Sympathetic Quiet and Active Region Filament Eruptions

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Abstract
We present the observations of three sympathetic filament eruptions occurring on 19 July 2015, namely F1, F2, and F3. The events were observed in UV and EUV by the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory and in Hα by the Mauna Loa Solar Observatory (MLSO) of the Global Oscillation Network Group. As filament F1 starts to erupt, a part of it falls close to the locations of filaments F2 and F3. Our observations indicate that this drives the eruption of F2 and F3, which merge in the process, and trigger a coronal mass ejection and a long-duration GOES C2.1 class flare. We discuss the dynamics and kinematics of these three filament eruptions and related phenomena.

Keywords Sun - flares · Sun - filament eruptions · Sun - magnetic fields

1. Introduction

Solar filaments or prominences are well-known phenomena in the solar atmosphere. They are a variety of cool and dense structures ranging from long-lived quiescent filaments to short-lived active region filaments. Their nature is described in many studies (van Ballegooijen and Martens, 1989; Chae, 2001; Labrosse et al., 2010; Mackay et al., 2010; Schmieder,
It is believed that the plasma forming them is supported in magnetic dips (Aulanier, DeVore, and Antiochos, 2002; Mackay et al., 2010; Gibson, 2018).

When the balance between magnetic pressure and magnetic tension in the magnetic configuration becomes unstable by any kind of mechanism, filaments can erupt. Observations show that filaments can erupt fully (Gopalswamy et al., 2003; Schrijver et al., 2008; Chandra et al., 2010) or partially (Gibson and Fan, 2006; Joshi et al., 2014; Cheng, Kliem, and Ding, 2018; Monga et al., 2021) and sometimes the eruption can fail (e.g. Liu, Wang, and Alexander, 2009; Kumar et al., 2011; Joshi et al., 2013). Full or partial eruptions are usually associated with coronal mass ejections (CMEs), which later become interplanetary CME (ICME), responsible for space weather disturbances (Gopalswamy, Yashiro, and Akiyama, 2007; Schmieder et al., 2020).

Sometimes, merging of filaments is also observed (Schmieder et al., 2004; Chandra et al., 2011; Jiang et al., 2014; Luna et al., 2017). Merging can tell us about the formation and dynamical evolution of the filaments. Cases are reported, where two filaments merge and the result can be a stable or an eruptive filament. Merging of magnetic flux ropes has been simulated in high $\beta$ plasma conditions by Linton (2006) and in low $\beta$ plasma coronal conditions by Aulanier, DeVore, and Antiochos (2006) and Torök et al. (2011).

Occasionally, eruptions occur in a short interval of time at the same or different locations on the solar surface (Biesecker and Thompson, 2000; Moon et al., 2002; Wang et al., 2002; Zhukov and Veselovsky, 2007; Liu, Wang, and Alexander, 2009). Consecutive eruptions, occurring in the same active region within a relatively short time interval, are defined as sympathetic eruptions. Other cases can be also recognized as sympathetic eruptions, such as recurrent or successive eruptions at different locations above the solar surface. Such events can occur in both quiet and active regions (Moon et al., 2002; Wheatland and Craig, 2006; Schrijver and Title, 2011). Sympathetic eruptions were observed in the past (Richardson, 1936, 1951; Becker, 1958) and it is believed that they can be physically connected by coronal loops. It was found that in sympathetic eruptions multiple flux systems erupt. First, the eruption starts in one active region, pushing the overlaying magnetic structure and causing other flux systems to erupt (Delannée and Aulanier, 1999; Wang et al., 2002; Liu, Webb, and Zhao, 2006; Zhukov and Veselovsky, 2007). Another possibility was suggested by Khan and Hudson (2000). According to these authors, the propagation of EUV waves can destabilize the adjacent loop systems and ultimately lead to another eruption.

Sympathetic eruptions were modeled in magnetohydrodynamic (MHD) numerical simulations. Ding, Hu, and Wang (2006) performed the 2.5 D time-dependent MHD model. In this model, they investigated the catastrophic behavior of a multiple flux rope system, which contained three magnetic flux ropes in three sets of separate loop arcades. They concluded that the eruption of the first flux rope system disturbed the stability of the second and third one and forced them to erupt. According to the model proposed by Wheatland and Craig (2006), if a flare occurs at the location of a separator, it consequently increases the probability of flaring at all separators (a complex of reconnecting structures). Torök et al. (2011) presented a 3 D MHD simulation of two magnetic-flux ropes and reproduced the eruptions of quiet-Sun filaments observed on 1 August 2010. Their results support the hypothesis that the trigger mechanisms of sympathetic eruptions can be related to the large-scale coronal magnetic field. Despite the numerous observations and simulations, the exact origin of the sympathetic eruptions is still not well understood.

In this work, we present the observations of three sympathetic erupting filaments. Each eruption was associated with a CME. In addition, the observations also show the merging of two filaments. The article is organized as follows. Section 2 describes the data sets used in
the study. The results of our analysis are presented in Section 3. Finally, the discussion and summary are presented in Section 4.

2. Observational Data Sets

For this study, we used data from the following sources:

1. SDO/AIA data: For the evolution, dynamics and kinematics study of the filament eruptions, we used data from the Atmospheric Imaging Assembly (AIA: Lemen et al., 2012) on board the Solar Dynamics Observatory (SDO: Pesnell, Thompson, and Chamberlin (2012)). AIA consists of seven extreme ultraviolet (EUV) and three ultraviolet (UV) channels which probe the solar corona with a pixel resolution of 0.6” and an average cadence of 12 s. The AIA image field-of-view (FOV) reaches 1.3 solar radii. For the present study, we used 1 min cadence data from AIA 171, 193 and 304 Å channels.

2. Hα data: Hα images recorded from Mauna Loa Solar Observatory (MLSO) of the Global Oscillation Network Group (GONG: Harvey et al., 1996) were used to study the chromospheric evolution of filament eruptions. We used the full Sun Hα images with a cadence of 1 min and a pixel resolution of 1″.

3. SDO/HMI magnetic field data: The line-of-sight (LOS) magnetograms taken by the Helioseismic and Magnetic Imager (HMI: Scherrer et al., 2012; Schou et al., 2012) on board SDO were used to explore the photospheric magnetic fields in the corresponding regions. The HMI LOS magnetograms used in this study have a cadence of 10 min and a pixel size of 0.5″. The 1σ noise level for the HMI LOS magnetograms is 10 G (Liu et al., 2012). The HMI magnetograms and AIA images were coaligned by using the UV AIA 1600 Å images, which were consequently aligned with the AIA EUV channels. All data were corrected for projection effect and derotated to 23:20 UT on 18 July 2015.

4. SOHO/LASCO data: The CME association of the erupted filaments was traced in the field of view (FOV) of the C2 coronagraph (2.2 – 6 R⊙) of the Large Angle and Spectrometric Coronagraph (LASCO: Brueckner et al., 1995) on board the Solar and Heliospheric Observatory (SOHO) satellite.

3. Results

On 19 July 2015, three filaments erupted sympathetically. The first one was a quiescent filament, while the other two filaments were situated in an active region. The dynamics and kinematics of these eruptions are presented in the following sections.

3.1. Dynamics

We named the three filaments as F1, F2, and F3 respectively. Filament F1 was located in the northern hemisphere, whereas filaments F2, and F3 were located in southern one. The locations of all these three filaments are shown in Figure 1a and b in AIA 304 Å and Hα respectively. In panel c of this figure, the AIA 304 Å filament contours are overlaid on the photospheric magnetic field using green, pink, and blue colors. This image was obtained before the eruption on 18 July 2015. Filament F1 was a large filament (projected length ≈ 450 Mm) that was observed on the solar disk between 11 – 19 July 2015. It survived around eight days on the solar disk and erupted on 19 July 2015. Filaments F2 and F3 were
Figure 1 Three visible filaments in AIA 304 Å (a) and Hα (b) on 18 July 2015. The contours of the 304 Å filaments F1, F2, and F3 are plotted over the HMI magnetogram (c) in green, purple and blue colors, respectively.

located in the NOAA active region (AR) 12384. Initially these filaments were observed as a single filament up to 16 July 2015, while on 17 July 2015 it splitted into two smaller parts, named as F2 and F3.

Figure 2 illustrates the filament eruption evolution in AIA 304 Å and 171 Å wavelengths in the top and bottom rows, respectively. To make the evolution more clear, we have created Multiscale Gaussian Normalization (MGN) processed images in 171 Å. This method is proposed by Morgan and Druckmüller (2014). It is based on localized normalization of the data at different spatial levels. There are several parameters in this code, which can be changed according to the waveband namely $\gamma$, $k$, $h$. The $\gamma$ parameter is useful for the global gamma transformation of the image, the parameter $k$ controls the sharpness of the gamma transformation and $h$ is the approximate weight of the globally normalized image. We used the original default values of $\gamma$ and $k$ described in the original code as 3.2 and 0.7, respectively. We modified slightly the value of $h$ to 0.9, as it can be changed depending on the type of input image and desired output. Before applying the MGN technique, the AIA data is preprocessed using the aia_prep procedure and all images are aligned at a fixed time, to compensate for the solar rotation effect, using the drot_map routine available in the Solar Software package. Such image processing is useful to present clearly the structural evolution of the eruption (Devi et al., 2021). Here we discuss the eruption evolution of the filaments step-by-step. Filament F1 started to rise $\approx$ 01:00 UT on 19 July 2015. The erupted material went into two major directions. Part of the erupted filament moved towards the northwest. This erupted part became visible in the LASCO C2 field of view (FOV) as a CME at $\approx$ 03:36 UT with a speed of $\approx$ 126 km s$^{-1}$. When the filament erupted, two parallel, elongated brightenings along the photospheric inversion line (PIL), where the F1 filament was situated before its eruption, were observed. These two ribbons were very faint. We could not see any enhancement of the GOES X-ray flux at this time. This could be due to the weak reconnection occurrence during the filament eruption, as discussed in the study of Chandra et al. (2021).

The remaining part of the erupted F1 filament moved towards the south, as shown by the cyan arrows in Figure 2. Finally, it fell down towards filament F2 and reached its northern
Figure 2  Evolution of the event in AIA 304 Å and 171 Å bands in the top and bottom rows, respectively. (a) and (e) show the filaments F1, F2, and F3 with green, purple and blue arrows, respectively. (b) shows the erupting filament F1 pointed by a green arrow and a cyan arrow indicates the filament material falling downwards (towards filament F2), which triggers the eruption of filament F2 (d). The yellow arrow in (e) and (g) points to the merging of filaments F2 and F3. The AIA 171 Å images are processed with the MGN method. The black arrows in panel a shows the pre-eruptive brightening in the vicinity of filament F1. Movies of these data are available in the electronic supplementary materials (AIA304.mpeg; MGN171.mpeg).

feet (see Figure 2b). As a result, filament F2 started to rise and merged with filament F3 at around 04:33 UT. Filament F3 partially erupted and appeared as a very faint CME in the LASCO C2 FOV at 05:24 UT.

The merged filament started to rise slowly in the southwest direction at \( \approx 05:10 \) UT. This eruption was associated with a C-class GOES solar flare and a partial halo (width \( \approx 194^\circ \)) CME with a linear projected speed of \( \approx 782 \) km s\(^{-1}\), which was first observed in the LASCO C2 FOV at \( \approx 09:48 \) UT at a projected height of \( \approx 2.9 \) R\(_{\text{sun}}\).

The chronology of these eruptions and related events are presented in Table 1.

### 3.2. Kinematics

To investigate the temporal and spatial connection between the three erupted filaments, we performed a time-distance analysis. This technique is based on the exploration of the motion of the plasma along an artificial slit. For this purpose, we have selected different slits in different directions. These slits were named S1, S2, S3, and S4, respectively.

Slit S1 was selected in order to analyze the kinematic behavior of the eruption F1 in the northwest direction. The selected slit and the corresponding time-distance plot are shown in Figure 3. We have selected some points along the time-distance slice and overplotted them in the same image (Figure 3b) using plus symbols in green color. Further, these data points were fitted with a combination of linear and exponential functions, namely \( (ae^{bt}+c)t + h_0 \), as done by Cheng et al. (2020). Where \( a, b, c, \) and \( h_0 \) are arbitrary constants and the
Table 1  Chronology of the eruptions.

| Time (UT) | Events | Notes |
|----------|--------|-------|
| 23:40* – 00:50 | Activation of filament F₁ | * Time one day earlier |
| 00:50 – 03:20 | Part of F₁ material moved northwest | – |
| 03:36 | CME appearance in LASCO FOV | Related with northwest part |
| 01:30 – 04:00 | Part of F₁ material moved southward | Reached F₂ |
| 04:11 | Activity in filament F₂ | Partial eruption |
| 04:33 | Start of the merging of F₂ and F₃ filaments | – |
| 04:33 – 05:10 | Small oscillations in F₃ | – |
| 05:24 | Small CME in LASCO FOV | Related to F₂ partial eruption |
| 05:00 | Final merging of F₂ and F₃ filaments | |
| 05:10 | F₃ starts to rise | Low velocity (few km s⁻¹) |
| 07:00 | F₃ starts to move faster | Velocity ≈ 12 km s⁻¹ |
| 09:00 | F₃ acceleration phase | Velocity ≈ 138 km s⁻¹ |
| 09:10 | GOES C2 flare onset | Long duration flare (≈ 7 hrs) |
| 09:48 | CME appearance in LASCO FOV | A partial halo CME |

Figure 3  (a) Corresponds to the AIA 304 Å image from 19 July 2015 02:00 UT showing the direction of S₁. (b) Shows the time-distance plot corresponding to S₁. The green plus symbols in panel b are the data points chosen from the time-distance plot and the blue solid line is the fitting curve for these data points. The fitted function is $ae^{b(t-t_0)} + ct + h_0$. The eruption speed estimated from the fitting is found to be ≈ 120 km s⁻¹.

time $t_0$ is fixed at 23:50 UT on 18 July 2015. The fitted function is plotted as a blue solid line in Figure 3b. The computed projected speed is ≈ 120 ± 6 km s⁻¹. To determine the exact start time of the eruption, we used the equation $t_{start} = \frac{1}{b} \ln\left(\frac{c}{ae}\right)$. According to our results, the eruption started at ≈ 00:42 UT on 19 July 2015.

Slit S₂ was chosen along the southward direction in which part of the F₁ material was observed to move. The slit position and the time-distance plot are depicted in Figure 4. The speed of the material going in this direction was computed using a straight-line fit. The estimated speed value is about 100 ± 2 km s⁻¹, which is comparable but slightly slower than the filament speed in the northwest direction. This slower speed could be due to the following possibilities. Due to the long curved path of S₂ along the closed loop channel (evidenced by the potential-field source-surface (PFSS) extrapolation in Figure 12), the material ejected
Figure 4 (a): Image of AIA 171 Å on 19 July 2015 at 03:30 UT with the curved slit S₂ shown by the black arrow, in the direction of the material falling from filament F₁ towards F₂. (b): Time-distance plot corresponding to S₂ in panel a.

Figure 5 (a) and (b): Image of AIA 171 Å showing S₃ and the time-distance plot corresponding to this slice. The time-distance plot shows the merging of the filaments.

from filament F₁ decelerated resulting in a slower speed. Another reason could be the expansion of filament F₁. The erupting filament material reached the feet of filament F₂ at ≈ 03:20 UT.

Slit S₃ is placed between filaments F₂ and F₃. The purpose of this slit is to comprehend the observed merging of these two filaments. The results are plotted in Figure 5. The time-distance plot indicates that filament F₂ was in a stationary state up to ≈ 04:10 UT and started to rise at ≈ 04:20 UT. Around this time filament F₂ became unstable due to the continuous flow of plasma material from filament F₁. As a result, filament F₂ merged with F₃ at around 05:00 UT.

To examine the eruption of the filament after merging, we have fixed slit S₄ as shown in Figure 6. From the time-distance plot shown in this figure, it is evident that the eruption
started at $\approx 05:10$ UT, just after the F2 and F3 merging. Further from the image, it is noticeable that the eruption had three phases. The first phase, starting at $\approx 05:10$ UT was a slow phase with a speed of $\approx 4$ km s$^{-1}$ and lasted up to 07:00 UT. After 07:00 UT the second phase started, when the eruption speed increased to about 17 km s$^{-1}$. The second phase lasted up to 09:00 UT. Another interesting feature observed in this phase was the oscillations during the filament eruption. Finally, the third phase started, when the eruption speed reached a maximum of $\approx 138$ km s$^{-1}$. The eruption of this filament produced a large partial halo CME.

### 3.3. Magnetic Field Analysis

To examine the photospheric magnetic field evolution we performed a careful inspection of the HMI magnetic field movies (see the online movie, HMI.mpeg) and found regions of small-scale flux emergence and cancellation at the F1 filament site and much more flux cancellation at the location of F2 and F3.

Figure 7 presents the magnetic field evolution between 14 – 19 July 2015, with filament positions overplotted in panels b and d. The analyzed region, located at $\approx 41^\circ$ from the central meridian, is marked with a red box in panel c.

The photospheric magnetic field shown in Figure 7 indicates that F1 lies along the PIL. F1 eastern part is ending in a bipolar region ($500^\prime$, 371$^\prime$), where at 00:42 UT an emerging flux (EF) was observed. At the same time, i.e. at 00:42 UT, filament F1 started to erupt and part of its material lifted in the northwest direction up to 03:20 UT, when it escaped the AIA FOV. Moreover, between 01:30 UT and 03:20 UT, we observed a part of F1 material moving down in the southward direction to the F2 position. In Figure 8 we depict a coaligned image of AIA 304 (with a rising F1) and a LOS HMI magnetic field image. The close-up of the magnetic field evolution, indicates the quiet state of the magnetic field in Figure 8e, while during the pre-eruptive state (Figure 8 f, g) the cancellations and the emergence of the magnetic field are shown.

The emerging flux close to F1 location is well visible in the time-distance plot shown in Figure 9. The slit position is shown in Figure 7b by a white vertical line. The time variations of both positive and negative LOS magnetic fluxes in the cancellation region, estimated in the red box shown in Figure 7c from 23:19 UT on 18 July to 10:19 UT on 19 July, are presented in Figure 10. During the pre-eruptive phase of F1 eruption, the positive flux steeply
decreased up to 00:00 UT, which was the start time of flux emergence close to the eastern F1 footpoint (see Figure 8). Then, it underwent a small increase up to the F1 eruption onset. After the eruption, the positive flux gradually decreased. During the pre-eruptive phase, the negative magnetic flux showed a similar behavior. After the eruption, it gradually decreased until 04:30 UT and then the negative flux steeply decreased up to 09:00 UT. In the pre-eruption phase (i.e. 18 July 23:30 UT – 19 July 00:00 UT), the decrease in both positive and negative fluxes can be considered as evidence of flux cancellation at the PIL where the filament lay (Sterling et al., 2010; Green, Kliem, and Wallace, 2011). Hence, there were sites of flux emergence and cancellation in and around the filament, influencing its stability.

The pre-eruptive EUV brightening was observed in the vicinity of the filament channel prior to F1 eruption, between 23:40 UT on 18 July and 00:50 UT on 19 July (see Figure 2). This pre-eruptive brightening represents a series of small-scale patches aligned along the PIL beneath the filament. The brightening was visible not only in 304 Å and 171 Å channels, but also in the high temperature AIA channels 193 Å, 131 Å and 94 Å. The flux cancellations present prior to F1 eruption were probably caused by the slow magnetic reconnections between the moving negative fluxes and their nearby positive fluxes (Wang and Shi, 1993),

**Figure 7** Evolution of HMI LOS magnetic field during 14–19 July 2015 before the onset of the eruption. The locations of the filaments are overlaid on panels b and d. The white line in panel b denotes the slit position, used for the time-distance plot shown in Figure 9. The red box in panel c marks the region used for the magnetic flux analysis, shown in Figure 10. See also the accompanying movie (HMI.mpeg).
which had led to some small-scale activity as, for example, the EUV brightenings (Chen et al., 2019).

The pre-eruptive brightening in the vicinity of F₂ and F₃ was visible in all AIA channels. In Figure 11 the evolution of the EUV brightening is presented in three high-temperature AIA channels, such as 171 Å, 193 Å, and 211 Å. We found that the first indications of the pre-eruptive brightening enhancement occurred after 02:40 UT. This brightening enhance-
Figure 10  Curves of the normalized (to the maximum) magnetic fluxes, obtained from the red box, shown in Figure 7c. The vertical line represents the onset time of the eruption of F1.

Figure 11  Evolution of the EUV brightening in the vicinity of F2 and F3 filaments in three different AIA channels. Top panel: AIA 171 Å, middle panel: AIA 193 Å, bottom panel: AIA 211 Å. All data are derotated to 04:58 UT.

ment was slow and fragmented, i.e. in different small-scale locations in the filament vicinity along the PIL. Such brightening could be caused by slow reconnection acting in the course of the flux cancellations process during the pre-eruptive phase (Chen et al., 2019). After 04:00 UT significant and dynamic changes in the brightening occurred. The brightening
enhancement covered all the filament vicinity, rapidly increasing and reaching a peak at 04:30 UT, i.e. when the extreme brightening was observed in some parts of the interacting and merging F2 and F3 flux ropes (FRs). Afterwards, the brightening rapidly decreased and after 05:00 UT, when the F2–F3 compound flux rope rose up, it returned to its initial value.

4. Discussion and Summary

We analyze the sympathetic eruption of three filaments observed on 19 July 2015. Filament F1 was a quiet filament located in the northern hemisphere, while F2 and F3 were located in NOAA AR 12384 in the southern hemisphere. The main results of this study are summarized as follows:

- All the eruptions are sympathetic and associated with CMEs.
- The time-distance analysis and the morphology of the filaments suggest that filament F1 triggered the eruption of F2, and consequently that of F3.
- We have found that flux emergence and cancellation play an important role in the observed filament eruptions. We suggest that the emergence and cancellation of magnetic fluxes near F1 causes the flux rope to rise.
- In addition to these processes, the motion of material from F1 to F2-F3 location can additionally contribute to the F2–F3 compound destabilization.
- Our observations can be explained by the combination of the models proposed by Ding, Hu, and Wang (2006) and Török et al. (2011).

Our analysis of the magnetic flux evolution beneath the eastern part of filament F1 suggests that the flux emergence caused the destabilization of F1. An important feature of the evolution of F1, F2, and F3 is the pre-eruptive EUV brightening. During the slow rise of filaments F2 and F3, extreme EUV brightening occurred at some part of the F2 and F3 merging (see Figure 11), which suggests a sequence of partial merging episodes. Such brightening could be caused by plasma heating due to the energy released from the reconnection site below the rising prominence (Su et al., 2015).

The merging of F2 and F3 is due to the stronger instability of the lower portion of the flux rope (FR) F2 in comparison to that of the upper F3 FR, which, according to Kliem et al. (2014), is the condition for the merging mechanism of FRs to work. Another condition for
the merging of the two filaments could be the magnetic flux cancellation between them. Such a condition for the two filament merging was discussed in the article by Chandra et al. (2011). They found that the continuous decrease in the magnetic flux between the filaments brings them close to each other until they merge. Later, similar observations were simulated by Török et al. (2011), who confirmed these results.

As for the eruption of the F2–F3 compound FR, it is important to note the suggestion of Aulanier et al. (2010) that flux cancellation and tether-cutting reconnection are key pre-eruption mechanisms for the buildup and the slow rise of a magnetic FR, but they cannot trigger a solar eruption by themselves. Moreover, the authors suggest a torus instability as an additional destabilizing mechanism.

Another event that can also cause significant EUV brightening and subsequently affect the F2 stability is the inflow of F1 material in the vicinity of F2. Such brightening is considered an observational signature of falling material and its impact on the solar atmosphere (Gilbert et al., 2013). Moreover, plasma instabilities associated with the falling material have recently been described by Innes et al. (2012). There are two mechanisms, compression and reconnection, that can explain the EUV brightening observed in the SDO/AIA channels. Which of them is responsible or dominant depends on the amount of energy associated with the observed emission. As Gilbert et al. (2013) pointed out, whatever the dominance of one mechanism over the other, both are likely occurring, since the falling material undoubtedly carries frozen-in magnetic flux. Therefore, the falling of F1 material in the vicinity of F2 could be considered as an additional mechanism that also facilitates the destabilization of F2. Furthermore, this event provides observational evidence for the physical linkage between the three eruptions.

Ding, Hu, and Wang (2006) proposed the 2.5D MHD model for sympathetic eruptions. They consider three FRs embedded in different arcade systems within the same large scale magnetic field. When one FR becomes unstable (or erupts) due to the catastrophic behavior, the global shared magnetic field changes significantly. As a result, these undisturbed FRs become catastrophically unstable and erupt.

The 3D MHD simulation was proposed by Török et al. (2011) for the sympathetic eruption of 1 August 2010. According to their model, two mechanisms occurred. The first FR erupted due to converging flows and the other two FR eruptions were triggered by the removal of the magnetic flux above them due to magnetic reconnection triggered by the first FR eruption.

In the present observations, we believe that the first F1 eruption could allow the reconnection of the open field lines with the overlying field lines of F2 and F3 systems. As a result, the magnetic tension above F2 and F3 becomes weaker and they start to erupt. After comparing our reported observations with the above models, we believe that our events can be explained by the combination of both of them.

To explain the possible scenarios of the observations, we have performed the PFSS extrapolation of the photospheric magnetic field. The result is presented in Figure 12. In panel a, the PFSS extrapolation on 19 July 2015 at 00:00 UT is presented. In panel b, the PFSS extrapolation is shown from a different viewpoint.

Using this figure, we present the following explanation for the current eruption. The erupted part of the filament F1 partially went through the open field lines (shown in green color in the figure) in the northwest direction, which was later observed as a CME. A major portion of the erupted filament F1 went towards the location of filament F2 through the channel of closed field lines (shown by a red arrow). This part disturbed filament F2 allowing it to erupt. Since the erupted material was probably channeled under the closed magnetic field, the observed case can be similar to the scenario of Wang et al. (2016), i.e. the filament F1
does not completely erupt under the closed field lines, but triggers the eruption of filament F2 near the open field lines. Another scenario for the sympathetic eruptions can be explained by panel c of Figure 12. In this scenario, filament F1 and F2-F3 are connected by the following set of loops: loop system L1 connects site 1 to site 2, loop system L2 connects site 2 to site 3, and similarly site 3 is connected to site 4 by loops L3. The erupted material from F1 went towards F2-F3 through loop systems L1, L2, and L3 and it disturbed the stability of filaments F2 and F3. As a result of this disturbance, filaments F2 and F3 erupted.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11207-022-01981-y.

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**Data Availability** The HMI and AIA images and spike files used in this article are publicly available from the JSOC at jsoc.stanford.edu. The Hα data are freely available through the GONG network at http://gong.nso.edu.

**Declarations**

**Disclosure of Potential Conflicts of Interest** The authors declare that they have no conflicts of interest.

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