A Study of External Magnetic Reconnection that Triggers a Solar Eruption

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Abstract

External magnetic reconnection (EMR) is suggested to play an essential role in triggering a solar eruption, but is rarely directly observed. Here, we report on a filament eruption on 2014 October 3 that apparently involves the process of an early EMR. A total of $1.7 \times 10^{20}$ Mx flux was first canceled along the filament-related polarity inversion line over 12 hr, and then the filament axis started to brighten in extreme ultraviolet (EUV). An impulsive EUV brightening began 30 minutes later, and we attribute this to EMR, as it is located at the center of a bidirectional outflow with a velocity of 60–75 km s$^{-1}$ along large-scale magnetic loops from active regions NOAA 12178 and 12179, respectively, and over the filament mentioned above. Following the EMR, the filament was activated; then, partial eruption occurred 6 minutes later in the west, in which the decay index above the magnetic flux rope (MFR) reached the critical value of 1.5. The observations are interpreted in terms of underlying magnetic flux cancelation leading to the buildup and eventual formation of the MFR with a filament embedded in it, and the MFR is elevated later. The activated MFR rises and pushes the overlying sheared field and forms a current sheet causing the EMR. The EMR in turn weakens the constraining effect of the overlying field, leading to the arising of the MFR, and subsequently erupting due to torus instability.

Key words: Sun: activity – Sun: atmosphere – Sun: evolution – Sun: filaments, prominences

Supporting material: animations

1. Introduction

Solar eruptions are generally believed to involve magnetic reconnection, a process in which the efficient release of magnetic energy gives rise to plasma heating and particle acceleration in a narrow region (Petschek 1964; Coppi & Friedland 1971). But the exact details of the reconnection process, and the role of reconnection in the eruption, are still debated (e.g., Forbes 2000).

Solar eruptions show that there exist two kinds of magnetic reconnections, internal magnetic reconnection (IMR) and external magnetic reconnection (EMR), which largely depend on the proposed pre-eruption magnetic topology. In a bipolar magnetic configuration, IMR, instead of EMR, would happen to initiate a corresponding eruption, as exemplified by the classical “CSHKP” reconnection scenario, i.e., the “standard flare model” (e.g., Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976). However, in a multipolar magnetic structure, as has been suggested in the well-known “break-out model” (Antiochos et al. 1999), a key magnetic reconnection may occur above the erupting field, e.g., at the null point above the underlying sheared arcade. Such external reconnection may allow the erupting structure to burst open, or even lead to the formation of a flux rope during the eruption. In this Letter, the term “EMR,” refers to a reconnection that occurs above a magnetic structure to be erupted, which is much different from the traditional IMR.

Existing models of solar eruptions provide different important mechanisms for initiating eruptions mostly based on IMR instead of EMR. A flux rope was proposed to form, and would probably erupt due to IMR in the “tether-cutting model” (e.g., Moore et al. 1991, 2001) and “flux-cancellation model” (Linker et al. 2003). In the “magnetic catastrophe model” (e.g., Lin et al. 2002; Zhang et al. 2005), the IMR plays the essential role of driving a solar eruption. In addition, a flux rope/filament was also discussed to lose equilibrium and erupt owing to a torus instability, not necessarily involving an active role of magnetic reconnection (e.g., Fan 2005; Rust & LaBonte 2005; Kliem & Török 2006). As mentioned earlier, EMR is often indicated at the interface above the flux domain in a multipolar magnetic configuration, e.g., the “break-out model” (Antiochos et al. 1999; Karpen et al. 2012) and the “flux emergence model” (Chen & Shibata 2000), as a key process to destabilize the magnetic system, leading to the eruption. In order to better understand the solar eruption mechanism, it is important to directly observe the EMR and find its relationship with other processes involved in solar eruptions.

However, EMR is expected to be weak, and thus difficult to directly observe. It has not been well investigated in observations. The role of EMR in solar eruptions has only been studied in a few papers. Sterling & Moore (2001) proposed two sequences of EMRs contributing to the onset of homologous solar flares. Joshi et al. (2016) suggested that magnetic reconnection could occur between an expanding flux rope and the nearby arcades overlying another filament, and further destabilize the filament.

Another component of this work is on flux cancellation, an essential process that forms a unique magnetic structure leading to eruption. Wang & Shi (1993) proposed a two-step reconnection scenario in which the first-step reconnection represented by flux cancellation in the lower atmosphere would eventually lead to the second-step reconnection in the corona in the form of explosive energy release. Flux cancellation was
suggested to contribute to the formation of filaments (e.g., Martin et al. 1985; van Ballegooijen & Martens 1989), and sustaining newly formed filaments (Mackay et al. 2010), as well as modifying the magnetic field configuration of filaments, to trigger the eruption (e.g., Van Driel-Gesztelyi et al. 2014). Combining observations of flux cancellation together with EMR, one can learn how magnetic reconnections in different layers of the solar atmosphere act on each other to cause a solar eruption, which can bring new clues for understanding the eruptive mechanisms.

In this investigation, we analyze excellent observations on 2014 October 3 of how photospheric flux cancellation drove the buildup of a filament and a possible flux rope, and, in particular, how EMR occurred in this system. We argue that EMR was followed by a torus instability and a subsequent eruption. In Section 2, we present the observations and results, which are followed by discussions and conclusions in Section 3.

2. Observations and Results

The studied region and structure are located between two active regions (ARs): NOAA 12178 and 12179, at N11°E05° in heliographic coordinates on 2014 October 3. The eruption process of this case was studied by Xue et al. (2016), who suggested a internal reconnection occurring between the ambient fibrils and the filament itself to relax magnetic tension during the eruption. From a different perspective, here we focus on the whole process, especially the role of EMR, before the eruption.

The analysis is based on Extreme Ultraviolet (EUV) imaging data from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012), and magnetograms from HMI on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012), for which the typical cadences are 12 and 45 s, and the pixel sizes are 0.6 and 0.5 arcsec, respectively. The Hα images from the New Vacuum Solar Telescope (NVST; Liu et al. 2014) are also used to check the filament activity. The solar rotation effect on all SDO data is removed through registering to 07:00 UT on October 3, at which time the Hα images have been coaligned.

2.1. Photospheric Flux Evolution Prior to the Eruption

Data from SDO/HMI present the distribution and evolution of magnetic flux density in the region of interest. Figure 1(a) shows an HMI image at 18:00 UT on October 2. The filament is situated above the PIL as indicated by the yellow dotted line between ARs 12178 and 12179. Before the EUV emission along the PIL is enhanced, photospheric flux undergoes continuous cancellation in the white box region in Figure 1(a) from 18:00 UT on October 2. Figures 1(b)–(e) show the detailed evolution of magnetic field within the white box in Figure 1(a). The opposite fluxes on two sides of the PIL continuously approach each other, resulting in continuous flux cancellation along the PIL as time passes. A total of $1.7 \times 10^{20}$ Mx of flux is cancelled in the white box over about 13 hrs from 18:00 UT on October 2 to 07:04 UT on October 3 before the filament loses balance. The average rate of flux disappearance is $1.3 \times 10^{19}$ Mx hr$^{-1}$.

Figures 1(f)–(j) present the coaligned Hα images from NVST, which show the filament activity. Figures 1(g)–(j) are a subset of Hα images in the black box denoted in Figure 1(f). In this figure as well as in the following ones, the cyan (or red later) and dark blue contours show the positive and negative longitudinal magnetic field obtained by SDO/HMI at the levels of ±[100, 1000] G respectively. The filament stays in balance until 07:28 UT, following which it will be activated to experience a partial eruption in the west. We look into the possible triggering process based on an analysis of EUV data.

2.2. External Magnetic Reconnection

Thanks to the EUV observations from SDO/AIA, a clear signature of EMR is manifested right above the region of photospheric flux cancellation. Figures 2(a)–(h) show the morphology of the EMR in seven different AIA passbands at 07:10 UT; the location of EMR is indicated by the white arrows in Figures 2(b)–(h). An Hα image at 07:26 UT is presented in Figure 2(i) to show the EMR (see the red cross symbol) occurring above the northern part of the associated filament (see the black arrow). The detailed process of the EMR and its triggering of the torus instability of the underlying flux system are explained below as shown in Figures 3 and 4.

After about 13 hrs of flux cancellation, the EUV emission along the PIL started to increase at about 06:32 UT on October 3 as shown in the EUV running-difference images, especially in the 304 Å passband (see the black arrows in Figures 3(a)–(c)). About 20 minutes later, at ≈07:04 UT, the onset of an impulsive EUV brightening occurred that reached a peak at about 07:10 UT (see the yellow arrows in Figures 3(c)–(d)). The impulsive brightening is likely caused by the EMR. At about 07:28 UT, the filament becomes unstable with its axial body brightening and expanding. At ≈07:34 UT, the filament starts to convert the twist into an upward writhhe (see Figure 3(f)), which may indicate an internal kink instability (e.g., Török & Kliem 2003; Fan & Gibson 2004).

As shown in the running-difference images in the 171 Å passband, a new coronal structure is clearly produced by the EMR (see the yellow arrows in Figures 3(g)–(l), and also the one in Figure 3(e)). In Figure 3(g), two yellow curves outline two sets of coronal loops that form an X-type structure where the EMR occurs at the X-point. These loops originate from ARs 12178 and 12179, respectively. The EMR creates a new set of longer coronal loops denoted by the yellow curve in Figure 3(k)), which connects the negative polarity of AR 12179 and the positive polarity of AR 12178.

We use a time-slice stacking plot made from a sequence of EUV images to reveal the detailed dynamic process associated with the EMR. Figure 4(b) presents such a plot from 304 Å images with the slice chosen along the PIL as indicated by the curve connecting A–B (see the black mark in Figure 4(a)); the time is from 06:30 to 08:30 UT. In Figure 4(b), the EUV brightening occurs first near the middle of the filament axis; then propagates toward the site of occurrence of the EMR as indicated by the two dotted rectangles; the EMR occurred at ≈07:04 and finished at ≈07:25 UT (see the two vertical solid lines). About 3 minutes later, the filament becomes unstable, manifested by increasing EUV brightening along its axis and a writhing action in the middle from 07:28 to 07:35 UT.

The time-slice diagram also reveals that the flow produced during the EMR changes its direction from the earlier bidirectional flow to a unidirectional one at a later time, Figure 4(d) presents the EUV brightness variation in the 304 Å passband along the slice C–D marked in Figure 4(c). This curved slice encloses both the coronal loops joining the X-point of the EMR and the later newly produced loops. It shows that a
Bidirectional flow is dominant at the beginning of the EMR, then is gradually replaced by a unidirectional flow during the EMR. Based on a linear fitting (see the dashed lines in Figure 4(d)), the bi- and unidirectional flows are estimated to have similar velocities of 60–75 km s$^{-1}$; the flow velocity increases to 100 km s$^{-1}$ when the filament is erupting. The change of flow direction provides good evidence to confirm that new coronal structures are produced by the EMR. In other words, the EMR apparently modifies the topology of the magnetic field overlying the filament.

In addition, Figure 4(f) presents a time-stacking plot along the slice across the writhed section of the filament (see the slice E–F in Figure 4(e)) to show the writhing motion of the filament. As indicated by the black arrows in Figure 4(f), there are at least three groups of threads of the filament writhing together to indicate a kink instability inside the filament. When the west half of the filament started a continuous eruption at 07:36 UT (see the white arrow in Figure 4(f)), the writhed part did not show an outward eruption, but a backward motion toward the solar disk, which was pushed by the west erupting part.

### 3. Discussions and Conclusion

Based on the observations and sequence of activities from AIA and HMI instruments on board SDO, and H$\alpha$ images from
NVST, we construct a cartoon model to illustrate the evolution process of this event (Figures 5(a)–(d)). Figures 5(b) and (d) are side views of the 3D cartoon, corresponding to the top views in Figures 5(a) and (c). First of all, as shown in Figure 5(a), the quadrupole magnetic field system is assumed to contain a magnetic flux rope (MFR), which is manifested by the associated filament (see the yellow twisted curves) along the PIL. The northern part of the flux rope is held down by the overlying field represented by the blue field lines in AR 12178. Continuous flux cancellation leads to the buildup or strengthening of the flux rope, and drives a continuous rising; a similar scenario was shown in Zhou et al. (2016). The rising flux rope pushes against the overlying arcade field, leading to the formation of an external current sheet (see Zhou et al. 2011) and subsequently, EMR occurs between the field lines marked by purple and blue lines in Figures 5(a)–(b), which are from AR 12179 and 12178, respectively. As a result, the EMR changes the coronal structure, producing larger coronal loops as marked by the cyan color at the top and shorter coronal loops by the red color at the lower height close to the PIL in Figures 5(c)–(d). The plasma flow produced by the EMR first propagates along the purple and blue field lines, and later along the newly formed cyan lines. This is why the bidirectional flow is gradually replaced by the unidirectional one. Finally, the

Figure 2. EMR shown in EUV images of eight wavelengths (see the arrows in panels (a)–(h) and in an Hα image by a red cross above the filament (see the black arrow) in panel (i). (An animation of this figure is available.)
Figure 3. EUV running-difference images showing the filament axial brightening (see black arrows in panels (a)–(c)), and the EMR (see yellow arrows in panels (c)–(e)) at 304 Å, as well as newly produced structures at 171 Å (see yellow arrows in panels (g)–(l)). Two yellow curves in panel (g) denote the arcade field associated with the EMR. The long yellow curve in panel (k) marks one of the resulting field lines.

(An animation of this figure is available.)
EMR weakens the constraining effect of the overlying sheared
arcade, leading to the torus instability of the flux rope, as
illustrated in Figures 5(c)–(d).

EUV and HMI observations indicate a quadrupole field for the pre-existing topology, which is supported by the 3D coronal magnetic structure based on an extrapolated potential field model (Wheatland 2007) shown in Figure 5(e). The quadrupole field is denoted by purple, green, blue, and red field lines. Owing to the limitation of the potential field method, the flux rope system is not reproduced from the extrapolation. The configuration of the quadrupole field indicates a null point or separatrix in the region, but the correct locations of which would be too sensitive to be found by the computations in the actual 3D magnetic field. Furthermore, the presence of a flux rope underneath may change the position of the null point or make it “invisible” from the extrapolation. This might be one of the reasons why we do not actually find a null point using the method of Zhao et al. (2008). However, the EUV images from observations, e.g., Figures 2–4, and the extrapolated topology features are suggestive of the presence of a 3D null point, or a configuration in favor of the occurrence of EMR. The activated filament may push the “invisible” null point or separatrix to cause the EMR. Then the EMR reduces the overlying field to cause the filament instability.

Why only the west part of the filament first erupted can be learned from the distribution of the decay index (n) of the external field above the PIL, which must be sufficiently big for the stability of MFRs/filaments (e.g., Filippov et al. 2014). This

Figure 4. Time-stacking plots of EUV brightness at 304 Å (panels (b), (d), and (f)) along the slices A–B, C–D, and E–F as marked in panels (a), (c), and (e), respectively. Two dotted rectangles in panel (b) denote EUV brightening along the filament axis propagated toward the position of the EMR. Dashed lines in panel (d) shows linear fits to the flow velocities during the EMR. In panel (f), three black arrows denote the kinked threads of the filament, but the eruption begins a few minutes later at 07:36 UT (see the white arrow).

(An animation of this figure is available.)
Decay index \( n \) describes the vertical gradient of the external field. According to Bateman (1978), \( n \) is defined as \( n = \frac{d \ln B_{\text{ex}}}{d \ln Z} \), where \( B_{\text{ex}} \) is the horizontal component of the external field, and \( Z \) refers to the coronal height. A critical value of 1.5 was often reported as the theoretical threshold for the onset of the instability of flux ropes/filaments (e.g., Török & Kliem 2007; Aulanier et al. 2010; Liu et al. 2016; Zuccarello et al. 2016). Figure 5(f) presents the distribution of the decay index above the filament PIL, calculated from the potential field model. The yellow dashed curve in Figure 1(a) is the PIL. We show in Figure 5(f) the values of the decay index at heights \( Z \) above the photosphere for each point along the yellow dashed curve. The horizontal axis in Figure 5(f) is the distance along the PIL in arcseconds. The black line in Figure 5(f) denotes the critical value \( n = 1.5 \). The critical value of \( n \) has a height decreasing from east to west. It is reasonable that the west part of the filament erupted first according to the model of torus instability. When the eruption began, the untwisting motion of the filament was explained by Xue et al. (2016) as a reconnection occurring between the ambient fibrils and the filament to relax magnetic tension.

Here we summarize the timeline of the observed sequence of activities that involve a rarely observed EMR.
1. From 18:00 UT on October 2 to 07:04 UT on October 3, photospheric flux is cancelled along the PIL between ARs 12178 and 12179. A total of $1.7 \times 10^{20}$ Mx of flux is cancelled before the filament eruption. We believe that the photospheric flux cancellation causes the buildup of a flux rope and the appearance of the associated filament, and also drives the gradual rising of the flux rope system.

2. From 06:32 to 07:04 UT on October 3, EUV emission is enhanced along the filament axis, and propagates through the corona toward the EMR. Such axial enhanced EUV emission is explained as reconnection at the interface between the rising flux rope/filament and the ambient coronal field.

3. From 07:04 to 07:25 UT, an EMR event manifests itself as impulsive EUV brightening with a peak at 07:10 UT, during which time a bidirectional flow is observed first and is gradually replaced by an unidirectional flow later. It is considered that the ascending flux rope/filament pushes against the overlying sheared arcades, forming a strong current sheet and triggering the EMR. New long coronal loops are produced by the EMR to carry the unidirectional flow.

4. From 07:28 to 07:35 UT, the filament is activated, showing an expanding motion and enhanced EUV brightening. The filament also converts parts of its twists to writhe in the middle to indicate a kink instability. This occurs because the EMR is weakening the constraining effect of the overlying sheared arcade, allowing the flux rope and the embedded filament to expand and rise up with a noticeable velocity.

5. After 07:35 UT, the west part of the filament starts to erupt, which is consistent with the model of torus instability, since the critical value of the decay index above the flux rope/filament is located much lower in the west than in the east.

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