DIRECT OBSERVATION OF HIGH-SPEED PLASMA OUTFLOWS PRODUCED BY MAGNETIC RECONNECTION IN SOLAR IMPULSIVE EVENTS

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Received 2007 February 22; accepted 2007 April 20; published 2007 May 15

ABSTRACT

Spectroscopic observations of a solar limb flare recorded by SUMER on SOHO reveal for the first time hot, fast magnetic reconnection outflows in the corona. As the reconnection site rises across the SUMER spectrometer slit, significant blue- and redshift signatures are observed in sequence in the Fe xix line, reflecting upflows and downflows of hot plasma jets, respectively. With the projection effect corrected, the measured outflow speed is between ~900 and 3500 km s⁻¹, consistent with theoretical predictions of the Alfvénic outflows in magnetic reconnection region in solar impulsive events. Based on theoretic models, the magnetic field strength near the reconnection region is estimated to be 19–37 G.

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

Online material: color figures

1. INTRODUCTION

It is generally accepted that the free magnetic energy stored in the coronal magnetic field is explosively released through magnetic reconnection (Priest & Forbes 2000), a process in which oppositely directed magnetic field lines break and reconnect with each other in a small area in the corona. The residual magnetic tension in the newly reconnected field causes the magnetic field and plasma to be expelled from both sides of the reconnection region, forming high-speed outflows at near-Alfvén speed (thousands of kilometers per second). Indirect observational evidence have been found in past studies, for example, the separation motion of flare ribbons formed in the lower atmosphere, cusp-shaped soft X-ray flare loops (Tsuneta et al. 1992), loop-top hard X-ray sources (Masuda et al. 1994), and double hard X-ray sources above the flare loop top with opposite temperature gradients (Sui & Holman 2003).

The search for inflows and outflows is important since they are a direct consequence of the reconnection process, and their measurements can yield estimates of the reconnection rate. There have been some observations interpreted as the inflow or outflow. Apparent bidirectional motion of coronal structures around a flare loop discovered with SOHO EIT has been considered to be the signature of reconnection inflow (Yokoyama et al. 2001). There has been, however, only indirect evidence of reconnection outflows, mostly based on morphological changes. For example, plasma blob ejections (Shibata et al. 1995) and downward plasma motions (McKenzie & Hudson 1999) seen in X-ray images were thought to be a consequence of upward or downward outflows, but the deduced outflow velocities are much lower than predicted values. In this Letter, we present the first direct measurement of high-speed reconnection outflows in a flare event using combined imaging and spectroscopic observations.

2. OBSERVATIONS

The flare studied in the Letter occurred very close to the northwest limb of the Sun in NOAA AR 9901 on 2002 April 16. It was a GOES M2.5-class flare and associated with a slow coronal mass ejection (Goff et al. 2005). The X-ray light curves in two energy bands (6–12 and 25–50 keV) obtained with RHESSI are shown in Figure 1a. The flare started with enhancement in soft X-rays at 12:52 UT. The impulsive phase as shown in >25 keV hard X-ray (HXR) started at 13:06 UT and lasted ~11 minutes. The RHESSI X-ray images below 25 keV show a compact flare loop and a separated, outward moving coronal source (Fig. 2, contour images). Figure 2 also shows the 195 Å bandpass images obtained with the Transition Region and Coronal Explorer (TRACE), in which a bright, compact loop and a faint, outward moving loop can be identified. Goff et al. (2005) reported that the faint loop was rising with a velocity of 45–75 km s⁻¹. The outward-moving X-ray coronal source appeared to be trailing the front of the large-scale loop seen in TRACE images (Fig. 2, arrow).

The flare was observed throughout its duration by the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer on SOHO with the 300° × 4° entrance slit at a fixed position above the active region (Figs. 2 and 3a). The spectra were recorded with a 50 s cadence in three lines: Si iii 1113.2 Å (0.06 MK), Ca x 557.7 Å (second order, 0.6 MK), and Fe xix 1118.1 Å (8 MK). Figure 1b shows the time series of the Fe xix line intensity profiles along the slit. From 12:58 to 13:04 UT, the line intensity increased significantly, appearing as a crescent-shaped structure passing the slit. The timing and location (relative to the slit) of this structure suggest that it is the moving, large-scale (faint) loop seen by TRACE (see Fig. 2). This structure is not seen in the SUMER cooler Ca x line (Fig. 3b), indicating that the loop seen at TRACE 195 bandpass was due to emissions of hotter lines (i.e., Ca xvii 193 Å at 5 MK and Fe xxiv 192 Å at 20 MK) (Warren et al. 1999). After the passage of this rising loop, the Fe xix intensity decreased by about an order of magnitude (from ~13:04 to 13:08 UT). Then it gradually increased again over a larger region, seen as a cusp-shaped brightening (Fig. 1b), which indicates apparently growing hot, dense cusp-shaped loops across the slit. This could be the evidence of progressive reconnection of field lines toward higher altitudes in time.

The most striking signature in SUMER observations is a plasma jet with a large blueshift in the Fe xix line (Figs. 3b and 4) lasting for ~8 minutes during the impulsive phase of the flare. The jet had a width of ~6° along the slit, and was located at ~5° south of the top of the faint, rising loop. This high-blueshift jet was first seen at 13:05 UT, when the main impulsive phase...
of the flare started as revealed by the RHESSI 25–50 keV light curve (Fig. 1a). At this time, both the top of the erupting hot loop seen by SUMER and TRACE and the X-ray coronal source seen by RHESSI had passed the slit. Therefore, the high-speed outflow was trailing the coronal features moving outward. The Fe xix line profile shows a blueshift component corresponding to a line-of-sight (LOS) Doppler velocity of up to 600 km s\(^{-1}\) (Fig. 3c). Taking into account the projection effect, the outflow velocity can be as high as 1800–3500 km s\(^{-1}\) (see discussion in § 3). Figure 4 shows the jet evolution as observed in Fe xix spectra. We do not see any significant change in the line profile during the first 4 minutes, although the line intensity continued to increase (Fig. 1a, hatched line). The jet became weaker after 13:10 UT and eventually disappeared at 13:14 UT.

A high-redshift jet in the Fe xix line, although not as strong as the blueshift jet, is also observed after 13:16 UT (Fig. 4, bottom row). This indicates a downward-moving plasma flow passing through the slit. The redshift jet was at ∼5′ north of the blueshift jet. The maximum Doppler velocity was 300 km s\(^{-1}\). With the projection effect corrected, we get a downward velocity between 900 and 1800 km s\(^{-1}\). This redshift jet disappeared after 13:21 UT when the 25–50 keV HXR emission dropped to the background level (Fig. 1a).

3. DISCUSSIONS

We note that, since the blueshift jet seen by SUMER was located near the southern leg of the rising faint loop seen by TRACE (Fig. 2, top right and bottom left and middle panels), it may be falsely interpreted as the signature of upward flows in the loop. However, there are several arguments against such an interpretation: (1) as both the northern and southern legs of the rising loop crossed the slit, if the blueshift is caused by the upward flow in the loop, then we would expect to see two
strong Doppler-shift jets along the slit; (2) after the southern leg of the TRACE loop passed through the jet location, we still observed the high-blueshift jet (Fig. 2, bottom right panel); and (3) a plasma flow with such a high speed is not expected and has never been reported in erupting loops.

By combining all the observations presented above, we conclude that the observed upward and downward jets are both high-speed outflows from the magnetic reconnection site. When the upflowing jet was observed, the reconnection site was below the slit, and later when the downflowing jet was observed, the reconnection site had moved above the slit. We interpret the essential observations in terms of the standard magnetic reconnection picture:

1. The initial faint, rising loop observed with SUMER and TRACE is an erupting (twisted) flux rope, below which magnetic reconnection took place. The high temperature (>6 MK) of this loop suggests the presence of a preheating process which may be involved in the trigger of its eruption.

2. At the onset of the flare impulsive phase, the high-speed upflows were expelled outward from the magnetic reconnection region. This plasma upflow passed through the SUMER slit and produced the high-blueshift jet seen in the Fe xix line. The estimated upflow speed agrees with the typical Alfvén speed in the corona.

3. After the reconnection site (e.g., current sheet) passed through the slit, the observation showed the cusp-shaped, newly reconnected field retracting downward and forming reconnection downflows, which were observed as the redshift jet by SUMER. The relatively smaller downflow velocity may imply that the downflow is slowed down by the density increase due to chromospheric evaporation along the reconnected loops. Similar asymmetry between upflow and downflow velocities was also found in bidirectional jets observed in explosive events in the solar chromosphere (Innes et al. 1997).

4. After the impulsive phase, the reconnection rate decreased significantly (inferring from its temporal correlation with hard X-ray flux, Qiu et al. 2004) and, therefore, no high-speed reconnection outflow can be detected with SUMER.

See a sketch at http://solar.physics.montana.edu/qiuj/sketch-model.pdf.

Fig. 3.—Observations of a high-speed plasma outflow. (a) TRACE 195 Å image showing the compact flare loop. A sketch of the faint, rising loop (dark curve) as seen in the TRACE difference image (Fig. 2) is also indicated to show its spatial relation to the SUMER slit. The SUMER slit position is co-aligned with the TRACE image with an accuracy of ∼1″ in the Y-direction based on common features seen in both the SUMER Ca x line and TRACE intensity profiles along the slit. (b) SUMER spectra along the slit in a window containing a coronal line, Ca x 557.7 Å (second order) and a hot flare line, Fe xix 1118.1 Å. (c) The spectral line profile of Fe xix (top curve) at the highly blueshifted position (panel b, dashed line), indicating a plasma flow with the LOS component up to 600 km s⁻¹. The bottom curve is the Fe xix line profile taken about a half hour before the event, showing the stationary profile. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 4.—Time series of SUMER Fe xix spectra showing a high-blueshift jet (top two rows) and a redshift jet (marked by an arrow in bottom row), indicating a high-speed plasma upflow and downflow, respectively. The images are on a logarithmic scale. The continuum background and Ca x line emissions have been subtracted. There is a data gap between −395 and −276 km s⁻¹ in each image. [See the electronic edition of the Journal for a color version of this figure.]
The outflow is in the direction of the line linking the midpoint of the loop to the LOS of 80°. The line linking the midpoint of the two feet to the loop apex (dark solid line) is indicated to have an orientation toward (≈5° above) the high-shift jet seen by SUMER. The direction of this line has an angle to the LOS of 70°. The white line representing a direction in the loop plane and pointing just toward the jet position has an angle to the LOS of 80°. Therefore, we assume the outflows in the direction that has an angle to the LOS between 70° and 80° in the text. [See the electronic edition of the Journal for a color version of this figure.]

5. The narrow width of the observed outflows suggests the presence of a vertical current sheet in side view.

6. The X-ray coronal source is closer to the reconnection region than the rising loop, therefore, it has a higher temperature (30 MK) (Sui 2004).

Both this above-the-loop X-ray coronal source and the lower compact X-ray source could be heated by termination shocks formed by the reconnection outflows above and below the current sheet (Tsuneta 1997; Masuda et al. 1994). These interpretations are consistent with the results of Sui & Holman (2003), Sui et al. (2004), and Sui (2004). Based on the RHESSI observations that the temperature of the flare loop increased toward higher altitude and the temperature of the above-the-loop coronal source increased toward lower altitude in the event studied here and another homologous event, Sui et al. concluded that the magnetic reconnection occurred between the flare loop and the above-the-loop coronal source.

Now we estimate the true jet speed based on Figure 5. If we assume that the outflow is radial from the active region, then it would be at ∼80° relative to the LOS. If we fit the inner side of the TRACE compact flare loops by a circular arc in a three-dimensional geometry (Aschwanden et al. 2002) and assume that the outflow is in the direction of the line linking the midpoint of the two loop feet and the loop apex, the angle is ∼70°. Thus, the maximum blueshift of 600 km s⁻¹ gives an outflow velocity as high as 1800–3500 km s⁻¹, taking into account the projection effect. Since the reconnection outflows had a velocity close to the Alfvén speed \( V_A = 3000\sqrt{B/20\, G}\left(n_e/2 \times 10^6\, \text{cm}^{-3}\right)^{1/2} \text{km s}^{-1} \), where \( B \) is the magnetic field and \( n_e \) is the electron density, we can estimate the magnetic field strength near the reconnecting region. Given \( n_e \sim 5 \times 10^6 \text{cm}^{-3} \) as the average active region coronal density at a height of ~40 Mm (SUMER slit height; Del Zanna & Mason 2003), with \( V_A \) of 1800–3500 km s⁻¹, we get \( B \sim 19–37 \, \text{G} \), which agrees well with the mean magnetic field strength of coronal loops at similar heights measured from observations of coronal loop oscillations (Nakariakov & Ofman 2001; Aschwanden et al. 2002; Wang et al. 2007). The measurements of outflow speed and magnetic field strength near the reconnection region are essential for our understanding of the plasma heating and particle acceleration in flares.

High-temperature flows of ∼1000 km s⁻¹ have been observed with SUMER in a couple of other flares (Innes et al. 2001, 2003). However, since observations of those events provide no information of the location of the reconnection region, it is difficult to pinpoint the origin of these flows or directly relate these flows to the energy release region. For example, Innes et al. (2003) observed blueshifts of 800–1000 km s⁻¹ in the Fe xxi line from the boundary along the tail of dark downflows. The physical nature of dark downflows is not fully understood. McKenzie & Hudson (1999) interpreted the dark downflows as signatures of reconnection outflows, although the speeds are slower than typically expected and high Doppler shifts at the tail boundary are hardly explained in their picture. Innes et al. (2003) suggested another way that these shifts may be due to a fast wind generated behind the downflows.

The combined observations of SUMER, RHESSI, and TRACE of a very well observed event studied in this Letter allow us to determine unambiguously the spatial relationship between the high Doppler-shift flows and the reconnection region and thus provide direct evidence of high-speed magnetic reconnection outflows in the current sheet in the corona. The observations lend strong support to the magnetic reconnection theory and the bipolar reconnection model of solar eruptive events. To better understand magnetic reconnection on the Sun, it requires a further analysis based on 3D models which have shown many different properties from the 2D CSHKP model (e.g., Archontis et al. 2005).

We thank D. E. Innes, B. R. Dennis, and G. D. Holman for their valuable discussions and suggestions. We also thank the Max-Planck-Institut für Sonnensystemforschung for providing the SUMER data. T. W. and J. Q. are supported by NASA grant NNG06GA37G and NASA grant NAS5-38099. L. S. is supported by NASA grant 370-16-20-16 and the RHESSI project.

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