Interaction of Two Active Region Filaments Observed by NVST and SDO

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Abstract

Using high spatial and temporal resolution Hα data from the New Vacuum Solar Telescope (NVST) and simultaneous observations from the Solar Dynamics Observatory, we present the rare event of the interaction between two filaments (F1 and F2) in AR 11967 on 2014 January 31. The adjacent two filaments were almost perpendicular to each other. Their interaction was driven by the movement of F1 and started when the two filaments collided with each other. During the interaction, the threads of F1 continuously slipped from the northeast to the southwest, and were accompanied by the brightenings at the junction of two filaments and the northeast footpoint of F2. Part of F1 and the main body of F2 became invisible in Hα wavelength due to the heating and the motion of F2. At the same time, bright material initiated from the junction of two filaments were observed to move along F1. The magnetic connectivities of F1 were found to be changed after their interaction. These observations suggest that magnetic reconnection was involved in the interaction of two filaments and resulted in the eruption of one filament.

Key words: Sun: activity – Sun: corona – Sun: filaments, prominences – Sun: flares

Supporting material: animations

1. Introduction

Filaments are relatively cool and dense plasma suspended in the hot corona. They are usually observed to form and to be maintained in a magnetic channel (Martin 1998). Recent observations show that the material of filaments are supported by magnetic flux ropes, which can be visible when filaments are activated or erupted (Cheng et al. 2011; Li & Zhang 2013a, 2013b, 2013c; Yang et al. 2014; Yan et al. 2015). Filaments are known to have magnetic patterns of handness or chirality (Martin 1998). Viewing the filament from the positive-polarity side, the chirality is defined to be dextral if the filament axial field is directed rightward and sinistral if directed leftward. Generally, filaments follow a handness rule, in which dextral filaments dominate in the north hemisphere and sinistral filaments dominate in the south one (Martin et al. 1994). It is believed that the filament chirality and the magnetic helicity sign have a one-to-one correspondence, in which dextral filaments have negative (left hand) magnetic helicities and sinistral filaments have positive (right hand) helicities (Chae 2000).

Previous observations revealed that two nearby filaments can approach and interact with each other (e.g., D’Azambuja & D’Azambuja 1948; Li & Ding 2012; Kong et al. 2013; Xue et al. 2016b). Some authors have presented observations where filaments of the same chirality, sharing a common filament channel, could merge into a single filament at their neighboring ends (Deng et al. 2000; Schmieder et al. 2004; Bone et al. 2009; Joshi et al. 2014; Zhu et al. 2015). Su et al. (2007) showed that two sinistral filaments along different channels could merge by body coalescence and form a common filament channel. More recently, Jiang et al. (2014) reported that the intrusion of the erupted material of one sinistral filament into the filament channel of the other sinistral filament caused the merging of the two filaments. Unlike the above observations, Kumar et al. (2010) and Chandra et al. (2011) found that two dextral filaments—observed on 2003 November 20—first approached each other, then merged at their middle parts, and finally separated in opposite directions. Consequently, the two filaments changed their footpoint connections to form two newly linked filaments. Similar observations were also reported by Jiang et al. (2013).

Under convective zone conditions, Linton et al. (2001) simulated the collision of two highly twisted, identical flux ropes. In their numerical simulation, four types of interaction were found based on the helical sign and contact angle of the two flux ropes. They were bounce, merge, slingshot, and tunnel, in which magnetic reconnection was involved. The interaction was called bounce when the two collided flux tubes bounced off each other, and was called merge when they merged into one. The slingshot interaction occurred when the two flux ropes with opposite helicities collided with each other in an appropriate contact angle. As a result, two new flux ropes with exchanging footpoint connections formed and then slingshotted away from the interaction region. In the following work of Linton (2006), the collision of two lowly twisted and unequal flux ropes with the same helicity also produced the slingshot interaction. Under coronal conditions, Török et al. (2011) also found the slingshot interaction of two flux ropes with the same helicity, which was based on the event that occurred on 2003 November 20. Note that the opposite and same helicities mentioned above refer to the sign of helicity. The tunnel and slingshot interaction had the same initial condition. Nevertheless, the slingshot reconnected once at the collision site and finally formed two new flux tubes. The tunnel reconnected twice at two different places and exchanged the section between the two reconnection points, which made the flux tubes to pass through each other. Among the interactions, the slingshot interaction was the most energetic because the magnetic flux was annihilated and twist-cancelled. In addition,
DeVore et al. (2005) performed numerical simulations of the formation and interaction between pairs of head-to-tail filaments within the sheared-arcade model. Four possible basic combinations of chiralities (identical or opposite) and axial magnetic fields (aligned or opposed) between the filaments have been considered. The numerical experiments suggest that tether-cutting reconnection occurred between filaments with aligned axial fields, which was irrespective of their chiralities.

Two main mechanisms exist that lead to the instability of filaments and trigger the energy release and eruptions. One is the nonideal process (i.e., magnetic reconnection; Antiochos et al. 1999; Lin & Forbes 2000; Moore et al. 2001; DeVore & Antiochos 2008; Shen et al. 2012; Li et al. 2016; Xue et al. 2016a), and the other is an ideal magnetohydrodynamic (MHD) process (i.e., kink and torus instabilities; Török & Kliem 2005; Kliem & Török 2006; Srivastava et al. 2010; Yan et al. 2014; Bi et al. 2015). Observations have indicated that magnetic reconnection during the filament interaction can lead to filament eruptions. Kim et al. (2001) observed a filament that was partially erupted after a rapid change of connectivity in a bundle of filament threads. Su et al. (2007) pointed out that one filament eruption resulted from the sudden mass injections produced by external bodily magnetic reconnection between two filaments. More recently, Chen et al. (2016) reported that tether-cutting reconnections between filaments triggered filament eruptions.

To our knowledge, observational evidence of filament interaction is relatively rare and need to be studied further, which is helpful to understand physical mechanisms of such interaction. In this paper, we present a detailed analysis of the interaction of two filaments with the high-resolution, multi-wavelength observations from the New Vacuum Solar Telescope (NVST; Liu et al. 2015) and the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). We describe the observational data in Section 2 and present analysis results in Section 3. Conclusions and discussions are given in Section 4.

2. Observations and Data Analysis

The NVST has a multi-channel high-resolution imaging system, which is used to observe the fine structures in the photosphere and the chromosphere. Up until now, it can image the Sun in three channels: TiO, G-band, and Hα. The Hα channel is centered at 6562.8 Å, with a bandwidth of 0.25 Å. It can provide off-band observations in the range of ±5 Å with a step size of 0.1 Å. In the present paper, the Hα line center images from 06:55:00 UT to 07:59:59 UT on 2014 January 31 were employed to analyze the interaction of the two filaments in the chromosphere. These images have a pixel size of 0″162 and a cadence of 12 s. The field of view (FOV) is 150″ × 150″. The Hα data are first processed by dark current subtraction and flat field correction, and then are reconstructed by speckle masking (Weigelt 1977; Lohmann et al. 1983).

The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the SDO provides full-disk images taken in seven EUV passbands and three continuum bands. The spatial resolution and cadence of these images are 1″5 and 12 s, respectively. Here, all seven EUV channels were used, which cover a temperature range from 0.05 MK to 20 MK. The differential emission measure (DEM) using the almost simultaneous observations of six AIA EUV lines (131, 94, 335, 211, 193, and 171 Å formed at coronal temperature) was reconstructed, and the DEM-weighted average temperature was calculated (Cheng et al. 2012). We also used the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) line-of-sight magnetograms and vector magnetic field data from the SDO. The line-of-sight magnetograms were used to extrapolate the potential fields above the photosphere, which were used to calculate the decay index of magnetic fields overlying on the F2. They have a cadence of 45 s and a sampling of 0″5 pixel−1. The vector magnetic field data were obtained by using the Very Fast Inversion of the Stokes Vector algorithm (Borrero et al. 2011). The 180 azimuthal ambiguity was resolved based on the minimum intensity value (Metcalf 1994; Metcalf et al. 2006; Leka et al. 2009). These data have a pixel size of 0″5 pixel−1 and a cadence of 12 minutes. We processed the AIA images and the HMI line-of-sight magnetograms by using the standard routine aia_prep.pro in the SolarSoftWare packages (Freeland & Handy 1998) and rotated all of the images to a reference time (07:30 UT on 2014 January 31). In addition, the Global Oscillation Network Group full-disk Hα image was used to align the SDO and NVST data.

3. Results

On 2014 January 31, the observations of the NVST covered the interaction process of two filaments (F1 and F2), which were located close together in a complex NOAA AR 11967 (S14E41). Figure 1 shows their locations outlined by the blue dashed lines in the SDO/AIA 304 Å and Hα images with the SDO/HMI radial component of the vector magnetic field superimposed before F1 began to move. The black and white contours indicate the negative and positive magnetic field. The level of the contours is ±100 G. It is clear that F1 is roughly oriented along the east–west direction, while F2 is oriented along the north–south direction. The axes of the two filaments were nearly perpendicular to each other (see Figures 1(a) and (b)). When viewed at the positive-polarity side, the axial field direction of F2 was leftward. Therefore, F2 is a sinistral filament, which is consistent with the preferential filament pattern in the southern hemisphere (Martin et al. 1994). As it can be seen in Figure 1(b), F1 was not strictly located on the polarity inversion line (PIL), but its location was close to the PIL. It is supposed that F1 might be suspended high in the corona, and the misalignment between F1 and the PIL was due to the projection effect.

Figure 2 displays the interaction of the two filaments and the subsequent filament eruptions in Hα, 304, and 335 Å wavelengths, respectively. Prior to the interaction, the two filaments can be identified as dark structures not only in the cool channels such as Hα and AIA 304 Å channels, but also in the hot channels such as AIA 335 Å channel (see Figures 2(a)–(c)). At about 06:55 UT, the central part of F1 was activated and began to move to the southwest direction (see the online animated Figure 2). As a result, F1 gradually approached F2 from the northeast to the southwest direction (see Figures 2(b)–(d)). Such approaching motion can be clearly seen in the stack plots along the slit “A–B,” in which the two filaments can be identified as dark tracks (see Figures 5(b)–(d)). At about 07:22 UT, F1 impinged on the northeast part of F2 and the brightenings appeared at the junction of the two filaments. The brightenings were enhanced with further filament interaction, which were marked by the white arrows in Figures 2(c)–(e). Simultaneously with the appearance of the brightenings, the cool plasma of filament heated up and started to move along F1. The moving heated plasma was observed as bright
structures in Figures 2(c1), (c2), (d1), and (d2), which were marked by the thin white arrows. It was exhibited as many bright stripes in the stack plots along the slit “C–D” (see Figure 5(e)). At the same time, part of F1 and the main body of F2 became invisible in the Hα wavelength (see Figure 2(c)), while they appeared as obvious brightenings at 304 Å wavelength (see Figure 2(c1)). The disappearance of F1 might mainly be due to the heating of the filament plasma, but that of F2 might have two probabilities: one is the heating of the filament plasma, and the other is the motion of F2.

Unfortunately, NVST has no off-band observations on that day. At about 07:25 UT, F2 started to erupt. Meanwhile, it underwent an anticlockwise rotation during its eruption. Three minutes later, F2 collided with its overlying large-scale loops and began to interact with them, as shown in Figure 3. These large-scale loops were brightened by the interaction and can be clearly seen in Figure 3(b). As the interaction was processed, the overlying large-scale loops were continually stretched and the material of F2 was found to be falling down along them (see Figure 3(c) and the online animation). The interaction led to the deflection of F2. F2 finally developed to a fan structure (as marked by the thick white arrows in Figures 2(d)–(d2)). At about 07:28 UT, two flare ribbons appeared on opposite sides of the eruptive F2 (marked as “FR” in Figures 2(d)–(d2)). It was too weak to be recorded as a flare, which is similar to observations shown by Yang et al. (2008). Several minutes later, another pair of flare ribbons appeared at the east of F1 in the same active region. It was related to a GOES C2.3 flare, which started at 07:35 UT and peaked at 07:57 UT. There wasn’t a coronal mass ejection associated with this eruption.

In order to present the filament interaction in more detail, we extracted the interaction region (as marked by the white square in Figure 2(b)) and analyzed its evolution process at Hα and 304 Å wavelengths, as showed in Figure 4(a)–(l). The southwest border of F1 was traced out by red dashed curves in Figure 4(a)–(g). Because of the high spatial resolution of the NVST, the filament threads can be clearly distinguished (see Figure 4(a)–(h)). We noticed that the F1’s threads extended to the east before its interaction with the threads of F2, as shown in Figure 4(a). At about 07:22 UT, the southwest bunch of F1’s threads collided with the northeast bunch of F2’s threads. It seems that the two bunches of threads joined together (see the online animated Figure 4). One minute later, they began to separate, and F1’s threads continued to move to the southwest direction (see the red dashed lines in Figures 4(b)–(h)). Note that the bunch of F1’s threads that was involved in the filament interaction changed their directions, and curved to the southwest direction, indicating that the magnetic connectivities of F1’s threads have changed. As the interaction continued, the magnetic connectivities of F1’s threads changed continuously, which was exhibited as a slipping motion from the northeast to the southwest direction (see the online animated Figure 4). The F1’s threads finally rooted in the weak network region where the northwest footpoint of F2 was originally located (see Figure 4(h)). The newly formed magnetic structure was depicted by the yellow dashed line in Figure 4(h). We also noticed that the brightenings appeared at the northwest footpoint of F2 when the two filaments collided with each other (see the online animated Figure 4). Following the movement of F1’s threads, the brightenings were gradually strengthened and extended to the northwest direction, which also showed up as a slipping motion (see the thick red arrows in Figures 4(b)–(g)). These kind of brightenings were ever observed by Kim et al. (2001) in a pre-eruption reconnection event, and were considered to be caused by the downward draining filament material produced by the magnetic reconnection. More notably, the brightenings appeared at 304 Å wavelength when the F1’s threads collided with the F2’s threads, as shown by the yellow arrow in Figure 4(j). They were enhanced as the interaction in progress and can be clearly identified in chromospheric and coronal lines (see Figure 4(k), (m)–(o), and the online animated Figure 4). The temperature map obtained with the DEM method was shown in Figure 4(p), and it is found that the temperature of the brightenings can
Figure 2. NVST Hα (a–d), SDO/AIA 304 Å (a1–d1), and 335 Å (a2–d2) images showing the interaction of the two filaments and subsequent filament eruptions. The line “A”–“B” marks the slit position of space–time plots of panels (b)–(d) in Figure 5. The curve line “C”–“D” marks the slit position of the space–time plot of the panel (e) in Figure 5. “FR” represents the flare ribbons involved in this event. The white square in panel (b) gives the FOV of Figure 4. The thick white arrows in panels (c)–(c2) point to the erupting F2. The thin white arrows in panels (c1), (c2), (d1), and (d2) point to the mass motions. The thick white arrows in panels (d)–(d2) indicate the fan structure of F2 after its eruption. An online animation of the NVST Hα, SDO/AIA 304 and 335 Å images is available. The ∼32 s animation covers from 6:55 to ∼8:00 UT.

(An animation of this figure is available.)
reach up to 20 MK. These observations suggest that magnetic reconnection might occur between F1 and F2 during the interaction process. The brightenings at the northwest footpoint of F2 indicate that magnetic reconnection during the filament interaction altered the stable environment of F2. We speculate that the downward magnetic tension force could have decreased when magnetic reconnection occurred, which could have triggered the eruption of F2.

To investigate the brightenings at the junction of the two interactive filaments, we selected a small region marked by the white box in Figure 4(j) to calculate the variation of Hα, SDO/AIA 304, and 335 Å brightness over time, as shown in Figure 5(a). We note that these curves started to increase at about 07:22 UT (as marked by the yellow vertical line), which was the time when the two filaments encountered each other. For tracing the eruption of F1 before interaction, we made time slices from Hα, 304, and 335 Å images along a slit “A–B” (as marked by a white line in Figure 2(a)). As seen from the Figure 5(b)–(d), the filaments appeared as dark tracks. Clearly, F1 was slowly approaching F2 at a speed of 3–5 km s⁻¹. During this process, F2 almost did not move. In order to trace the mass motions along F1, we made a time slice from AIA 304 Å images along a slit “C–D” (as marked by a white line in Figure 2(b1)). It is noted that these mass motions started at about 07:22 UT and had a velocity of 150 km s⁻¹.

In order to better understand the eruption of F2 in this event, the magnetic topology and the decay index over the filament were obtained by performing the local potential field extrapolation (Alissandrakis 1981; Gary 1989). The decay index is defined as $n = -d\ln(B)/d\ln(h)$, where $B$ is the transverse strength of the magnetic field and $h$ is the height measured from the photosphere. Here decay indexes were derived from a central cross section of F2 (marked by the red line in Figure 6(a)) at a height range from 0.9 to 22 Mm. The results were shown in Figure 6(b). Here, the height of F2 was estimated. We assumed that F2 has a loop-shape vertical to the solar surface and its footpoints are rooted in the same atmospheric level. The line of sight has a 37° angle relative to the solar surface. So the maximum height of F2 is estimated to be about 12.9 Mm, which was marked by the blue dashed line in Figure 6(b). The red line in Figure 6(b) denotes where the cross section cut of F2. As seen in Figure 6(a), one can see that F2 was restricted by the overlying large-scale arcades (as marked by the golden field lines in Figure 6(a)). From Figure 6(b), we note that F2 was located on the intersection point of the red solid line and the blue dashed line, and that the decay index above F2 was lower than 0.3, which was far below the theoretical threshold value (1.5) of torus instability (Kliem & Török 2006). Therefore, the torus instability is not the mechanism of F2’s eruption. However, F2 erupted during the filament interaction, which suggests that F2’s eruption was mainly caused by the filament interaction.

4. Conclusions and Discussion

The interaction of two adjacent filaments (F1 and F2) was well observed by the NVST and SDO at the southeast of the Sun on 2014 January 31. F1 and F2 were close and almost perpendicular to each other. The interaction was driven by the movement of F1, which had a velocity of 3–5 km s⁻¹. The interaction occurred when F1 and F2 collided with each other and produced brightenings at the junction of these two filaments. The threads of F1 continuously slipped from the northeast to the southwest, which was accompanied by the brightenings at the northwest footpoint of F2. Moreover, the motions of bright material can be seen along F1 from the junction of the two filaments. The temperature of the brightenings at the junction of the two filaments was up to 20 MK. During the interaction, part of F1 and the main body of F2 became invisible in Hα wavelength but appeared as evident brightenings in the 304 Å wavelength, which might be due to the heating and the motion of F2. The interaction led to the change of the magnetic connectivities of F1’s threads. Finally, F2 erupted after their interaction.

The interaction was driven by the F1’s movement. Previous observations show that there are two kind of mechanisms driving the filament interaction. One is slow photospheric motions (Kumar et al. 2010; Chandra et al. 2011; Török et al. 2011) and the other is the eruption of one of the interactive filaments (Jiang et al. 2013, 2014; Kong et al. 2013). It is obvious that the filament interaction in this event was driven by the second mechanism.

Magnetic reconnection normally occurred during the filament interaction. Based on the observations of the converging motions of the two filaments, the subsequent appearance of a
hot plasma layer, and a coronal hard X-ray source near the interaction interface, Zhu et al. (2015) pointed out that the two filaments reconnected with each other during their interaction. In this event, evidence of magnetic reconnection in the filament interaction region was also presented, including high-temperature brightenings (up to 20 MK) at the junction of the interactive filaments, mass motions along F1, significant plasma heating, the magnetic connectivity change of F1, and brightenings at the northwest footpoint of F2. During the filament interaction, the connectivities of F1’s threads changed continuously and were accompanied by the slipping motion of the brightenings at the northeast footpoint of F2. To our knowledge, this is the first time that the details of filament interaction process have been displayed, especially the magnetic connectivity change of filament threads, which was owing to the high temporal and spatial resolution of the NVST.

In this event, clear observational signatures for bounce, merge or tunnel weren’t found. However, it is noted that F1’s magnetic connectivities changed after the interaction, which indicates that at least one new filament formed. Therefore, the interaction of this event might be inclined to support the slingshot interaction. This event was associated with a GOES C2.3 flare. Since the eastern leg of F1 was rooted in between the two flare ribbons and the interaction changed the magnetic connectivities of F1 and F2, this flare might be a result of the eruption of F2.
During the filament interaction, F2 became unstable and erupted. Previous observations show that magnetic reconnection during filament interaction can initiate solar eruptions. Su et al. (2007) presented observations that the overloaded mass ejection caused by the magnetic reconnection during the filament interaction led to the second filament eruption. Bone et al. (2009) pointed out that the build-up shear of long linking flux tubes by magnetic reconnection involved in the filament interaction, together with the removal of overlying field by magnetic flux reconnection, led to the instability and eventual eruption of the interactive filaments. Very recently, Chen et al. (2016) claimed that the tether-cutting reconnection between two filaments triggered solar eruptions. In this case, magnetic reconnection is also involved in the filament interaction that

![Figure 5](image_url)
might trigger F2’s eruption. According to the result of torus instability, F2 should be stable before the filament interaction. It was balanced under the upward magnetic pressure force, downward magnetic tension force, and downward gravity force. The downward magnetic tension force might decrease when magnetic reconnection occurred between the two filaments, which breaks the balance of F2’s strapping field and leads to the final eruption of F2.

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Figure 6. (a) SDO/HMI line-of-sight magnetogram with the extrapolated field lines superimposed, along with the pre-interaction F2. (b) Decay indexes measured in the cross section across the F2 marked by the red line in panel (a). The red line in panel (b) marks where the cross section cut of F2. The blue dashed line in panel (b) denotes the measured height of F2.