DIRECT OBSERVATIONS OF TETHER-CUTTING RECONNECTION DURING A MAJOR SOLAR EVENT FROM 2014 FEBRUARY 24 TO 25

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Received 2014 October 1; accepted 2014 November 16; published 2014 December 2

ABSTRACT

Using multi-wavelength data from the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory, we investigated two successive solar flares, a C5.1 confined flare and an X4.9 ejective flare with a halo coronal mass ejection, in NOAA active region 11990 from 2014 February 24 to 25. Before the confined flare onset, EUV brightening beneath the filament was detected. As the flare began, a twisted helical flux rope (FR) wrapping around the filament moved upward and then stopped, and in the meantime an obvious X-ray source below it was observed. Prior to the ejective X4.9 flare, some pre-existing loop structures in the active region interacted with each other, which produced a brightening region beneath the filament. Meanwhile, a small flaring loop appeared below the interaction region and some new helical lines connecting the far ends of the loop structures were gradually formed and continually added into the former twisted FR. Then, due to the resulting imbalance between the magnetic pressure and tension, the new FR, together with the filament, erupted outward. Our observations coincide well with a tether-cutting model, suggesting that the two flares probably have the same triggering mechanism, i.e., tether-cutting reconnection. To our knowledge, this is the first direct observation of tether-cutting reconnection occurring between pre-existing loops in an active region. In the ejective flare case, the erupting filament exhibited an \( \Omega \)-like kinked structure and underwent an exponential rise after a slow-rise phase, indicating that the kink instability might be also responsible for the eruption initiation.

Key words: Sun: activity – Sun: filaments, prominences – Sun: flares – Sun: UV radiation

Online-only material: animations, color figures

1. INTRODUCTION

Unraveling the triggering mechanism of solar eruptions has long been a challenge. A variety of models have been devoted to interpreting the eruption initiations (as reviewed by, e.g., Lin \& Moore 2005; Yurchyshyn et al. 2006; Sterling et al. 2007b; Kim et al. 2008; Green \& Kliem 2009; Liu et al. 2010, 2012, 2008) and has been mentioned in a large number of works in the literature. However, most of the evidence supportive of tether-cutting reconnection are indirect and are only derived from some associated observational phenomena, such as H\( \alpha \), EUV, or X-ray brightenings (e.g., Moore \& Labonte 1980; Sterling \& Moore 2005; Yurchyshyn et al. 2006), the slow-rise motion of filaments (e.g., Sterling et al. 2007b, 2011), the morphological changes of flaring structures (e.g., Kim et al. 2008; Liu et al. 2010), and photospheric sheared magnetic fluxes (e.g., Moore \& Roumeliotis 1992; Moore et al. 2001; Savcheva et al. 2012). So far, direct observations of the tether-cutting reconnection have been very rare. The ideal kink instability of twisted magnetic FRs is considered as another possible initial driver of solar eruptions (e.g., Török \& Kliem 2003; Kliem et al. 2004), which is supported by the frequently observed deformation of the FR axis during eruption (e.g., J\( \ddot{i} \) et al. 2003; Williams et al. 2005; Yang et al. 2012; Shen et al. 2012).

In this study, using the high-resolution, multi-wavelength data from the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory (AIA/SDO; Lemen et al. 2012), we present an unambiguous observation of tether-cutting reconnection during a major solar eruption, which occurred between the pre-existing loop structures in active region (AR) 11990 and most likely triggered the ensuing X4.9 flare and associated halo CME with a combination of kink instability of the filament.

2. DATA AND OBSERVATIONS

AIA/SDO provides full-disk images up to 0.5 \( R_\odot \) above the solar limb with \( \frac{1}{2} \) spatial resolution and 12 s cadence in 10 wavelengths. We mainly used the data (Level 1.5 images)
at seven EUV channels centered at 304 Å (He ii, 0.05 MK), 171 Å (Fe ix, 0.6 MK), 193 Å (Fe xii, 1.3 MK and Fe xxiv, 20 MK), 211 Å (Fe xiv, 2 MK), 335 Å (Fe xxvi, 2.5 MK), 94 Å (Fe xvii, 7 MK), and 131 Å (Fe xviii, 0.4 MK and Fe xx, 11 MK). We de-rotated the AIA data for each of the two flares to two respective times (February 24 21:30 UT and February 25 00:30 UT). The longitudinal magnetograms and continuum intensity images with 1′0 spatial resolution and 45 s cadence from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on SDO help us to analyze the connectivities of the loop structures in AR 11990. We also used RHESSI (Lin et al. 2002) X-ray observations to see the evolution of X-ray sources during the flare. The accuracy in the alignment between AIA and RHESSI images is estimated to be about 3″ (Zehnder et al. 2003).

2.1. Overview of the Event

According to GOES-15 observations, a C5.1 flare took place in NOAA AR 11990 (S12E82) from 21:31 UT on 2014 February 24. The AIA data show that no mass or magnetic structure escaped from the solar surface during the weak flare. Three hours later, an X4.9 flare occurred from the same location with a peak at 00:49 UT on February 25, accompanied by a filament eruption and a halo CME with a median velocity of ∼1041 km s⁻¹ (see the CACTus catalog, http://side.be/cactus). Our observations cover both events well.

2.2. A Flux Rope Appearing during the Confined Flare

Figures 1(a)–(e) display the general evolution of the confined flare in AIA 94 Å (see the animation in the online journal for more details). At 21:22:25 UT, about 8 minutes before the start of the flare, an obvious brightening B₁ appeared beneath the filament. As the flare began and developed, a twisted flux rope FR₁, which is outlined by the helical dotted lines in panels (c) and (d), was observed to wrap around the filament and move upward. Meanwhile, a small flaring loop FL₁ arose at almost the same location as B₁. From RHESSI observations, an X-ray source in the energy range of 10–20 keV (as shown by the red contours in panel (d)) appeared between FR₁ and FL₁ during the flare, suggesting magnetic reconnection is very likely occurring there. The black arrows in panels (c) and (d) point to the filament. It can be seen that the filament passed through and was supported by the dip of FR₁. From 21:34:22 UT to 21:37:48 UT, the top edge of FR₁ rose by about 14 Mm, which derived a mean upward velocity of ∼67.8 km s⁻¹. Then, its apex stopped at a projected height of ∼19 Mm. The kinetics of FR₁ is exhibited by the time-slit map (panel (f)), which is from the AIA 94 Å images along the slit in panel (d). Panel (e) shows the complex loop structures of AR 11990 after the confined flare. Besides the twisted flux rope FR₁, it appears that some other loop structures, such as ML₁ and ML₂, exist in the AR.

Applying the differential emission measure method (see Cheng et al. 2012 for more details) to the AIA simultaneous data in six EUV wavebands, we calculated the emission measure (EM) and the temperature of AR 11990 at the peak of the confined flare, which are displayed in Figures 1(g) and (h), respectively. According to the relationship between EM and density n, the density of FR₁ can be estimated by

\[ n = \sqrt{\frac{EM}{l}}, \]

where n is the density of FR₁, l is the length of FR₁, and EM is the emission measure. As a result, almost equal mean values of ∼8.0 × 10⁹ cm⁻³ of the density are outputted from the different widths (l₁ = 9840 km and l₂ = 4570 km) and the corresponding mean EMs (EM₁ = 6.3 × 10⁸ cm⁻² and EM₂ = 3.0 × 10⁹ cm⁻²) along the solid lines. According to the temperature map, the plasma in the main stem of FR₁ has an average temperature of T₁ = 10 MK. However, the average plasma temperature T₂ in the dip region is only ∼2 MK, which may be related to the cool filament material in the region wrapped by the twisted FR₁.

2.3. Tether-cutting Reconnection Triggering the Ejective X4.9 Flare

As mentioned above, about 3 hr after the confined flare, the filament erupted fully from AR 11990 with a strong X4.9 class flare and a halo CME. During the interval, the loop structures in AR 11990 underwent a series of evolutions and changes, and the most remarkable observational feature is the tether-cutting reconnection which occurred between the pre-existing loop structures in the AR. In Figure 2, we provide distinct evidence for the tether-cutting reconnection during the major solar eruption event.

The AIA 304 Å (panels (a)–(c)) and 94 Å (panels (d)–(f)) images in Figure 2 display the evolutions of the filament and the associated magnetic loops (ML₁, ML₂, ML₃, and ML₄) before the flare. Figure 2(g) is the same AIA 94 Å image as Figure 1(e), but with a larger field of view (FOV). In the 94 Å channel, it can be clearly seen that ML₁ has obviously interacted with ML₂ since ∼23:30 UT, which produced a brightening region (indicated by the red arrows) beneath the filament. Meanwhile, a flaring loop FL₂ (indicated by the yellow arrows) appeared just below the interaction region. We also observed in the 304 Å channel the associated brightening B₂ (panel (a)) underneath the filament and hot mass outflows (as shown by the curved blue arrows in panel (b)) from the interaction region. As the interaction between ML₁ and ML₂ proceeded, some new helical lines connecting the far ends of ML₁ and ML₂ gradually formed and continually added into FR₁, which resulted in the twisted flux rope FR₁ (indicated by the white arrows in panel (i)). Subject to magnetic pressure and tension, FR₁ gradually rose up and expanded with the filament. From the animation in 94 Å (see the animation in the online journal), we can clearly see that FR₁ separated from the interaction region at the onset of the eruption and FL₂ shrank downward simultaneously. All the observations described above are well consistent with the tether-cutting model (Moore et al. 2001). The interaction between ML₁ and ML₂ is very likely a kind of slow magnetic reconnection, which is similar to the photospheric flux cancelation (e.g., van Ballegooijen & Martens 1989; Wang & Shi 1993; Zhang et al. 2001), but occurred in the low corona. It cut the “tethers” constraining the filament and triggered the eruption. Additionally, one AIA 211 Å intensity image was given in panel (h) to display the fine structure of the erupting filament. The obvious spatial difference between the filament and FR₁ (panel (i)) can be easily discerned.

2.4. Tether-cutting Reconnection and Kink Instability Resulting in Filament Eruption

According to the multi-wavelength observations from AIA, the flux rope FR₁ resulting from the tether-cutting reconnection was only visible as emission in the 94 Å and 131 Å wavebands, which indicates that the plasma in FR₁ was very hot with
temperatures as high as $\sim$7–11 MK. Figure 3 displays the main eruption process of the cool filament and the hot FR$_1$ in 131 Å (see the animation in the online journal for more details). From panel (b), it can be seen that FR$_1$ (outlined by the black dashed curve) passed under the filament. At the beginning of the eruption, FR$_1$ seemed to impose an upward driving force to the filament. In the meantime, most likely due to magnetic reconnection, the filament was partially heated and appeared...
as both bright (hot) and dark (cool) erupting features, labeled HF and CF in panel (b), respectively. As the eruption went on, HF and CF both exhibited obvious twisted and kinked structures (see panels (c)–(f)), which suggests that the kink instability may also play a role in the destabilization of the filament.

From Figures 3(e) and (f), we can see that the filament displayed an $\Omega$-like erupting structure, which is quite distinct from the usual reversed-Y shape kink structure (e.g., Ji et al. 2003; Williams et al. 2005; Chen et al. 2013; Cheng et al. 2014) in morphology and rarely mentioned in previous studies. One similar observational case was reported by Romano et al. (2003) and numerically simulated by Török et al. (2010; see Figure 12(b) in their paper). In their works, a very high magnetic twist ($\sim 10^{-11}$) stored in the FR was proposed to explain the uncommon erupting morphology of the filament. For a comparison with their results, we made an estimation. In panel (f), one helical thread (indicated by the blue dotted line) winding around the other bright threads can be clearly identified in the filament. According to our calculation, the length of the filament axis (indicated by the red line) is about 31 Mm when the helix wind around the axis in a circle; the total axis length of the filament is about 194 Mm. Thus, on the assumption of a uniform twist along the axis of the filament, a total twist of $\sim 12\pi$ is derived. This result is comparable to those reported by Romano et al. (2003) and Török et al. (2010).

Additionally, ML3 and ML4 (see Figure 3(b)) are also involved in this eruption. According to the AIA observations, ML4 seemed to twine around HF and was finally ejected with the filament; like FR$'_{1}$, ML3 also passed under the top of the filament and erupted with the entire ejective system. However, due to the projection effect, it is difficult to discern the connectivity of ML3 during the eruption.

To reveal the kinetics of the filament, we made the time-slit map from the AIA 131 Å images and displayed it in Figure 4(a). Due to the limited FOV of Figure 3, the open narrow box in Figure 3(d) only indicates the lower part of the area where the slit image was made. Figure 4(a) shows the time profiles of the projected heights of CF and HF. Note that it is difficult to discern the top edge of CF in the 131 Å images during its rapid rise phase, so the kinetics of CF is not clear after about 00:44 UT. It can be seen that the evolution of the filament eruption within the FOV of AIA divided into two phases: a slow-rise phase and an impulsive acceleration phase. We used a function consisting of both a linear and an exponential component and a pure exponential function to fit the height–time measurements of CF and HF, respectively. The corresponding fitting results are displayed by the blue and red dotted lines in Figure 4(a). It can be found that the heights of CF and HF coincide well with the fitting curves. The exponential growth of the height profile is believed to be the fundamental kinematic feature of the FR eruption due to kink instability (e.g., Török & Kliem 2005). In this aspect, our observations also suggest that the kink instability may play a role in driving the filament eruption. Time variations of the velocities of CF and HF were derived from the fitting results and plotted in Figure 4(b). According to the velocity curves, CF rose slowly with a mean velocity of 2.7 km s$^{-1}$ prior to the flare, which was very likely caused by the tether-cutting reconnection, as reported in previous studies (e.g., Sterling et al. 2007a, 2011).
Figure 3. AIA 131 Å images showing the eruption of the filament and the associated hot flux ropes (also see the animation). The FOV is 200” × 150”.

(An animation and a color version of this figure are available in the online journal.)

As for HF, its velocity increased from tens of km s$^{-1}$ to more than 1200 km s$^{-1}$ during a period of ~6 minutes, which derives an average acceleration of ~3.5 km s$^{-2}$.

In addition, we calculated the AIA intensity fluxes of the tether-cutting reconnection region (as indicated by the dotted box in Figure 2(e)) in seven EUV channels. For convenience, each intensity flux was divided by its initial value. In Figure 4(c), the time profiles of the GOES 1–8 Å flux (dotted line) and the AIA intensity flux in 94 Å (blue), 304 Å (red), 131 Å (purple), 171 Å (black), 193 Å (orange), 335 Å (turquoise), and 211 Å (green) are plotted. It is apparent that the intensity fluxes in all seven AIA channels, especially in the 94 Å, 304 Å, and 131 Å channels, increased within the period of about 40 minutes before the X-class flare. The associated process of energy release very likely results from the tether-cutting reconnection.

3. SUMMARY AND DISCUSSION

We presented detailed observations of two successive flare cases occurring in NOAA AR 11990 in this work. Although one is a C5.1 confined flare and the other is an X4.9 ejective flare with a halo CME, some similar observational features, such as the preflare brightenings (B1 and B2), the small flaring loops (FL1 and FL2), and the large-scale twisted FRs (FR1 and FR’1), both appeared in the two cases. All these observations are well consistent with the tether-cutting model (Moore et al. 2001), which strongly suggests that the two flares probably have the same triggering mechanism, i.e., tether-cutting reconnection. Compared with the other similar observations in previous reports (e.g., Kim et al. 2008; Liu et al. 2010), our observations clearly exhibit the detailed process of tether-cutting...
reconnection, which occurred between the inner legs of pre-existing sheared magnetic loops in the AR. To our knowledge, this is the first direct observation of tether-cutting reconnection. According to our results, the reconnection region is most evident in the AIA 94 Å channel, indicating that the temperature of the plasma in the reconnection region is about 7 MK.

To describe the detailed process of the ejective eruption studied here, we have to think about the connectivity of ML3. According to the AIA observations, ML3 might connect with the filament or and ML4, or with ML1 through reconnection during the eruption. From Figure 2, it seems that the right (northern) end of ML3 was rooted in the same magnetic field region as that of ML2. Thus, we prefer to believe that the tether-cutting reconnection might also occur between ML1 and ML3 before the flare, which produced another large-scale FR like FR′1. In Figure 5, we drew a schematic diagram on the background of HMI continuum intensity images to display this possible scenario and describe the early phase of the ejective eruption. Before the onset of the eruption, the filament was located at the PIL of the AR, and overlaid by the sheared fields ML1, ML2, and ML3, which connected the positive polarity regions P2 and P1 with the negative polarity regions N3, N2, and N1, respectively. ML4 winded around the filament with one end rooted in the positive polarity region P3. While the inner legs of ML1, ML2, and ML3 approached each other, the reconnection occurred between ML1 and ML2 and between ML1 and ML3, resulting in the formation of the flux ropes FR′1 (enhanced FR1) and FR2 and the small flaring loop FL2. As the “tethers” (ML1, ML2, and ML3) were cut, the outward magnetic pressure was out of balance with the downward magnetic tension and then caused the whole field to expand. Meanwhile, the filament underwent an exponential rise and exhibited an Ω-like erupting structure subject to kink instability.

**Figure 4.** (a) Time-slit map from the AIA 131 Å images; (b) time variations of the projected velocities of CF and HF; (c) time profiles of the AIA intensity flux in 94 Å (blue), 304 Å (red), 131 Å (purple), 171 Å (black), 193 Å (orange), 335 Å (turquoise), and 211 Å (green) from 00:00 UT to 01:00 UT; The black dotted curves in panels (b) and (c) are the light curves from the GOES 1–8 Å channel.

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

**Figure 5.** A schematic diagram on the background of HMI continuum intensity images to display the possible scenario and describe the early phase of the ejective eruption.
Figure 5. Three-dimensional illustrations describing the early phase of the ejective eruption case. The backgrounds are HMI continuum intensity images. The FOV is 200′′ × 160′′.

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