**Multiwavelength Observation of a Failed Eruption from a Helical Kink-unstable Prominence**

Haqing Xu1,2, Jiangtao Su1,2, Jie Chen1,2, Guiping Ruan3, Arun Kumar Awasthi4, Hongqi Zhang1, Mei Zhang1,2, Kaifan Ji5, Yuzong Zhang1, and Jiajia Liu6

1 Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
2 School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing, People’s Republic of China
3 Institute of Space Sciences and School of Space Science and Physics, Shandong University, Weihai 264209, People’s Republic of China
4 CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Sciences, University of Science and Technology of China, Hefei 230026, People’s Republic of China
5 Yunnan Observatories, Chinese Academy of Sciences, Kunming, 650216, People’s Republic of China
6 Astrophysics Research Centre, School of Mathematics & Physics, Queen’s University Belfast, Belfast BT7 1NN, UK

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**Abstract**

Multiwavelength observations of a prominence eruption provide an opportunity to uncover the physical mechanism of the triggering and the evolution process of the eruption. In this paper, we investigate a prominence that erupted on 2012 October 14, recorded in Hα, EUV, and X-ray wavelengths. The process of the eruption gives evidence for the existence of a helical magnetic structure showing the twist converting to writhe. The estimated twist is \(\sim 6\pi \) (three turns), exceeding the threshold of the kink instability. The rising plasma reached a high speed of 228 km s\(^{-1}\), followed by a sudden rapid acceleration of 2715 m s\(^{-2}\), and was synchronous with a solar flare. Co-spatial cusp-shaped structures were observed in both 131 and 94 Å images from the Atmospheric Imaging Assembly, signifying the location of the magnetic reconnection. The erupted flux rope finally underwent a deceleration with a maximum value of 391 m s\(^{-2}\), which is larger than the freefall acceleration on the Sun (273 m s\(^{-2}\)), suggesting that the eruption finally failed, possibly due to an inward magnetic tension force.

**Unified Astronomy Thesaurus concepts:** Solar activity (1475); Solar flares (1496); Solar filaments (1495); Solar prominences (1519); Solar magnetic reconnection (1504)

**Supporting material:** animations

1. **Introduction**

Prominence eruptions are large-scale eruptive phenomena that are frequently observed in the corona. Observations show that ejective prominences (filaments) are often associated with coronal mass ejections (CMEs) and flares (e.g., Webb et al. 1976; Zhou et al. 2006; Filippov & Koutchmy 2008; Liever et al. 2013). This makes the investigations of these events crucial for understanding Sun–Earth connection. There are also prominence eruptions that are not accompanied by CMEs. In these events, the associated coronal structure remains in the corona, with the prominence material often falling back to the chromosphere. These events are called failed (confined) eruptions.

While successful eruptions are important for their association with CMEs, failed eruptions can also shed light on the pre- and post-eruption magnetic field configurations. Ji et al. (2003) analyzed a typical failed filament eruption and found that the energy release and reconnection point may occur at a location above the filament during its acceleration phase. Recently, data with high spatial and temporal resolution from ground-based and space-borne facilities, several observational studies of confined eruptions have been done (e.g., Netzel et al. 2012; Shen et al. 2012; Liu et al. 2014; Yang et al. 2014; Li & Zhang 2015; Xue et al. 2016a). Although the pre-eruptive structure is usually very complicated, the helical structure often becomes prominent during the acceleration phase (Vršnak et al. 1991). Dere et al. (1999) observed internal helical structures of CMEs, and interpreted them to be magnetic flux ropes. Cheng et al. (2011) presented an unambiguous observation of a flux rope in the formation phase in the low corona. The magnetic flux rope is a key feature in a prominence (e.g., Ali et al. 2007; Guo et al. 2010; Kumar et al. 2010; Koleva et al. 2012; Cheng et al. 2014; Yang et al. 2015). This observational phenomenon has also motivated many scientists to include magnetic flux ropes in their numerical simulations of solar eruptions (e.g., Lin et al. 1998; Titov & Démoulin 1999; Amari et al. 2000).

The mechanism of both ejective and failed eruptions is not yet fully understood, owing to the fact that the underlying magnetic structure is poorly known. It has been suggested that magnetic reconnection can trigger filament eruptions and CMEs (Feynman & Martin 1995; Wang & Sheeley 1999). However, it is difficult to observe magnetic reconnection directly because of the very small size of the diffusion region. Mostly it is observed through the consequences of the reconnection, such as the heating of the corona (e.g., Zhang et al. 2015), and inflows (Yokoyama et al. 2001; Su et al. 2013) and/or outflows indicated from both imaging and spectral observations (e.g., Savage et al. 2010; Tian et al. 2014; Reeves et al. 2015; Hong et al. 2016). Recently, Li et al. (2016) gave clear observational evidence of magnetic reconnection between an erupting filament and its nearby coronal loops. Xue et al. (2016b) presented comprehensive observational evidence of reconnection between a set of chromospheric fibrils and the threads of an erupting filament, which leads to the eventual untwisting of a flux rope.

Another widely accepted mechanism of solar eruption is the kink instability. It was initially suggested as the trigger of both confined and ejective prominence eruptions by Sakurai (1988). Magnetohydrodynamics simulation (Török & Kliem 2005)
confirmed that the helical kink instability of a twisted magnetic flux rope can be the mechanism of the initiation and the initial driver of solar eruptions, and the decrease of the overlying field with height is a main factor in deciding whether the instability leads to a confined event or a CME. Several observational studies also show that the kink instability is the driver of filament eruptions (e.g., Rust & LaBonte 2005; Williams et al. 2005). Of course, there are also some other mechanisms for solar eruptions, such as sunspot rotation and shearing motions (e.g., Tian & Alexander 2006; Ruan et al. 2014; Chen et al. 2015), wave disturbance (Uchida 1974), critical twist configuration (Vršnak et al. 1988) etc.

The study of twist provides an effective tool for analyzing the structure and stability of prominences. The twist of a flux rope is determined by the number of turns of the magnetic field line when counting from one footpoint to the other. The critical twist number for kink instability varies in different conditions. Hood & Priest (1979) found that, for a force-free uniformly twisted flux rope, there is a critical twist of $3.3\pi$, exceeding which the field will become kink-unstable. Török & Kliem (2003) simulated the formation of a twisted magnetic flux rope and found that the critical twist number is between $2.5\pi$ and $2.75\pi$, for a set of different parameters. Other simulations (Fan 2005; Török & Kliem 2005) also show that a magnetic flux rope becomes kink-unstable if the twist exceeds a critical value of $2\pi$. Models of flux ropes in an external field give values closer to $3.5\pi$ for the critical twist (Fan & Gibson 2003, 2004; Török et al. 2004). This value even increases with increasing aspect ratio of the loops involved (Baty 2001; Török et al. 2004). So it should be interesting and important to check the critical twist number from observations.

In this paper, we analyze a prominence eruption using observations from the Solar Magnetism and Activity Telescope (SMAT) at Huairou Solar Observing Station (HSOS) of the National Astronomical Observatories of China and from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). We also use observations from the Solar Terrestrial Relations Observatory (STEREO) mission to combine limb and on-disk observations. We aim at investigating the morphology as well as the kinematic and helicity evolutions of the prominence during its eruption. In Section 2, we describe the observations. In Section 3, we present the main results. Discussions and conclusions are outlined in Section 4.

2. Observations and Data Analysis

A prominence was observed on the northeast solar limb at 02:00 UT on 2012 October 14. It remained stable until 02:10 UT and then started to rise slowly, as shown in Hα image observed by SMAT (Figure 1). The full solar disk Hα (6562.81 Å) telescope of SMAT is operated by a collimated optics of 20 cm aperture and 180 cm effective focal length. The image size of the telescope is 9 mm × 9 mm, and the size of the CCD is 2029 × 2044 pixels. The spatial resolution is better than 2″ (Zhang et al. 2007) and the cadence of the acquired images is 1 second.

The SDO/AIA (Lemen et al. 2012) provides multiple, simultaneous high-resolution full-disk images of the transition region and the corona. The AIA observes seven EUV, two UV, and one visible-light wavelength bands. The spatial and temporal resolutions of AIA are 1″/2 (pixel size is 0″/6) and 12 s, respectively. The field of view is 1.3 $R_\odot$. The temperature response of the EUV emission line covers a wide range of material heated, from 1 to 20 MK.

The event was also observed as a filament eruption in the Extreme Ultraviolet Imager (EUVI) on board STEREO-B. The two STEREO spacecraft, launched in 2006 October, were placed into orbits around the Sun similar to Earth’s, but with STEREO-A ahead of Earth in its orbit and STEREO-B behind, and with both spacecraft gradually drifting away from Earth at a rate of about 22° per year (Howard et al. 2008). On 2012 October 14, the separation angle between STEREO-A (+B) and Earth was 126.3° (119°/8), and that between STEREO-A and -B was 113°. The EUVI detector has 2048 × 2048 pixels and the pixel size is 1″/6; it observes in four spectral channels that span the temperature range 0.1–20 MK (Wuelser et al. 2004). We used the 304 Å images with a cadence of 10 minutes to study the evolution of the filament.

For Hα data, all images are aligned to the image observed at 02:00 UT by computing the cross-correlation using the properties of the Fourier transform. We downloaded the level 1 AIA data, then derotated and coaligned the AIA images to the time of 02:10 UT.

RHESSI (Lin et al. 2002) provides high-resolution imaging and spectroscopy of X-ray (6 keV) to gamma rays (17 MeV), to diagnose the heated plasma and accelerated electrons. For this event, the RHESSI observations were available only from 02:50 UT. Here we used the hard X-ray emission primarily for locating the reconnection site and the source of thermal and non-thermal emission.

3. Results

3.1. The Morphology and Kinematic Evolution

The prominence appeared as two bright structures in Hα observations at 02:00:30 UT, wherein the lower part first started to rise up at 02:10:30 UT, as shown by the arrow in Figure 1(a). At 02:20:12 UT (Figure 1(b)), it became elongated and writhed as indicated by the red dotted line (a diagram of this structure is shown by the red solid line) while the clockwise rotation of the lower part of the prominence can be seen in the animation (see Figure 1). At 02:26:12 UT, the prominence comprised three parts: the large faint loops marked by L1 and L2 (green dotted line in Figure 1(c)) and bright writhed core marked by L3 (red dotted line in Figure 1(c)). These three parts appeared to be closely connected in the middle-lower part of the prominence. The writh is more obvious at this time. On the other hand, the upper footpoint of the loop is too faint to be traced. With the loop rising and expanding, at 02:31:12 UT, the top of the eruptive loop was out of the field of view of Hα images (Figure 1(d)), while the writhed part uplifted and became clearer. Subsequently, the prominence material fell down at 02:38:12 UT. The eruption process ended at about 02:59:11 UT.

In Hα images, the footpoints of the prominence were not very clear. Therefore we attempted to derive such information from the EUVI/STEREO observation. The prominence was seen as a filament in EUVI 304 and 195 Å images. It appeared to be in the quiet phase at 02:07:08 UT (Figure 2(a)). From the sequence of 195 Å images (available with 5 minute time cadence, see Figures 2(b) and (c)), filament splitting was discernible since 02:21:23 UT. At 02:27:08 UT, the two branches of erupting filament completely separated: the large faint arcade LP1 (green dotted line in Figure 2(d)) was located above the small helical
bright core LP2 (blue dotted line in Figure 2(d)). The eruption appeared to start with the writhe of the bright core (LP2), which appeared to drive the eruption of LP1. LP1 rose to a much greater height than LP2. The two legs of LP1 anchored at footpoints F1 and F2. Non-uniform thread density can be seen in at least three locations along loop LP1, which indicates its twisted nature (Figure 2(c)). The two legs of LP2 anchored at footpoints F3 and F4. The material moved to region “A” due to the flaring activity (see the animation with Figure 2). As the plasma fell back, the span of the brightened region increased around F2 and “B” due to energy deposited by the draining plasma, and the flare ribbons separated gradually (Figure 2(e)). The filament re-formed at almost the same location (Figure 2(f)), which indicated that the filament eruption failed.

The prominence appeared in all seven AIA EUV channels at 02:10 UT, in agreement with the Hα observations. We used AIA 304 Å images to quantify the evolution of the prominence at EUV wavelength. There is an obvious twist and writhe at the core of the rising loop at 02:20:07 UT (Figure 3(b)). This helical structure can also be seen in AIA hot passbands, which may relate to a magnetic flux rope. The helical structure kept rising and expanding. From 02:26:07 UT to 02:36:07 UT (Figures 3(c) and (d)), the prominence separated into three parts: two large diffuse loops marked by L1 and L2 with twisted fine threads and a writhe structure marked by L3. The south leg almost bifurcated into two loops (L1 and L2) with its footpoint attached to the surface. But the north leg only separated in the upper part and its footpoint could not be seen, suggesting that it was on the back side. In the lower part of the south leg, strong brightening appeared, which is indicative of the energy release following the magnetic reconnection. The loop rose, expanded, and unwrapped in the course of its evolution. The prominence became more diffused and some threads of L1 broke as shown in Figure 3(d). The fast upward flow brought the hot plasma into the higher corona. This flow was more evident in hot EUV channels. After 02:43:43 UT, the loops disrupted and the mass started to fall down along the two legs of the prominence (Figure 3(e)). The draining plasma deposited its hot materials on the solar surface and hence appeared brightened (Figure 3(f)). From the animation (Figure 3), clockwise rotation of L2’s lower southern part can be seen during the rising phase viewed from the top of L2.

In order to distinguish different loop structures, we retrieve the three-dimensional (3D) location of the filament derived by a triangulation technique called tie point (Inhester 2006). We use the routine SCC_MEASURE.PRO in the SSW package, which returns the location and height of the filament in 3D. The result
Figure 2. Evolution of the filament in STEREO-B EUVI 304 and 195 Å images (panels (b) and (c)). The white arrow in panel (a) points to the filament before eruption and that in panel (f) to the re-formed filament. The green and blue arrows in panel (c) point to LP1 and LP2 respectively. The green and blue dotted lines in panel (d) show the loops LP1 and LP2 respectively. The green (F1 and F2) and blue (F3 and F4) star symbols show the two footpoints of LP1 and LP2 respectively. “A” in panel (d) and “B” in panel (e) denote the locations of the bright ribbons. An animation of this figure is available. The video begins at 01:37:08 and ends at 09:07:08. The real-time duration is 9 s.

(An animation of this figure is available.)
is shown in Figure 4. Symbols (“*” on L1 and “+” on L2) represent the identified points on respective images, while the dotted lines are spline-fit to the identified coordinates. This confirms that L1 and L2 marked in Figures 1(c) and 3(c) correspond to a large fainter filament arch (LP1 and its vicinity) in Figure 2(d), and L3 corresponds to LP2 in Figure 2(d).

All of the aforementioned observations suggest that this region might be the so-called double-decker filament system as reported by Liu et al. (2012) and Kliem et al. (2014). The lower filament became unstable first due to kink instability, which then triggered the eruption of the upper filament.

We then investigated the kinematics of different structures within the prominence. We analyzed three slices as outlined by the cyan dotted lines in Figure 3. The slice A → B is 485 pixels long and 6 pixels wide, and our analysis starts from 02:10:07 UT. We averaged the pixel intensity across the width and synthesized a time–distance map as plotted in Figure 5(a). This reveals that there are three phases in the evolution: acceleration, constant speed, and deceleration. After 02:25:43 UT, a small portion of the prominence material kept rising while the rest started to drain downward, which caused three typical motion tracks during the deceleration phase.

In order to calculate the speed and acceleration/deceleration, we took several data points along the green dotted lines and fit them with either a polynomial fitting function $h = a + bt + ct^2$ (for the acceleration and deceleration phases) or a linear fitting...
function $h = a + bt$ (for the constant speed phase). From the best-fit functions, we found that the speed of the upflow increased to $\sim 65 \text{ km s}^{-1}$ at 02:19:55 UT and the acceleration was about $108 \text{ m s}^{-2} (a_1)$ during the acceleration phase 02:11:31–02:19:55 UT (five points were used for fitting). The speed is $\sim 228 \text{ km s}^{-1} (v_1)$ during the constant speed phase (15 points were used for fitting, from 02:20:55 to 02:25:43 UT). It is evident that there is a sudden rapid acceleration during 02:19:55–02:20:55 UT. This time interval is short, and by assuming a constant acceleration over this period, we deduced the acceleration to be $2715 \text{ m s}^{-2}$. This may mark the onset of the impulsive phase of the flare.

During the deceleration phase, the prominence material separated into several bunches. The speed of one fraction of the erupting prominence material (between the two blue stars marked in Figure 5(a)) decreased to $-73 \text{ km s}^{-1}$ with a constant deceleration of $\sim 391 \text{ m s}^{-2} (a_2)$ during 02:25:43–02:33:55 UT (10 points were used for fitting). However, after 02:33:55 UT, one portion of this plasma material still kept rising with a speed of $\sim 20 \text{ km s}^{-1}$ (six points were used for fitting), while most of the prominence material had drained back to the Sun. Another fraction of the erupting prominence material decreased to $\sim 4.8 \text{ km s}^{-1}$ with a constant deceleration $\sim 217 \text{ m s}^{-2} (a_3)$ during 02:25:31–02:39:55 UT (10 points were used for fitting). At 02:43:43 UT, the loops erupted and the material fell back to the surface of the Sun along the legs of prominence.

In order to determine the kinematics of the falling material, we placed a slice $E \rightarrow F$ along the prominence leg (cyan dotted lines in Figure 3(e)). It is 354 pixels long and 10 pixels wide, and the spacetime map has been synthesized since 02:40:07 UT. Similar to the technique applied in the aforementioned kinematical calculations, we took the average value of intensity across the width to produce the time–distance plot as presented in Figure 5(c). We found several bright thread structures that
Figure 6. Evolution of the twist in AIA images. Panels (a), (b), (e), and (f) are 171 Å images. Panel (c) is a 131 Å image. Panel (d) is a composite image of the AIA 171 Å (red), 94 Å (green), and 131 Å (blue) passbands. Their field of view is marked by the white box in Figure 3(b). White arrows in panels show: (a) the twist, (b) writhe and threads crossing, (c) kink structure (red dotted line). Green dotted lines in panels (e) and (f) mark the rotation of the threads. An animation of this figure is available. The AIA 131 Å (blue) and 171 Å (red) images are stacked together along with the AIA 94 Å (green) sequence. The video begins at 02:10:13 UT and ends at 02:39:49 UT. The real-time duration is 30 s. (An animation of this figure is available.)

indicate the uninterrupted motion of the plasma along the chosen slice. We chose one typical bright thread to estimate the velocity (green dotted line). The plasmas fell with a constant speed of $-192$ km s$^{-1}$ ($v_2$) (15 points were used for fitting). We placed slice C → D to study the kinematics of the upward flow in Figure 3(d). It is 158 pixels long and 10 pixels wide, and the spacetime map has been synthesized since 02:30:31 UT. We took the average value of intensity across the width to produce the time–distance plot in Figure 5(b). The inferred velocity is $\sim 137$ km s$^{-1}$ ($v_3$) (10 points were used for fitting). This upward flow can also be seen in the AIA hot channels at 94 and 131 Å.

3.2. The Twist Evolution

The twist and writhe (see definitions in Török et al. 2010) were clearly seen in all EUV channels recorded by AIA at around 02:20 UT. In order to make an in-depth investigation of the evolution of the twist, we extracted a rectangular region as denoted by the white box in Figure 3(b). The twist of the rope gradually becomes evident from 02:18:35 UT in Figure 6(a). As the prominence started rising and rotating, two crossing threads were apparent in the AIA 171 Å image at 02:20:35 UT, and the writhe was clearly seen in Figure 6(b). At nearly the same time, another writhe shape was evident in the 131 Å image, one of the very hot EUV passbands (Figure 6(c)). A sketch of twist evolution is shown in Figures 7(a) and (b). It is interesting that half of this structure appears to be very bright and narrow, while the other half appears to be much wider and very faint and only present in AIA 94 and 131 Å images (Figure 6(d)). We inferred that the prominence is composed of both hot and cool plasma based on this phenomenon, although the reason for its formation is not very clear. This hot structure presents a twisted or writhe axis in accordance with the general property of the flux rope investigated in Cheng et al. (2011) and Zhang et al. (2012). So we suggest that it is a flux rope. After 02:22:47 UT, the clockwise rotation (green dotted lines) of the flux rope was observed and the two crossing threads separated gradually (Figures 6(e) and (f)). The direction of rotation is outlined by green arrows in the sketch (Figures 7(c) and (d)). The whole evolution process can also be seen in the animation associated with Figure 6.

From an image at one time such as Figure 6(b), we can see two bright threads crossing each other three times, which indicates that the twist of the prominence was at least $3\pi$ (1.5 turns). To get an estimate of the twist number from the dynamics, we placed a slit perpendicular to the prominence (blue dashed line in Figure 6(b)) and obtained its time–distance plot (Figure 8). A similar method was used by Ryutova et al. (2008). The period $P$ is $\sim 20$ minutes, which is the time between the maxima of the intensity outline curve (between the two green asterisks marked in Figure 8). The speed $v_a$ ($13.2$ km s$^{-1}$) was estimated by linear fitting using the points between the two cyan asterisks, and $v_b$ ($15.9$ km s$^{-1}$) was estimated using the points between green and blue asterisks. The average speed $v_p$ is $\sim 14.6$ km s$^{-1}$. The pitch of the screw thread can be estimated as $h_p = P \times v_a = 17.5$ Mm. The total length ($L$) of the twisted loop is approximately 55 Mm, estimated at 02:20:35 UT when the twist is most clear. The twist can be estimated as $L/h_p \approx 3$ turns ($6\pi$), which exceeded the threshold of kink instability. At each crossing (indicated by the white arrows in panel (b)), the upper thread was left-skewed relative to the lower thread, indicating that the helicity of the prominence should be negative, according to the method proposed by Chae (2000). Chen et al. (2014) proposed another method to determine the chirality of an erupting filament on the basis of the skewness of the conjugate filament drainage sites, i.e., the right-skewed (left-skewed) drainage corresponds to sinistral (dextral) chirality. We applied this method to Figure 2(e): the skew of the drainage sites (F2 and B) is left, corresponding to dextral chirality (negative helicity). The results using these two methods are consistent with each other, showing that the chirality of this prominence was dextral and followed the hemispheric preference studied by Ouyang et al. (2014).
3.3. Magnetic Reconnection

The brightening around the filament footpoints, first appearing at 02:17:08 UT in the STEREO-B 304 Å image (Figure 9(a)), is interpreted as the result of a magnetic reconnection. Since the evidence of magnetic reconnection can be more clearly seen in hot channels such as AIA 94 and
131 Å, we took a time series of AIA 94 Å images (see animation associated with Figure 9) to study the reconnection process here. The red dotted line in Figure 9(b) shows the overlying large-scale field lines, while the yellow arrow points to the flux-rope structure. The thick blue arrows in panels (b)–(e) mark the direction of destabilization of the field lines. In panel (e), solid lines of different colors are drawn, tangent to the upper edge of the flux rope, at different times labeled correspondingly. Yellow dotted lines in panels (d) and (g) indicate the two slices that are to be used to derive the inward and upward flow profiles. The thin blue arrows in panels (f), (h), and (i) point to the reconnection position, the cusp structure, and the post-flare loops respectively. An animation of this figure is available. The video begins on 2012 October 14 at 02:10:13 UT and ends the same day at 03:10:37 UT. The real-time duration is 30 s. (An animation of this figure is available.)

Figure 9. Reconnection process as observed in STEREO-B EUVI 304 Å (panel (a)) and AIA 94 Å (panels (b)–(i)). The green arrow in panel (a) points to the brightening around the footpoint. The red dotted lines in panel (b) show the overlying large-scale field lines, while the yellow arrow points to the flux-rope structure. The speed of rising increased gradually, which is evident by comparing the distance between lines of different color (i.e., the distance between cyan (02:19:37 UT) and orange (02:20:49 UT) lines being larger than that between cyan and pink (02:18:37 UT) lines). This phenomenon is coherent with the kinematic character inferred from AIA 304 Å images. At 02:21:49, the flux rope erupted, which caused a decrease in internal pressure. This pressure imbalance between the interior and exterior caused the overlying large-scale field lines to curve toward the reconnection region (indicated by the blue arrow in
Figure 9(f)). At 02:30:25 UT, an upward reconnection jet was observed along the yellow dotted line in Figure 9(g). From 02:33:25 UT, a cusp structure (denoted by the blue arrow in Figure 9(h)) gradually formed below the reconnection site.

The source region of the X-ray emission, deduced from the RHESSI observations, is found to be spatially linked to the bright emission region in the EUV images (Figure 10), confirming that the energy is released due to the magnetic reconnection. The RHESSI coronal source appeared in the 6–12 and 12–25 keV energy ranges and indicates the presence of plasma at temperature >6 MK near the reconnection site. At 02:54 UT and 02:55 UT, the coronal source in 12–25 keV separated into two sources, which may indicate that the reconnection site changed during the decline of the eruption. At 03:05 UT, another coronal source appeared in 6–12 keV. This source is above the nearby loop, which indicates that the reconnection probably occurred between the prominence’s field lines and the nearby fields.

We analyzed a slice \( G \rightarrow H \) (yellow dotted line in Figure 9(d)) to study the reconnection inflow profile. It is 95 pixels long and 10 pixels wide, and the spacetime map has been synthesized since 02:10:13 UT. We took the average value of intensity across the width to produce the time–distance plot in Figure 11(a). The two red dotted lines indicate oppositely directed inflows with speeds of \( \sim 30.7 \) km s\(^{-1} \) \((v_4)\) and \( \sim 6.6 \) km s\(^{-1} \) \((v_5)\). Slice \( I \rightarrow J \) (yellow dotted line in Figure 9(g)) is 95 pixels long and 10 pixels wide, and the spacetime map has been synthesized since 02:28:13 UT. We took the average value of intensity across the width to produce the time–distance plot presented in Figure 11(b). The red dotted line indicates the upward flow with speed \( \sim 199.6 \) km s\(^{-1} \) \((v_9)\). It is worth noting that the upward flow was also observed in AIA 304 Å images, but the speed was lower than that deduced from 94 Å images. A higher speed of hot plasma might have resulted from the magnetic reconnection.

This magnetic reconnection process can be explained using the model developed in Shibata (1996), but the magnetic structure is more complex than that employed in the model.

4. Conclusions and Discussions

Through multiwavelength diagnostics we observed the whole evolution process of a failed prominence eruption. The initial state is a stable filament on the solar disk as observed by EUVI/STEREO, while it appears as a prominence on the solar limb in Hα images. The filament/prominence then became unstable and exhibited a rising motion. During this phase, the twist got converted to writhe. After the flare, the prominence rose in an accelerated manner, with reconnecting prominence threads and a cusp-shaped structure seen in hot channels of EUV images.

The twist of the filament was estimated to be approximately 6\( \pi \) (three turns), which exceeds the threshold of the kink instability. This suggests that this event may be triggered by the kink instability.

The largest rising speed was 228 km s\(^{-1} \). There was a sudden rapid acceleration at the time of the flare onset, with an estimated value of 2715 m s\(^{-2} \).

However, this eruption was not accompanied by a CME. The prominence material was seen to fall back to the chromosphere. A new filament was formed at almost the same location as the original one. The largest deceleration of one portion of the prominence was 391 m s\(^{-2} \), a value that is even larger than the solar gravitational constant \( (g = 274 \) m s\(^{-2} \)).

During the eruption, the magnetic reconnection can be identified by the clearly seen inflows and nice cusp structure. The RHESSI X-ray emissions further confirmed the co-spatial X-ray emission, which signifies the location of energy release of the reconnection.

The helical kink instability was regarded as an important triggering mechanism for solar eruptions (e.g., Rust & LaBonte 2005; Török & Kliem 2005). Whether the kink instability leads...
to a failed or eruptive event depends on the decrease in the overlying magnetic field with height (Török & Kliem 2005). A fast decrease in the external magnetic field of a flux rope with height could result in the torus instability and eventually in the eruption of a flux rope, otherwise it will lead to a failed eruption. We define the decay index as \( n = -\frac{d\ln(B_z)}{d\ln(z)} \) where \( B_z \) and \( z \) are the external magnetic field strength and height respectively. Theoretical and observational studies have found that the torus instability usually occurs when the decay index is above a certain threshold between 1.5 and 1.75 (Kliem & Török 2006; Wang et al. 2017; Fan 2010). The corresponding height above the solar surface where the decay index reaches the critical threshold is called the critical height.

In our case, the twist is clearly seen to be converting to a writhe motion following the appearance of a kink instability, which confirmed that the helical kink instability can trigger the prominence/filament eruption. However, in the absence of magnetic field observation, it is not possible to infer whether or not torus instability occurred during the eruption process. To determine the critical height of the filament eruption, we performed a potential field extrapolation using a Fourier transformation method (Alissandrakis 1981) from the vertical component of the vector magnetic field obtained from SDO/HMI active region patch 2117 with coordinates transformed to a heliographic cylindrical equal-area projection (Bobra et al. 2014) at 03:00 UT on 2012 October 18 (Figure 12(b)). Figure 12(a) is the simultaneous SDO/AIA 304 Å observation with the coordinates transformed to the same projection. The target filament is outlined by the blue dotted curve in both panels. The newly formed filament stayed relatively stable after the investigated event after it turned to the front side of the Sun. Following the solar rotation, the filament’s center was approximately 40° east of the central meridian at this time, allowing more accurate observations of the photospheric magnetic field than at earlier times. The decay index above the filament was then calculated from the potential field extrapolation, and is shown in Figure 12(c) where the \( z \)-axis is the distance along the filament from its left end and the \( y \)-axis is the height above the photosphere. Two dashed curves are contours of the decay index at levels of 1.5 and 1.75. Figure 12(d) shows the average decay index over the filament, with the two horizontal dotted lines at levels of 1.5 and 1.75. The average decay index reaches the critical points of 1.5 and 1.75 at heights of \( \sim 85 \) Mm and \( \sim 118 \) Mm, respectively. A portion of material in the investigated event started to fall at a height of \( \sim 100 \) Mm, which reached the lower critical height for torus instability. But the prominence eruption did not lead to a CME. There is a 4 day gap between the investigated event and the calculation of decay index, and the magnetic field may change during this period. Habbal et al. (2014) pointed out that the helical wavy patterns appear as a natural byproduct of the inherent dynamics of prominences that do not necessarily lead to CMEs, even when prominences erupt. The restraining force of the overlying flux and the cancellation of the upward Lorentz force were also suggested as one mechanism for the failed eruption (e.g., Xue et al. 2016b). Since we obtained the maximum deceleration speed to be 391 m s\(^{-1}\), which is larger than the solar gravitational constant, this may further suggest that this prominence eruption failed due to the inward magnetic tension force.

The magnetic reconnection process was first seen as the brightening observed around the footpoints in EUVI/STEREO images, which first triggered the flare eruption and then accelerated the filament. During the rising period, the magnetic reconnection between the prominence threads and overlying field occurred, as is evident from AIA 131 and 94 Å observations. The reconnection rate is an important parameter for magnetic reconnection and it is defined as the magnetic flux reconnected per unit time. The dimensionless form of the reconnection rate is the Alfvén Mach number \( M_A = V_{in}/V_A \), where \( V_{in} \) is the inflow speed of reconnection and \( V_A \) is the Alfvén speed. For the studied case, the inflow speed is 6.6–30.7 km s\(^{-1}\) and the outflow speed is 199.6 km s\(^{-1}\). Assuming the outflow speed to be equal to the Alfvén speed, we can estimate the reconnection rate as \( M_A \approx V_{in}/V_{out} \approx 0.03–0.15 \). Our estimation is roughly consistent with the model of Petschek (1964) (\( M_A = 0.01–0.1 \)) and the estimation for several observed solar events, e.g., 0.01–0.23 (Lin et al. 2005), 0.055–0.2 (Takasao et al. 2012), 0.05–0.5 (Su et al. 2013), and 0.08–0.6 (Xue et al. 2016b).
In recent years, a series of comparative studies about successful eruptions, confined (failed) eruptions, and partial eruptions have been done (e.g., Shen et al. 2011; Zhang et al. 2015; Liu et al. 2018b). It is shown that some parameters, i.e., the decay index, field strength at low corona etc., had no significant difference for failed and successful eruptions (Shen et al. 2011). Liu et al. (2018a) suggested that a failed eruption may be the result of a combination of several mechanisms including the weaker non-potentiality in the core region, smaller Lorentz force impulse during the eruption, and the local torus-stable region in the coronal magnetic fields. The trigger mechanism and energy release process of a solar eruption are still not very clear and require further study.

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**ORCID iDs**

Haiqing Xu @ https://orcid.org/0000-0003-4244-1077  
Jie Chen @ https://orcid.org/0000-0001-7472-5539  
Guiping Ruan @ https://orcid.org/0000-0002-3232-0071  
Arun Kumar Awasthi @ https://orcid.org/0000-0003-5313-1125  
Jiajia Liu @ https://orcid.org/0000-0003-2569-1840

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**Figure 12.** The newly formed filament at the same location as the investigated event after it turned to the front side of the Sun on 2012 October 18. (a) SDO/AIA 304 Å observation. (b) The vertical component of the magnetic field (with saturation limits of ±500 G) observed by SDO/HMI. The target filament is outlined by the blue dotted curve in both panels. (c) The decay index above the filament with the x-axis as the distance along the filament from its left end and the y-axis as the height above the photosphere. Two dashed curves are the contours of the decay index at levels of 1.5 and 1.75. (d) The average decay index over the filament, with the two horizontal dotted lines at levels of 1.5 and 1.75.
