A Two-step Magnetic Reconnection in a Confined X-class Flare in Solar Active Region 12673

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Abstract

Solar flares are often associated with coronal eruptions, but there are confined ones without eruptions, even for some X-class flares. How such large flares occurred and why they are confined are still not well understood. Here we studied a confined X2.2 flare in NOAA Active Region 12673 on 2017 September 6. It exhibits two episodes of flare brightening with rather complex, atypical ribbons. Based on topology analysis of the extrapolated coronal magnetic field, we revealed that there is a two-step magnetic reconnection process during the flare. Prior to the flare, there is a magnetic flux rope (MFR) with one leg rooted in a rotating sunspot. Neighboring the leg is a magnetic null-point structure. The sunspot drives the MFR to expand, pushing magnetic flux to the null point, and reconnection is first triggered there. The disturbance from the null-point reconnection triggers the second reconnection, i.e., a tether-cutting reconnection below the rope. However, these two reconnections failed to produce an eruption, because the rope is firmly held by its strapping flux. Furthermore, we compared this flare with an eruptive X9.3 flare in the same region 2 hr later, which has a similar MFR configuration. The key difference between them is that, for the confined flare, the MFR is fully below the threshold of torus instability, whereas for the eruptive one, the MFR reaches entirely above the threshold. This study provides good evidence supporting that reconnection alone may not be able to trigger eruption; rather, MHD instability plays a more important role.

Key words: Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: magnetic fields

Supporting material: animation

1. Introduction

Solar flares and coronal mass ejections (CMEs) are the most violent activities on the Sun. Now it is well recognized that they are different manifestations of the same process: sudden reconfiguration and energy release of the magnetic field in the solar corona. Observations show that flares and CMEs are closely related to each other (Zhang et al. 2001, 2004; Qiu et al. 2004; Temmer et al. 2008). Statistical studies reported that ~90% of X-class flares are associated with CMEs (Yashiro et al. 2005; Wang & Zhang 2007). There are also CME-less X-class flares, and some of them are totally confined, that is, no eruption can be seen during the flares, which is different from flares in which coronal eruption can be seen but fails to escape into the interplanetary space (e.g., Ji et al. 2003). For example, in NOAA Active Region 12192, six X-class flares occurred, with the largest one reaching X3.1, but none of them were associated with CMEs or coronal eruption. How such large flares occurred and why they are confined are still not well understood.

Magnetic reconnection is the central mechanism in producing flares, and many theoretical models have been proposed to explain how the coronal magnetic field can be led to reconnect and/or erupt. A major part of the models (e.g., Török & Kliem 2005; Kliem & Torok 2006; Fan & Gibson 2007) assumes that, prior to flare, there exists a coherent set of twisted magnetic flux, known as the magnetic flux rope (MFR), which is subjected to some kind of ideal magnetohydrodynamics (MHD) instabilities and erupts during the flare, forming a CME. During the eruption, reconnection can then be triggered below the rising MFR. It has been suggested that the occurrence of a CME is determined by the decay index of the strapping field of the MFR, which is derived from the torus instability (TI) of a theoretical MFR model (Kliem & Torok 2006).

On the other hand, some models consider that the reconnections can happen without the necessity of a preexisting MFR. In the well-known tether-cutting model (Moore & LaBonte 1980; Moore et al. 2001), the pre-flare magnetic fields are strongly sheared, and photospheric converging flows or flux cancellation can push the sheared fields on opposite sides of the neutral line toward one another, resulting in reconnection of them. If the reconnection becomes runaway, that is, a feedback between the reconnection and upward expansion of the reconnected long field lines is triggered, a flare will result. Then, an MFR will form through the continuous reconnection, the MFR can erupt to a CME, or it is confined by a strong overlying field. In another commonly invoked model, known as the magnetic breakout model (Antiochos et al. 1999), it is proposed that reconnection is triggered above the sheared arcades, which are embedded in a quadrupolar configuration that contains a magnetic null point. The shearing of the inner arcade increases its magnetic pressure, making the arcade expand, which will press the null point and trigger the reconnection. The reconnection weakens the constraint of upper magnetic loops and triggers the eruption through a feedback between the expansion of the inner arcade and null-point reconnection.

Unraveling what determines the condition for eruptive or noneruptive (i.e., confined) flares is critical in understanding the mechanism of CMEs. Attempts have been made in observational studies. For instance, Sun et al. (2015) suggest that some relative measure of magnetic nonpotentiality may determine the eruptiveness of active regions. Liu et al. (2016a) suggest that the existence of CME seeds, e.g., some sheared or twisted core field, and the weak enough constraint of background magnetic field are required...
for producing an eruption. Numerical MHD simulations have also been performed to investigate this question. Török & Kliem (2005) simulated two cases of evolution of a kink-unstable MFR. One successfully erupts, while the other is confined because of a stronger overlying field. DeVore & Antiochos (2008) also showed a set of simulations of a confined filament/sigmoid. They found that the erupting filaments are decelerated by the background magnetic field in the high corona. It seems that the overlying field plays a key role in determining whether CMEs will be formed. Furthermore, in a simulation of the formation and eruption of a sigmoidal MFR by Aulanier et al. (2010), it is indicated that reconnection alone is unlikely able to produce the eruption. The MFR can only erupt when it reaches the height to trigger the TI.

In this paper, we investigated an interesting X-class flare event, in which all three structures as proposed in the theoretical models, namely, an MFR, a tether-cutting configuration, and a magnetic null point, are involved, while the flare is still confined. This flare of X2.2 class occurred in NOAA AR 12673 just 2 hr before the well-known X9.3 eruptive flare in the same region (the largest flare in solar cycle 24; see Yang et al. 2017; Hou et al. 2018; Li et al. 2018; Yan et al. 2018). Observations show that there are two episodes of flare brightening, but without eruption. With a magnetic analysis, it is found that during the flare magnetic reconnection is triggered first at the null point beside the MFR, and then followed by a tether-cutting reconnection below the rope, while the rope is firmly confined by its overlying flux. By comparing the magnetic configuration of this flare with that of the X9.3 flare, an important insight can be gained into understanding the key factor determining the eruptiveness of flares. The rest of the paper is organized as follows. Data and methods are presented in Section 2, then the results are given in Section 3, and finally conclusions are made in Section 4.

2. Data and Methods

For obtaining the full temporal and spatial structures of the X2.2 flare, we used the extreme-ultraviolet (EUV) images taken by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO). It provides seven EUV filtergrams with a spatial resolution of 0′′.6 pixel⁻¹ and a cadence of 12 s simultaneously. The magnetogram, which can help us understand the underlying physical process, was taken by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012;
Schou et al. (2012), also on board SDO. Since the 3D coronal magnetic field can hardly be measured, we extrapolated it from the HMI vector magnetogram, in particular, the Space-weather HMI Active Region Patch (SHARP; Bobra et al. 2014) data set. Furthermore, the photospheric motion, which is closely related to the evolution of the coronal magnetic field, is derived from the HMI continuum map, which has a spatial resolution of 0.5 arcsec and a cadence of 45 s, using the Fourier local correlation tracking (FLCT) method (Welsch et al. 2004). Finally, the soft X-ray (SXR) flux gained from the GOES-13 satellite is used in our study in order to determine the temporal evolution of the flare.

The coronal magnetic field is extrapolated based on the nonlinear force-free field (NLFFF) model using the CESE–MHD–NLFFF code developed by Jiang & Feng (2013), which is an MHD-relaxation method. It solves a set of modified MHD equations in the zero-\(\beta\) environment with a friction force. It uses an advanced conservation-element/solution-element (CESE) spacetime scheme on a nonuniform grid with parallel computing (Jiang et al. 2010). It was well tested by different benchmarks, such as the analytic force-free solutions (Low & Lou 1990) and numerical MFR models (Titov & Demoulin 1999; van Ballegooijen 2004). Its applications to the SDO/HMI vector

Figure 2. Basic configuration of the pre-flare coronal field extrapolated for the time of 08:36 UT. The purple lines in all panels indicate the MFR. In panel (a), the background is plotted for the photospheric \(B_z\) map, and the green lines are the strapping field lines of the MFR. In panel (b), the background shows the twist number \(T_w\) map computed for the bottom surface. (c) Continuum image overlaid with derived transverse velocity \((v_x, v_y)\) of the photospheric motion. The red line shows the contour of the area with high curl of the photospheric transverse velocity. (d) Longitudinal cross section and its position, which are shown in panel (b) by the thick line. The background is the distribution of magnetic twist number \(T_w\). The black line denotes the position where the decay index of the strapping field is \(n = 1.5\). In all panels the yellow curves are contours of \(T_w = 1.5\).
magnetograms enable us to reproduce magnetic configurations in very good agreement with corresponding observable features, including coronal loops, sigmoids, and filaments (Jiang & Feng 2013; Jiang et al. 2014).

The magnetic field data are then analyzed through calculating the magnetic twist number $T_w$, magnetic field decay index $n$, and magnetic squashing factor $Q$. The twist number $T_w$, which is defined by

$$T_w = \int L \frac{(\nabla \times B) \cdot B}{4\pi B^2} dl,$$

quantifies the winding turns between two infinitesimally close field lines (Liu et al. 2016b). The decay index $n$, which is calculated by $n = -\partial (\log B)/\partial (\log h)$, describes the decaying speed of the strapping field strength $B$ with distance $h$ from the bottom surface. Here $B$ is approximated by the potential field, specifically, its component perpendicular to the path direction along which we compute $n$. Previous works indicate that the torus instability of the constrained MFR will be triggered when $n > 1.5$ (Bateman 1978; Kliem & Torok 2006). For analyzing the magnetic topology, we calculated the magnetic squashing factor $Q$ (Titov et al. 2002), which can be used to locate thin layers across which the magnetic field line mapping changes drastically (Demoulin 2006). Such layers are so-called quasi-separatrix layers (QSLs), where 3D magnetic reconnection is prone to occur.

3. Results

3.1. Observations

Figure 1 displays SXR flux and AIA observations (in channels 304 and 94 Å) of the X2.2 flare. The SXR light curve
Figure 4. Comparison between AIA 94 Å images and extrapolated structures, for the pre-flare phase (panel (a)) and the post-flare phase (panel (b)). In the left panels, we use the same colors to indicate the magnetic structures as shown in Figure 3, and the blue lines show the magnetic lines the wave-like disturbance is propagating along. In the right panels, the magnetic field is extrapolated for the post-flare state at time 08:36 UT. The cyan lines represent the newly formed post-flare loops, the purple lines show the newly magnetic lines connected to two far-end polarities, and the red lines are for the post-flare null-point configuration. Panels (c) and (d) are a side view of panels (a) and (b), respectively.

shows that this flare starts at 09:01 UT and peaks at 09:10 UT. Interestingly, there is a short bump of the light curve between the beginning and peak of the flare, and the derivative of the SXR flux exhibits two peaks, one at 09:04 UT and the other at 09:08 UT. Such a two-peak feature indicates that there are two episodes of magnetic reconnection during the flare. Indeed, from the AIA observations, it can be found that at 08:58 UT a cusp in the north of the flare core becomes bright (see Figures 2(b) and (f)), along with some small-scale material ejecting outward. Immediately, a wave-like disturbance, as can be seen in the 304 Å image, propagates outward from the bright cusp. Then, the first flare ribbons formed (denoted as ribbons 1 in Figure 1(c)). The left part of ribbons 1 is shorter and brighter than the right part. With the wave-like disturbance propagating to the end of a hook-like bright loop, the second set of flare ribbons, which is much brighter than ribbons 1, are observed (denoted as ribbons 2 in Figure 1(d)). The left part of ribbons 2, which is still short and bright, seems to be closer to the PIL than that of ribbons 1, while its right part extends to the north of that of ribbons 1. This means that these two sets of flare ribbons, although close to each other, are associated with different reconnection events. Furthermore, there is no separation motion of the flare ribbons between each other. With the brightening of ribbons 2, an inverse S-shaped hot loop is seen in the AIA 94 Å channel (Figure 1(h)). About 30 minutes after the flare onset, post-flare loops can obviously be seen in the same channel (Figure 1(i)). From observation of AIA, no eruption can be seen accompanying this flare. Also from the SOHO/LASCO observation, CME is not detected during this flare (Liu et al. 2018).

3.2. Magnetic Field Configuration

Figure 2 shows the basic configuration of the pre-flare coronal field, reconstructed for a time of 08:36 UT. From the distribution of magnetic twist number, it can be seen that there is a set of twisted field lines with more than one and a half turns ($T_r < -1.5$), which constitutes an MFR lying roughly along the main PIL. The northern (negative-polarity) foot of the MFR is found to coincide with a counterclockwise-rotating sunspot (see also Yan et al. 2018), and particularly, the area of strongest twist is cospatial with the strongest vorticity of the photospheric surface motion. This provides strong evidence that the rotating sunspot built and was further strengthening the MFR. In Figure 2(d), we show the decay index $n$ of the overlying field of the MFR at a central cross section of the volume. It can be seen that the rope is fully below the line with $n = 1.5$, which is found to be a typical threshold of TI in theoretical and numerical calculations for a line-tied arch MFR (Aulanier et al. 2010; Zuccarello et al. 2016). This suggests that the rope is firmly confined by its overlying field, which can explain why the flare is not eruptive, or, at least, this MFR did not erupt during the flare. Indeed, by comparing the
pre-flare and post-flare magnetic field, there is very limited variation of the magnetic twist distribution (to be discussed in Section 3.3).

Then, what causes this flare? Analysis of the magnetic topology provides important insight. Figure 3 shows the basic building blocks of the magnetic topology of the pre-flare field. There exists a null-point configuration in the north of the MFR, and the field lines constituting the spine-fan configuration of the null extend over the rope (see the red lines in Figure 3), although the null itself does not overlie the rope. Furthermore, there is a QSL with squashing factor $Q > 10^5$ right below the rope, and field lines threading this QSL form the typical configuration in the tether-cutting model (see the yellow and green lines in Figure 3). One set of these field lines (the green ones) connects to the northwest, and the other set (colored in yellow) forms a hook shape around the MFR’s northern foot, extending close to the null point. As these field lines, as well as the null-point configuration, are prone to take part in reconnection, in Figure 4(a) we show them in the same viewing angle as SDO and overlaid on the AIA 94 Å image. A nice match of the field lines with the loops can be seen. As mentioned in Section 3.1, the flare first brightens at a cusp-like...
configuration, and when compared with the magnetic field lines, it is evident that this cusp corresponds to the null-point structure, and reconnection here produced the flare ribbons 1. The location of flare ribbons 2 is also in good agreement with the footpoints of the tether-cutting configuration. Particularly, the field lines colored in yellow (see Figures 3 and 4(a)), whose north footpoints are rooted in the left flare ribbon, are well cospatial with the aforementioned hook-shaped loops. Also, the south footpoints of the green lines are rooted in the right flare ribbon. The inverse S-shaped hot loop in Figure 1(h) is a result of this tether-cutting reconnection.

From the above analysis, we suggest a scenario for this flare process. The rotating sunspot twists the MFR at its footpoint; thus, the MFR expands (Yan et al. 2018) because of increasing magnetic pressure. Meanwhile, the sunspot moves northward, also stressing the MFR. Both the expansion of the MFR and the stressing motion can push magnetic flux to the null point, leading to a current sheet forming there, and finally triggering reconnection when coronal resistivity takes effect in the current sheet. Thus, the null-point reconnection results in the cusplike brightening. Meanwhile, this null-point reconnection will release the magnetic tension force that confines the MFR (but with only a little bit because the post-reconnected field is still closed rather than open). The MFR then quickly expands upward a little following the null-point reconnection. Consequently, magnetic pressure below the rope is weakened, which can trigger the tether-cutting reconnection. Also, the wave-like disturbance from the null-point reconnection propagates along the field lines (see the blue one in Figure 4(a)) and can perturbate the field underlying the rope, which also might provide a trigger for reconnection there. The tether-cutting reconnection results in a short, inverse-S-shaped post-flare loop (see the field lines colored in cyan in Figure 4(b)) and long field lines connecting the two far-end polarities in the south and north (the purple one), respectively. We note that the null-point configuration still exists after the flare as suggested by the extrapolation for the post-flare field. As can be seen in Figures 4(c) and (d), the null point was lifted up slightly from ~4 to ~6 Mm.

3.3. Comparison with the X9.3 Flare

In the same region of this confined flare, after only ~2 hr, the X9.3 flare occurred with a large eruption and a CME (Yan et al. 2018). With such a short time interval, the basic magnetic configuration should be similar for these two flares. Thus, it is important to understand what is the key factor that determines the eruptiveness. We extrapolate the magnetic fields of the X9.3 flare as well, and in Figure 5 we compare the distributions of magnetic twist $T_n$ and decay index $n$ in the central cross section, from pre-flare to post-flare state, for the two flares. As can be seen, both pre-flare states have magnetic flux of high twists of around 1.5 turns, which form the pre-flare MFRs. Furthermore, the locations of decay index $n = 1.5$ (i.e., the theoretical TI threshold line) are similar for both pre-flare states, suggesting that the strapping flux configuration is similar. In contrast, the pre-flare locations of the MFR differ considerably. For the X2.2 flare, the MFR is fully underneath the TI threshold line (Figure 5(a)), while for the X9.3 flare, the major part of the MFR is above the threshold line (Figure 5(c)). For the post-flare states, the high-twist flux, i.e., the MFR, of the X2.2 flare still exists and stays in the position similar to its pre-flare state (see panel (b)), but the MFR of the X9.3 flare disappeared because of the eruption (see panel (d)).

Interestingly, by comparing Figures 5(a) and (b), the post-flare MFR is at a slightly lower height than that of the pre-flare one, which seems to be contradictory to our scenario, i.e., the MFR is supposed to be lifted up. This is probably due to the limitation of NLFFF extrapolation. The AIA observation indicates that the post-flare loops are still forming and evolving, indicating that actually the coronal magnetic field is still rather dynamic, which cannot be modeled by the static extrapolation. Thus, in a dynamic state, the flux rope could be higher than the extrapolated one.

4. Conclusion

In this paper, we studied an interesting confined flare of X2.2 class that took place in NOAA AR 12673. It exhibits rather complex flare ribbons with two episodes of brightening, while no eruption is observed. For understanding the underlying magnetic process, we extrapolated the coronal magnetic field using an NLFFF model, and by analyzing the magnetic topology, it is revealed that three important magnetic structures are involved within the flare. They are, respectively, a well-defined MFR, a magnetic null point, and a tether-cutting configuration, that is, two sets of magnetic field lines ready for tether-cutting reconnection. The null is situated close to the northern leg of the MFR, with part of its spine-structure overlying the MFR. The tether-cutting field lines run below the MFR, forming a QSL there. One set of the tether-cutting field lines also extends close to the null point, forming a hook around the northern leg of the MFR. In particular, the MFR’s northern leg is found to be rooted in a rotating sunspot moving toward the direction of the null point. Previous studies have found that such photospheric motions play an important role in transporting energy and triggering reconnection for the X-class flares that occurred in this AR (Romano et al. 2018; Verma 2018). From the complex magnetic configurations and the photospheric motions, we suggest that the rotating sunspot drives the MFR to expand, which pushes magnetic flux to the null point, and reconnection is first triggered there. Then, the disturbance from the null-point reconnection and the subsequent upward expansion of the MFR trigger the second reconnection, i.e., the tether-cutting reconnection. Such a scenario is compatible with the AIA observations, as the modeled field lines show a good match with the observed loops and their footpoints match the flare ribbons very well. Interestingly, neither the null-point reconnection nor the tether-cutting process results in an eruption. The key factor that determines the confinement of the flare is found to be the MFR’s strapping field, since, by calculating its decay index, we indicate that the strapping flux can firmly hold the MFR during the flare. Furthermore, we compared the configuration of this flare with that of the eruptive X9.3 flare just 2 hr later, which has a similar MFR configuration. The key difference between them is that, for the confined flare, the MFR is fully below the TI threshold, while for the eruptive one, the main body of the MFR reaches above the threshold.

In summary, we observed a confined X-class flare and provided a scenario for the magnetic mechanism of the flare through a sophisticated analysis of the extrapolated coronal magnetic field. Although the magnetic configuration is complex with different topological structures involved in the flare, the determining factor of the confinement is the strapping
field that stabilizes the MFR or the eruptive current system in the AR’s core. The study of this flare provides good evidence supporting that reconnection might not be sufficient to trigger eruption, in which MHD instability plays a more important role.

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