Magnetic Field Modeling of Hot Channels in Four Flare/Coronal Mass Ejection Events

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Abstract

We investigate the formation and magnetic topology of four flare/coronal mass ejection events with filament-sigmoid systems, in which the sigmoidal hot channels are located above the filaments and appear in pairs before eruption. The formation of hot channels usually takes several to dozens of hours, during which two J-shaped sheared arcades gradually evolve into sigmoidal hot channels and then keep stable for tens of minutes or hours and erupt, while the low-lying filaments show no significant change. We construct a series of magnetic field models and find that the best-fit preflare models contain magnetic flux ropes with hyperbolic flux tubes (HFTs). The field lines above the HFT correspond to the high-lying hot channel, whereas those below the HFT surround the underlying filaments. In particular, the continuous and long field lines representing the flux rope located above the HFT match the observed hot channels well in three events. However, for the SOL2014-04-18 event, the flux bundle that mimics the observed hot channel is located above the flux rope. The flux rope axis lies in a height range of 19.8 and 46 Mm above the photosphere for the four events, among which the flux rope axis in the SOL2012-07-12 event has a maximum height, which probably explains why it is often considered as a double-decker structure. Our modeling suggests that the high-lying hot channel may be formed by magnetic reconnections between sheared field lines occurring above the filament before eruption.

Key words: Sun: activity – Sun: coronal mass ejections (CMEs) – Sun: filaments, prominences – Sun: flares – Sun: magnetic fields

1. Introduction

Filament eruptions, coronal mass ejections (CMEs), and solar flares are different manifestations of a single physical process and the most spectacular explosive phenomena in the solar system. They eject a large quantity of plasma and magnetic flux, as well as relativistic particles with intense brightness enhancement (Yashiro et al. 2004). According to Tang (1985), the most commonly seen flare morphology is two flare ribbons that usually appear in pairs and separate with time. Flare loops are located above the flare ribbons, with new magnetic field lines reconnecting at higher and higher altitudes, interpreting the ribbons’ separation and flare loops’ expansion according to the classic CSHKP model (Svestka & Cliver 1992). If the high-speed magnetized plasma and energetic particles arrive at the Earth, they will interact with the magnetopause and ionosphere and may seriously affect the safety of satellites and astronauts in outer space and may lead to damage of communications and power transport.

Theoretical solar physicists thought that magnetic free energy stored in the corona plays a major role in driving the explosion. A magnetic flux rope (MFR) is proposed to be the fundamental structure in the flare/CME dynamic process (e.g., Shibata et al. 1995; Titov & Démoulin 1999; Chen 2011; Vourlidas et al. 2013). Photospheric magnetic cancellations (van Ballegooijen & Martens 1989), the emergence of a helical flux rope (Okamoto et al. 2009), and the tether-cutting reconnection (Sturrock et al. 1984) are main mechanisms for the buildup, as well as the initial rising of MFR structures in the solar corona. A number of studies (e.g., Inoue et al. 2011; Liu et al. 2012a, 2013; Vemareddy & Zhang 2014) have presented examples of the formation of MFRs.

Filament eruptions are categorized into full eruptions, partial eruptions, and failed eruptions (Gilbert et al. 2007). Partial eruptions are more complicated to define observationally. The first type of partial eruption occurs when the entire magnetic structure erupts, with the eruption containing either some or none of its supported preeruptive filament mass. The second type of partial eruption occurs when the magnetic structure itself partially escapes with either some or none of the filament mass. Gibson & Fan (2006) presented a three-dimensional (3D) numerical magnetohydrodynamic (MHD) simulation of a CME and found that the loss of equilibrium of a twisted flux rope resulted in the splitting of the rope into two, with one rope being expelled successfully and the other remaining behind. The critical factors that lead to the partially expelled rope are its three-dimensionality and its possession of dipped field lines grazing the photosphere (i.e., a bald patch (BP)). It is possible that the degree of emergence of a preeruption flux rope—that is, whether it possesses a BP or whether it is high enough in the corona to possess an X-line—determines whether the rope is expelled totally or partially. If this is indeed so, then partially erupting filaments should be more likely to possess a BP (or BPs) than are totally erupting filaments.

In the past, there were mainly two groups of models for the preeruption magnetic configuration. One group suggests that an MFR forms above the polarity inversion line (PIL) and may keep stable for several hours and then erupt for some reason (Forbes & Isenberg 1991; Wu et al. 1997; Krall et al. 2000). In the other group, an MFR does not exist before eruption but is formed through reconnection between two sheared arcades during the eruption (Mikic & Linker 1994; Manchester 2003). Therefore, an MFR is present during the eruption in both cases.
Observations of interplanetary magnetic clouds have confirmed the existence of the flux rope (Burlaga 1991). Lately, the observations of a double-decker filament by Liu et al. (2012b) further complicate the preeruption magnetic configuration. They found that the active-region dextral filament is composed of two branches separated in height by about 13 Mm. A transient hard X-ray sigmoid appears between the two original filament branches during the impulsive phase of the flare. They thus suggest that there are two types of force-free magnetic configurations that are compatible with the data: a double flux rope equilibrium and a single flux rope situated above a loop arcade.

Because most models of flare/CME events contain an MFR, various observations and simulations have been performed to find evidence of the MFRs and to understand their formation, structure, and eruption and the associated phenomena, such as coronal waves and dimming. Soft X-ray and extreme ultraviolet (EUV) observations show that forward or reversed sigmoidal structures are proxies of flux ropes in the corona (Gibson et al. 2002; Savcheva et al. 2014) and often considered as progenitors of CMEs. Filaments (e.g., Mackay et al. 2010) and filament channels (e.g., Gaizauskas 1985) can also serve as indicators of MFRs. Other evidence includes dark cavities at the solar limb, the descending motion of filament materials along a helical trajectory (e.g., Yang et al. 2014; Zhang et al. 2015), spinning motions (Low & Hundhausen 1995; Li et al. 2012), and “lagomorphic” structure of linear polarization in cavities (Bjêk-Stešlicka et al. 2013). EUV observations show that “coronal waves” and “dimming” (Zhubkov & Auchêre 2004; Zhang et al. 2017) are closely linked to the origins of CMEs.

Upon eruption, the magnetic loops are rooted in the dimming regions (as suggested to be the locations of flux rope footpoints), which are open to the solar wind, and then plasma expands and escapes along the open field lines to make the regions become dark (Thompson et al. 2000). Various case studies have been performed to analyze the formation and eruption of MFRs (e.g., Sterling et al. 2000; Schmieder et al. 2013; Vemareddy & Zhang 2014).

Lately, Zhang et al. (2012) and Cheng et al. (2013) reported that the MFR appears as a coherent hot channel structure when seen off the solar limb before the eruption (also see Tripathi et al. 2013; Joshi et al. 2015). Cheng & Ding (2016) summarized the characteristics of the hot channel: (1) It is often observed as an EUV sigmoidal structure in the high-temperature passbands of the Atmospheric Imaging Assembly. (2) In the other low-temperature passbands, it appears as a dark cavity. (3) It is located above the main PIL, but its axis has a significant deviation from the PIL. (4) One footpoint of the hot channel originates in the penumbra or penumbra edge with a stronger magnetic field, whereas the other footpoint lies in the moss region with a weaker magnetic field. Below the hot channel, a filament channel is often observed. Cheng et al. (2014b) and Chen et al. (2014) concluded that the hot channel is most likely the MFR system and that the prominence corresponds to cool materials in the bottom of the helical field lines. The hot channel may separate from the associated prominence and drive a CME. Furthermore, Cheng et al. (2014a) performed a case study and identified that the hot channel can evolve smoothly from the inner into the outer corona, retaining its coherence, and that its morphology coincides with the CME cavity in the white-light images. Nindos et al. (2015) performed a statistical study and found that almost half of major eruptive flares contain a hot channel-like structure. All of these studies support the idea that EUV hot channels or blobs correspond to MFRs.

Guo et al. (2017) reviewed the 3D magnetic field models that include theoretical force-free field models, numerical nonlinear force-free field (NLFFF) models, and MHD models. Theoretical force-free field models contain potential fields in the cartesian coordinate system (e.g., Schmidt 1964) and the spherical coordinate system (e.g., Altschuler & Newkirk 1969), as well as NLFFF models (e.g., Low & Lou 1990). NLFFF models are constructed from boundary conditions and proper initial conditions. There are various numerical algorithms to compute NLFFF models, such as the Grad-Rubin, vertical integration, MHD relaxation, optimization, and boundary integral equation methods (Wiegelmann & Sakurai 2012). To study the dynamics of an MFR, we need MHD numerical simulations that can be divided into zero-$\beta$, isothermal, ideal, resistive, and full MHD models, with the order of increasing physical details included, and that can also be divided into purely theoretical simulations (Amari et al. 2000; Zuccarello et al. 2012) and data-driven/data-constrained simulations (Jiang et al. 2013, 2016; Amari et al. 2014; Inoue et al. 2015) according to the adopted initial and boundary conditions.

The Coronal Modeling System (CMS; van Ballegooijen 2004) used to model nonpotential magnetic fields in the corona has been proven to be effective in studies of the magnetic field before the eruption, such as active regions (Bobra et al. 2008; Su et al. 2009a, 2009b, 2011; Su et al. 2018), coronal X-ray sigmoids (Savcheva & van Ballegooijen 2009; Savcheva et al. 2015), and polar crown prominences (Su & van Ballegooijen 2012; Su et al. 2015). As opposed to the typically used extrapolation methods, which extrapolate the observed photospheric vector field into the corona (e.g., Canou & Amari 2010; Guo et al. 2010; Zhao et al. 2016), CMS inserts an MFR into the potential field of an active region and then applies magneto-frictional relaxation to evolve the field into NLFFF or unstable states (Yang et al. 1986; van Ballegooijen et al. 2000), so it is also referred as the “flux rope insertion method.” The shape of the inserted MFRs is constrained by observed filaments, filament channels, or PIL. The axial flux (along the axis) and poloidal flux (ringing around the axis) of the MFR can be adjusted as initial conditions. The flux rope insertion method can achieve large coronal volume in and around the target region and high spatial resolution in the lower corona owing to variable grid spacing.

In this work, we study four flare/CME events with filament-sigmoid systems that contain a hot channel located above a filament near the disk center. The eruption of the hot channel leads to a CME, while the low-lying filament remains fully or partially. Observational studies of these four events have been presented by Cheng & Ding (2016). Other detailed information about the four events can be obtained from the literature (e.g., Cheng et al. 2014b; Dudík et al. 2014, 2016; Savcheva et al. 2015; Joshi et al. 2017b, 2015; Zhao et al. 2016; Zhang et al. 2017). Observations and extrapolations suggest that EUV hot channels and filament channels are the most promising evidence of MFRs. Case studies using NLFFF extrapolations like that of Zhao et al. (2016) have shown good correspondence of the hot channel and the MFR. Using the flux rope insertion method, we revisit these four events in order to understand the detailed magnetic topology and the formation mechanism of these systems. In Section 2, we introduce data and instrumentation. In Section 3, we briefly review the observations. Results of
magnetic modeling are presented in Section 4. Section 5 presents summary and discussions.

2. Instruments

Observational data are taken with Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA; Lemen et al. 2012) and SDO/Helioseismic Magnetic Imager (SDO/HMI; Schou et al. 2012). AIA has a large field of view (>1.3 solar diameters) and ten visible channels (seven EUV and three ultraviolet [UV]) with 12 s or 24 s cadence and 0.6" pixel size. The primary ions and emission temperature for seven EUV passbands are listed in Table 1. HMI observes the full solar disk in 6173 Å, it provides line-of-sight magnetograms and vector magnetograms with time cadences of 45 s/720 s and pixel size of 0.65.

3. Observations: Formation and Structure of the Filament-Sigmoid Systems

Observational studies on the formation of each of the four filament-sigmoid systems can be found in the literature (e.g., Cheng & Ding 2016). In this section, we briefly review the observations. Figure 1 presents the formation of the hot channel in the first event (SOL2012-07-12T) as shown in the AIA 94 Å and 304 Å images. AIA 94 Å images show that the hot core structure initially appears as two J-shaped loops marked with red arrows in panel a, then evolves into a continuous S-shaped hot channel traced with a red dashed line in panel b. At 07:00 UT the middle part lights up (marked with a red arrow in panel b), which suggests magnetic reconnection may take place. Cheng et al. (2014c) found that the entire sigmoid furthermore evolves into a double-decker MFR structure, the high-lying one (traced with a yellow dashed line in panel c) and the low-lying one (traced with a red dashed line in panel c), which are manifest as the hot channel and the filament, respectively. The system keeps stable (panel c) for a few hours and then its high-lying part becomes unstable (panel d) and erupts, leading to a CME, while the low-lying part does not erupt. In the meanwhile, the AIA 304 Å images show that the low-lying filament (marked with a green arrow) roughly keeps stable.

For the second event (SOL2013-04-11T: Figure 2), we obtained a similar impression. At 03:59 UT, there are brightenings at the middle part (marked with a red arrow in panel b), then the hot channel (traced with a red dashed line in panel c) is formed by the merging of two J-shaped sheared arcades marked by red arrows in panel a. Unlike the first event, this region seems to contain two hot channels. When it becomes unstable (panel d), the high-lying hot channel traced with yellow dashed line starts to kink and then erupts, followed by the eruption of the low-lying sigmoidal hot channel traced with red dashed line, as suggested by Joshi et al. (2017a) and Vernareddy & Zhang (2014). From the AIA 304 Å images, we find that the left part of the filament marked with a green arrow is not as evident as that in the right part associated with brightenings in panel d. The eruption only leads to the disappearance of the hot channels while the low-lying filament appears to remain there at least partly.

The third event (SOL2014-04-18T) is a good example of hot channel formation due to tether-cutting reconnection. Analyzing Interface Region Imaging Spectrograph (IRIS) spectral data and images of SDO, Cheng et al. (2015) concluded that the formation of the continuously sigmoidal loops in the hot channel is mainly via tether-cutting reconnection in the chromosphere. Joshi et al. (2015) also agreed that tether-cutting reconnection plays a major role. Figure 3 presents the formation of the hot channel, just like the first event, whereby two sheared arcades (marked with red arrows in panel a)
gradually evolve into long S-shaped threads traced with a red dashed line in panel c. When the structure becomes unstable (panel d), the eastern part of the brightening moves toward the south with the rising of the high-lying hot channel. No clear filaments can be identified in the corresponding 304 Å images except several dark filamentary threads marked with green arrows.

For the SOL2014-09-10T event (Figure 4), the left sheared loops together with the right sheared loops (red arrows in panel a) make up the whole sigmoidal structure (red dashed line in panel c). In the early phase of the eruption (panel d), the hot channel is already unstable, and long S-shaped loops are formed at the sigmoid center. Panels a and b show that brightenings take place at the right and the left parts of the hot channel, respectively, which suggests that the reconnection occurs not only between the two J-shaped loops but also in the surroundings. Using IRIS spectral lines, Cheng et al. (2015) found that the reconnection occurs at a lower height. The low-lying filament consists of two sections, and the western section undergoes failed eruption, while most parts of the filament

**Figure 2.** Red dashed line traces the hot channel and yellow dashed line traces the overlying flux bundle, others are the same as Figure 1 but for the SOL2013-04-11T event.

**Figure 3.** Three green arrows mark the filament channel others are the same as Figure 1 but for the SOL2014-04-18T event.
remain unchanged (Dudík et al. 2016). In the end, the high-lying hot channel erupts, while the low-lying filament stays behind.

The target four filament-sigmoid systems appear as forward (SOL2012-07-12T and SOL2014-04-18T events) and reversed (SOL2013-04-11T and SOL2014-09-10T events) sigmoids. Observations suggest that the low-lying filament is formed first. Before the eruption, two groups of sheared arcades gradually evolve into a long sigmoidal hot channel located above the other, but found that this does not lead to the desired result. The reason is that, during magneto-frictional evolution, the marginally unstable model is located between the stable and unstable states. The marginally unstable model is the best-fit model. Consequently, this method produces 3D magnetic fields heavily constrained by observations. Su et al. (2011) found that increasing the axial flux or poloidal flux of the inserted flux rope can lead to instability; hence, there are critical values for both the axial flux and poloidal flux. If the axial flux or the poloidal flux is larger than the critical value, the model will evolve into an unstable state; otherwise, it will remain stable. The marginally unstable model is located between the stable and unstable states.

4. Modeling

4.1. Flux Rope Insertion Method

It is generally accepted that filament eruptions, flares, and CMEs are phenomena in the corona and that the coronal magnetic field plays an important role during the eruption. Unfortunately, we usually cannot measure the coronal magnetic field directly, although recently some progress has been made (see, e.g., Judge 1998; Solanki et al. 2003; Lin et al. 2004). These direct measurements are available for only a few individual cases, and usually one has to extrapolate the coronal magnetic field from photospheric magnetic measurements. For more details, please refer to Wiegelmann (2008). To reconstruct NLFFF, we use the flux rope insertion method developed by van Ballegooijen (2004), which is different from most other extrapolation methods. This method only requires line-of-sight (LOS) photospheric magnetograms, whereas the aforementioned extrapolation methods usually require vector magnetic fields as boundary conditions. In particular, the flux rope insertion method involves inserting an MFR into the 3D potential field and then uses magneto-frictional relaxation to drive the field to force-free equilibrium. The model contains the region of target (the HIRES region e.g., an active region) with high spatial resolution (0.001 $R_\odot$ for SOL2014-09-10T event and 0.002 $R_\odot$ for the other three events at low corona) and more distant surrounding region (GLOBAL region: global potential field) with lower resolution ($\sim 1''$). The HIRES region is reconstructed on the basis of the HMI LOS magnetogram, and the GLOBAL region is extrapolated using the HIMI synoptic map.

Four steps are required to reconstruct coronal magnetic fields for a target active region: (1) extrapolating the potential field on the basis of the observed LOS magnetogram, (2) creating a cavity in the potential field model and then inserting MFRs along the selected filament paths according to observations, (3) adjusting axial flux (along the axis) and poloidal flux (circling around the axis) of the inserted MFR to create a grid of models, and (4) starting magneto-frictional relaxation (Yang et al. 1986) to evolve the models into NLFFF or unstable states, which are compared to observations to find the best-fit model. Consequently, this method produces 3D magnetic fields heavily constrained by observations. Su et al. (2011) found that increasing the axial flux or poloidal flux of the inserted flux rope can lead to instability; hence, there are critical values for both the axial flux and poloidal flux. If the axial flux or the poloidal flux is larger than the critical value, the model will evolve into an unstable state; otherwise, it will remain stable. The marginally unstable model is located between the stable and unstable states.

NLFFF models with partial double-decker configurations (in which only part of the double-decker flux ropes shares the same PIL; e.g., one flux rope is longer than the other one) have been constructed using both extrapolations (Liu et al. 2016a, 2016b; Awasthi et al. 2018) and flux rope insertion method (Xue et al. 2016; Li et al. 2017). However, we have not been able to produce double-decker configurations with two stable flux ropes sharing exactly the same PIL, as proposed by Liu et al. (2012c). We attempted to produce such a configuration by inserting two twisted flux ropes into the model, one located above the other, but found that this does not lead to the desired result. The reason is that, during magneto-frictional evolution,

![Figure 4](image-url)
Table 2
Characteristics of the Four Events

| Case       | Position | Shape   | Flare | L-path | H-x     | H-PR    | H-null |
|------------|----------|---------|-------|--------|---------|---------|--------|
| 2012 Jul 12 | S13W03   | S-shape | X1.4  | ~158.9 Mm | ~16.9 Mm | ~46.0 Mm | ~50.5 Mm |
| 2013 Apr 11 | N07E13   | I-S-shape | M6.5  | ~232.4 Mm | ~8.4 Mm  | ~34.2 Mm | None   |
| 2014 Apr 18 | S20W34   | S-shape | M7.3  | ~293.3 Mm | ~9.8 Mm  | ~35.7 Mm | ~82.5 Mm |
| 2014 Sep 10 | N11E05   | I-S-shape | X1.6  | ~182.0 Mm | ~4.9 Mm  | ~19.8 Mm | None   |

Note. Observational characteristics include dates, positions, and shapes of hot channels, and classes of flares are listed in the left four columns. The length of the inserted flux ropes, the heights of the HFTs, and the flux rope axis, as well as the overlying null points (if they exist) in the best-fit model for each event, are presented in the right four columns.

Table 3
Parameters of Models for the Four Events

| Case       | Models       | Axial Flux $10^{20}$ Mx | Poloidal Flux $10^{10}$ Mx cm$^{-1}$ | Helicity $10^{12}$ Mx$^2$ | Free Energy $10^{32}$ erg |
|------------|--------------|-------------------------|--------------------------------------|---------------------------|--------------------------|
| 2012       | Best-fit model | 55                      | -10                                   | 76.39                     | 10.46                    |
|            | Stable model 1 | 20                      | 0                                    | 36.27                     | 4.05                     |
|            | Stable model 2 | 40                      | 0                                    | 67.31                     | 9.98                     |
|            | Marginally unstable model | 50               | 0                                    | 80.77                     | 11.95                    |
|            | Unstable model | 60                      | 0                                    | 93.03                     | 13.29                    |
| 2013       | Best-fit model | 15                      | 0                                    | -6.98                     | 1.04                     |
|            | Stable model 1 | 5                       | 0                                    | -2.72                     | 0.19                     |
|            | Stable model 2 | 10                      | 0                                    | -4.98                     | 0.66                     |
|            | Marginally unstable model | 15             | 0                                    | -6.98                     | 1.04                     |
|            | Unstable model | 20                      | 0                                    | -8.60                     | 1.19                     |
| 2014       | Best-fit model | 15                      | 0                                    | 17.19                     | 2.77                     |
|            | Stable model 1 | 5                       | 0                                    | 6.33                      | 0.64                     |
|            | Stable model 2 | 10                      | 0                                    | 12.25                     | 1.68                     |
|            | Marginally unstable model | 15              | 0                                    | 17.19                     | 2.77                     |
|            | Unstable model | 20                      | 0                                    | 21.79                     | 3.58                     |
| 2014       | Best-fit model | 25                      | 10                                   | -23.35                    | 5.24                     |
|            | Stable model 1 | 10                      | 0                                    | -11.81                    | 2.22                     |
|            | Stable model 2 | 15                      | 0                                    | -17.59                    | 3.77                     |
|            | Marginally unstable model | 20          | 0                                    | -23.15                    | 5.23                     |
|            | Unstable model | 25                      | 0                                    | -28.51                    | 6.57                     |

Note. Parameters for the best-fit model and four models from stable to unstable for each event. Columns 3–6 present the initial axial flux and poloidal flux of the inserted flux ropes, as well as the total coronal magnetic helicity and magnetic free energy in the whole computational domain of each model.

the flux ropes coalesce, so the relaxed model invariably contains only a single flux rope (hyperdiffusion is imposed during the relaxation process to produce a smooth magnetic field). In our models, the HFT typically lies at a height of only 7 to 12 grid points, which has difficulty in accommodating a stable, weakly twisted flux rope below the HFT. Vector-field extrapolation methods are also unable to reproduce double-decker configurations for our studied events in the literature, so this problem is not unique to our model. In future modeling with higher spatial resolution, it may become possible to produce double-decker configurations, but for now we have to accept this limitation of our method. Therefore, in the present work, we focus on reproducing the larger flux rope associated with the hot channel above the HFT and do not attempt to produce a second flux rope in the region below the HFT.

4.2. Structure of the Filament-sigmoid Systems

To find the best-fit model before the flare, we construct a series of models (Table 3) through adjusting axial flux and/or poloidal flux. Our models are constructed on the basis of the LOS magnetograms taken tens of minutes before the flare; at this time, the hot channels have been formed and are close to the unstable state. Tens of minutes later they will erupt. Detailed model parameters are listed in Tables 2 and 3. We find that the magnetic free energy in the best-fit model for each event is larger than $10^{32}$ erg, which is sufficient to power the observed major flares ($>\text{M6.0}$). Model results for the four systems are presented in Figures 5–8. Panel a in Figures 5–8 shows longitude-latitude maps of the radial components of the photospheric magnetic fields in the HIRES region for the four events. The blue curves terminating with two circles represent the path along which we insert flux ropes. The yellow lines refer to the locations of vertical slices of electric currents displayed in panels b–d of Figures 5–8. Selected model field lines above (panels c, g) and below (panels d, h) the X-point at a view different from the observations are shown in panel e of Figures 5–8. AIA images in 94 and 304 Å are presented in panels f–g and panel h of Figures 5–8, respectively.

For all of the four events, the best-fit models contain an MFR with HFT (X-point) as shown in the vertical slices of electrical currents’ distribution (panel b of Figures 5–8). The height of the X-point ranges from 4.9 to 16.8 Mm, and the height of the
flux rope axis is located in a range between 19.8 and 46 Mm as shown in Table 2. Magnetic reconnection occurs at the X-points between the two parts, the high-lying part may separate from the low-lying part and erupts, and the low-lying part of the double-decker stays behind. Observations show a similar scene: the high-lying hot channel erupts and forms a CME while the low-lying filament stays in the original location. The observed hot channels correspond to the field lines above the X-point, while the low-lying filaments are surrounded by the field lines below the X-point as shown in panels c, d, g, and h of Figures 5–8. For three events (SOL2012-07-12T, SOL2013-04-11T, and SOL2014-09-10T), the long and continuous field lines representing the flux ropes located above the X-point can mimic the observed S-shaped hot channels, while the intermittent and shorter sheared field lines below the X-point appear to surround the underlying filament. In particular, there are two groups of flux bundles in the best-fit model of SOL2013-04-11T event. From
Figures 6(e)–(g) we see that the S-shaped hot channel is consistent with the S-shaped flux rope above the X-point, whereas the first erupted overlying hot blob (Vemareddy & Zhang 2014) matches the overlying field lines above the flux rope. However, for SOL2014-04-18T event, the observed hot channel appears to be consistent with the flux bundle (green arrows) located above the flux rope near the overlying null point as shown in Figure 7. Typical tether-cutting reconnection configuration is shown in Figures 7(g)–(h) in which two J-shaped sheared arcades (pink arrows) evolve into one MFR (red arrows).

4.3. Topology of the Filament–sigmoid Systems

Magnetic reconnection plays an important role in accumulation and release of magnetic energy in solar flares/CMEs. Confirming the locations of magnetic reconnection is crucial to determine the eruption mechanisms. Magnetic topology is defined as the unchangeable geometrical properties of the magnetic field and can be represented by the magnetic field line linkages. Quasi-separatrix layers (QSLs; Priest & Démoulin 1995; Demoulin et al. 1996) are defined as the places where the linkages are continuous but change drastically. In other words, QSLs are regions where magnetic gradient is large and thus the reconnection most likely takes place. They divide different magnetic domains, and two QSLs converge at a location defined by an HFT (Titov et al. 2002). Titov et al. (2002) proposed an invariant quantity called the squashing factor $Q$, which is uniform along a magnetic field line to measure the mapping of magnetic field lines. Previous studies, such as those by Savcheva et al. (2015, 2016) and Janvier et al. (2016), have shown good correspondence...
between magnetic topology (e.g., QSL and HFT) and active region features (e.g., flare ribbons).

To understand the 3D topology of the source regions of the events we studied, we adopt the code developed by Guo et al. (2013) and Yang et al. (2015) to calculate the squashing factor $Q$ of the reconstructed magnetic fields. QSL maps at different views overlaid with selected field lines similar to those in Figures 5–8 are presented in Figures 9–12.

**Figure 9.** QSL maps overlaid with selected magnetic field lines from the best-fit model for SOL2012-07-12 event. Panel a shows top view of the photospheric QSL map with two slits, the vertical slices along which are displayed in panels b and c. Three-dimensional combined views from the top and the side are shown in the bottom row. The HFT and null point marked by green arrows are located in panels b and c, respectively. Magnetic field lines below (gray) and above the HFT (red) as well as those near the overlying null point (green) are displayed in panels d, e, and f. The unit is the cell size of the model which are the same as Figure 5.

**Figure 10.** Same as Figure 9 but for the SOL2013-04-11T event at 06:50 UT. Blue magnetic field lines mimic the observed overlying flux bundles.
from which typical topology skeletons, such as HFT, overlying null point, fan, and spines, are identified in one or more events. We find that two roughly parallel high $Q$ (white) ribbons in the photospheric QSL maps (panel a) correspond to the footpoints of the HFTs displayed in panel b of Figures 9–12. Magnetic field lines below the HFTs (gray) appear to be sheared arcades with footpoints located at the two parallel high $Q$ ribbons, as shown in panel d of Figures 9–12, whereas magnetic field lines above the HFTs (red) are continuous and long S-shaped that make up the MFRs with two footpoints located at the two ends of the high $Q$ ribbons (panel e of Figures 9–12(e)).
In particular, the blue magnetic field lines that match well with the first erupted hot blobs in SOL2013-04-11T event (marked by dashed yellow line in Figure 2(d)) are shown in Figures 10(c), (e), and (f). Overlying null points above the filament-sigmoid system are identified in the SOL2012-07-12T (Figure 9(c)) and SOL2014-04-18T (Figure 11(b)) events. Figures 11(c), (e), and (f) show the fan-spine structure and the footpoints match well with the rectangular high Q ribbons, which are consistent with the observed postflare quasi-circular flare ribbons, as shown in Joshi et al. (2015). The pink field lines in panels c and f of Figures 11 above the flux rope near the overlying null point correspond to the observed hot channels.

4.4. Formation of the Filament-sigmoid Systems

To understand the formation of the filament-sigmoid system, we built a series of magnetic field models from stable to
unstable by increasing the initial axial flux of the inserted flux rope. Figures 13–16 show selected magnetic field lines of these models. The top row of Figures 13–16 shows field lines in the direction of observation, and the bottom row displays the same field lines in another view. For each event, we present four models; the first two are stable models, the third one is a marginally unstable model, and the last one is unstable. Parameters of these models are listed in Table 3. With the increase of axial flux, the models evolve from nearly potential to more nonpotential state, during which double J-shaped field lines merge into long continuous S-shaped field lines. This is similar to the aforementioned observations in Section 3 (Figures 1–4). It suggests that the high-lying hot channel is more likely formed by increasing axial flux through magnetic reconnections such as tether-cutting reconnection.

In this work, we consider the filament and hot channel as a filament-sigmoid system, the formation of which is illustrated in Figure 17. At first, the region contains a low-lying filament with overlying potential fields (panel a). The overlying potential fields are gradually driven to be sheared due to processes such as shear and/or converging flows (panel b). Magnetic reconnection takes place in the sheared fields above
the low-lying filament, which leads to the formation of the high-lying hot channel and the low-lying postflare loops and/or brightenings surrounding the underlying filaments (panel c). The formation mechanism of the low-lying filament formed much earlier than the hot channel is out of the scope of this work.

5. Summary and Discussion

In this paper, we study magnetic field configuration of four flare/CME events (SOL2012-07-12T, SOL2013-04-11T, SOL2014-04-18T, and SOL2014-09-10T) that occurred in four different active regions with high-lying sigmoidal hot channels and low-lying filaments that make up the filament-sigmoid systems. Hot channels in the first and the third events display an S-shape, whereas inverse S-shaped hot channels appear in the other two events. The eruption of all of these hot channels is followed by CMEs and flares. Comprehensive observational study of the hot channels in these four events has been performed by Cheng & Ding (2016), who were unable to obtain magnetic field lines that fit the observed hot channels using normal NLFFF extrapolations. To understand the magnetic structure of hot channels, we constructed a series of magnetic field models for these active regions using the flux rope insertion method through adjusting axial flux and/or poloidal flux of inserted flux rope and performed magnetic field topological analysis. Our main results and discussions are summarized as follows.

AIA observations show that two groups of sheared arcades gradually evolve into a sigmoidal hot channel during tens of (or several) hours before the flare. Once the hot channel forms, it is usually stable for a while and then erupts suddenly with its footpoints moving toward further locations. During the formation of the hot channel, the preexisting underlying filaments remain barely changed. Our modeling shows that the same set of field lines in different models with increasing axial flux of inserted flux rope can mimic the observed formation process of hot channels (i.e., two groups of J-shaped field lines merge into one group of long sigmoidal field lines). This is consistent with the previous observational findings for these four events that the continuous sigmoidal hot channel is built up from two groups of sheared arcades near the main PIL before the eruption (Cheng et al. 2014c, 2015; Joshi et al. 2015, 2017a), which is also similar to the simulation on the formation process of sigmoidal flux ropes for other events in the literature (Savcheva & van Ballegooijen 2009; Savcheva et al. 2012; Jiang et al. 2014). In our work, we consider the filament and sigmoid as a system, and the hot channel is formed by increasing of axial flux due to magnetic reconnections, such as tether-cutting reconnection (Sturrock et al. 1984; Moore et al. 2001) that occurred high above the low-lying filament.

An observational study by Cheng & Ding (2016) suggested that the hot channel ascended to a high altitude because of the observed significant deviation between the axis of the hot channel and the PIL (or the associated filament). The hot channels contain high-temperature plasma because they appear in the AIA high-temperature passbands. Zhang et al. (2012) and Cheng et al. (2013) speculated that the coherent channel-like hot structures are MFRs that exist before the eruption. Through magnetic modeling of the four flare/CME events, we
find that the best-fit models composed of an MFR with HFT where magnetic reconnection most likely occurs can represent the filament-sigmoid systems before the flare onset. The height of the X-point/HFT is in the range of 4.9–16.8 Mm, and the height of the flux rope axis is located in a range between 19.8 and 46 Mm above the photosphere. The sigmoidal hot channels correspond to magnetic field lines located above the HFT, whereas those below the HFT surrounds the low-lying filament. In particular, the continuous and long field lines representing the flux rope located above the HFT are corresponding to the hot channels in three events, whereas the flux bundle that mimics the observed hot channel in SOL2014-04-18 is located above the flux rope. It is worth noting that the NLFFF model built for the 2014-09-10T event using the Grad-Rubin method (Zhao et al. 2016) and the model built for SOL2012-07-12 event by Cheng et al. (2014c) also contain an MFR with HFT. The heights of the HFT and flux rope axis in the first and second cases are slightly or much lower than those in our models, respectively.

As time goes on, the high-lying hot channel rises faster and then separates from the low-lying filament. In the end, the high-lying hot channels erupt and lead to CMEs and flares, while the low-lying filaments remain in full or in part. This behavior is similar to the so-called partial eruptions (Gibson & Fan 2006; Gilbert et al. 2007). The only difference may be that the MHD simulations by Gibson & Fan (2006) suggest that the partial eruption is caused by the splitting of one flux rope. Figure 1 of Gibson & Fan (2006) shows that the surviving parts of the MFR are the set of dipped field lines and flux rope field lines that graze the BP as the BP separatrix surface below the reconnection cusp, and the escaping parts are the newly formed field lines of reconnection above the reconnection regions.
However, we think that, in the filament-sigmoid system, the high-lying hot channel might be formed by the merging of two sheared arcades overlying the filament, rather than splitting of one flux rope. Moreover, the magnetic structures derived from our current models suggest that the lowing filament is more likely to be supported by sheared arcades rather than a flux rope. However, we are not able to exclude the possibility of the existence of a low-lying flux rope as suggested by Cheng et al. (2014c), in which Figure 9 shows many BPs along the PIL below the filament for SOL2012-07-12 event.

For the SOL2012-07-12 event, some authors like Cheng et al. (2014c) think that the AR may contain a double-decker flux rope including a high-lying MFR and a low-lying MFR. Liu et al. (2012c) perform an observational study of a double-decker filament and suggest two types of force-free magnetic configurations that are compatible with the data, a double flux rope equilibrium and a single flux rope situated above a loop arcade. The follow-up work (Kliem et al. 2014) performed MHD simulations and found that a double-decker flux rope can lead to eruptions under conditions typical of solar active regions. However, no magnetic field reconstructions based on observational magnetic fields can reproduce this double-decker flux rope structure so far, and neither does our current modeling. In our model, magnetic field lines below the HFT appear to be consistent; the observed low-lying filament and the high-lying hot channel are represented by field lines above the HFTs. This suggests that the observed double-decker structure may be separated by the HFTs, which is a representation of filament-sigmoid system similar to Figure 12(b) of Liu et al. (2012c). The heights of the X-point and the flux rope axis are 16.8 Mm and 44.8 Mm, which are much higher than those in the other three events. This might explain why this event is considered as a double-decker MFR structure.

The preflare magnetic configurations in these four events are divided into two groups: filament-sigmoid system without overlying null points and filament-sigmoid system with an overlying null point. A sketch of the basic magnetic structure of these two groups of events is presented in Figure 18. The height of the overlying null point is about 84.5 and 55.3 Mm for SOL2014-04-18T event and SOL2012-07-12T event, respectively. Null points usually refer to a location where \( B = 0 \) in the fan-spine configuration (Lau & Finn 1990; Liu et al. 2011). Magnetic reconnection may take place at the null point, which opens the overlying magnetic field and leads to eruptions such as CMEs and jets. Antiachos et al. (1999) and Aulanier et al. (2000) proposed the “magnetic breakout” model, whose central idea is that reconnection at the overlying null point removes background magnetic fields. For SOL2014-04-18T event, Joshi et al. (2015) provide several observational pieces of evidence, such as the existence of a closed dome-like structure and a large scale circular ribbon, to support the existence of an overlying null point that is not identified in their NLLFF models. However, an overlying null point with fan-dome topology is identified in our magnetic field model. The best-fit models for the two events with overlying null points (SOL2012-07-12T and SOL2014-04-18T) are marginally unstable models, whereas the best-fit model for SOL2014-09-10T event without an overlying null point is an unstable model. A marginally unstable model is also identified as the best-fit model for the SOL2013-04-11T event, and the first erupted overlying flux bundle might play a role in the initiation of this event as suggested by Vemareddy & Zhang (2014). “Marginally unstable state” refers to a state at the boundary between stable and unstable states in parameter space. When the magnetic structure reaches a marginally unstable state, it is easy to erupt, and if the model is unstable, the ideal MHD instabilities are most likely to occur. In our previous work (Su et al. 2009a, 2009b, 2011), we often found that the best-fit preflare models are generally stable, unlike the modeling in the current work, which suggests that before eruption each region is already marginally unstable, and a small disturbance such as tether-cutting/breakout reconnection can lead to the explosive eruption. The existence of an overlying null point might play a role in the instability of the region. Further analysis is required to obtain conclusive statements.

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**References**

Altschuler, M. D., & Newkirk, G. 1969, SoPh, 9, 131

Amari, T., Canou, A., & Aly, J.-J. 2014, Natur, 514, 465

Amari, T., Luciani, J. F., Mikic, Z., & Linker, J. 2000, ApJL, 529, L49

Antiochos, S. K., DeVore, C. R., & Klimchuk, J. A. 1999, ApJ, 510, 485

Aulanier, G., DeLuca, E. E., Antiachos, S. K., McMullen, R. A., & Golub, L. 2000, ApJ, 540, 1126

Awasthi, A. K., Liu, R., Wang, H., Wang, Y., & Shen, C. 2018, ApJ, 857, 124

Bajk-Stęsiłcka, U., Gibson, S. E., Fan, Y., et al. 2013, ApJL, 770, L28

Bobra, M. G., van Ballegooijen, A. A., & DeLuca, E. E. 2008, ApJ, 672, 1209

Burlaga, L. F. 1991, PCS, 21, 1

Canou, A., & Amari, T. 2010, ApJ, 715, 1566

Chen, B., Bastian, T. S., & Gary, D. E. 2014, ApJ, 794, 149

Chen, P. F. 2011, LRSI, 8, 1

Cheng, X., & Ding, M. D. 2016, ApJS, 225, 16

Cheng, X., Ding, M. D., & Fang, C. 2015, ApJ, 804, 82

Cheng, X., Ding, M. D., Guo, Y., et al. 2014a, ApJ, 780, 28

Cheng, X., Ding, M. D., Zhang, J., et al. 2014b, ApJ, 789, L35

Cheng, X., Ding, M. D., Zhang, J., et al. 2014c, ApJ, 789, 55

Chen, X., Zhang, J., Ding, M. D., Liu, Y., & Poomvises, V. 2013, ApJ, 763, 43

Demoulin, P., Henoux, J. C., Priest, E. R., & Mandrini, C. H. 1996, A&A, 308, 643

Dudik, J., Janvier, M., Aulanier, G., et al. 2014, ApJ, 784, 144

Dudik, J., Polito, V., Janvier, M., et al. 2016, ApJ, 823, 41

Forbes, T. G., & Isenberg, P. A. 1991, ApJ, 373, 294
