Untwisting and Disintegration of a Solar Filament Associated with Photospheric Flux Cancellation

Huadong Chen1,2, Ruisheng Zheng3,4, Leping Li1,2, Suli Ma1,4, Yi Bi1,5, and Shuhong Yang1,2

1CAS Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China; hdchen@nao.cas.cn
2School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
3Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, and Institute of Space Sciences, Shandong University, Weihai 264209, People’s Republic of China
4College of Science, China University of Petroleum, Qingdao 266580, People’s Republic of China
5Yunnan Astronomical Observatory, Chinese Academy of Sciences, Kunming 650011, People’s Republic of China

Received 2018 November 4; revised 2018 December 6; accepted 2018 December 17; published 2019 February 4

Abstract

Using the high-resolution observations from the New Vacuum Solar Telescope (NVST) jointly with the Solar Dynamics Observatory data, we investigate two successive confined eruptions (Erup1 and Erup2) of a small filament in a decaying active region on 2017 November 10. During the process of Erup1, the overlying magnetic arcade is observed to inflate with the rising filament at the beginning and then stop during the explosion. In the hot EUV channel, a coronal sigmoidal structure appears during the first eruption and fades away after the second one. The untwisting rotation and disintegration of the filament in Erup2 are clearly revealed by the NVST Hα intensity data, hinting at a pre-existing twisted configuration for the filament. By tracking two rotating features in the filament, the average rotational angular velocity of the unwinding filament is found to be ~10.5 min⁻¹. A total twist of ~1.3π is estimated to be stored in the filament before the eruption, which is far below the criteria for kink instability. Several hours prior to the event, some photospheric flux activities, including the flux convergence and cancellation, are detected around the northern end of the filament, where some small-scale EUV brightenings are also captured. Moreover, strongly sheared transverse fields are found in the canceling magnetic features from the vector magnetograms. Our observational results support the flux cancellation model, in which the interaction between the converging and sheared opposite-polarity fluxes destabilizes the filament and triggers the ensuing ejection.

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

Supporting material: animations

1. Introduction

Solar filaments, also known as prominences, consist of relatively cool, dense plasma that is suspended in the hot tenuous solar corona. They are always located above polarity inversion lines (PILs) separating opposite polarities of radial fields in the photosphere (Babcock & Babcock 1955), which can be inside or at the border of active regions (ARs) or on the quiet Sun. Substantial observed characteristics, including the direct magnetic field measurements of filaments (Leroy 1989; Paletou & Aulanier 2003) reflect that they are present in highly non-potential magnetic structures (e.g., Tandberg-Hansen 1995; Démoülin 1998; Labrosse et al. 2010; Mackay et al. 2010). However, the basic magnetic configuration of the filament and its relationship with the surrounding coronal structures are still under debate (e.g., Berger et al. 2011; Cheng et al. 2014b; Yang et al. 2014a; Shen et al. 2015). It has been commonly accepted that the heavy filament material is supported by magnetic tension force from the dipped coronal fields (Kiepenheuer 1953), which could have normal or inverse polarity (Kippenhahn & Schlüter 1957; Kuperus & Raadu 1974; Leroy et al. 1984; Bonnier & Leroy 1998), i.e., the component of magnetic field perpendicular to the body of the filament has a direction that is the same as or the opposite of that of the potential field.

In the flux rope theoretical model (e.g., Malherbe & Priest 1983; Démoülin & Priest 1989; Aulanier & Démoülin 1998; Amari et al. 1999; van Ballegooijen et al. 2000), the inverse polarity configuration means that the filament is embedded in a helical or twisted field structure, which stores much more energy than the normal polarity configuration. Even in the three-dimensional sheared arcade model, as proposed by DeVore & Antiochos (2000) and Aulanier et al. (2002), such a twisted field geometry of filaments is expected to form due to the reconnection between the sheared and external fields in a large shear case. Assuming a frozen-in condition (due to the high electrical conductivity of the solar atmosphere), the fine thread structures of the filament matter probably reflect the magnetic topology therein. Helical twisted thread structures have been directly observed in both quiescent and eruptive prominences (e.g., Vršnak et al. 1988, 1991; Dere et al. 1999). Sometimes, filaments or jets exhibit apparent unwinding rotational motions during their ejections (e.g., Vršnak et al. 1991; Shen et al. 2011b; Chen et al. 2012, 2017, 2018; Hong et al. 2013; Yan et al. 2014a, 2014b; Li et al. 2015b; Yang et al. 2015), also suggesting a very likely pre-existing twisted magnetic topology for the ejected structures. Bi et al. (2013) proposed that the rotation of the eruptive filament might originate from the action of the asymmetric deflection, which was caused by the interaction between the erupting and surrounding magnetic fields.

It has been well established that a flux tube will be subject to ideal magnetohydrodynamic (MHD) kink instability when the magnetic twist in the flux tube exceeds a critical value $\Phi_c$ (e.g., Raadu 1972; Hood & Priest 1979; Einaudi & van Hoven 1983;
Velli et al. 1990; Baty 2001). The kink instability of a coronal magnetic flux rope can trigger not only confined but also ejective solar eruptions. The decrease of the overlying field with height plays an important role in deciding whether the event is confined or ejective (Török & Kliem 2005), which involves another MHD instability—torus instability (e.g., Bateman 1978; Kliem & Török 2006). For a straight, cylindrically symmetric flux tube, its total twist can be expressed as

$$\Phi = \frac{l B_\phi(r)}{r B_z(r)}$$

where $l$ is the length, $r$ is the minor radius, and $B_\phi$ and $B_z$ are the azimuthal and axial field components, respectively. The critical value for determining stability or instability, $\Phi_c$, rests on the details of the considered flux system in the model, such as the aspect ratio of the loop, the effect of line-tying, the ratio of the plasma to magnetic pressure, the radial profile of the twist, and the stabilizing influence of the overlying magnetic arcade. Investigations of numerical calculations and MHD simulations have revealed that a typical value of $\Phi_c$ ranges from 2.5$\pi$ to 6$\pi$ for a straight cylindrical or an arched, line-tied twisted flux tube (Hood & Priest 1979, 1981; Mikic et al. 1990; Van Hoven et al. 1995; Török & Kliem 2003; Török et al. 2004, 2014).

Besides ideal MHD instabilities, there are many other mechanisms suggested to be triggers of solar eruptions, such as sunspot rotation (e.g., Amari et al. 1996; Yan & Qu 2007; Zhang et al. 2007; Yan et al. 2009), twisting overlying field (Török et al. 2013), shearing of magnetic arcade (e.g., Mikic et al. 1988), tether-cutting (e.g., Moore & Roumeliotis 1992; Moore et al. 2001; Liu et al. 2010; Chen et al. 2014), magnetic breakout (e.g., Antiochos et al. 1999; Chen et al. 2016b), flux feeding or injection (e.g., Chen 1989, 1996; Liu et al. 2012; Kliem et al. 2014; Zhang et al. 2014), and flux emergence or cancellation (e.g., Heyvaerts et al. 1977; Livi et al. 1989; Van Ballegooijen & Martens 1989; Inhester et al. 1992; Wang & Shi 1993; Feynman & Martin 1995; Wang & Sheeley 1999; Chen & Shibata 2000; Lin et al. 2001; Amari et al. 2003a; Jing et al. 2004; Roussev et al. 2004; Zuccarello et al. 2012) etc., as recently reviewed by Chen (2011) and Green & Kliem (2018). According to the definition by Livi et al. (1985) and Martin et al. (1985), flux cancellation refers to the mutual disappearance of photospheric magnetic flux in closely spaced features of opposite polarity, which can be observed throughout the quiet Sun, at the edge of or in ARs and sometimes may take place concurrently with the flux emergence (Feynman & Martin 1995; Wang & Sheeley 1999; Chen et al. 2008; Louis et al. 2014; Li et al. 2015a). The likely theoretical interpretations of the flux disappearance during cancellation mainly embrace the submergence of a small $\Omega$-like loop (e.g., Harvey et al. 1999), upward expulsion of U-shaped flux tube (e.g., Spruit et al. 1987), and annihilation of magnetic flux (e.g., Martin et al. 1985; Amari et al. 2010). A prevailing thought is that these processes result from the reconnection of the canceling magnetic components (e.g., Zwaan 1978, 1987; Wang & Shi 1993).

The reconnection associated with flux emergence or cancellation may play two important roles in prompting solar eruptions. On one hand, it triggers an explosion by modifying the configuration of the overlying field restraining the filament or flux rope, as modeled and simulated by Chen & Shibata (2000), Lin et al. (2001), and Kusano et al. (2012) and supported by the observations of Wang & Sheeley (1999), Jiang et al. (2007), Li et al. (2015a), and Louis et al. (2015). In this case, it could also be the tether-cutting reconnection occurring between the strongly sheared core fields, which was first suggested by Moore & Labonte (1980) and Moore et al. (2001) and then reported by many other works (e.g., Sterling & Moore 2005; Yurchyshyn et al. 2006; Sterling et al. 2007; Kim et al. 2008; Green & Kliem 2009; Liu et al. 2010; Chen et al. 2014, 2015, 2016a; Yang et al. 2016). On the other, flux cancellation is a likely formation mechanism of sigmoidal flux ropes (van Ballegooijen & Martens 1989; Green et al. 2011; Savcheva et al. 2012; Yardley et al. 2016). It is worth pointing out that the two roles of flux cancellation in motivating eruptions should be not mutually exclusive and they may work cooperatively in a single event (e.g., Sterling et al. 2011; Chen et al. 2014).

Up to now, the initiation mechanism of solar eruptions is still not sufficiently understood. In addition to numerical study, more high-resolution observations are needed to present the real magnetic configuration of the erupting system. This would be useful to elucidate the precise origin of the eruption, which is of key importance to the forecasting of space weather. In this work, we use the high-resolution observations from the New Vacuum Solar Telescope (NVST; Liu et al. 2014) together with Solar Dynamics Observatory (SDO; Pesnell et al. 2012) data to scrutinize two successive confined eruptions of a small filament occurring in a decaying AR. The untwisting rotation and disintegration of the erupting filament are disclosed by the NVST H$_\alpha$ line-center and off-band intensity data, reflecting a preceding twisted structure of the filament before its eruption. However, the results from a detailed calculation indicate that the twisted filament probably was not subjected to the kink instability. According to the evolution of the associated photospheric magnetic flux, we suggest that the flux convergence and cancellation detected in the vicinity of one end of the filament may play a main role in triggering the eruptions. This article is organized as follows. In Section 2 we describe the observational data used in our study. In Section 3 we present detailed evolutions of the successive filament eruptions (Sections 3.1 and 3.2) and the associated photospheric magnetic flux (Section 3.3). We provide a summary and discuss our results in Section 4.

### 2. Observations

On 2017 November 10, a solar filament with a length of $\sim$17 Mm successively erupted two times for $\sim$1 hr in a small decaying AR near the solar disk’s center ($\sim$S10E05). According to the observation from the Large Angle and Spectrometric Coronagraph (Brueckner et al. 1995) on board Solar and Heliospheric Observatory, no coronal mass ejection relates to this event. The two confined eruptions mainly took place during the periods of 02:07–02:25 UT (Erup1) and
Our observations reflect that the overlying background field of the AR probably played an important role in confining the eruptions. In this situation, the strong downward magnetic tension from Ar stopped the erupting filament material escaping from the solar atmosphere. According to the theory of MHD instability, we predict that the overlying restraining field’s strength did not fall off fast enough with the height so as to allow the occurrence of torus instability (Kliem & Török 2006; Aulanier et al. 2010). Similar processes have been reported by some observational works (e.g., Ji et al. 2003; Guo et al. 2010; Cheng et al. 2011; Shen et al. 2011a; Zheng et al. 2012; Chen et al. 2013; Song et al. 2014; Yang et al. 2014b; Li et al. 2018; Ning et al. 2018) and numerically simulated by Török & Kliem (2005) and Fan & Gibson (2007).

An interesting phenomenon is found in the hot AIA 211 Å channel in which a transient sigmoid structure surrounding the filament appeared during Erup1 (Figure 2). Generally, coronal sigmoids are the observational signatures of sheared and/or twisted fields (e.g., Rust & Kumar 1996; Green & Kliem 2009; Green et al. 2011; Savcheva et al. 2012). Two possibilities are responsible for the appearance of the sigmoid. First, the sigmoid had existed before eruption and just brightened due to the reconnection heating during the eruption. Second, the S-shape formed during the eruption might have been due to the reconnection of sheared fields (Moore et al. 2001) or the injection of the poloidal field (Priest 2014). Since there were also some activities taking place in the AR several hours before the event but no similar S-shaped configuration arose, we are inclined to accept the second situation. The sigmoid faded away after Erup2 and did not come into being again, implying a permanent destruction or change of its structure during Erup2. In the hotter AIA 335 Å and 94 Å passbands, the observational signals of the bright sigmoid were detected to be faint. These results indicate that the plasma in the sigmoid primarily had a temperature as high as ~2 MK, which is the central formation temperature of the AIA 211 Å emission.

3. Results

3.1. Successive Filament Eruptions in the AIA EUV Channel

The host AR started to emerged from November 7 and peaked at the end of November 8. When the event occurred on November 10, the AR had been in its decaying phase. The AIA 171 Å images in Figure 1 present the main processes of the two confined eruptions. Before Erup1, the filament was basically aligned along the north–south direction in the AR. At about 02:07 UT, an EUV brightening appeared near the northern end of the filament and thereafter the eruption commenced. The filament first rose up to a (projected) height of ~5 Mm, and then partially fell back to the surface, while a different part of the filament was expelled toward the south (roughly following the magnetic neutral line; see panels (a3) and (a4)). Meanwhile, the overlying arcade structure (labeled “Ar” in Figure 1(a2)) of the AR remained intact throughout the event; that is, the eruption did not burst through that overlying field. After Erup1, the filament appeared again at its former location (see Figure 1(b1)).

At 02:40 UT, 15 minutes after the end of Erup1, similar EUV brightenings arose near the northern footpoint of the filament. Then, the filament broke away from this end and bifurcated into several threads, as its southern end remained anchored onto the photosphere. Due to the small scale of the filament as well as the overlying coronal emission from the hot EUV line, the detailed dynamical evolution of the filament during Erup2 was not clearly revealed by the AIA data. But we can still detect the rapid rotation of the southern root of the filament during the eruption (see Figure 1(b4) and the animated version of Figure 2). After 03:05 UT, the filament gradually disappeared in the EUV lines.

In the studied event, only the second confined eruption Erup2 was captured by NVST. The NVST Hα line-center intensity data (Figures 3(a1)–(a6)) of higher spatial resolution clearly revealed that the filament underwent an untwisting motion during Erup2 (also see the the online animated version of Figure 3). From Figures 3(a1) to (a2), we can see that some filament threads formerly twined around together split into several strands due to unwinding. Subsequently, the untwisting motion developed southward along the filament and the southern end began to rotate counterclockwise. As a result, the filament threads kept loosening from a tight state. After ~02:48 UT, it can be observed that some threads stripped away from the main structure and proceeded to spin and unwind from each other until ~03:03 UT, as indicated by the thick and curved arrows in Figures 3(a3)–(a5).

Panels (b1)–(b3) of Figure 3 are Hα Doppler intensity images, which were obtained by subtracting the Hα blue-wing (B030) data from the red-wing (R030) data. For the filament, the dark (bright) features in the Doppler images correspond to the parts with redshifts (blueshifts). From Figure 3(b1), it can be seen that the filament spine exhibited a twisted structure with blueshift, while the two legs appeared as redshifted features, implying that some twist had been stored in the filament and the filament experienced a slow rise prior to the
eruption. The redshift characteristics of the filament legs may be related to the downward flows along the field lines. When the filament unwinds after the commencement of Erup2, we can see that the uniform redshift or blueshift signature arose in the same thread structure (Figure 3(b2)). This is consistent with the scenario in which the plasma has similar dynamics in one strand of the filament if considering the freezing-in effect of the plasma–magnetic field coupling. In Figure 3(b3), we can see that as the southern end of the filament rotated, the leg connecting with it formed a helical structure and showed ejective characteristics.

The untwisting motion of the filament presented here reflects that some twist may have been kept in the filament before its eruption. An important question arises regarding how much the total stored twist was, the answer to which will provide a clue for clarifying the triggering mechanism of the filament eruptions in this event. To get the answer, the rotational motion of the filament was first investigated in detail. We chose two apparent rotating features (“RF1” and “RF2” in Figures 3(a3) and (a5)) in the filament near the southern endpoint and traced their motions, which are displayed in Figure 4. The dotted lines in Figures 4(a1)–(a3) represent the profiles of the same filament thread at different times. RF1 is chosen at the intersection point between the dotted line and the circle, along which RF1 turned around the center. RF1 rotated about 72° in 6 minutes, which derives an average angular speed.
Figure 2. AIA 211 Å images displaying the changes of the coronal structure in the AR before (a), during (b) Erup1, and after Erup2 (c) (also see the online animation). The dotted line in panel (b) indicates the location of the filament before eruption. The animation runs from 02:00 to 03:30 UT on 2017-11-10.

(An animation of this figure is available.)

of 12\(^\circ\) minutes\(^{-1}\). As for RF2, it circled \(\sim 32\(^\circ\)\) around the center from 02:57:52 to 03:01:30 UT, which outputs an average angular velocity of \(\sim 9\(^\circ\)\) minutes\(^{-1}\). If we take the mean value of the two average angular velocities, i.e., 10.5 minutes\(^{-1}\), as the average untwisting motion speed of the filament, then the peak value of the stored twist can be derived by the average untwisting motion speed of the filament, then the peak value of the stored twist can be derived by the opposite-polarity fields reaches \(\sim 300\) G and the shear angle is nearly 90\(^\circ\). Although it is hard to clarify the connectivities of the associated magnetic loops, these sheared fluxes strongly suggest that the canceling fluxes, or at least part of them, do not come from the footpoints of a single loop. Sheared fields are often observed in solar ARs

3.3. Photospheric Flux Evolution

Essentially, solar eruption results from the loss of equilibrium of a magnetic system due to an imbalance between magnetic tension and compression (Forbes & Isenberg 1991). Sometimes, this situation can be caused by the interaction between the erupting structure and its nearby magnetic field; for example, the aforementioned flux cancellation (Chen & Shibata 2000; Lin et al. 2001). Thus, we also investigated the photospheric magnetic evolution associated with this event (see Figures 5 and 6 and the animated version of Figure 5). The HMI magnetogram in Figure 5(a) shows the photospheric longitudinal fields of the AR and its spatial relation to the filament projected in the surface. We can see that the positive field of the AR was more concentrated than the negative field and there was no obvious magnetic neutral line in the AR. The two ends of the filament were separately anchored onto the northern positive flux and the negative flux in a southern remote area.

We focused on the flux changes in the region close to the filament northern end (Figures 5(b1)–(b5), as some small-scale activities (EUV brightenings) had taken place there before the eruptions. The HMI data clearly reveal that some negative fluxes started to be enhanced near the filament footpoint from \(\sim 22:00\) UT and reached their maximum at \(\sim 23:15\) UT on November 9. Then, they moved westward and collided with the neighboring positive fluxes, as indicated by the arrows in Figure 5(b2). Until 02:05 UT on November 10, i.e., just prior to Erup1, these moving fluxes were almost completely canceled by the opposite-polarity fluxes and disappeared. We also calculated the positive and unsigned negative longitudinal magnetic fluxes in the cancellation region (marked by the box in Figure 5(b2)) from 21:00 UT on November 9 to 03:00 UT on November 10. The time variations of the fluxes are presented in Figure 5(c). It can be seen that the unsigned negative flux apparently mounted from \(\sim 22:00\) UT and reached the peak value of \(\sim 6 \times 10^{18}\) Mx at \(\sim 23:15\) UT on November 9. Since then, it dropped gradually, with small-amplitude oscillations, and the positive flux declined as well. Until Erup1, the negative flux had decreased to a level less than that before it augmented on November 9. The flux-time curves likewise reflect the flux enhancement and cancellation processes occurring near the filament end 5 hr prior to the eruption.

The flux cancellations presented above are probably caused by the slow magnetic reconnections between the moving negative fluxes and its nearby positive fluxes (Wang & Shi 1993), which would lead to some small-scale activities observed as the EUV brightenings on some occasions. The high degree of temporal and spatial correlations between the flux cancellations and the filament evolution make us believe that there is an intimate connection between these activities. It is very likely that the interactions between the converging and collisional fluxes at the end of the filament first affected the mechanical equilibrium of the filament, then resulted in the filament activations and disturbances and finally triggered the following explosions.

Figure 6 shows the close-up of the flux convergence and cancellation region with the HMI vector magnetograms. It is found that some transverse fields between the canceling fluxes, as marked by the circles, were strongly sheared. The strength of the strongest sheared transverse fields reaches \(\sim 300\) G and the shear angle is nearly 90\(^\circ\). Although it is hard to clarify the connectivities of the associated magnetic loops, these sheared fluxes strongly suggest that the canceling fluxes, or at least part of them, do not come from the footpoints of a single loop. Sheared fields are often observed in solar ARs
According to the scenario described by Moore et al. (2001), the strongly sheared core fields are favorable to the occurrence of the tether-cutting reconnection, which would give rise to the eruption by weakening the magnetic tethers holding the filament down. The flux cancellation model proposed by van Ballegooijen & Martens (1989) also suggests a similar physical process. In this event, the sheared transverse fields presented by the vector field data further indicate the important role of the flux cancellation in causing the eruptions. Using the vector magnetograms without resolution of the 180° ambiguity, Wang & Shi (1993) and Zhang et al. (2001) found that the opposite polarities in the canceling magnetic features are not the footpoints of a single flux loop, but rather are the footpoints from two separated loops, and strong shear would develop at the interface of the opposite polarities. Our observations confirm their results and likewise imply the reconnection essence of the flux cancellation.

Figure 3. NVST Hα line-center ((a1)–(a6)) and Doppler ((b1)–(b3)) intensity data showing the evolution of the filament during Erup2 (also see the online animation). The thick arrows in panels (a2)–(a4) aim at the bifurcated structure of the filament due to untwisting during Erup2. The curved arrows in panels (a2) and (a5) denote the rotation of the filament at its southern root. The rectangles in panels (a2) and (a5) indicate the fields of view (FOV) of the top and bottom panels of Figure 4, respectively. The red and blue arrows in panels (b1)–(b3) point to the red- and blueshifted parts of the filament, respectively. The curve in panel (b3) indicates the helical structure of the filament rooted in its southern endpoint. The animation features CENT, R030, and B030 intensity images, and runs from 02:24 to 03:30 UT. (An animation of this figure is available.)
4. Summary and Discussion

We study the kinematics and morphology of an erupting filament during its two successive confined eruptions (Erup1 and Erup2) in a decaying AR. Our observations unambiguously present evidence for the confinement of the eruption from the overlying magnetic arcade and the rotational motion of the erupting filament due to unwinding, suggestive of a preceding twisted configuration of the filament. The total stored twist of $\sim 1.3\pi$ is obtained by analyzing and calculating the rotational angles of the filament during its untwisting, which is far from satisfying the criteria for kink instability. We note that the photospheric longitudinal fluxes around the filament underwent conspicuous changes, especially the flux convergence and cancellation in the vicinity of the northern end of the filament, during the period several hours prior to the eruptions. Strongly sheared transverse fields are also found in the canceling magnetic features from the vector magnetograms. These results support the flux cancellation model (e.g., van Ballegooijen & Martens 1989) in which the interaction between the converging and sheared fluxes of opposite polarity gradually destroys the balance between the magnetic tension and compression of the filament system, activating the filament and triggering the final ejection. It is worth noting that we are not claiming that the erupting filament behavior that we observe in the present event is typical of all eruptions, and we expect filaments to evolve differently for different eruptions. Here, we would like to compare the observations of Yan et al. (2014a) and Yan et al. (2014b). In their cases, the erupting filaments also exhibited untwisting motions, suggesting the structures of a flux rope. Differing from ours, their results showed that the total twists of the filaments were separately $\sim 3\pi$ and $5\pi$, exceeding the typical threshold ($2.75\pi$; Török & Kliem 2003) for kink instability. Consequently, they proposed the kink instability as the triggering mechanism of their studied eruptions.

Note that we only observed the untwisting motion of the filament during Erup2. Although the NVST observations with better spatial resolution did not cover Erup1, no rotational motion or kinked structure was detected during the first eruption from the AIA intensity images. Hence, the twist stored in the filament and released during Erup2 was perhaps formed during Erup1, which is in good agreement with the appearance of the coronal sigmoidal structure in the meantime (Figure 2). The main process of the event we studied might be explained by this
scenario: first, under the influence of the flux cancellation, the filament was gradually destabilized, accompanied by the EUV brightenings and finally ejected to form Erup1, when the system reached the point where no nearby equilibrium was accessible.

During Erup1, perhaps due to the reconnection of sheared fields or the injection of the poloidal field, some twist was stored in the filament-carrying field, corresponding to the production of the coronal sigmoid. Then, the twist was released in the following eruption observed as the untwisting of the filament during Erup2. Allowing for a “double-decker” configuration of filament or flux rope (e.g., Liu et al. 2012; Li & Zhang 2013; Cheng et al. 2014a; Kliem et al. 2014; Zhu & Alexander 2014; Dhakal et al. 2018; Tian et al. 2018) or even a multi-flux-rope system (e.g., Awasthi et al. 2018; Hou et al. 2018), there is a second possibility besides the situation described above. It might be that there are two sets of erupting fields, one on top of the other. The
upper field erupts to cause the first eruption, and the lower field erupts to cause the second eruption. The lower field could contain twist, but it is being held down by a less-twisted upper field. The flux cancellation results in the overlying top field erupting outward (Erup1), which is not strong enough to escape as a CME. During this eruption, the filament and the field containing it rose up, and also moved toward the south, roughly following the AR’s PIL, which caused new brightenings to occur along the magnetic neutral line. Since the neutral line naturally has an approximate sigmoidal shape, the additional brightenings made the overall structure appear as a sigmoid in 211 Å. Then,

with the upper field removed, the lower, more twisted field had a chance to erupt upward and unwind (Erup2). Again, it did not have enough energy to escape as a CME, so it too remained as a confined eruption.

We thank the referee for constructive comments that helped us improve the paper. The data are used courtesy of the NVST and SDO science teams. This work is supported by NSFC (11790304, 11533008, 11790300, 41331068, 11673034, 11673035, 11773039), and Key Programs of the Chinese Academy of Sciences (QYZDJ- SSW-SLH050).
References

Amari, T., Aly, J.-J., Mikic, Z., & Linker, J. 2010, ApJL, 717, L26
Amari, T., Luciani, J. F., Aly, J. J., Mikic, Z., & Linker, J. 2003a, ApJ, 585, 1073
Amari, T., Luciani, J. F., Aly, J. J., Mikic, Z., & Linker, J. 2003b, ApJ, 585, 1073
Amari, T., Luciani, J. F., Aly, J. J., Mikic, Z., & Linker, J. 2000, ApJ, 545, 524
Chen, P. F., & Shibata, K. 2000, ApJ, 545, 524
Chen, P. F. 2011, LRSP, 8, 1
Chen, J. 1996, JGR, 101, 27499
Amari, T., Aly, J.-J., Mikic, Z., & Linker, J. 2010, ApJL, 717, L26

The Astrophysical Journal, 871:229 (11pp), 2019 February 1

ORCID iDs

Huadong Chen @ https://orcid.org/0000-0001-6076-9370
Ruisheng Zheng @ https://orcid.org/0000-0002-2734-8969
Leping Li @ https://orcid.org/0000-0001-5776-056X
Suli Ma @ https://orcid.org/0000-0002-5431-6065
Yi Bi @ https://orcid.org/0000-0002-5302-3404
Shuhong Yang @ https://orcid.org/0000-0002-6565-3251

Hou, Y. J., Zhang, J., Li, T., Yang, S. H., & Li, X. H. 2018, A&A, 619, A100
Inhester, B., Binz, J., & Hesse, M. 1992, Softs, 138, 257
Ji, X., Wang, H., Schmahl, E. J., Moon, Y.-J., & Jiang, Y. 2003, ApJL, 595, L135
Jiang, Y.-C., Shen, Y.-D., & Wang, J.-X. 2007, ChJAA, 7, 129
Jing, J., Yurchyshyn, V. B., Yang, G., Xu, Y., & Wang, H. 2004, ApJ, 614, 1054
Kippenheuer, K. O. 1953, in The Sun, ed. G. P. Kuiper (Chicago: Univ. Chicago Press), 322
Kim, S., Moon, Y.-J., Kim, Y.-H., et al. 2008, ApJ, 683, 510
Kippenhahn, R., & Schlüter, A. 1957, ZA, 43, 36
Klimchuk, B., & Török, T. 2006, PrPhRL, 96, 255002
Klimchuk, B., Török, T., Titov, V. S., et al. 2014, ApJ, 792, 107
Kuperus, M., & Raadu, M. A. 1974, A&A, 31, 189
Kasano, K., Bamba, Y., Yamamoto, T. T., et al. 2012, ApJ, 760, 31
Labrosse, N., Heinzel, P., Vial, J.-C., et al. 2010, SSRv, 151, 243
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17
Leroy, J. J. 1989, in Dynamics and Structure of Quiescent Solar Prominences, ed. E. R. Priest (Dordrecht: Kluwer Academic Publishers), 77
Leroy, J. L., Bommier, V., & Sahal-Brechet, S. 1984, A&A, 131, 33
Li, L., & Zhang, J. 2013, A&A, 552, L11
Li, T.-Y., Yang, S., Zhang, Z. H., & Jiang, Z. 2018, ApJ, 859, 122
Li, T., Zhang, J., & Ji, H. 2015a, SoPh, 290, 1687
Lin, J., Forbes, T. G., & Isenberg, P. A. 2001, JGR, 106, 25053
Liu, R., Kliem, B., & Török, T. 2012, ApJ, 756, 59
Liu, R., Liu, C., Wang, S., Deng, N., & Wang, H. 2010, ApJL, 725, L84
Liu, Z., Xu, J., Gu, H., Li, L., & Qu, B. 2014, ApJL, 783, 162
Livi, S. H. B., Martin, S., Wang, H., & Ai, G. 1989, SoPh, 121, 197
Livi, S. H. B., Wang, J., & Martin, S. F. 1985, ApJL, 38, 855
Lohmann, A. W., Weigelt, G., & Wirtzner, B. 1983, ApOpt, 22, 4028
Lem, R. E., Kliem, B., Ravindra, B., & Chintzoggou, G. 2015, SoPh, 290, 3641
Lem, R. E., Puschmann, K. G., Kliem, B., Balthasar, H., & Denker, C. 2014, A&A, 562, A110
Mackay, D. H., Karpen, J. T., Ballester, J. L., Schmieder, B., & Aulanier, G. 2010, SSRv, 151, 133
Malherbe, J. M., & Priest, E. R. 1983, A&A, 123, 80
Martin, S. F., Livi, S. H. B., & Wang, J. 1985, ApJ, 309, 929
Mikić, Z., Barnes, D. C., & Schnack, D. D. 1988, ApJ, 328, 830
Mikić, Z., Schnack, D. D., & van Hoven, G. 1990, ApJL, 361, 690
Moore, R. L., & Labonte, B. J. 1980, in IAU Sym. 91, Solar and Interplanetary Dynamics, ed. Dryer & E. Tandberg-Hanssen (Dordrecht: Reidel), 207
Moore, R. L., & Roumeliotis, G. 1992, in IAU Coll. 133, Eruptive Solar Flares, Lecture Notes in Physics, ed. Z. Svestka, B. V. Jackson, & M. E. Machado (Berlin: Springer), 69
Moore, R. L., Sterling, A. C. H., & Lemen, J. R. 2001, ApJ, 552, 833
Ning, H., Chen, Y., & Wu, Z. 2018, ApJL, 854, 178
Paletou, F., & Aulanier, G. 2003, in ASP Conf. Ser. 236, Solar Polarization Workshop 3, ed. J. Trujillo Bueno & J. Sánchez Almeida (San Francisco: ASP), 458
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, Softs, 275, 3 Priest, E. (ed.) 2014, Magnetohydrodynamics of the Sun (Cambridge: Cambridge Univ. Press), 392
Raadu, M. A. 1972, SoPh, 22, 425
Roussev, I. I., Sokolov, I. V., Forbes, T. G., et al. 2004, ApJL, 605, L73
Rust, D. M., & Kumar, A. 1996, ApJ, 478, 907
Rust, D. M., & Kumar, A. 1996, ApJL, 478, 907
Ruvolo, I., & Luongo, J. A. 1996, SoPh, 162, 345
Rust, D. M., & Kumar, A. 1996, ApJL, 478, 907
Savcheva, A. S., Green, L. M., van Ballegooijen, A. A., & DeLuca, E. E. 2012, ApJ, 759, 105
Shu, Y., Liu, Y., Liu, D., et al. 2015, ApJL, 814, L17
Shen, Y., Liu, Y., & Liu, R. 2011a, RAA, 11, 594
Song, H. Q., Zhang, J., Cheng, X., et al. 2014, ApJL, 784, 48
Spruit, H. C., Title, A. M., & van Ballegooijen, A. A. 1987, SoPh, 110, 115
Sterling, A. C., & Moore, R. L. 2005, ApJL, 630, 148
Sterling, A. C., Moore, R. L., & Forrest, T. E., et al. 2007, PASI, 59, 823
Sterling, A. C., Moore, R. L., & Forrest, T. E., et al. 2007, PASI, 59, 823
Sun, X., Hoeksema, J. T., Liu, Y., et al. 2012, ApJ, 748, 77
Sterling, A. C., Moore, R. L., Berger, T. E., et al. 2007, PASI, 59, 823
