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LARGE DOPPLER SHIFTS IN X-RAY PLASMA: AN EXPLOSIVE START TO CORONAL MASS EJECTION

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ABSTRACT

We report observations, taken with the Solar Ultraviolet Measurements of Emitted Radiation spectrometer, of spatially resolved high red and blue Doppler shifts (up to 650 km s^{-1}) from X-ray–emitting plasma in the corona above a flare. The high Doppler shifts are seen minutes after a fast, faint optical front is seen racing through the same part of the corona in images taken with the Mirror Coronagraph for Argentina. The association of the large-scale fast optical emission front with soft X-ray emission and high Doppler shifts suggests plasma heating and acceleration in the wake of a shock.

Subject headings: Sun: flares — Sun: UV radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

Soft X-ray and extreme-ultraviolet (EUV) images of flares reveal a complex array of rapid loop and footpoint brightenings, plasma jets, and ejecta (Shibata et al. 1992; Canfield et al. 1996; Shimojo et al. 1996; Sterling et al. 2000). On the large scale, flares are associated with fast coronal waves (EUV and Moreton waves) and coronal mass ejection (CME) into interplanetary space (Moreton & Ramsey 1960; Thompson et al. 1999; Wills-Davey & Thompson 1999; Klassen et al. 2000). The link between the local, rapid brightenings and the larger scale CMEs is a question of some debate (Kahler 1992; Harrison 1995; Nitta & Akiyama 1999).

One aim of a recent campaign with instruments on the *Solar and Heliospheric Observatory* (*SOHO*), with the soft X-ray telescope (SXT) on *Yohkoh*, and with the Mirror Coronagraph for Argentina (MICA) was to determine the three-dimensional flow geometry of the jetlike brightenings. The plan was to measure Doppler shifts in lines with formation temperatures spanning as wide a range as possible using the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer and to coalign the spectra with images from the EUV Imaging Telescope (EIT), SXT, and MICA. With measurements of Doppler shifts in the various EUV and X-ray structures, we are able to distinguish real plasma flow from a moving emission front, and hence a jet from an illuminated structure.

The campaign was run for several tens of hours on limb active regions, with the hope of catching a flare. Several flares were observed, and the strongest is discussed here. It occurred just over the northwest limb of the Sun on 1999 May 9 (17:58 UT), probably in active region NOAA 8526. The soft X-ray flux began at 17:53 UT and reached a maximum, *GOES* M7.6, at 18:07 UT. The hard X-ray (50–400 keV) light curve obtained by the Oriented Scintillation Spectrometer Experiment (OSSE) showed a single spike lasting 5 minutes with a maximum at 17:57:40 UT. A large partial halo CME was seen at 18:27 UT using the Large-Angle Spectroscopic Coronagraph.

2. DATA ANALYSIS

The event was observed by a combination of instruments that provided EUV and soft X-ray images, high-resolution UV spectra, white-light coronagraph images, hard X-ray fluxes, and high-energy particle fluxes. In this Letter, we concentrate on the remote sensing data. The particle fluxes are discussed in Torsti et al. (2001). Accurate coalignment of data from the various instruments is critical to the analysis presented here. Coalignment was made easier because there was always an appropriate loop structure in the EUV images that the other data could be aligned with. The EUV images were obtained by EIT (Delaboudinière et al. 1995) in the 195 Å channel centered on an Fe XII emission line. The image cadence was 12 minutes, and the pixel size was 5″.24.

Ultraviolet spectra were obtained with the SUMER spectrometer (Wilhelm et al. 1995). SUMER is able to observe simultaneously any selected 40 Å window within its 660–1600 Å wavelength range. SUMER was in the middle of obtaining a spectral scan of the hot active region corona (described in Feldman et al. 2000) when the flare erupted. During the spectral scan, the spectrometer slit was held at a fixed position while the wavelength range was stepped in increments of 20 Å. Each exposure was 5 minutes. The observations reported here show two windows with lines in the temperature range of 10^5–10^7 K. The first window contains O III λ703 (10^5 K), Cr XVI λ1410 (5×10^6 K), and Mg IX λ706 (10^6 K). The second contains Fe XX λ721 (10^7 K) and Si VIII λ1446 (8×10^5 K). Before moving to its fixed position in the corona, SUMER made a raster scan across the limb and active region loop structure. There were common, well-defined loops in both the EIT images and the SUMER raster. It was possible to coalign to within 5″.

The coronagraph images obtained with MICA (Stenborg et al. 1999) were taken using a filter centered on the Fe XIV λ5303 line and a pixel size of 3″.8. A large fraction of the observed emission in this filter is from the continuum. The images shown have had the preevent continuum removed. Therefore, they show both the Fe XIV emission and the changes in the continuum due to the event. After continuum subtraction, the brightest emission is Fe XIV from the active region loop system, and this can be coaligned with the EIT images.

SXT (Tsuneta et al. 1991) on *Yohkoh* started obtaining full- (2″.5 pixel), half-, and quarter-resolution partial frame images about 7 minutes after the flare onset time given by *GOES*. Again, due to the presence of bright low-lying loop structures, coalignment with EIT was possible to within about 5″.

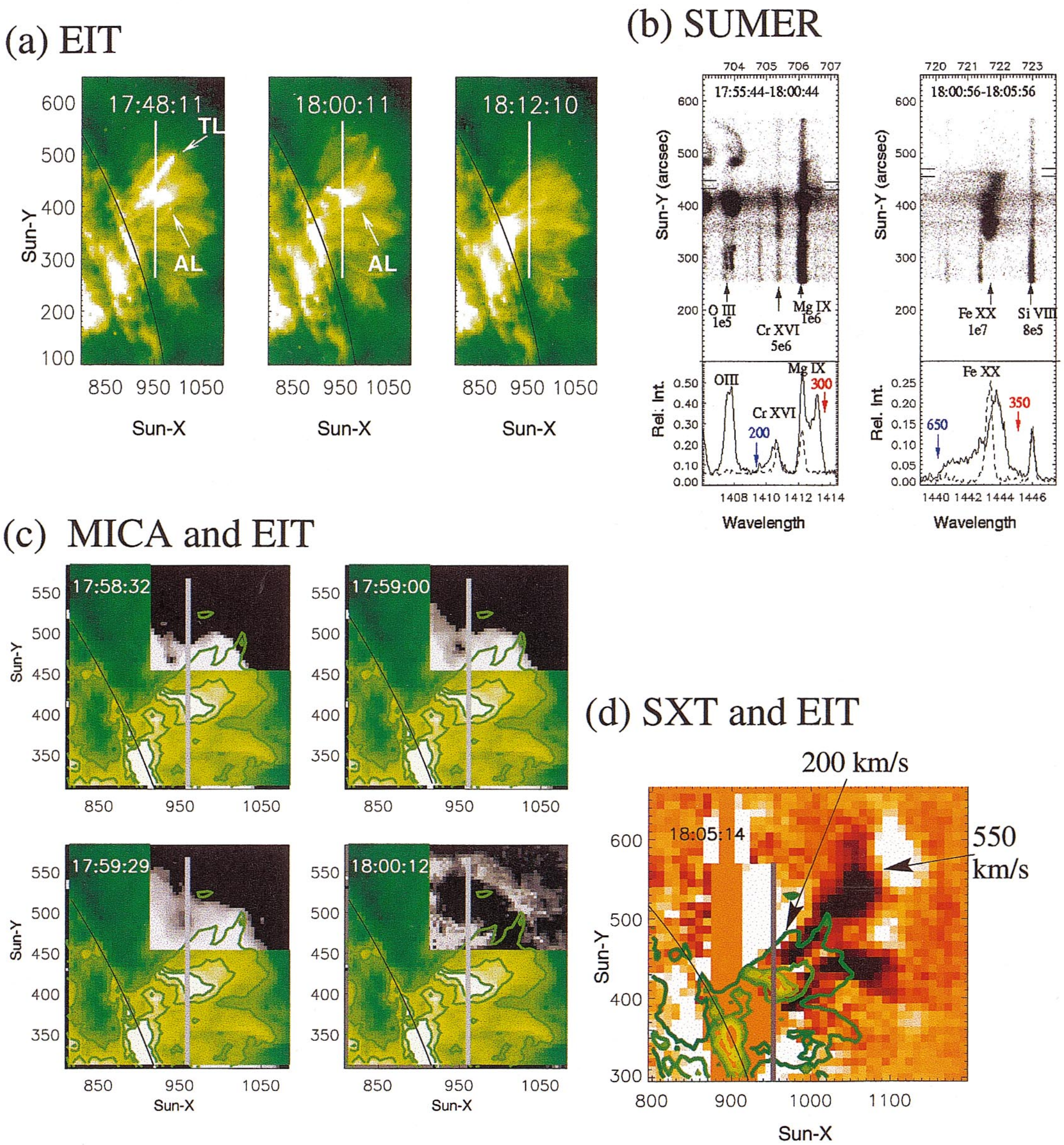

FIG. 1.—Association between structures seen by different instruments at flare onset. The position of the SUMER slit is shown as a vertical line in the EIT, MICA, and SXT images. (*a*) EIT 195 Å images with the observation times marked. The main preflare structures are the tall loop (TL), which stretches over 150″ into the corona, and the bright top of the arcade of loops (AL). (*b*) SUMER stigmatic images (*top*) and line spectra taken with an exposure time of 5 minutes. The line spectra are the integrated emission along the section of the slit marked by extended ticks on the image above. The dashed line shows the unshifted profile from a spectrum taken 3.5 hr later. The maximum velocities are marked in red and blue. (*c*) The MICA gray-scale images are inset in the 18:00:11 EIT image, and EUV contours are drawn to show the position of the erupting loop relative to the optical front. The exposure time of the MICA images is 20 s, and marked times are the midway times. The last frame (18:00:12) shows the intensity difference between the images taken at 18:00:12 and 17:59:29. (*d*) Difference of *Yohkoh* SXT images taken at 18:05:14 and 18:04:14 represented by the red tones. Black (white) signifies higher emission in the earlier (later) image. EUV contours as in (*c*) are overlaid. Material is expanding outward into the corona with a speed of 550 km s^{-1} and northward, along the SUMER slit, with a speed of 200 km s^{-1}.

3. OBSERVATIONS

The EUV images of the flare show the evolution of the 10^6 K coronal loop structures from their preflare to their postflare configuration (Fig. 1*a*). During the preflare, a bright elongated looplike structure, stretching high into the corona (TL in Fig. 1*a*), overlaps the bright top of a lower lying arcade of loops (AL in Fig. 1*a*). Together, they form a V-like emission pattern in the EUV image taken at 17:48:11 UT. During the flare, this structure seems to disrupt sequentially. First, as seen in the middle EUV image, taken at 18:00:11 UT, the tall bright loop disappeared. Then, 12 minutes later, the arcade top is no longer visible.

The evolution of the EUV images can be related to features seen with the other instruments. In particular, the disappearance of the tall loop is associated with bright Mg IX redshifted emission seen in the SUMER spectrum at about Sun-Y = 430″ and the fainter Mg IX redshifts to the north (Fig. 1*b*, *left-hand image*). Probably the most obvious feature in this first SUMER spectrum is the curling O III profile. The O III emission does not line up with any of the structures seen in the EUV images but with a fast, faint optical front seen in white-light coronagraph images from MICA (Fig. 1*c*). In Figure 1*c*, a section of the MICA image has been inset into the EUV image of the erupting loop (taken at 18:00:11 UT). The optical front is best seen against the dark corona to the north of the EUV arcade of loops. It was moving with a plane-of-sky speed of 400 km s^{-1}. In the fourth image of this series (labeled 18:00:12), the MICA inset is a difference image. It highlights the fact that the optical emission front extends into the bright 10^6 K loops. The inner edge of the front coincides

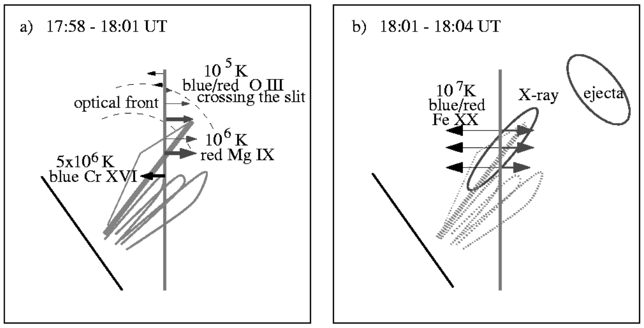

FIG. 2.—Sketch indicating the active region plasma loop temperatures and observed positions of large Doppler shifts. The arrows indicate Doppler shifts with Earthward flows (blue) pointing to the left. (*a*) The disruption of the preflare loop structure (*gray loops*) and the expansion of the optical front (*dashed lines*) were accompanied by high Doppler shifts in lines with the same formation temperature as the loops. (*b*) A few minutes later, the loops had disappeared (*dashed gray lines*). Soft X-ray emission with high Fe XX Doppler shifts was observed at the position of the Mg IX loop, and soft X-ray ejecta were seen moving outward into the corona from the position of the Cr XVI loops.

with the top of the EUV-erupting loop, but the extent of the optical front is significantly broader and the inner and outer edges sharper. We believe this difference occurs because the faint optical front emission is predominantly scattered photospheric light that is proportional to the electron column density, whereas the EUV emission only outlines the 10^6 K plasma. Thus, the moving optical front indicates a large-scale sweeping up of plasma irrespective of temperature.

This interpretation is supported by the SUMER spectra. In the first spectrum (Fig. 1*b*, *left*), three distinctly different temperatures are represented. There are lines from 10^5 K O III, 10^6 K Mg IX, and 5×10^6 K Cr XVI plasmas. Large Doppler shifts are seen in all lines and at all positions along the spectrometer slit overlapping with the erupting loop and the optical emission front. The line profile variations seen along the slit may be because the spectra were taken over a period of 5 minutes. For example, during the first 5 minute exposure, the optical front seen in the MICA images (Fig. 1*c*) moves 100″ northward along the spectrometer slit. As it expands, different parts of the front cross the slit. The O III profile probably shows the change in the line-of-sight velocity of the plasma in the optical front as new sections of the front cross the spectrometer's field of view. The line shifts can be interpreted as an expanding loop as first one leg, then the top, and then the other leg cross the slit or the twisting motion of a large plasmoid. The Mg IX line is redshifted along about 80″ of the slit, indicating that the whole loop structure is moving away. The hotter Cr XVI plasma that is almost hidden in the bright continuum from the arcade top is blueshifted along about 20″ of the slit.

It is not until the second SUMER spectrum, taken between 18:00:56 and 18:05:56 UT, that a line, Fe XX, from 10^7 K X-ray–emitting plasma falls in the observed spectral window. This line has the highest Doppler shifts seen in the event. The Fe XX profile is illustrated in the right-hand spectrum of Figure 1*b*. High-velocity blue- and redshifts are along 50″ of the slit starting from the position of the blueshifted Cr XVI in the previous spectrum. Later spectra show that this hot, fast-moving plasma is replaced by hot stationary plasma that expands to fill the whole northern section of the SUMER slit (Feldman et al. 2000). The position of the SUMER slit is shown in the SXT difference image (Fig. 1*d*) on which the contours from the EIT image, taken at 18:00:11 UT, have been superposed in order to reveal the relationship of the expanding soft X-ray emission to the position of the preflare arcade top. In this SXT difference image, there is a dark channel leading directly from the arcade top to a bright soft X-ray plasmoid. The plasmoid appears to be material ejected from the arcade top. If one extrapolates the position of the plasmoid back in time using its measured plane-of-sky speed, 550 km s^{-1}, the plasmoid would have left the arcade top between 18:00:00 and 18:00:30 UT. This is consistent with the observation of blueshifted Cr XVI emission in the SUMER spectrum taken between 17:55:44 and 18:00:44 UT. The bright, slightly elongated region along the northern edge of the channel at location (950″, 470″) is producing the Fe XX line emission and high Doppler shifts. Unfortunately, the structure in the SXT image is confused by a brightening on the left of the SUMER slit position coming from behind the SXT overexposure spike. Nevertheless, one can see a bright extension along the dark channel boundary. In later SXT images, the plasmoid at the head of the channel disappears, and in the difference images, the boundaries to the north and south become more elongated. For at least 10 minutes after the flare, the channel continues to expand outward to the north and south with a plane-of-sky speed of about 200 km s^{-1}.

A sketch showing the relationship between the multi-temperature loops is shown in Figure 2. The Mg IX and Cr XVI shifts coincide with the position of preflare loops seen in lines in earlier spectra with similar formation temperature. This indicates that in the initial stages, there is rapid acceleration of plasma from the loops as the optical front sweeps through the corona. Subsequently, the corona heats up, and the spectra show very high red and blue Doppler shifts from hot, 10^7 K, plasma at the position of the tall 10^6 K (Mg IX) loop that was seen to erupt in the EIT image at 18:00:11 UT.

4. DISCUSSION

These data reveal two new features of plasma flow at the time of flare and CME onset. The first is an elongated X-ray structure with high red and blue Doppler shifts at every observed position. The shifts are unlikely to be a signature of reconnection jets. Jets would produce red and blue Doppler shifts (e.g., Innes et al. 1997), but these shifts would be localized and directed along the jet's axis away from the reconnection point. The shifts we see here are from all parts of the expanding X-ray plasma that crossed the SUMER field of view. The second is the disruption of the active region EUV loop structure and appears to be directly associated with a fast, faint optical front. The optical front was seen less than 1 minute after the hard X-ray maximum at a height of 120″. Assuming its measured plane-of-sky speed, 400 km s^{-1}, it would have been 65″ off the solar limb at the time the hard X-ray emission was first detected by OSSE.

An explanation, consistent with the data presented here, is the interaction of a shock wave with the active region loop structure. A shock would heat and accelerate all loops as it sweeps through the region. It also explains the very fast plasma velocities seen simultaneously both transverse and along the line of sight. Also, a shock front would be slower in higher density regions, and thus, as observed, one would expect to see the X-ray ejecta behind the main front. Also, some loops, those in front of the energy release site, would be blueshifted, and some would be redshifted. Others on the side would be expected to have both red- and blueshifted components. A shock wave interpretation is also consistent with the analysis of the arrival time and spectral evolution of the high-energy proton fluxes measured at *SOHO* by the Energetic and Relativistic Nuclei and Electron instrument (Torsti et al. 2001).

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