Witnessing a Large-scale Slipping Magnetic Reconnection along a Dimming Channel during a Solar Flare

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Abstract

We report the intriguing large-scale dynamic phenomena associated with the M6.5 flare (SOL2015-06-22T18:23) in NOAA active region 12371, observed by RHESSI, Fermi, and the Atmospheric Image Assembly (AIA) and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO). The most interesting feature of this event is a third ribbon (R3) arising in the decay phase, propagating along a dimming channel (seen in EUV passbands) toward a neighboring sunspot. The propagation of R3 occurs in the presence of hard X-ray footpoint emission and is broadly visible at temperatures from 0.6 MK to over 10 MK through the differential emission measure analysis. The coronal loops then undergo an apparent slipping motion following the same path of R3, after a ∼80 minute delay. To understand the underlying physics, we investigate the magnetic configuration and the thermal structure of the flaring region. Our results are in favor of a slipping-type reconnection followed by the thermodynamic evolution of coronal loops. In comparison with those previously reported slipping reconnection events, this one proceeds across a particularly long distance (~60 Mm) over a long period of time (~50 minutes) and shows two clearly distinguished phases: the propagation of the footpoint brightening driven by nonthermal particle injection and the apparent slippage of loops governed by plasma heating and subsequent cooling.

Key words: Sun: activity – Sun: flares – Sun: magnetic fields

Supporting material: animations

1. Introduction

Two flare ribbons separating away from the magnetic polarity inversion line (PIL) and the apparent growth of coronal loops have long been observed and regarded as compelling evidence for the standard magnetic reconnection model (see Shibata & Magara 2011 for a review). This model, however, deals only with a two-dimensional magnetic configuration with a translational symmetry along the reconnecting X-line. In the three-dimensional (3D) solar magnetic field, magnetic reconnection takes place in a more complex configuration and thus the resulting flares may exhibit a variety of forms that cannot be accommodated by the standard reconnection model (Aulanier et al. 2012; Janvier 2017 and references within). In some cases, flares display circular ribbons (e.g., Masson et al. 2009; Reid et al. 2012; Wang & Liu 2012; Vemareddy & Wiegelmann 2014; Liu et al. 2015), three quasi-parallel ribbons (Wang et al. 2014), or X-shaped ribbons (Li et al. 2016; Liu et al. 2016a), signifying a complicated magnetic topology.

Theoretical/numerical models have demonstrated that magnetic reconnection is intrinsically related to two classes of topological structures, separatrices (Gorbachev & Somov 1988; Mandrini et al. 1991) and quasi-separatrix layers (QSLs; Démoulin et al. 1996; Demoulin et al. 1997). Separatrices are made up of magnetic field lines passing through either a coronal null point (NP; Lau 1993) or a bald patch (Titov et al. 1993). Across separatrices the connectivity of field lines changes discontinuously (see Longcope 2005 for a review). Reconnection of separatix field lines through NPs is in a pairwise fashion, which is the essential idea underlying the magnetic breakout model (Antiochos et al. 1999) for coronal mass ejections (CMEs). In contrast, QSLs, quantified by the squashing factor \( Q \gg 1 \) (Titov et al. 2002), are thin volumes where the connectivity of field lines changes drastically but still continuously (Priest & Démoulin 1995; Demoulin et al. 1997). Due to the strong distortion of magnetic mapping at QSLs, the generic buildup of intense electric current sheets along QSLs is expected analytically (Demoulin et al. 1996) and confirmed later on by numerical simulations (e.g., Aulanier et al. 2005; Effenberger et al. 2011; Craig & Effenberger 2014). In the case of QSLs, the continuous exchange of connectivity between neighboring field lines induces an apparent “slipping” motion of field lines, which is termed “slipping reconnection” if the speed is sub-Alfvénic, or “slip-running reconnection” if the speed is super-Alfvénic (Aulanier et al. 2006). Slipping reconnection along QSLs is theoretically predicted in solar eruptions (Aulanier et al. 2012; Masson et al. 2012; Janvier et al. 2013), and expected to be more general than reconnection at separatrices where \( Q \rightarrow \infty \), a limiting case of QSLs.

Apart from the long-developed theoretical concept of the slipping-type reconnection, observations of such reconnections especially those related to solar flares have been rare (Aulanier et al. 2007; Testa et al. 2013; Dudík et al. 2014, 2016; Li & Zhang 2014, 2015; Gou et al. 2016; Sobotka et al. 2016; Zheng et al. 2016). This is mainly in that the high-quality observations required for an accurate depiction of slipping reconnection were only available a few years ago with ever-increasing spatiotemporal resolutions of solar instruments such as the Atmospheric Image Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO). Compared to the propagating kernel brightenings at
the footpoints of coronal loops (e.g., Dudík et al. 2014; Sobotka et al. 2016), the apparent slippage of loops appears more perceptible. However, the newly reconnected hot coronal loops may not be detectable immediately in the narrowband EUV images in the initial energy release phase, but become visible later on as plasma cools down through radiative losses and thermal conduction. In this Letter, "slippage of loops" is used to describe an apparent propagation of the most noticeably heated loops in EUV passbands.

Here, we present the observation of an intriguing M6.5 flare. The precursor and fine-scale structure of this flare have been discussed by Wang et al. (2017) and Jing et al. (2016), respectively. This study focuses on the large-scale dynamics associated with the flare. Our results are in favor of a slipping-type reconnection followed by thermodynamic evolution of coronal loops.

2. Data and Analysis Tools

We used SDO/AIA UV 1600 Å images to study the flare morphology. Differential emission measure (DEM) analysis was performed with the six AIA EUV passbands (94, 131, 171, 193, 211, 335 Å) using the sparse inversion method (Cheung et al. 2015). This method provides a number of benefits: (1) it has been validated against a diverse range of thermal models, (2) it returns positive definite DEM solutions, and (3) it is fast and can be used to generate sequences of DEM images. Full-disk images from aia.lev1 series at the AIA-HMI Joint Science Operations Center were de-rotated to a reference time set to be 18:00 UT, and co-aligned and sampled onto a common plate-scale with a pixel size of 0.6 arcsec. For our region of interest, DEM solutions were obtained on a pixel-by-pixel basis on a temperature grid with \( T = 5.7, 5.8, \ldots, 7.6, 7.7 \).

To study the magnetic configuration of the active region (AR), we extrapolated the 3D nonlinear force-free field

Figure 1. (a) Light curves of GOES SXR flux (black) and Fermi HXR flux (red; not available during 18:19–18:48 UT and 20:00–20:25 UT). Three vertical dashed lines mark the three Fermi HXR peaks. (b)-(d) AIA 1600 Å images showing three flare ribbons R1, R2, and R3. The green curves delineate the magnetic PILs. The red contours show RHESSI HXR intensity integrated in the time intervals b (18:22:30–18:23:30 UT) and d (19:26:30–19:27:30 UT), in the 25–50 keV energy range. The contour level is 60% of the intensity maximum. (e) HMI line-of-sight (LOS) magnetogram. (f)-(i) AIA 211 Å images showing the evolution of coronal configuration. The arrow points to a \( \nabla \)-shaped dimming region caused by a jet (not shown in this figure). The box in (g) encloses the dimming channel. The western footpoints of the loops (blue circles) show an apparent slipping motion.

(An animation of this figure is available.)
(NLFFF) and potential field with the weighted optimization method (Wiegelmann 2004) and Greens function method, respectively. We used hmi.sharp_cea_720s series obtained by the SDO/Heliospheric and Magnetic Imager (HMI; Schou et al. 2012) as the boundary conditions. The magnetograms were re-mapped using a cylindrical equal area (CEA) projection and presented as \( B_\theta, B_\phi, B_z \) in heliocentric spherical coordinates corresponding to \( (B_x, B_y, B_z) \) in heliographic coordinates (Sun 2013). The extrapolation was performed within a box of \( 840 \times 448 \times 448 \) uniform grid points, corresponding to \( \sim 300 \times 160 \times 160 \) Mm. We then calculated the squashing factor \( Q \) in the box volume of the potential field with the code introduced by Liu et al. (2016b). The reason to use a potential field model instead of an NLFFF is that structural skeletons of magnetic field are very robust as demonstrated by many earlier studies (e.g., Démoulin 2006, 2007; Liu et al. 2014).

3. Observations and Analysis

The M6.5 flare appeared in NOAA AR 12371 and was associated with a halo CME. As shown in Figure 1(a), the flare emission shows three peaks (at 17:52, 17:58, and 18:12 UT) in Fermi hard X-ray (HXR) flux and reaches maxima in GOES soft X-ray (SXR) flux at 18:23 UT. During the early and impulsive phases, the flare exhibits two ribbons in the chromosphere (denoted by R1 and R2 in Figure 1(b)) with the primary magnetic PIL (green curve) in between. Two HXR footpoint sources (red contours) are seen lying within R1 and R2. Then, R2 displays a fast elongation motion in the southward direction. The elongated brightenings quickly evolve into a V-shaped form (Figures 1(b) and (f)), from which a jet stream of material erupts out abruptly near 18:12 UT. Immediately after the eruption, a \( \nabla \)-shaped dimming region appears in the EUV passbands, then shrinks in size, and is finally closed, leaving only a dim slit open in the west (Figure 1(g)). The dim slit is about 60 Mm long and 6–7 Mm wide, oriented in a direction nearly perpendicular to the primary PIL between R1 and R2, and channeling the flaring region to a neighboring sunspot. Hereafter, we use the term “dimming channel” to describe this structure. The third ribbon of interest (denoted by R3 in Figures 1(c) and (d)) appears at approximately 18:40 UT in the eastern end of the dimming channel, then propagates along the dimming channel to its western end (Figures 1(c) and (d)). During this period, R2 gradually fades away. Two HXR footpoint sources that were initially associated with the R1/R2 ribbon pair are now transitioned to the R1/R3 pair (Figure 1(d)). The propagation of R3 is followed by the apparent slippage of loops, particularly notable at their western ends in the negative polarities (blue circles in Figures 1(h) and (i)).

Four slits, denoted by S1–S4 in Figure 2(a), are set to construct the distance–time stackplots displayed in Figures 2(b)–(d). The section in Figure 2(b) constructed using S1 shows the evolution of the \( \nabla \)-shaped dimming region. Figure 2(c) is a composite stackplot, in which we used S2 to detect the motion of the jet-like eruption and S3 to detect the propagation of R3. When the \( \nabla \)-shaped dimming region reaches its maximum areal extent near 18:12 UT, the jet-like ejection takes place abruptly and travels at a projected speed of 217 km s\(^{-1}\) from the dimming region to a remote site southeastward to the AR. At about 18:40 UT, R3 appears and propagates westward. The speed of R3 propagation is not uniform—it is relatively slow (4–6 km s\(^{-1}\)) at the beginning and at the end of the propagation in stronger magnetic field (\( B_z \sim -580 \) G), and faster (23 km s\(^{-1}\)) in between when crossing over weaker field (\( B_z \sim -140 \) G). In Figure 2(d), the distance–time stackplot constructed with S4 shows the
apparent slippage of the western legs of coronal loops. The apparent slippage is actually along the path of R3, but the position of S4 is slightly displaced from that of S3 to avoid the influence of R3 on the detection of loops. Through S4 the apparent slippage of loops starts around 20:00 UT, ~80 minutes after the onset of R3 propagation and with a rather uniform speed (4 km s$^{-1}$).

Figure 3 shows magnetic field and topology of the pre-flare AR. In the NLFFF (Figure 3(b)), an inner flux-rope-like structure resides between R1 and R2, the rise of which and the subsequent reconnection are presumably pertinent to the observed ribbon pair R1/R2 on the onset of the flare. Note that the field lines in the potential field (Figure 3(c)) show a well-organized pattern—those emanating from the southern portion of R1 are more compact and connecting to R2, whereas those emanating from the northern portion are progressively higher and gradually landing westward. The diverging locations of the footpoints are more readily matched to R3. This potential magnetic configuration schematically explains the transition from R1/R2 to R1/R3 as the reconnection proceeds northward and toward higher altitudes.

Figure 4(a) shows the photospheric $\text{log}Q$ map, where $\text{log}Q = \text{sign}(B_z)\log_{10}Q$ (Titov et al. 2011). The high-$Q$ structures outline the footprints of the prominent QSLs. Although the $\text{log}Q$ map here is rather complicated with many small-scale features, we see two large-scale high-$Q$ structures in the AR complex: a C-shaped one on the left-hand side of the map in the positive polarities (denoted by C), and a roughly transverse Y-shaped one in the negative polarities (denoted by transverse Y). The two arms of the Y interlock loosely with the C, and the trunk of the Y is composed of two high-$Q$ lines extending to the right. To compare with the ribbon morphology, this $\text{log}Q$ map was blended with the maps of AIA 1600 Å (Figure 4(c)) and 211 Å (Figure 4(d)). All the maps were acquired at approximately the same time, 19:36 UT. At this time, R2 is already fading away, whereas R1 and R3 are still seen nearly on their full extent. We see that R1 is roughly matched by a segment of the C, while R3 coincides well with the trunk of the Y, especially the top high-$Q$ line of the Y. We traced the potential field lines from the top high-$Q$ line of the Y. The conjugate footpoints of these field lines land at the same place of the C where R1 is situated (Figure 4(e)). Such a connectivity of the field lines bears a similarity to the apparent slipping loops seen in the AIA EUV passbands.

Figure 5 shows the DEM maps at 19:00 UT. A time series of such DEM maps is available. In the animation of Figure 5, one can clearly identify the apparent propagation of a plasma bulk over the period of 18:40–19:40 UT, which is co-spatial and co-temporal with the R3 propagation, and accompanied by an HXR footprint source (Figures 5(h) and (i)). The propagation of the plasma bulk is best seen in log $T/K \in [5.95, 6.25]$ and is also broadly visible at other temperature bins up to $[6.85, 7.15]$. The thermodynamic evolution of loops is also demonstrated in the animation of Figure 5. The composite DEM image of log $T/K \in [6.55, 6.85]$ (green) and $[6.85, 7.15]$ (red) shows a clear color transition from cooler loops to hotter ones, in a direction consistent with the apparent slipping loops of loops.

4. Discussion and Conclusion

The flare starts as a typical two-ribbon flare (R1/R2), followed by three episodes related to the evolution of R3: a jet-like ejection, the formation of a dimming channel, and the propagation of R3 along the dimming channel. The potential field model as shown in Figure 3 schematically illustrates the spatial relationship among the flare loops. It appears that R1 and R2 are connected by the low-lying field lines above the inner flux rope, whereas R1/R3 connection involves higher field lines, the connectivity of which are continuous while strongly diverging. Furthermore, it is found that: (1) the path of R3 propagation shows a good spatial correlation with a portion of prominent QSL footprints, and (2) the observed R1/R3 loop system can be reproduced by the linkage of a set of modeled...
field lines related to the QSLs. The results are strongly in favor of a slipping-type reconnection for R3.

Presumably, the context scenarios are as follows. When the inner flux rope starts to rise, magnetic reconnection occurs and produces a two-ribbon flare R1/R2. As the reconnection proceeds toward higher altitudes and crosses the QSLs, slipping reconnection sets in and contributes to the ribbon pair R1/R3. Prior to the transition to the slipping reconnection, a jet-like eruption occurs nearby. Its relation to the flare is not clear. Here, we speculate that this jet may alleviate constraints, by pushing aside some of overlying field lines, to facilitate the transition. As the ejecta leave the corona, a full or partial opening of magnetic field occurs that leads to depletion of plasma and a corresponding EUV intensity dimming underneath. The dimming channel evolves from the region associated with the ejection and represents footpoints of field lines that are opened up by reconnections associated with the jet. The apparent slippage of coronal loops manifests the interplay between successive fading of old loops and the appearance of new ones during the cooling process of the reconnection, in the same manner as the apparent growth of post-flare loops commonly seen in two-ribbon flares.

In comparison with the previously reported slipping reconnection events, this one proceeds across a particularly long distance (∼60 Mm) over a long period of time (∼50 minutes). The propagation speed of R3 suggests that

Figure 4. (a) The slogQ map at $z = 0$ (photosphere) scaled between $-\sigma = 5$ (blue/red). The white regions are related to field lines that are open when reaching the lateral/top boundaries of the computational domain. (b)–(d) The slogQ map blended with the maps of HMI $B_z$, AIA 1600 Å, and 211 Å. All maps are re-mapped with the CEA projection. (e)–(f) Top and side views of potential magnetic field lines (colored curves) that are traced starting from the top high-$Q$ line of the Y.
the reconnection is in the regime of slow slipping rather than the slip-running at super-Alfvénic speed. The 80 minute time delay between the propagation of R3 and the apparent slippage of loops of \( \sim 80 \) minutes is probably with respect to the loop length.

The shape of QSL footprints in this event (Figure 4) is similar to that in the MHD simulation by Aulanier et al. (2005) and as depicted in their Figure 3 where two strong high-\( Q \) footprints whirl around each other in a quadrupolar magnetic configuration in a similar way as the C and the top high-\( Q \) line of the Y do in this case (see Figure 4). In other cases of simulation, two high-\( Q \) footprints display an asymmetric double-J shaped pattern (e.g., Aulanier et al. 2012; Janvier et al. 2013). These simulations demonstrate that QSLs are preferable sites for the formation of intense current sheets and reconnection, much like we noted for the spatial coincidence between the QSL footprints and the ribbon pair R1/R3. In both our observation and the simulations, the speed of the slipping reconnection is not uniform. It is yet unclear whether the magnetic field plays a role in determining the reconnection speed, but there is seemingly a correlation between the two, which, of course, requires further investigation.

The DEM analysis provides important information on the thermal behavior of the flare that corroborates the general reconnection scenario. The magnetic reconnection and the resulting flare produce high-temperature plasma initially. In this
case, the loops in the core region can be heated to over 10 MK. The plasma temperature of R3 is found to be widely distributed from 0.6 MK up to 10 MK. The presence of hot plasma at temperatures around 10 MK is presumably attributed to the "chromospheric evaporation" process driven by pressure balance across the transition region (Hirayama 1974). Evaporation fills the reconnected loops with >∼10 MK plasma that have been heated at the footpoints, then these loops gradually cool down.

To summarize, the observation showcases a spectacular propagation of a flare ribbon that indicates a large-scale, long-duration, slipping-type reconnection. The observation reveals two distinct phases: the propagation of footpoints driven by nonthermal particle injection, and the apparent slippage of loops governed by radiative plasma cooling. The key feature of this study is that the thermal evolution of the slipping reconnection has been explored. As a result we found the considerable differences, in timing and speed, between the footpoint propagation and the apparent loop slippage.

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