PARTIAL ERUPTION OF A FILAMENT WITH TWISTING NON-UNIFORM FIELDS

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ABSTRACT

The eruption of a filament in a kinklike fashion is often regarded as a signature of kink instability. However, the kink instability threshold for the filament’s magnetic structure is not widely understood. Using Hα observations from the New Vacuum Solar Telescope, we present a partial eruptive filament. During the eruption, the filament thread appeared to split from its middle and to break out in a kinklike fashion. In this period, the remaining filament material stayed below and erupted without the kinking motion later on. The coronal magnetic field lines associated with the filament are obtained from nonlinear force-free field extrapolations using the twelve-minute-cadence vector magnetograms of the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamic Observatory. We studied the extrapolated field lines passing through the magnetic dips which are in good agreement with the observed filament. The field lines are non-uniformly twisted and appear to be composed of two twisted flux ropes winding around each other. One of them has a higher twist than the other, and the flux rope with the higher twist has its dips aligned with the kinking eruptive thread at the beginning of its eruption. Before the eruption, moreover, the flux rope with the higher twist was found to expand with an approximately constant field twist. In addition, the helicity flux maps deduced from the HMI magnetograms show that some helicity is injected into the overlying magnetic arcade, but no significant helicity is injected into the flux ropes. Accordingly, we suggest that the highly twisted flux rope became kink unstable when the instability threshold declined with the expansion of the flux rope.

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

Supporting material: animation

1. INTRODUCTION

Kink instability is often considered a candidate mechanism for filament eruption. When kink instability sets in, the flux rope’s axis will experience a writhing motion due to the conservation of magnetic helicity in the highly conducting corona. Thus, the rotation of the eruptive filament is often thought to be an observational appearance of kink instability (Rust & Labonte 2005; Green et al. 2007; Liu 2008; Bi et al. 2012; Thompson et al. 2012; Yang et al. 2012; Jiang et al. 2013; Yan et al. 2014). The writhing motion induced by the kink instability mainly acts in the lower corona, below a height comparable to the footpoint distance (Kliem et al. 2012); this is different from the rotation that is guided by the surrounding magnetic field in the higher corona (e.g., Cohen et al. 2010; Kliem et al. 2012; Bi et al. 2013).

The ideal stability of the kink mode is mainly controlled by the total twist. Kink instability occurs if the amount of magnetic twist exceeds a critical value. The flux tube twist is usually expressed as $\Phi_{tw} = |B_\phi/rB_z|$, where $B_\phi/B_z$ is the ratio of the azimuthal and axial field components of the flux tube and $l/r$ is the length-to-width ratio of the tube. The threshold for the onset of instability is dependent on the detailed magnetic structure. For a force-free magnetic loop with photospheric line tying (Hood & Priest 1981), the instability threshold is an amount of twist equal to about 1.25 turns. The MHD simulation of Fan (2005) showed that a line-tied flux rope becomes kink-unstable when the field line twist reaches about 1.7 turns. Consistent with this, the critical average twist for a magnetic loop simulated by Török et al. (2004) is about 1.75 turns. Moreover, the authors concluded that the instability threshold rises with the rising aspect ratio of the loop.

An inhomogeneous twisted flux rope was investigated by Birn et al. (2006) using magnetohydrodynamic simulations. Their results show that a flux rope will be broken into two portions when the more strongly twisted portion becomes kink-unstable and rapidly moves outward. The bifurcation of a flux rope during eruption was first discussed by Gilbert et al. (2000) and was classed as a partial eruption by Gibson & Fan (2006), who demonstrated that part of the flux rope is expelled from the corona when it reconnects internally and with the surrounding field so that it breaks into two (Gibson & Fan 2006). Their simulation implies that the writhing motion induced by the kink instability is essential for forming a current sheet within the flux rope where it can break into two. The observations of partial eruption (e.g., Tripathi et al. 2009, 2013; Shen et al. 2012) show that the splitting of the flux rope is often accompanied by writhing motion. The authors accounted for these events using the model of Gibson & Fan (2006), but it seems that not all of these events show a clear signal of internal magnetic reconnection.

The twisted flux rope is often found above the magnetic neutral line in the nonlinear force-free magnetic field (NLFFF) extrapolated from vector magnetograms. Using various NLFFF extrapolation algorithms, several authors found flux rope systems in their studied active region with twists of about 1 turn (Yan et al. 2001; Canou et al. 2009; Inoue et al. 2011; Guo et al. 2013). Some filaments investigated (Régnier & Amari 2004; Guo et al. 2010; Jing et al. 2014; Jiang et al. 2014) were also described as a twisted flux rope with a twist value of approximately 1 turn, which means that these structures are stable against kink instability. Interestingly, Guo et al. (2013) reconstructed a flux rope, which has a twist of about 1.9 turns about two hours before it started to erupt. It is worth noting that the ratio of the radius to the length of the flux
rope they studied is less than 1/15, which is slightly lower than the ratio that was chosen by Török et al. (2004) in their parameter investigation. To our knowledge, however, few investigations have focused on the evolution of the field twist associated with a filament showing kinking motion.

Magnetic helicity quantifies the magnetic topological complexity and is a valid tool for measuring how much a magnetic flux rope is twisted and writhed, or how much a magnetic arcade is sheared (see the review by Démoulin 2007 and references therein). As inferred from the evolution of the photospheric magnetic field, magnetic helicity transported across the photosphere is often used to diagnose the helicity that is instantaneously injected into the higher solar atmosphere. Some investigators showed that the local injection of helicity with opposite signs played a role in triggering the eruptions of the studied filaments (Romano et al. 2011; Dhara et al. 2014). Romano et al. (2005) found impulsive input of helicity at the beginning of the eruption of a kinked filament. Their results supported the idea that the amount of magnetic helicity in the filament exceeds the limit for kink instability primarily due to the transport of helicity through the photosphere.

In this article, we present the partial eruption of a filament. One portion of the filament shows the evident kinking motion in the eruption. We present observations of the event and comparisons with the topologies of the NLFFF-extrapolated field lines and the photospheric helicity injection associated with the filament. This enables us to investigate the structure and evolution of the magnetic field related to the kinking eruption.

2. OBSERVATION AND DATA ANALYSIS

2.1. NVST and SDO Observations

Our primary data to be used to present the eruption of the filament are the Hα images obtained by New Vacuum Solar Telescope (NVST; Liu & Beckers 2001; Liu et al. 2014) and the 304 Å images from the Atmospheric Imagining Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamic Observatory (SDO). The NVST obtains solar images in three channels, i.e., the Hα, TiO, and G bands, with a field of view (FOV) of 180° × 180°, a cadence of 12 s, and a pixel size of 0′′168. The observational data acquired at NVST are now available (http://fso.ynao.ac.cn). The NVST Hα images adopted here were obtained from 04:00 to 07:00 UT on 2014 November 4, and the whole FOV of the NVST/Hα image is displayed in Figure 1(a). All of the NVST images are aligned to the same FOV based on a high accuracy solar image registration procedure (Feng et al. 2012; Yang et al. 2014). The AIA takes full-disk EUV images with a pixel size of 0′′6 and 12 s cadence.

The Helioseismic and Magnetic Imaging (HMI) vector field (Turmon et al. 2010) is computed using the Very Fast Inversion of the Stokes Vector (Borrero et al. 2011) code and the remaining 180° azimuth ambiguity is resolved with the Minimum Energy code (Metcalf 1994; Leka et al. 2009). Now, HMI provides continuous coverage of the vector field in the so-called HMI Active Region Patches (HARPs) region. Figure 1(b) presents a line of sight (LOS) magnetogram in CCD coordinates, with the same FOV as the HARPs region surrounding the targeted filament. The HARP vector field data has been remapped to a Lambert Cylindrical Equal-area (CEA) projection and then transformed into standard heliographic spherical coordinates. Figure 1(c) displays the CEA map-projected field in the radial direction normal to the solar surface.

2.2. Coronal Magnetic Extrapolation

The “NLFFF” package available in SSW wans developed by Jim McTiernan to perform a NLFFF extrapolation using the optimization method of Wheatland et al. (2000), which is one of the best-performing NLFFF extrapolation methods (Schrijver et al. 2006; Metcalf et al. 2008). The procedure is fulfilled in Cartesian and spherical coordinates and includes the weighting function (Wiegelmann 2004) and a preprocessing procedure to drive the observed data toward suitable boundary conditions for extrapolation (Wiegelmann et al. 2006). In this
study, the coronal field in the spherical geometry is extrapolated by means of the “NLFFF” package as follows. To ensure the vector data to be used in the NLFFF modeling efforts span as large an area as possible (De Rosa et al. 2009), first, the field covering a relatively large area of $21^\circ \times 21^\circ$ (indicated by the dashed box in Figure 1(b)) is calculated within the computational domain of $200 \times 200 \times 240$ grids. The CEA vector field is used as the boundary condition and the results of the potential-field source surface (Schatten et al. 1969; Schrijver & De Rosa 2003) model provide the initial conditions for this process. Second, the solution field is applied as the initial conditions for further extrapolation within a domain covering an area of $16^\circ \times 9^\circ$ which includes the region of interest (indicated by the solid box in Figure 1(b)).

The domain is resolved by $534 \times 301 \times 477$ grids to ensure that the value of the grid is same as the pixel size of the HMI data. To better estimate the spatial distribution of the helicity flux, Pariat et al. (2005) considered the helicity injected into an elementary flux tube, which can be written as the sum of $G_\Phi$ at both photospheric footpoints of the corona connection. The authors introduced a connectivity-based helicity flux density proxy, $G_\Phi$, such that

$$G_\Phi(x_{\pm}) = \left( G_\Phi(x_+) + G_\Phi(x_-) \right) \left| \frac{B_r(x_{\pm})}{B_r(x_{\mp})} \right| f_\pm$$

where $x_+$ and $x_-$ are the locations of the opposite polarities with coronal linkage, and $f$ ranges from 0 to 1. Then, the proxy $G_\Phi$ stands for the helicity flux for each individual flux tube. Obviously, the integral of $G_\Phi$ has the same value as that of $G_\Phi$ over a large enough region, but $G_\Phi$ masks some false opposite sign signals in $G_\Phi$; these are canceled out in the integral of $G_\Phi$ over the region including all magnetic polarities with coronal linkage.

3. RESULTS

Close views of the filament in the Hα and 304 Å images are shown in Figure 3. The filament is located in NOAA active region AR 11884 at position (S11, W24) on 2013 October 4. The length of the filament is approximately 30 Mm, slightly longer than that of the named mini-filament defined by Wang et al. (2000). At 05:28 UT, a thin filament thread starts to split from the middle portion of the filament (as indicated by the arrows in Figures 3(c)–(d)). The separated thread was found to rotate clockwise. As observed from the Hα image (Figure 3(c)), the rotation angle about the undisturbed filament axis is approximately $30^\circ$ at 05:36 UT (see also the animation accompanying Figure 3). At 05:38 UT, the eruptive filament thread has disappeared from the Hα image (Figure 3(e)) and it evolved into a brightened one in the AIA 304 Å image (Figure 3(f)). The left portion of the filament remained undisturbed until after the previous eruptive thread has disappeared in the AIA 304 Å image. Moreover, no evident
rotating motion is identified in the subsequent eruption of the left portion (Figures 3(g)–(h)), which started about 05:45 UT. Ultimately, a flare of X-ray class C3.2 took place with start, peak, and end times around 05:36, 05:44, and 05:52 UT, respectively.

The modeled magnetic dips exist if the field lines are locally horizontal and curve upwardly, and they are widely accepted to support the filament plasma. In Figures 4(a) and (b), the green curves overlying the Hα images show the magnetic dips calculated from the extrapolated NLFFF field at 04:12 and 05:12 UT, respectively. At these two moments, the locations of the dips seem to be very well aligned with the filament over its length.

The field lines traced from all of the dips are displayed in $\phi - R$ and $\phi - \theta$ planes (Figure 5). After checking the character of each field line, we assign the field lines to two groups: the field lines are colored red if their endpoints (as shown in Figures 4(c)–(d)) are anchored in the negative
polarity region with field strength higher than 1200 G; otherwise, the field lines are colored cyan. After such a grouping, the field lines seem to be made up of two flux ropes winding around each other (see the first two rows of Figure 5). The red field lines show a double-peak structure with their two peaks being located above most of the cyan field lines, while the majority of the cyan field lines have their peaks lying between the two peaks of the red field lines. Moreover, the dips of the red field lines match well the middle segment of the observed filament (Figure 4(e)). In Figure 4(f), the eruptive filament thread appears to be lying across the middle part of the filament, where the dips are approximately located.

After obtaining the value of the twist and writhe for each field line using the Equation (2), we found that the extrapolated field lines are non-uniformly twisted. The values of the twists range from 0.8 to 2.0 turns and average about 1.2 turns. Furthermore, the average twist for each red field line is higher than the average for the cyan field line. The average value for red (cyan) is 1.55 (1.25) at 04:12 UT and 1.51 (1.1) at 05:12 UT. The value of the writhe is smaller than that of the twist. The average writhe of the red field lines has the value of 

\[-0.04\] at 04:12 UT and 

\[-0.02\] at 05:12 UT.

Possessing higher twist, the red flux rope is extracted to be investigated further in the last two rows of Figure 5. The flux rope has a height of about 7 Mm with respect to the solar surface, and has a length of about 30 Mm. Comparing the two panels, we find that the flux rope evolves to become fatter. The average radius of the flux rope is about 2 Mm (4 Mm) at 04:12 (05:12) UT. Hence, the ratio between the radius and length of each flux rope is about 1/15 and 1/8 at these two moments, respectively.

Figure 6(b) displays the time-averaged helicity flux map computed with the proxy $G_\theta$ using a series of HMI magnetograms with twelve-minute cadence from 04:12 to 05:36 UT. Figure 6(a) exhibits one of the magnetograms, on which the two negative polarities is referred to as N1 and N2, respectively. From the NLFFF, we note that N1 is where the eastern endpoint of the filament is anchored and N2 is connected to the field overlying the filament; there is no other negative patch flux associated with this filament. The part with the positive polarity around the western footpoint of the

Figure 4. (a)–(b): the NVST/Hα images overlaid with all of the extrapolated magnetic dips. (c)–(d): the radial component of the HMI vector field overlaid by the endpoints of the fields traced from the location of the dips. The endpoints are colored red if their corresponding fields are anchored in the negative region with field strength higher than 1200 G; otherwise, they are colored cyan. (e)–(f): the NVST/Hα images overlaid with the extrapolated magnetic dips, which are associated with fields that are anchored in the negative region with field strength higher than 1200 G. All of these images are remapped to CEA coordinates.

(An animation of this figure is available.)
filament connects the large-scale field that is anchored far away from the filament. Accordingly, we choose $f = 1$ to compute $G_\phi(x_-)$ (Figure 6(c)), which assumes helicity is injected from the negative polarity. In the $G_\phi(x_-)$ map, therefore, the helicity flux from the N1 and N2 is roughly equivalent to the total helicity injection into the filament.

As shown in Figures 6(b)–(c), both $G_\theta$ and $G_\phi$ maps display mixed signals in N1. However, the $G_\phi$ map presents more positive flux on the right side of N1, and the total helicity flux in N1 of $G_\phi$ is close to 0. It is consistent with the result deduced from the extrapolated field lines, which show that no magnetic helicity increase was discovered in the magnetic structure associated with the filament. In contrast, the distributions of $G_\theta$ and $G_\phi$ are similar in N2, which is completely filled with positive helicity flux.

4. CONCLUSIONS AND DISCUSSION

Using observations from NVST and SDO, we analyzed a partial filament eruption. The eruption starts with a thin filament thread separating from the filament, and the thin thread breaks out in a kinklike fashion. We regarded the field lines with their dips aligning with the observed filament to be the magnetic structure associated with the filament, and investigated the twists and writhes of the field lines based on their geometries. The result demonstrates that the magnetic system consists of two flux ropes, and one of them is estimated to be more highly twisted than the other. Moreover, the highly twisted flux rope has its dips aligned well with the thin filament thread that shows kinking motion in eruption. Therefore, the splitting during the eruption may result from the more strongly twisted portion of the magnetic system becoming kink-unstable (Birn et al. 2006).
For each field line constituting the more twisted flux rope, the average twist is found to decrease slightly, with a small increase in the average writhe as time passes. Hence, some twist may have been quasi-statically converted into writhe during this period. A similar equilibrium configuration was obtained in the MHD simulations of Fan (2005), who showed a mildly kinked equilibrium with some finite writhe of the flux rope axis. Moreover, the helicity for the highly twisted flux rope, which is equivalent to the sum of the values of the twist and writhe according to Equation (1), amounts to $1.51 \Phi^2$ and $1.49 \Phi^2$ at 04:12 and 05:12 UT, respectively. It indicates that no increase in the amount of magnetic helicity was detected in the flux rope before eruption. In this case, the question is how the flux rope develops to become nonlinear kink-unstable as implied by the observed strong rotation of the filament thread.

As mentioned in the Section 2, the value of $T_w$ is slightly smaller than that of the twist $\Phi_{nw} = l B_\Phi / r B$ for the same flux rope. It implies that the twist $\Phi_{nw}$ for our modeled flux rope should be slightly greater than 1.5 turns deduced from the proxy $T_w$. Török et al. (2004) estimated $\Phi_{nw} = 1.75$ turns as the threshold of the kink instability of a magnetic loop with a defined loop aspect ratio of about 5, which amounts to a ratio of 11.2 between the width and the length of the loop. In our extrapolation, the width–length ratio of the modeled flux rope increases from 1/15 to 1/8 before eruption, i.e., from less than to greater than that given by Török et al. (2004). As the instability threshold increases with increasing aspect ratio (Török et al. 2004), it is possible that the threshold for the kink instability is greater than 1.75 turns at 04:12 UT and is less than 1.75 turns at 05:12 UT in our extrapolation. Hence, the field structure may become kink unstable when it expands with an approximately constant twist.

On the other hand, the helicity flux from the photosphere is obtained using both proxies $G_\theta$ and $G_\phi$. Since the proxy $G_\phi$ involves field connectivity of each elementary flux tube, the proxy $G_\phi$ is better than the proxy $G_\theta$ for presenting the distribution of photospheric helicity flux density per flux tube. However, direct interpretation of the distribution of the helicity flux should be made with caution, because determining the helicity flux requires gauge selection to define the vector potential $A (\nabla \times A = B)$ and both the helicity proxies $G_\theta$ and $G_\phi$ are calculated with the classical gauge of $\nabla \times A_\rho = 0$ and $A_\rho \cdot n = 0$. In contrast, there is no gauge involved in $T_w$ and $W_f$ according to Equations (2) and (3). In our study, the results from both methods show that no significant magnetic helicity is injected into the magnetic flux rope passing through the magnetic dips.

Moreover, both proxies $G_\theta$ and $G_\phi$ show that some positive helicity is injected from a patch flux (referred to as N2) which connects the magnetic arcade overlying the studied filament. The local injection of helicity may play a role in twisting the overlying arcades. If the overlying field is weakened by the twisting, as suggested by Török et al. (2013), the underlying flux rope would undergo a quasi-static expansion. Therefore, the helicity injection into the overlying arcade may have a role in expanding the flux rope as shown in our extrapolation.

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