FORMATION OF A COMPOUND FLUX ROPE BY THE MERGING OF TWO FILAMENT CHANNELS, THE ASSOCIATED DYNAMICS, AND ITS STABILITY

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ABSTRACT

We present observations of compound flux rope formation, which occurred on 2014 January 1, via merging of two nearby filament channels, the associated dynamics, and its stability using multiwavelength data. We also discuss the dynamics of cool and hot plasma moving along the newly formed compound flux rope. The merging started after the interaction between the southern leg of the northward filament and the northern leg of the southward filament at ≈01:21 UT and continued until a compound flux rope formed at ≈01:33 UT. During the merging, the cool filament plasma heated up and started to move along both sides of the compound flux rope, i.e., toward the north (≈265 km s⁻¹) and south (≈118 km s⁻¹) from the point of merging. After traveling a distance of ≈150 Mm toward the north, the plasma cooled down and started to return back to the south (≈14 km s⁻¹) after ≈02:00 UT. The observations provide a clear example of compound flux rope formation via merging of two different flux ropes and the occurrence of a flare through tether cutting reconnection. However, the compound flux rope remained stable in the corona and had a confined eruption. The coronal magnetic field decay index measurements revealed that both the filaments and the compound flux rope axis lie within the stability domain (decay index <1.5), which may be the possible cause for their stability. The present study also deals with the relationship between the filament’s chirality (sinistral) and the helicity (positive) of the surrounding flux rope.

Key words: Sun: activity – Sun: filaments, prominences – Sun: flares – Sun: magnetic fields

Online-only material: animations, color figures

1. INTRODUCTION

Solar eruptive events are magnetic transient events on the Sun that occur due to the release of magnetic energy via magnetic reconnection. These are solar flares, prominences/filament eruptions, jets, surges, coronal mass ejections (CMEs), etc. (see review articles by Benz 2008; Shibata & Magara 2011 and references cited therein). Filaments are cool and dark plasma material suspended in the hot, low-lying corona supported by a magnetic field (Mackay et al. 2010; Labrosse et al. 2010). Filaments are known to lie in the dips of the surrounding magnetic flux ropes. These magnetic flux ropes become visible in the corona when the hot plasma moves along it (Litvinenko & Martin 1999; Chae 2003; Wang & Muglach 2013; Li & Zhang 2013; Joshi et al. 2014). Filaments can have either sinistral or dextral chirality, depending on the axial magnetic field directions and can be estimated from various observations (Martin 1998). Association of filament chirality and helicity of the surrounding magnetic field has been reported in the last few decades (Rust & Kumar 1994; Martin 1998, 2003; Chae 2000; Pevtsov et al. 2003; Muglach et al. 2009; Chandra et al. 2010; Joshi et al. 2014). Two nearby filaments sometimes show merging dynamics when they come closer to each other due to magnetic shearing. Some authors have reported observations showing this kind of merging (Schmieder et al. 2004), while others have produced numerical simulations and presented various condition of filament merging (DeVore et al. 2005; Aulanier et al. 2006).

Filaments are generally formed due to the reconfiguration of coronal field lines due to flux emergence, cancellation, various kinds of surface motions, and the emergence of toroidal magnetic field (Rust 2001; Magara & Longcope 2003). These filaments undergo eruptions due to the imbalance between upward magnetic pressure and downward magnetic tension and gravitational forces. After the eruptions, these structures produce huge CMEs, which are the ejection of plasma and magnetic field from the Sun into interplanetary space (Chen 2011; Forbes 2000). These CMEs are mainly responsible for the interplanetary consequences as well as near-Earth disturbances (Joshi et al. 2013b). Several efforts have been carried out to understand the physical mechanism behind the eruption of filaments as well as flux ropes (Chen 2011 and references cited therein). Shearing and/or twisting of magnetic field lines are known to be responsible for the eruption (Hagyard et al. 1984; Fan & Gibson 2004; Inoue et al. 2011; Sun et al. 2012). Magnetic flux emergence and cancellation has also been reported as a cause for these eruptions (Magara & Longcope 2003; Magara 2006; Archontis & Török 2008). Ideal magnetohydrodynamics instabilities such as “kink” and “torus” instabilities are also known to play a key role for the global eruption of these structures (Török et al. 2004; Török & Kliem 2005; Kliem & Török 2006; Srivastava et al. 2010, 2013). Several models such as “tether cutting,” “magnetic breakout,” and various numerical simulations have also been given in order to explain the eruption phenomena (Antiochos et al. 1999; Moore et al. 2001; DeVore & Antiochos 2008; Démoulin & Aulanier 2010; Fan 2010; Chen 2011; Inoue et al. 2014).

Sometimes the filaments as well as the flux ropes show confined eruptions that later settle down to their original positions, even after strong disturbances. These are called failed or confined eruptions and have been studied before (Ji et al. 2003; Török & Kliem 2005; Liu et al. 2009; Kumar et al. 2011; Shen et al. 2012; Kuridze et al. 2013; Joshi et al. 2013a, 2014; Filipov 2013). The overlying coronal magnetic field is known to play an important role in these kinds of stable eruptions (Ji et al. 2003; Török & Kliem 2005; Liu et al. 2009; Guo et al. 2010; Kumar et al. 2011; Kuridze et al. 2013; Joshi et al. 2014). Ji et al. (2003) studied a failed eruption and interpreted that the
overlying closed magnetic field was responsible for the failed ejection. Török & Kliem (2005) modeled the confined as well as eruptive kink-unstable flux ropes and identified the decrease of the overlying coronal magnetic field with height as a key factor that decides the confinement or eruption of the flux ropes. Liu et al. (2009) presented observations of a failed filament eruption and found that the asymmetric coronal background field can also influence the full eruption of filaments. Guo et al. (2010) studied the onset and stability conditions of a confined eruption and found that the value of the decay index was below the critical value for torus instability to occur above the erupting flux rope. Kuridze et al. (2013) also studied a failed filament eruption and found that the overlying large-scale magnetic loop arcade may have caused the confinement of this eruption. Recently, Joshi et al. (2014) reported observations of a confined filament eruption and associated flux rope and found that the whole filament axis lies within the region where the values of the decay index is less than one. This caused the confined ejection of the filament and flux rope. Apart from these observational studies, numerical simulations have also been carried out in order to understand stability (Török & Kliem 2005; Guo et al. 2010; Démoulin & Aulanier 2010; An & Magara 2013). Filaments sometimes also show re-formation dynamics mainly after confined or partial failed eruptions (Gilbert et al. 2007; Koleva et al. 2012; Joshi et al. 2014).

In the present work, we present multiwavelength observations on 2014 January 1 of a compound flux rope formation, the associated plasma dynamics, and its stability. We also attempt to find a relationship between the filament chirality and surrounding flux rope helicity. The observational data set used in the present work is described in Section 2. Morphological interpretations of the event in different wavelengths are presented in the Section 3. The relationship between the filament chirality and helicity of the surrounding magnetic structure is presented in Section 4. Section 5 deals with the description of the coronal magnetic field measurements. Our results and discussions are presented in the final section.

2. OBSERVATIONAL DATA SET

Hα observations for the current study are collected from Global Oscillation Network Group (GONG) network archive (http://halphा.nso.edu/archive.html). GONG provide Hα images that are observed from seven stations all over the Earth with spatial resolution and cadence of around 1″ and 1 min, respectively (Harvey et al. 2011). The Hα observations are used to study the dynamics of cool filament plasma along the magnetic flux rope. The Atmospheric Imaging Assembly (AIA) and Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) are two instruments on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). AIA observes the full solar disk in ultraviolet (UV) as well as ultraviolet (EUV) wavelengths and provided images having pixel size of 0.6″ and cadence of 12 s (Lemen et al. 2012). SDO/AIA has a pixel size of 0.6″ and minimum cadence of 12 s. Therefore, it provides multi-temperature and high-resolution observations of the whole Sun. HMI observes the magnetic field of the Sun and provides full-disk magnetogram images with resolution and minimum cadence of 1″ and 45 s, respectively. We have used SDO/HMI magnetogram data to investigate the magnetic configuration around the filaments and flux rope as well as to estimate the values of the decay index at different heights in the solar corona over the flux rope. To see the X-ray sources during the flare, we reconstructed X-ray images from the Reuven Ramaty High-Energy

Solar Spectroscopic Imager (RHESSI; Lin et al. 2002). We reconstructed the X-ray images in the two energy bands, viz., 6–12 and 12–25 keV, using collimators from 3F to 9F and the CLEAN algorithm (Hurford et al. 2002).

3. MULTIWAVELENGTH OBSERVATIONS OF MERGING OF FILAMENT CHANNELS AND ASSOCIATED PLASMA DYNAMICS

Figure 1 shows the full disk images from GONG in the Hα wavelength (left panel) as well as from SDO/AIA in the 304 Å wavelength (right panel) on 2014 January 1 at 00:00 UT. Boxes in each figure show the locations of the filaments. It is evident from Figure 1 that the filaments lie near the disk center (i.e., ≈S09 E09) and oriented along the north–south direction. There was a small active region, NOAA AR 11938, situated near the filaments. Figure 2 shows the closed view of the region under study in this work. Panels (a) and (b) show the existence of two different filaments and associated magnetic channels in the AIA 304 Å and 171 Å wavelength images, respectively. Panel (c) shows the SDO/HMI images overlapped by the tracked filaments visible in the AIA images. It is clear that the southern leg of the northward filament and the northern leg of the southward filaments cross. The northern leg of the southward filament is located under the southern leg of the northward filaments, which makes it less visible in on disk projection. In the upcoming subsections we will discuss the merging of two filaments, and the associated magnetic field channels and dynamical motion of hot and cool plasma along the newly formed flux rope in different wavelengths using GONG Hα and SDO/AIA EUV observations.

3.1. Hα, X-Ray, and EUV Observations

Figure 3 represents the selected images showing the dynamics of cool filaments plasma in Hα wavelength observed by GONG. Hα images provide crucial information regarding the chromospheric region of the Sun as well as the filament dynamics. Figures 4–6 show the selected images displaying the dynamics of the filament plasma as well as the flux rope in 304, 171, and 131 Å EUV images observed by SDO/AIA, respectively. SDO/AIA 304 Å images provide information at the chromospheric and transition regions, while the SDO/AIA 171 and 131 Å images give the quiet corona region and flaring regions, respectively. The initial brightening appears near the junction of two filament legs at ≈01:21 UT (see Figures 3(a), 4(a), 5(a), 6(a), 7(a), 7(e) and 7(i)). This brightening may be due to the reconnection between the low-lying field lines of two filament channels. The field lines of the two filament channels reconnect and merge continuously during ≈01:21 to ≈01:33 UT (see Figure 7 and associated animations). Figure 7 displays the selected SDO/AIA 171, 304, and 131 Å wavelength images showing the merging of two filament channel field lines (i.e., flux ropes) and the formation of a new flux rope. After this, the newly formed flux rope will be referred to as a “compound flux rope” through the paper. The brightening in the merging region also increases which may be due to the heating via continuous merging/reconnection of field lines. During this process we also observed a C-class flare at the merging site, starting at ≈01:27 UT (see Figures 7(c), (g), and (k)). The flare peaked at ≈01:33 UT and ended at ≈01:47 UT (per the NOAA record of an SF class flare). Soon after the flare triggers we observed the formation of two ribbons around ≈01:31 UT in the SDO/AIA 1600 Å
wavelength (see Figure 8). The sudden brightening and formation of two ribbons are also observed in the GONG Hα images (see Figures 3(b) and (c)). It is observed from Figures 8(a) and (b) that both flare ribbons lie in different polarity regions. The southern and northern ribbons lie on the negative and positive magnetic polarities, respectively. In between the flare ribbons we also observed the RHESSI 6–12 and 12–25 keV X-ray sources (see Figures 3(b) and (c), and 8(c)). From these observations the triggering of flares may be well interpreted using the tether cutting model via filament channel field lines reconnection. In Figure 9 we plotted an illustration of the reconnection scenario.

Simultaneously with the merging, the filament’s cool plasma heated up and started to move toward the north and south directions along the compound flux rope, (see Figures 3(b), 4(b), 5(b), and 6(b)). The heated plasma moved toward the north and south with an average speed of around $\approx 265$ km s$^{-1}$ and $\approx 118$ km s$^{-1}$,
respectively. Figure 10(a) shows the distance–time plot of the northward (black curve) and southward (blue curve) moving hot plasma constructed using \textit{SDO}/AIA 171 \AA\ wavelength images. The red color shows the \textit{GOES} soft X-ray curve at 1.0–8.0 \AA\ wavelengths. Comparing \textit{GOES} curve with the distance–time profiles, it is observed that the hot filament material was moving toward the north and south simultaneously with the flare occurring. The approximate trajectories along which these measurements have been performed are shown by the dotted black and blue lines in Figure 5(e). During the northward motion of hot plasma, the filament disappeared, which may be due to the heating and shifting of the H\textalpha\ center absorption line. The filament disappears during \textit{\approx}01:30–01:45 UT from the H\textalpha\ images (see Figures 3(b)–(d)). The hot plasma continued to move toward the north along the northern part of the compound flux rope and is observed clearly in the EUV wavelengths during \textit{\approx}01:24 to \textit{\approx}01:35 UT (see Figures 4(b)–(d), 5(b)–(e), and 6(b)–(e)). High-resolution \textit{SDO}/AIA EUV images provide

Figure 3. Selected GONG H\textalpha\ images showing the dynamics of the cooler filament’s plasma. Dotted white line in panel (i) represents the approximate trajectory along which the distance–time plot of southward moving cool plasma has been measured. The red and blue contours are the \textit{RHESSI} X-ray contours at 6–12 and 12–25 keV energy bands. The contour levels are 60\%, 70\%, 80\%, and 95\% of the peak intensity. The integration time is 20 s.

(An animation and a color version of this figure are available in the online journal.)
the opportunity to see the surrounding compound flux rope after the hot plasma filled the whole flux rope. The complete S-shaped sigmoid structure of the compound flux rope is visible at ≈01:39 UT (see Figures 4(e), 5(f), and 6(f)). Along with the northward motion, the surrounding flux rope also gets right-handedly twisted and can be seen in EUV channels (see Figures 4(e)–(f), 5(e)–(f) and 6(e)–(f)). After reaching a distance of around ≈150 Mm to the north, some cool as well as hot material move toward the northern footpoint of the compound flux rope during ≈01:35 UT to ≈01:44 UT with an average speed of around ≈150 km s\(^{-1}\) (see Figures 4(f), 5(g), and 6(g)). Figure 10(b) shows the distance–time plot of the moving plasma toward the northern footpoint of the compound flux rope, estimated using AIA 171 Å images. The approximate trajectory along which this measurement has been performed is shown by the dotted black line in Figure 5(g). High-resolution images of SDO/AIA 171 Å also show its various northern and southern footpoints (see Figures 4(f), 5(g),
Figure 5. Selected SDO/AIA 171 Å images showing the overall dynamics of the twisted flux rope at coronal temperature. Dotted black/blue lines represent the approximate trajectories along which the distance–time plot of the northward and southward moving hot plasma has been measured. The green/blue contours in panel (f) show the positive/negative polarity regions. The contour levels are ±100, ±200, and ±400 gauss.

(An animation and a color version of this figure are available in the online journal.)

and 6(g)). It is also evident that the northern/southern footpoints of the compound flux rope lie in the positive/negative polarity regions (see Figures 4(e), 5(f), and 6(f)). The appearance of a compound flux rope in all EUV channels shows that the flux rope consists of multi-thermal plasma. The complex fine structure of the compound flux rope can be seen in the high-resolution AIA images (see Figures 4(g)–(h), 5(g)–(h), and 6(g)–(h)).

The filaments as well as compound flux rope have not erupted even after the strong disturbance during the merging of the filament channels and triggering of the flare. After reaching a distance of ≈150 Mm on the disk toward the north, most of the filament material stopped and started returning/restoring southward motion along the compound flux rope (see Figures 3(g)–(h) and 4(g)–(h)). This returning motion started at ≈02:00 UT. The returning motion continues along
Figure 6. Selected SDO/AIA 131 Å images showing the overall dynamics of the coronal plasma at hot coronal temperature. The green/blue contours in panel (f) show the positive/negative polarity regions. The contour levels are ±100, ±200, and ±400 gauss. (A color version of this figure is available in the online journal.)

From the observations, it seems that the compound flux rope moves upward, remains stable, and returns to its original position. The same magnetic field channel and re-formed the filament on the northern part of the compound flux rope (see Figures 3(i) and 4(i)) with an average slow speed of ≈14 km s⁻¹. Figure 10(c) shows the distance–time plot of the moving plasma along the compound flux rope toward the south, estimated using the GONG Hα images. The approximate trajectory along which these measurements have been performed is shown by the dotted white line in Figure 3(i). Along with the formation of the northern filament, the southern filament also appeared in the southern part of the compound flux rope. Re-formed filaments can be seen in the Hα image at around 03:36:54 UT (see Figure 3(i)), although the re-formation and reappearance of cool plasma (i.e., filaments) also continue up to several minutes after ≈03:36 UT. The overall dynamics can also be clearly seen in the Hα and SDO/AIA movies (i.e., animations associated with Figures 3, 4, and 7).
Figure 7. Selected SDO/AIA 171, 304, and 131 Å images showing the merging of two filament channels. In the last panel the contours are the RHESSI X-ray contours at 6–12 keV (red) and 12–25 (blue) keV energy bands. The contour levels are 60%, 70%, 80%, and 95% of peak intensity. The integration time is 20 s. (An animation and a color version of this figure are available in the online journal.)

position (see animations in Figures 4–6). The confined erupted compound flux rope also disturbed the overlying corona arcades; as a result the arcade started to oscillate with some small amplitudes (see Figures 5(c)–(g) and associated animation). This also gives the signature of the confined upward eruption of the stable compound flux rope. However, the exact height of the flux rope is hard to determine due to the on-disk projection. It is also evident that as the hot plasma material cooled down, the flux rope also simultaneously became invisible (see Figures 5(i) and 6(i)). For more details, please refer to the SDO/AIA 171 and 131 Å animations (i.e., please refer to the SDO/AIA 171 and 131 Å animations). In order to help with the understanding of the plasma dynamics of the event, we made a cartoon shown in Figure 11.
4. CHIRALITY AND HELICITY OF FILAMENT AND FLUX ROPE

In this section, we will discuss the observational manifestations of the filament’s chirality and the helicity of the surrounding compound flux rope. Figure 12(a) shows one selected GONG Hα image a few hours before the event, i.e., at 22:42:34 UT on 2013 December 31, in order to study the chirality of the filaments. It is clear from this image that the fine threads and fibrils are oriented leftward from the filament’s axis, which provides evidence that the chirality of the filaments should be sinistral (Martin 1998). Figure 12(b) represents the SDO/AIA 171 Å image overplotted by SDO/HMI magnetogram at 01:00:11 UT. It shows that the southern footpoints of both the filaments lie on the negative polarity while the northern footpoints lie on the positive polarity regions, which show evidence of the sinistral chirality of filaments (Martin 1998). Also, the right-skewed alignment of the overlying coronal arcade provides a key observational evidence showing the existence of the sinistral chirality (Martin 1998). From these observational facts we can confirm that the filaments have sinistral chirality.

Figure 13(a) presents the SDO/AIA 171 Å image at 01:28:11 UT, showing that the bright hot plasma is moving behind the dark cool plasma material. In this way, we have observed a crossing of bright (below) and dark (above) material in the EUV images. According to the Pevtsov et al. (2003)
interpretation, our situation is of type I, which corresponds to positive helicity of the flux rope. SDO/AIA 171, 131, and 94 Å wavelength images clearly show the right-handed twist in the magnetic field of the compound flux rope, which shows the signature of positive helicity (see Figures 13(b)–(d)). Careful inspection shows that the flux rope has \( \approx 2 \) turns around its axis (see Figures 13(b)–(d)). Also from the well-known hemispheric helicity rule the northern/southern hemispheres have negative/positive helicity (Pevtsov et al. 2003). Our observation is also in agreement with this rule. On the bases of these discussions we can say that these observations confirm the relationship between sinistral chirality and positive helicity.

5. CORONAL MAGNETIC FIELD MEASUREMENTS

To check the overlying magnetic field conditions we estimated the decay index over the compound flux rope axis. We used the method of potential field extrapolation to estimate the decay index over the filament axis (Sakurai 1982). The decay index is defined as

\[
    n = -\frac{\partial \log B}{\partial \log h},
\]

where \( B \) denotes the strength of the magnetic field and \( h \) is the height above the photosphere.
Figure 11. Schematic of the filaments’ cool and hot plasma dynamics within the compound flux rope. The dotted black line represents the polarity inversion line. Thick black and blue lines represent the northern and southern filaments. The red line represents the re-formed filament. Twisted flux ropes are in brown, with the solid/dashed lines showing the front and back parts of the field lines around the flux rope. The red patch in panel (a) shows the brightening (i.e., flare) at the crossing. Flare ribbons are represented by the yellow lines below the flux rope in panel (b).

(A color version of this figure is available in the online journal.)

Figure 14, top panel, shows the radial component of the magnetic field (a) and the potential field extrapolated over it (b). Blue lines show the magnetic field lines. Figure 14, bottom panel, shows the decay index measured over the compound flux rope and filament’s axis at (c) 86.4 Mm, (d) 108 Mm, and (e) 129.6 Mm. It is evident that most of the filament’s and compound flux rope’s axis lie in the region where the decay index is less than 1.5 at 86.4 Mm. Even at 108 Mm height, the contour level of decay index 1.5 partially appears near the flux rope axis. This results also suggests that the flux rope is stable against the torus instability if located lower than 86.4 Mm. However, the compound flux rope is observed on the disk, so it is difficult to measure the on-disk height. Therefore, we used the overlying coronal arcade to estimate the approximate height of the flux rope. We selected one potential field line matching best with the overlying arcade and calculated the height of this potential field line from the photosphere (see Figure 15(a)). The top of the potential field line comes out to be 86.4 Mm (see Figure 15(b)). During the confined upward eruption, the compound flux rope was only able to disturb the overlying arcade; as a result of this, the arcade started to oscillate with small amplitude (see animation associated with Figure 5). Hence, from this observation we can confirm that the flux rope does not reach up to a height of 86.4 Mm, which is the height of the top of arcade (see Figure 15). If we consider this height to be the maximum height achieved by the compound flux rope during its confined eruption, then its axis will be at a height of 43.2 Mm, although the actual height of the top of the compound flux rope will be less than 86.4 Mm. From the decay index measurement it is evident that the flux rope remains stable below a height of around 86.4 Mm (see Figure 14, bottom left panel), which is the assumed to be the height of the top of the flux rope and coronal arcade (see Figure 15). Hence the filament flux rope remains stable because it is situated in a region of stability, i.e., decay index < 1.5.

6. RESULTS AND DISCUSSIONS

We present high-resolution multwavelength observations on 2014 January 1 of the merging of filament channels, the associated plasma dynamics, and the stability of the compound flux rope. The main results of the present study are as follows.

1. The observations clearly show the merging of two filament channels, triggering of a solar flare, and the formation of a compound flux rope via the tether cutting magnetic reconnection scenario.
2. The compound flux rope shows stability in the corona because it does not reach a height where the decay index is greater than 1.5, which makes it stable against torus instability.

3. We also found a clear association between the filament’s chirality (sinistral) and magnetic helicity (positive) of the surrounding flux rope.

The overall scenario of the flare and formation of the compound flux rope can be interpreted via the tether cutting reconnection model (Moore et al. 2001). According to this model, the initial onset of an explosion is unleashed by internal tether-cutting reconnection between the sheared low-lying field lines. Then, afterward, a new flux rope forms, which either remains confined or erupts (for details, please see Figure 1 of Moore et al. 2001 for reference). Based on the detailed analysis of the present event using multiwavelength observations, we have drawn schematics explain the whole event (see Figures 9 and 11). In our case, we found the signature of tether cutting reconnection in the form of brightening at the junction of two filament legs, which can be considered as the reconnection between the low-lying sheared field lines (see Figures 4(a), 5(a), 6(a), 7, 9(b), and 11). The newly formed flux rope (i.e., compound flux rope) formed after this reconnection, with the hot plasma moving northward and southward alongside it (see Figure 7 and associated animation); the flux rope then moved upward in the corona with the reconnection occurring beneath it (see Figure 9(b)–(c)). This reconnection produced a solar flare with flare ribbons (see Figure 8). The RHESSI 6–12 and 12–25 keV sources formed near the merging area, which provides a strong signature of reconnection (see Figures 7 and 8(c)). The formation of flare loops (see Figure 5(g)) at the point of merging provides the signature of formation of compact low-lying field lines, which are in good agreement with the model (see Figures 5(g) and 9(c)). Overall, the observations clearly show the tether cutting due to the filament legs and associated filament channel field line interaction, which allows the partial eruption of the newly formed flux rope, triggering the flare underneath it (please see schematics in Figures 9 and 11). However, the compound flux rope shows a confined eruption in the corona. To the best of our knowledge, we have observed for the first time filaments interacting/merging, the formation of a twisted compound flux rope, and the triggering of a flare in one event. However, there have been other papers that deal with the observational signature of tether cutting reconnection via flux cancellation between two low-lying sheared arcades (Liu et al. 2010, 2013).

It has been reported in observations as well as in numerical simulations that the merging of two filaments is possible if the filaments have the same axial magnetic fields (Schmieder et al. 2004; DeVore et al. 2005; Aulanier et al. 2006). We have clear observations showing the merging of two filaments having sinistral chirality (see Figure 7 and associated animations).

The initial onset conditions for these confined eruptions are also important to investigate. Liu et al. (2009) explained that the initial onset was due to kink instability at unstable heights, while Kuridze et al. (2013) explained the magnetic breakout scenario as the condition for the onset of confined eruption. Recently, Joshi et al. (2014) explained that the eruption of the eastern eruptive part destabilized the overlying magnetic field of the stable filament, which may have allowed its confined initial onset. However, in the present case, we found, for the first time, that the tether cutting reconnection between the two filament legs was responsible for the initial onset of the confined eruption of the compound flux rope (see Figures 7–9).

Fine structures of the huge flux rope are rarely observed in the solar corona. This is possible only after the hot plasma tracked
Figure 13. (a) SDO/AIA 171 Å image at 01:28:11 UT showing the moving bright hot plasma under the dark cool filament plasma material. The schematic is also overplotted in this figure. SDO/AIA 171 (b), 131 (c), and 94 Å (d) images at ≈01:39 UT showing the right-handed twisted flux rope. The schematic is also presented in panel (c). The two visible flux rope field lines are represented in panel (c) by white and yellow lines. Solid/dotted lines show the part of field lines over and under the flux rope axis. All these figures show evidence of the positive helicity of the surrounding flux rope.

(A color version of this figure is available in the online journal.)

the fine flux tubes and made them visible (Li & Zhang 2013; Joshi et al. 2014). Recently, Li & Zhang (2013) examined the fine structure of two flux ropes and found that they are composed of 85 ± 12 and 102 ± 15 fine-scale structures, each having ends with multiple footpoints. Our observations also show that the compound flux rope has several fine structures with both ends of the flux rope consisting of multiple footpoints (see Figures 4(f), 5(g)–(h), 6(g)–(h), and 13(b)–(d)).

The compound flux rope is stable against eruption in the corona and confines the eruption (see Figures 3–6 and animations). For stable equilibrium, the value of the decay index of the ambient magnetic field should not exceed the critical value, i.e., 1, for a straight current channel and 1.5 for a circular current channel, depending on the different flux rope geometries (Filippov & Den 2001; Démoulin & Aulanier 2010). To check the stability, we have calculated the decay index near the compound flux rope axis and found that the whole axis lies in the region where the value of the decay index is less than the critical value (i.e., less than 1.5) up to 86.4 Mm. Our measurements also suggest that the maximum height of the flux rope as well as its axis should be less than the 86.4 Mm and 43.2 Mm coronal heights, respectively (see Section 5 for details). Hence, the overlying coronal magnetic field plays a crucial role in the stability of the filaments and compound flux rope against torus instability. Also, for the kink instability to erupt, a flux rope should contain two to three turns (Török et al. 2004). But in our observations, we found that the flux rope has fewer than two turns (see Figure 13(b)–(d)), which also makes the flux rope stable against the kink instability. In the future, in order to understand more clearly the merging, reconnection, and stability of flux ropes, we are going to simulate these kinds of stable flux rope eruptions in the solar corona.

It has been observed that in general the northern/southern filaments have dextral/sinistral chirality and hence negative/positive helicity, respectively (Chae 2000; Pevtsov et al. 2003). However, some authors have also reported signatures of the opposite characteristics as well as evidence of mixed helicity in the solar corona (Pevtsov et al. 2003; Martin 2003; Muglach et al. 2009). Recently, Joshi et al. (2014) also reported the relationship between the filament chirality (sinistral) and helicity (positive) of the flux rope and also found a good correlation. In the present work, we also discussed the relationship between
filament chirality and associated flux rope helicity and found a clear relationship. Using various observational manifestations, we found that the filaments have sinistral chirality (see Section 4 and Figure 12 for more details). From the apparent motion of the plasma within the compound flux rope as well as from the complete twisted geometry of the flux rope in EUV images, we confirm that the surrounding magnetic flux rope has positive helicity (see Section 4 and Figure 13). Overall, this observation is another clear example showing the relationship between chirality and helicity.

More observational and simulation works are needed in order to understand the filaments’ interaction/merging dynamics in detail. The eruption of such big disk-center filaments and flux ropes are mainly responsible for the fast Earth-directed CMEs and other interplanetary and near-Earth consequences. However, they are sometimes stable under the coronal magnetic field conditions. Therefore, observational studies as well as numerical simulations of filament stabilization/eruption may play a significant role in forecasting the initial eruption conditions as well as space weather.
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