EVIDENCE FOR HOT FAST FLOW ABOVE A SOLAR FLARE ARCADE

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ABSTRACT

Solar flares are one of the main forces behind space weather events. However, the mechanism that drives such energetic phenomena is not fully understood. The standard eruptive flare model predicts that magnetic reconnection occurs high in the corona where hot fast flows are created. Some imaging or spectroscopic observations have indicated the presence of these hot fast flows, but there have been no spectroscopic scanning observations to date to measure the two-dimensional structure quantitatively. We analyzed a flare that occurred on the west solar limb on 2012 January 27 observed by the Hinode EUV Imaging Spectrometer (EIS) and found that the hot (>30MK) fast (650 km s−1) component was located above the flare loop. This is consistent with magnetic reconnection taking place above the flare loop.

Key words: Sun: corona – Sun: flares – Sun: UV radiation

Online-only material: animation, color figures

1. INTRODUCTION

A solar flare is a sudden brightening observed in almost all wavelengths. The energy released by a flare is so huge that the total amount of energy often reaches 1032 erg within an hour. Solar flares are sometimes associated with coronal mass ejections (CMEs) which can trigger geomagnetic storms. These sudden huge energy releases can also be observed on other magnetized astronomical objects. Therefore, over the last few decades, considerable effort has been devoted toward understanding how magnetic energy is converted to plasma energy during solar flares. The so-called standard model of eruptive flares, which is based on magnetic reconnection, has been proposed (the CSHKP model Carmichael et al. 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976), and some of the predicted characteristics have been verified by observations (e.g., cusp-like structure in soft X-ray images: Tsuruta et al. 1992), a hard X-ray source above the flare loop: Masuda et al. (1994), chromospheric evaporation: Terraca et al. (2003); Imada et al. (2008), reconnection inflows: Yokoyama et al. (2001), reconnection outflows (off limb: Innes et al. 2003; Liu et al. 2013), on disc: Hara et al. 2011), plasmoid ejection: Ohnaka & Shibata (1998), and CMEs: Svestka & Cliver 1992; Imada et al. 2007, 2011b).

One of the typical characteristics predicted by the CSHKP model is that magnetic reconnection occurs above the flare arcades. Therefore, hot (a few 10 MK) and fast (~1000 km s−1) plasma flows should be observed above the flare arcades. The magnetic reconnection region is sandwiched between two slow-mode shocks and hence should appear as a narrow structure (like a spear). However, other physical mechanisms such as a blast wave (Innes et al. 2001; Tothova et al. 2011) can explain the presence of hot fast flows above the flare arcade, so it is crucial to observe the hot fast flow structure quantitatively in order to understand the solar flare process. So far, many observations at the solar limb have been made to confirm the presence of hot fast flows above the flare arcade. Observations at the limb have the advantage that the height information can be clearly determined. For example, supra-arcade downflows (SADs) are observed by coronal imagers which are interpreted as the reconnection outflows predicted from the flare model. X-ray dark voids and sometimes bright features are observed to move sunward (downward) from the high corona with an apparent velocity of a few 100 km s−1, especially during the late phase of flares (McKenzie & Hudson 1999; McKenzie 2000; Savage et al. 2012). However, equivalent spectroscopic observations are very rare because of slow spatial scanning and small fields of view. Only a few spectroscopic limb observations have reported the presence of hot fast flows above the flare arcade (Innes et al. 2003; Wang et al. 2007). These studies are from a single slit position above the flare arcades, and hence two-dimensional spatial information of the hot fast flows was not available. In this Letter, we show the first spectral scanning observation of hot fast flows above a flare seen on the solar limb.

2. OBSERVATION AND DATA ANALYSIS

On 2012 January 27, Hinode (Kosugi et al. 2007) observed a large solar flare (GOES X1.7, peak time 18:37) at the northwest solar limb (30°N, 90°W). The EUV Imaging Spectrometer (EIS) aboard Hinode is a high spectral/spatial resolution spectrometer aimed at studying dynamic phenomena in the corona (Culhane et al. 2007). The Hinode EIS observed the flare with a slit scanning mode with a 2′′ wide slit and an exposure duration of 5 s at each scanning point. The observing period is from 18:16 to 18:29 UT, which is during the rise phase of the flare. This was the first raster scanning observation (~10 minutes for one raster scan), before the fast sparse raster scanning began (~5 minutes cadence). To process the EIS data we used the software provided by the EIS team (eis_prep), which corrects for the flat field, dark current, cosmic rays, and hot pixels. During the flare, EIS successfully obtained EUV images and line-of-sight (LOS) velocities (Doppler shift) in several emission lines, including the Fe xxiv line at 192 Å (window width ~0.535 Å), with ~1500 km spatial resolution. By using the hot Fe xxiv emission line (see CHIANTI, Dere et al. 1997; Landi et al. 2013), we can reveal the fine-scale structure and dynamics of
the high-temperature (∼10^7 K) plasma in the flaring region. We also have the other flare lines (e.g., Fe xxiii (263.77 Å), Fe xxiv (255.11 Å)) and cooler lines (e.g., Fe xi (188.23 Å), Fe xiv (274.20 Å)) for this observation. These lines are useful to check the blending effect in the Fe xxiv line at 192 Å. The Fe xxiv line at 192 Å is blended with Fe xi and Fe xiv. By comparing the Fe xxiv at 192 Å result and the other flare/cooler lines results, we can distinguish the flare plasma information from the blended emission. Simultaneously, the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) instrument acquired full-Sun images with a spatial resolution of 1000 km. We use the AIA spectral channels at 94, 131, and 193 Å to analyze the high temporal evolution of the flaring plasma (∼24 s). Each of the AIA channels has different temperature coverage. The AIA 94, 131, and 193 Å channels represent 10^{6.8}, 10^{7.0}, 10^{7.3} K plasma, respectively, in the case of flares as discussed by Boerner et al. (2012).

The AIA images taken in the different channels show the behavior of the flare loop structure at different temperatures (Figure 1). The development of the flaring loops can be clearly seen in the AIA movie (movie S1). To clarify whether the hot (a few 10 MK) Alfvénic flows (∼1000 km s^{-1}) are located above the flaring loops, as predicted by CSHKP model, or not, we analyze the AIA images. The downward (sunward) moving features above the flare arcades in the highest temperature range (193 Å channel) are clearly observed (movie S1). Even in the 131 Å channel we can also see some downward moving features, but in the 94 Å channel, as the temperature decreases, there is no clear signature of flows. This can be interpreted as evidence for hot downward moving loops. We can estimate the temperature from the intensity ratio between the 193 and 131 Å channels, and we find that the downward moving loops are roughly ∼30 MK. To estimate the apparent velocity of the downward moving loops, we create a time–distance plot along the white line in Figure 2(a). The time–distance plot (Figure 2(b)) shows patterns in the flow with transverse velocity with a typical value of 350 km s^{-1}. In Figure 2(b), we can also see the development of the bright flare loops associated with the downward moving features.

EIS Fe xxiv (192 Å) images are shown in Figure 3. The line-center image of Fe xxiv (Figure 3(b); stationary in LOS direction, 192.03 ± 0.156 Å) shows the flare loops which are
similar to those observed in the AIA 193 Å channel. This indicates that the AIA 193 Å images show the structures filled with >10 MK plasma. The blue-wing 191.8 ± 0.0223 Å image (Figure 3(a)), which corresponds to plasma flowing toward 

\[ \text{Hinode} \]

with a velocity of 400 km s\(^{-1}\), shows a totally different shape from the line-center image. The red-wing 192.6 ± 0.0223 Å image is also shown in Figure 3(c). We have compared Figures 3(a)–(c) to the figure made from the other flare lines or cooler lines in the same way, and confirm that Figures 3(a)–(c) are definitely the results from Fe \text{xxiv}. In the line-center image, we see a cross-shaped fringe pattern which is due to diffraction. There is no diffraction pattern in the blue/red-wing image, because the bright flare arcades do not have a strong blue/red-wing component. We think this is one of the reasons why we can see a lot of structure in the blue/red-wing image. In the northeastern part of the flare, where AIA observations show the hot and fast apparent flow, we can see the diffuse structures in the blue-wing image (Figure 3(a)), which cannot be seen in the

Figure 2. (a) AIA 193 Å channel image taken at 18:20:34 UT on 2012 January 27 with the position of the CCD pixels (slit) used for preparing (b) shown superimposed as a white bar. The dashed box indicates the EIS field of view. (b) A time–distance diagram generated from the intensity distribution along the slit shown in (a). The vertical axis shows distance along the slit, and the horizontal axis indicates time in minutes from 2012 January 27, 18:15:22 UT. The dashed line represents the transverse velocity of 350 km s\(^{-1}\). The arrow shows the observing time of the distorted line profile in Figure 3(d) by EIS.

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

Figure 3. (a) EIS \text{Fe xxiv} blue-wing image (191.8 Å, −400 km s\(^{-1}\)) of the flare on 2012 January 27. (b) EIS \text{Fe xxiv} center image (192.0 Å, 0 km s\(^{-1}\)) of the flare. (c) EIS \text{Fe xxiv} red-wing image (192.3 Å, 400 km s\(^{-1}\)) of the flare. (d) An example of the Fe \text{xxiv} line profile in the blue-wing enhanced region (marked by a + in (a)–(c)). (e) An example of the Fe \text{xxiv} line profile in the center of the flare (marked by a circle in (a)–(c)). (f) An example of the Fe \text{xxiv} line profile in the red-wing enhanced region (marked by an x in (a)–(c)). The ranges B, C, and R in (d)–(f) represent the blue-wing, center, and red wing of Fe \text{xxiv}, respectively.

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

Shock?

Perpendicular Flows

Turbulence?

EIS: Broad Line Profiles

EIS: Diffuse Structure in Doppler Obs.

AIA: Downward Moving Loops

Flare Arcade

Parallel Flows

EIS LOS

Parallel Flows

EIS: Red-shift in Doppler Obs.

Figure 4. Schematic illustration of the X-class flare on 2012 January 27. The large arrows demark the flow signatures observed by EIS Doppler velocity. The small arrows are flows which cannot be observed by EIS Doppler velocity because of the LOS effect. The entire flare arcade structure is defined by the combination of AIA and other view angle observation (STEREO). The figure is illustrated from the STEREO viewpoint. EIS and AIA view from left-hand side of the figure. (A color version of this figure is available in the online journal.)

3. DISCUSSION AND SUMMARY

EIS successfully reveals hot fast flows through the observation of Doppler shifts. These appear as a diffuse structure in the Doppler images 20 arcsec above the flare loop. At the same time and location we also observe downward flowing loops (apparent speed \( \sim 350 \text{ km s}^{-1} \)). Because the Doppler (EIS LOS direction) and apparent (seen in the AIA images) velocities are similar, the downward flowing loops could be inclined toward the northwest (\( \sim 45^\circ \)). Therefore, we can interpret that the diffuse structure is associated with \( \sim 600 \text{ km s}^{-1} \) flow perpendicular to the magnetic field. Figure 4 shows the schematic illustration of the observation. The large arrows represent the flow signature observed by EIS Doppler velocity. The small arrows are flows which cannot be observed by EIS Doppler velocity because of the LOS effect. The entire flare arcade structure is defined by the combination of the \textit{Hinode}/\textit{SDO} and \textit{STEREO} observation (not shown here), the latter of which has a different viewing angle of \( \sim 110^\circ \) from the Sun–Earth line. Unfortunately, the \textit{STEREO} observations were saturated during the main phase of the flare, although the entire flare structure can be determined from the post-flare loops. The observed hot fast flow \( \sim 20 \text{ arcsec} \) above the flare loop is likely to be associated with magnetic reconnection, because it is accompanied by hot fast perpendicular flow. However, the structure of this hot fast flow is diffuse and round rather than spear-like. This might indicate that the observed hot flows are not the reconnection outflow itself, but are illustrating the interaction of the flow with the preexisting flare loop forming a...
fast-mode shock. Some numerical simulations (e.g., Yokoyama et al. 2001) show the formation of fast-mode shock above the flare loops. We can speculate that our finding is the hot fast flow in the downstream of fast-mode shock, which is caused by reconnection outflow. The signature of the turbulence in the hot fast flow also supports our interpretation. Liu et al. (2013) have reported on the relationship between the flare outflow and the hard X-ray source. According to their result, the high energy electron (25–50 keV) seems to be located just above the flare loop where the fast flows are terminated. This result may also support the idea that the fast-mode shock could be located just above the flare loop. Unfortunately, we do not have hard X-ray observation from our flare event. The relationship between the high energy particles and the diffuse structure which we observe is a topic for future work. Recently, Imada et al. (2011a) claimed that the outflow region of magnetic reconnection cannot reach ionization equilibrium because of its short Alfvén timescale. Thus, in some cases, the reconnection outflow region might be much fainter than we expect. Downstream of the fast-mode, shock ionization proceeds much faster because of the high density and temperature conditions. This might be one of the reasons why we can only observe the downstream region. Therefore, we think that the reconnection region is located far above the flare loops where there are very few photons.

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