\odot}\). Both background-subtracted and wavelet-processed images show clearly the formation of a new ray. The bright feature along the UVCS slit is well aligned with the WL ray. The pre-CME and post-ray coronal images in the \([\text{Fe}^{xviii}]\) line do not show any sharp emission at the location of the ray. In Figure 4, we compare the normalized LASCO intensities along the white segment marked in Figure 3.
with the normalized intensity of [Fe xviii] (red line) along the UVCS slit at 1.53 $R_\odot$ (top right panel) and 1.67 $R_\odot$ (bottom left panel). The ray was not detected in the Ly$\alpha$, O vi, or Si xii lines; see Table 1. [Fe xviii] is the only line in which we detected a bright peak at the location of the WL ray, and this implies a temperature of $10^{6.5}$ K or higher. The black and blue lines correspond to the background-subtracted and wavelet-processed LASCO images, respectively. While the LASCO intensities are extracted at 2.5 $R_\odot$ and the position of the UVCS entrance slit is below the LASCO occulter, the WL and UV rays are in good agreement. The UV ray at 1.53 $R_\odot$ is offset toward north by about 2$^\circ$, probably because the ray is not exactly radial.

**Coronal ray (2001 May 12).** The LASCO C2 images of the events are in Figure 5 and show the pre-CME corona (top row), the ray in the wake of the CME (middle rows), and the post-ray corona (bottom row). The figure also shows the Si xii 499 Å images along the UVCS slit. Before the CME and after the ray disappeared the UVCS slit was located below the occulter disk while during the lifetime of the ray, UVCS observed at 1.67 and 2.42 $R_\odot$. The ray is clearly visible in the background-subtracted and wavelet-processed images. Si xii 499 Å images show a narrow bright area at the position of the ray. Similar peaks are also observed in O vi and Ly$\alpha$ lines indicating typical coronal temperatures. This narrow bright area is not present in the UV spectra of the pre-CME and post-ray corona. As with the previous event the normalized intensities extracted along the white dashed lines in LASCO images or at the same location of the UVCS slit when it is located above the occulter and Si xii 499 Å are plotted in Figure 6. In the top right panel WL and Si xii intensities are at the same height, 2.42 $R_\odot$, while in the bottom left panel Si xii intensity was detected at 1.67 $R_\odot$. Again the WL ray and UV bright narrow spots are well aligned.

**Cool ray (1998 April 23).** A cool ray is that associated with the CME on 1998 April 23 at 05:27 UT. The ray appeared in WL images at 10:55 UT at PA 95$^\circ$. LASCO background-subtracted and wavelet-processed images are shown in Figure 7. In UVCS, the ray is observed in Ly$\alpha$ and O vi at several heights but not in Si xii. In the middle panel of Figure 7, the O vi intensities show very clearly the ray at 2.74, 2.29, and 1.95 $R_\odot$. The UV lines overlap very well with the WL ray as is also shown in the normalized intensities of Figure 8. In this figure, the WL intensities were extracted along the white dashed line of Figure 7 at a height of 2.4 $R_\odot$ and compared in the middle panel with the UV O vi 1032 Å intensities at three heights.

From the 60 of the 157 WL-selected rays which were also detected in UV spectra, only 10 were observed in the [Fe xviii] line. Of the remaining rays, 34 did not have the necessary wavelength range to observe the [Fe xviii] line, and in 16 the [Fe xviii] line was within the wavelength band but not observable due to blending with the bright Ly$\alpha$ line in the

![Figure 4](image-url)
Table 1
Rays with [Fe xviii] Emission

| CME     | LASCO Ray | MK4 | Sel | ∆t | UVCS | Lines |
|---------|-----------|-----|-----|-----|------|-------|
|         |           |     |     |     |      | \(10^{38} \text{ photons s}^{-1} \text{ cm}^{-2} \text{ s}^{-1}\) | \((10^8 \text{ cm})\) |
| Time    | PA        | Duration |     |     | Time | PA | \(R_{\odot}\) | [Fe xviii] | Si xii | O vi | Lyα | \(T_{\text{ref}}\) |
| 01-04-26 17:57 | 102 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-27 18:06 | 103 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-28 18:15 | 104 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-29 18:24 | 105 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-30 18:33 | 106 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-31 18:42 | 107 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-32 18:51 | 108 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-33 19:00 | 109 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-34 19:09 | 110 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-35 19:18 | 111 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-36 19:27 | 112 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-37 19:36 | 113 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-38 19:45 | 114 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-39 19:54 | 115 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-40 20:03 | 116 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-41 20:12 | 117 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-42 20:21 | 118 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-43 20:30 | 119 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-44 20:39 | 120 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-45 20:48 | 121 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-46 20:57 | 122 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-47 21:06 | 123 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-48 21:15 | 124 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-49 21:24 | 125 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-50 21:33 | 126 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-51 21:42 | 127 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-52 21:51 | 128 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-53 22:00 | 129 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-54 22:09 | 130 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-55 22:18 | 131 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-56 22:27 | 132 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-57 22:36 | 133 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
| 01-04-58 22:45 | 134 | 52 | Y | W | 5.8 | 05:12:28 | 71 | 1.35 | 5.5 | x x 7 | 15 | 6.75 |
redundant path. For further analysis, we have reorganized the 60 WL-selected rays and the 18 UVCS-selected features into a set of events that shows [Fe xviii] (Table 1) and a set that does not (Table 2). The [Fe xviii] provides a strong constraint on the plasma temperature, and events where it is measured merit more detailed analysis than the events that do not.

A common characteristic of the UV rays is that hot and coronal lines are often offset. An example is shown in Figure 9. The figure shows the ray observed on 2003 November 4 after the CME at 19:54 UT (Caravella & Raymond 2008). The comparison among the lines of [Fe xviii] (left panel), Si xii λ521 (middle panel), and O vi λ1032 (right panel) shows the displacement between coronal and hot lines. While characteristics of the rays, such as line intensities and widths, are quite simple to compute in those lines not usually present in the solar corona, e.g., [Fe xviii] and [Ca xiv], the separation of the ray peak from the surrounding background corona is sometimes ambiguous for typical coronal lines, e.g., Si xii, O vi, Lyα, etc. For that reason we report the line intensities and widths for the rays observed in [Fe xviii], and in those cases we also report the intensities for
the cooler lines. We select the same spatial regions for all the lines, subtracting a background based on the intensity distribution along the slit. The widths were computed as FWHM of the spatial distribution of the [Fe xvii] line.

4.1. Hot Rays

The 28 rays with [Fe xvii] emission are listed in Table 1. Only 10 of the rays selected from the WL ray catalog show [Fe xvii] emission. The remaining 18 candidates come from the UVCS CME catalog and 15 of them are outside the time periods selected for the LASCO study. It is important to note that the PA of the WL and UV rays in Table 1 are different for several reasons. First, the PAs of WL rays are measured above the occulter disk (i.e., \( \geq 2.5 R_{\odot} \)) at the time of first detection, while UV rays are mostly observed below the occulter, often later than the WL rays. Moreover, the rays are often not radial and move during their lifetime. The temperatures listed in Table 1 were computed using the ratio between [Fe xvii] and Si xii lines under the assumption of ionization equilibrium. For the events in which only [Fe xvii] was observed, the temperature is not easily constrained. We used “hot” to indicate that the temperature in the ray is higher than in the case in which Si xii was also present.

In 12 cases, the narrow [Fe xvii] emission has either no associated WL ray or a ray which did not satisfy the CS selection criteria. For those events, no delay time is listed. For the remaining rays, the delay time varies from cases in which the rays were detected earlier than in WL (negative numbers) to the most extreme UV observation where the ray was detected 21 hr later. In some cases, the ray has been observed at several heights. All the heights at which [Fe xvii] has been detected are below the LASCO C2 occulter disk, with the highest at 1.9 \( R_{\odot} \).

Figure 10 shows the [Fe xvii] line intensities as a function of the heliocentric distance for all the rays listed in Table 1. In the top panel, crosses, stars, diamonds, and triangles correspond to different ranges of delay time. The squares are [Fe xvii] bright narrow features with no corresponding rays in WL images. For those cases, it was not possible to evaluate the delay time. The [Fe xvii] line intensity ranges over three orders of magnitude or \((0.3–190) \times 10^8\) photons cm\(^{-2}\) s\(^{-1}\). In the bottom panel, the rays associated with halos, partial halos, and narrow CMEs are plotted using diamonds, dots, and triangles, respectively. The [Fe xvii] line intensity in the ray decreases with the height but it does not show correlation with the delay time of the observation. Rays associated with energetic events such as halo and partial halo CMEs do not show the highest intensities in [Fe xvii] line. The four rays associated with halos have intensities above \(10^9\) photons cm\(^{-2}\) s\(^{-1}\) but the partial halos are scattered over the entire range of the observed intensities. In halo and partial halo events, the ray might be far from the plane of the sky, so that the actual position observed is greater than the apparent height. This likely accounts for the lack of correlation.

The [Fe xvii] line intensity as a function of the associated CME speed is plotted in Figure 11. One might expect that CME speed is related to Alfvén speed and that the magnetic energy available to heat the plasma is roughly proportional to \(V_A^2\). In the top and bottom panels of the figure, the CME linear and the second-order speed from LASCO catalog are used. Rays associated with narrow, halo, and partial halo events are plotted with triangles, diamonds, and dots, respectively. The vertical dotted line indicates the LASCO average speed (445 km s\(^{-1}\)) for normal CMEs during the period 1999–2007 (Mittal et al. 2009).
More than 78% of the hot rays are associated with CMEs with speed higher than the average LASCO speed. Again no strong correlation is seen in these plots although rays associated with partial halos and halos show some correlation with the speed of the CMEs. Above 1200 km s$^{-1}$ [Fe xviii] line intensities increase with the CME speed.

One might expect that the densities within a CME would be larger in more massive events, and that the correspondingly higher emission measures would yield higher intensities. No mass and energy estimates are available in the LASCO catalog for partial halo, halo, and narrow CMEs. For all the other rays no strong correlation between [Fe xviii] line intensity and energy of the associated CME has been observed. It is possible that this lack of strong correlation results from the variation of temperature among the different events, since the [Fe xviii] intensity depends on both emission measure and temperature.

The spatial widths of the CS in Table 1 vary in the range (3–35) $\times$ 10$^9$ cm. While these widths are far larger than the widths expected for resistive reconnection in the corona, they are in reasonable agreement with predictions of turbulent reconnection (Lazarian & Vishniac 1999) or with the exhaust region of Petschek reconnection half a solar radius from the diffusion region, especially if the CS is not viewed edge-on. The widths of the [Fe xviii] features are generally much smaller than the widths of associated features seen in Si xii, O vi, or Ly$\alpha$. We found no dependence of the width on the heliocentric height, the observation delay, or the CME speed.

The ray temperatures range between ($\sim$3–8) $\times$ 10$^6$ K. The 10 events in which the ray has been observed in the [Fe xviii] line only, indicated with “hot” in Table 1, are not associated with particularly energetic events. The estimated temperature range is the range where the [Fe xviii] ionization fraction is large enough that the line is observable. Evidence for higher CS temperatures is found in the observations of [Fe xx] and Fe xxiv (Innes et al. 2003) and Fe xxii (Reeves & Golub 2011; Cheng et al. 2011). Recent Hinode/Extreme Ultraviolet Imaging Spectrometer observations of an event that shows Fe xv but no higher ionization states provide evidence for a CS cooler than 3 $\times$ 10$^6$ K (Landi et al. 2012).

4.2. Spatial Offsets

Half of the rays listed in Table 2 show a clear offset between the spatial positions of the peaks on [Fe xviii] and Si xii. Figure 9 is a good example in which the [Fe xviii] peaks on the northern edge of the ray, Si xii is a broad feature centered on the ray, and O vi peaks on the southern edge of the ray. The CS studied by
Figure 7. LASCO C2 images and wavelet-processed of the ray associated with the CME on 1998 April 23 at 05:27 UT. The top panels show the pre-CME corona on 1998 April 23 at 03:55 UT. The middle panel shows the ray at 15:27 UT with superimposed the O vi 1032 Å intensity image at several heights along the UVCS slit. The bottom panel shows the post-ray corona at 22:27 UT. The green dashed line marks the position of the white light ray, while the white dashed line marks the position along which LASCO data have been extracted for Figure 8.

(A color version of this figure is available in the online journal.)

Ko et al. (2003) is another good example (see Figure 12 of that paper). In a few cases, Si xii or O vi show two peaks, with the [Fe xviii] peak lying between them. In the cases where there is no offset, the [Fe xviii] peak is usually narrow, while the Si xii peak is broader and the O vi peak is even broader.

One possible interpretation of the offset is that the cooler material is ambient coronal plasma about to be swept into the CS. The transverse motions seen in the Extreme-ultraviolet Imaging Telescope images by Yokoyama et al. (2001), Lyα emission observed with UVCS by Lin et al. (2005), or AIA images by Takasao et al. (2012) show inflow speeds of the order of 5–100 km s⁻¹. At those speeds, the coronal material would be swept into the CS on timescales of order 1–10 hr. Since the coronal gas is generally located to one side of the hot material, the inflow into the CS would be very asymmetric, a situation simulated by Murphy et al. (2012). This can lead to transverse motion of the CS, as reported by Ko et al. (2003).

An alternate interpretation of the offsets is that the cool material is essentially separate from the CS, occupying nearby field lines in a streamer-like structure, in which the inflow time to the CS is longer than the flow time along the magnetic channel. This interpretation is suggested by the cool blobs that move beside the hot CS in the 2003 November 4 event (Ciaravella & Raymond 2008).

In general, it is difficult to discriminate between the two interpretations above, but detailed study of individual events should make it possible to distinguish between them in some cases.

4.3. Projection Effects

Since we are observing optically thin structures, it is difficult to tell whether the apparent width we observe is the actual thickness of the CS or the result of thin sheet of gas viewed at an angle. In a few cases the projection effects can be shown to be small, as in the observation of a gap (i.e., a region of very low line intensity), rather than a bright region, in Lyα (Lin et al. 2005), and the case in which the column density in WL and the emission measure from UVCS can be combined to separate the density and thickness of the structure (Ciaravella & Raymond 2008). The offsets discussed in the previous section show that projection effects cannot be too large in those events, as the [Fe xviii] and the other lines would be superposed if the angle to the line of sight was substantial.

4.4. Coronal Rays

Table 2 presents a list of events where [Fe xviii] emission was not observable due to the UVCS instrument configuration (indicated by −) or observable but not detected (indicated by x). We also indicate whether the ray was detected (indicated by +) or not in the Si xii, O vi, and Lyα lines. Of the 50 events in Table 2, 35 show both Si xii and O vi lines, so their temperatures are at least as high as that of the ambient corona. One shows Si xii without O vi or Lyα, indicating a temperature substantially higher than the ambient corona. However, as mentioned above there are often offsets between the features seen in different lines, so in some cases there may be a high temperature
adjacent to a cooler one. For example, the 2003 November 4 event shown in Figure 9 has a bright ray in \([\text{Fe xvi}]\) and \([\text{Si xii}]\), but \([\text{O vi}]\) lines are offset several degrees to the north.

No correlation has been observed between the rays with coronal temperatures and the speed or energy of the associated CMEs. The range of linear speed of those rays varies between 100 and 1500 km s\(^{-1}\). In particular, the ray with the highest temperature, “hot” in Table 2, is associated with a CME of speed \(\sim 100\) km s\(^{-1}\).

4.5. Cool Rays

Table 2 also lists 14 events that were detected in \([\text{O vi}]\) and/or \([\text{Ly}\alpha]\), but not in \([\text{Si xii}]\) or \([\text{Fe xvi}]\). The ranges of delay time and height of UVCS observations are similar to those of the coronal or hot rays. These features are cooler than the ambient corona. In some cases, lines of \([\text{C iii}]\) or \([\text{O v}]\) were detected, indicating much lower temperatures, on the order of \(10^5\) K. In some of those events, the line width of the \([\text{Ly}\alpha]\) line was clearly much smaller than the width of the coronal \([\text{Ly}\alpha]\) line, indicating proton temperatures of \(10^5\) K or less. Bright, long-lasting ray-like features in cool emission lines in the wakes of CMEs are not uncommon in UVCS spectra, but in most cases they do not satisfy the criteria for CSs in LASCO. They are rather surprising, in that they often last for many hours, which is much longer than the free-fall time from heights of 1.5 to 2 \(R_\odot\). These features may be prominence plasma from the CME core slowly draining back along particular magnetic field lines from much larger heights. Downflow of hot and cold material in the wake of a CME associated with an erupting prominence has been reported by Tripathi et al. (2007). As for the coronal rays, the cool rays are associated with CMEs with a wide range of speed and energy, including one halo and two partial halos.

4.6. No UV Ray

Many of the WL-selected rays, 97 out of 157, did not show any corresponding UVCS features, mostly because UVCS was observing a different region during the WL ray lifetime. We do not include them in this study, but they will be considered in a paper on the WL rays alone (D. F. Webb 2013, in preparation). In a few cases, there may be no identifiable UV feature because the temperature was so high that it lay outside the \(10^4–10^7\) K range covered by the UVCS lines. In that case, it might show up as a gap in all the lines, as in the event discussed by Lin et al. (2005). It might also appear in hard X-ray observations as in the event reported by Sui & Holman (2003). More commonly, however, the UVCS data were not taken at the right position during the duration of the WL ray. In other cases, UVCS data were too noisy due to short exposure time or confusion with other CME features, or the height of observation was too large.

5. SUMMARY AND CONCLUSIONS

A sample of 157 WL rays observed by LASCO, with an outward moving U- or V-shaped structure detected in the wake of CMEs, has been used to search archival UVCS data in order to study their UV spectra. The sample included rays selected during both solar minimum (1996 July–1998 December) and solar maximum (year 2001). In 60% of the WL sample, no UV rays were seen. Aside from the cases in which the UVCS instrument was observing a different target during the lifetime of the WL rays, a temperature higher than \(10^7\) K or a modest plasma emission measure would make the ray too faint for UVCS to detect. Sixty rays (40%) of the WL sample showed UV emission. Of those 60 WL rays, 14, or 23%, showed only cool gas, probably from prominence material draining back from the CME core. Of the 26 events for which
Figure 9. Composite image of the ray detected on 2003 November 4 by LASCO C2 at 23:54 UT, MK IV at 23:57 and UVCS from 20:12 to 20:51 UT. The three panels show UVCS images of [Fe xviii] (left panel), Si xii (middle panel), and O vi lines (right panel). (A color version of this figure is available in the online journal.)

Figure 10. [Fe xviii] line intensities as a function of the heliocentric distance. The symbols refer to different delay time in hour (top panel) and CME morphology (bottom panel). In the bottom panel, four CMEs are halos, seven partial halo, and two narrows with width of 14° and 44°.

[Fe xviii] could be detected if present, 10 of them, or 38%, did show [Fe xviii]. Many of the others had ordinary coronal temperatures, but a few showed strong enough Si xii emission to indicate relatively hot gas. Other rays may have been too hot to show [Fe xviii] ($T > 10^7$ K). We conclude that about 23% of the rays selected from LASCO images are magnetic flux tubes containing cold material, about 18% are hot features consistent with the CS interpretation, and the remaining 59% with ordinary coronal temperatures may be more quiescent streamers that have reformed after the eruption.

We also considered a sample of 18 more rays detected in the [Fe xviii] line by UVCS. Most of them were outside the periods selected from the LASCO study. Ten out of 18 UV-selected rays had no associated WL ray. While it is difficult to quantify the sensitivity of the WL search, since in many cases it is determined by the complex background of the evolving post-CME structure, it may be that the cases with no WL ray are examples of localized hot features with relatively small density enhancements or thicknesses.

Thus, WL images and UV spectra were analyzed for a total of 78 rays. The CME characteristics of the sample are quite broad in terms of speed, angular width, and energy. Eight halo and 12 partial halo CMEs are in the sample. Seventy percent of
the rays were associated with CMEs with linear speeds higher than the average speed of 445 km s$^{-1}$ obtained by Mittal et al. (2009) for the 1996–2007 period. This is expected as about 64% of the rays were detected during 2000–2003, the long-lasting solar maximum of Cycle 23, and more than 50% of the 28 rays detected during the solar minimum have speed higher than 445 km s$^{-1}$.

The 78 rays were divided into two sub-samples with (see Table 1) and without (see Table 2) [Fe XVIII] emission. The high temperature line [Fe XVIII] is not usually present in the solar corona and the rays observed appear more distinct from the background in this line than in typical coronal lines such as Si X, O VI, and Ly$\alpha$, providing a simpler estimate of the line intensity and width of the rays, and strong constraints on their plasma temperature. Based on the lines detected in the UV spectra, the temperature of the rays were estimated. Thirty-seven percent of the rays had high temperature as indicated by the presence of [Fe XVIII] emission; 45% had temperature similar to the surrounding corona as indicated by the presence of Si X, O VI, and H I Ly$\alpha$ lines; and 18% were cool rays detectable only in O VI and/or H I Ly$\alpha$ lines with temperatures around 10$^{5}$ K. Of the WL rays without [Fe XVIII], only in 14 cases was the line in the observed wavelength range and not detected. In all the other cases especially in those that had Si XII we cannot exclude that [Fe XVIII] could have been present as well.

Rays with [Fe XVIII] emission are mostly (85%) associated with CMEs occurring during solar maximum. In the sample of rays with no [Fe XVIII] only 52% are during solar maximum. Although the range of CME speed associated with the rays is very wide in both samples, the average and median speeds of the rays that show [Fe XVIII] are higher than those that do not. All the rays showing [Fe XVIII] emission have been observed at heights below the LASCO occulter disk.

The temperatures of the rays detected in [Fe XVIII] line are higher than 10$^{6.5}$ K, but this is essentially a selection effect due to the formation temperature of [Fe XVIII]. No dependence on the height has been observed. The spatial widths range between 3 and 3.5 $\times$ 10$^{6}$ cm and again no correlation with the speed, delay, and height exists. The WL widths of four of the hot rays with no [Fe XVIII] have also been estimated by Song et al. (2012) at 3 and 4 $R_{\odot}$, and they are in agreement with those obtained from the [Fe XVIII] emission. There is a trend of [Fe XVIII] intensity to decrease with the height. This is also observed in the few cases in which the same ray was observed at different heights.

A wide range of [Fe XVIII] line intensities has been detected, but no strong correlation has been observed with the delay time of the UV observations, or morphology of the associated CMEs. The intensity of the [Fe XVIII] line in the ray associated with the 2002 January 8 CME (Ko et al. 2003), measured with about a 50 hr delay, is among the highest. The four rays associated with halo CMEs have [Fe XVIII] intensities well within the range of intensities detected for the CS associated with other CMEs.

No significant correlation of the [Fe XVIII] intensity has been observed with CME speed or energy except for the halo and partial halo events. Above 1200 km s$^{-1}$ there is a weak trend of [Fe XVIII] intensity to increase with the speed.

The results outlined above provide a wide range of UV properties of WL rays, but no strong correlations with the associated CME speed, energy, and morphology have been found. While the hot and coronal rays may fit within the framework of the reconnection processes that bring ambient plasma into CS structures, the much lower temperatures observed in the cold rays suggest a different interpretation. These may be channels of cold prominence material draining back from the CME core as it moves outward through the solar corona.

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