NEW VACUUM SOLAR TELESCOPE OBSERVATIONS OF A FLUX ROPE TRACKED BY A FILAMENT ACTIVATION

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ABSTRACT

One main goal of the New Vacuum Solar Telescope (NVST) which is located at the Fuxian Solar Observatory is to image the Sun at high resolution. Based on the high spatial and temporal resolution NVST Hα data and combined with the simultaneous observations from the Solar Dynamics Observatory for the first time, we investigate a flux rope tracked by filament activation. The filament material is initially located at one end of the flux rope and fills in a section of the rope; the filament is then activated by magnetic field cancellation. The activated filament rises and flows along helical threads, tracking the twisted flux rope structure. The length of the flux rope is about 75 Mm, the average width of its individual threads is 1.11 Mm, and the estimated twist is $1\pi$. The flux rope appears as a dark structure in Hα images, a partial dark and partial bright structure in 304 Å, and as a bright structure in 171 Å and 131 Å images. During this process, the overlying coronal loops are quite steady since the filament is confined within the flux rope and does not erupt successfully. It seems that, for the event in this study, the filament is located and confined within the flux rope threads, instead of being suspended in the dips of twisted magnetic flux.

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

Online-only material: animations, color figures

1. INTRODUCTION

Coronal mass ejections (CMEs) are large-scale eruptive phenomena of the Sun and release a great deal of plasma and magnetic flux into the interplanetary space, consequently disturbing the space environment around the Earth (Gosling 1993; Webb et al. 1994). As identified in the white light disturbing the space environment around the Earth (Gosling and magnetic flux into the interplanetary space, consequently phenomena of the Sun and release a great deal of plasma (Illing & Hundhausen 1983; Chen 2011). The dark cavity is i.e., a bright leading front, a dark cavity, and a bright core caused by magnetic reconnection between the filament-carrying

1998; Lin et al. 2005) and their dynamic interactions can be

analyses reveal that magnetic flux ropes play a critical role in the

magnetic fields (Török et al. 2011; Jiang et al. 2013b). Detailed

analyses reveal that magnetic flux ropes play a critical role in the

formation and acceleration of CMEs (Patsourakos & Vourlidas 2012; Cheng et al. 2013).

Magnetic flux ropes can emerge directly from below the photosphere into the upper atmosphere. Using continuous vector magnetograms from the Hinode satellite, Okamoto et al. (2008) found that two abutting regions with opposite polarities connected by strong horizontal magnetic fields first grew and then narrowed, and the orientations of the horizontal fields along the polarity inversion line gradually changed from the normal polarity configuration to the inverse polarity one. Moreover, there were significant blueshifts at the strong horizontal magnetic field area. They suggested that they observed a magnetic flux rope that was emerging from the sub-photosphere. Helical flux ropes can also be formed through magnetic reconnection between two bundles of $J$-shaped loops which have been frequently observed as sigmoidal structures in the extreme ultraviolet (EUV) and X-ray lines (e.g., Canfield et al. 1999; McKenzie & Canfield 2008; Liu et al. 2010; Green et al. 2011). In simulations, magnetic reconnection between sheared loops are performed due to the imposed boundary movements, and thus can form magnetic flux ropes (Amari et al. 2000, 2003, 2011; Fan & Gibson 2003, 2004; Aulanier et al. 2010). Moreover, using nonlinear force-free field models, magnetic flux ropes can be reconstructed from vector magnetic field observations (Canou et al. 2009; Canou & Amari 2010; Guo et al. 2010, 2013; Jiang et al. 2010; Jiang et al. 2013a; Su et al. 2011; Inoue et al. 2013). After the launch of the Solar Dynamics Observatory (SDO; Pesnell et al. 2012), with the help of high-quality multi-wavelength data of the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012), many authors have reported the existence of flux ropes in their observations (Cheng et al. 2012; Zhang et al. 2012a; Li & Zhang 2013a, 2013b, 2013c; Patsourakos et al. 2013).

According to some previous observational studies, flux ropes are hot channels in the inner corona before and during solar eruptions (e.g., Zhang et al. 2012a; Cheng et al. 2012). They can be observed in high temperature lines (e.g., 131 Å), but are invisible in low temperature lines (e.g., 171 Å). Using differential emission measure analysis, Cheng et al. (2012) found that the temperature of twisted and writhed flux rope is higher than 8 MK. However, in the studies of Li & Zhang (2013a, 2013b) and Patsourakos et al. (2013), the flux ropes can be observed in all seven EUV lines formed from 0.05 MK to 11 MK. Specifically, for the two events investigated by Li & Zhang (2013b), the flux ropes were tracked by erupting material, leading to them becoming visible, while they could not be detected in all wavelengths at the pre-eruption stage.

The New Vacuum Solar Telescope (NVST; Liu & Xu 2011) is the most important facility of the Fuxian Solar Observatory in China. The diameter of NVST is 1 m and the pure aperture is
980 mm. One main goal of NVST is to image the Sun at high resolution. As one of the three channels (Hα, TiO, and G band) being used now, Hα is used to observe magnetic structures in the chromosphere. In this Letter, we investigate in detail a flux rope tracked by filament activation using NVST Hα observations for the first time. Combined with Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) and AIA data, we also study the activation and the movement of the filament, and present the corresponding appearance of higher layers revealed in different EUV passbands.

2. OBSERVATIONS AND DATA ANALYSIS

The data used in this study were obtained by the NVST in Hα 6162.8 Å from 02:00 UT to 03:30 UT on 2013 February 1. The Hα images are centered at N11◦E37′ with a field of view (FOV) of 159′′ × 159′′. The cadence of Hα observations is 12 s and the pixel size is 0′′162. In addition, we adopt the SDO/AIA multi-wavelength images observed from 02:00 UT to 03:30 UT and SDO/HMI line-of-sight magnetograms from 00:00 UT to 03:30 UT. From the 10 wavelengths of AIA, we choose the 304 Å, 171 Å, and 131 Å data with a pixel size of 0′′6 and a cadence of 12 s. The HMI magnetograms have a spatial sampling of 0′′5 pixel−1 and a cadence of 45 s. In addition, an NVST TiO image and an HMI intensitygram observed at 03:10 UT are adopted for the coalignment of observations from different instruments.

The Hα data are dark-current-subtracted and flat-field-corrected to Level 1, and then reconstructed to Level 1 + using the speckle masking method of Weigelt (1977). All the Hα images are coaligned with each other by applying the image cross-correlation method. The AIA images and HMI magnetograms are aligned using the standard routine aia_prep.pro, and then derotated differentially to a reference time (02:20 UT, 2013 February 1). The HMI intensitygram and NVST Hα image at 03:10 UT are coaligned with the TiO image by cross-correlating obvious features. Then all the AIA and HMI data are coaligned with the Hα images.

3. RESULTS

Figure 1 shows the overview of the whole FOV Hα image (left panel) and the simultaneous HMI magnetogram (right panel). The active region (AR) covered by the Hα observations is AR 11665 at N11◦E37′. The filament was located southeast of the main sunspot. The activation of the filament began at the northeast endpoint (outlined by square “1”) and then the filament material moved toward the southwest, tracking the pre-existing flux rope.

3.1. Activation of the Filament

At the area where the northeast end of the filament was located, the magnetic fields are shown in the top panels of Figure 2. The magnetic patches of positive and negative polarities moved toward each other (panel (a1)) and canceled gradually (panel (a2)). Using the inductive local correlation tracking method (Welsch et al. 2004), we calculate the horizontal velocities of the photospheric magnetic fields. In panel (a2), the horizontal velocities of the negative and positive polarities represented by the red and blue arrows indicate that the negative fields were encountering the positive ones, resulting in the cancellation between them. At 02:28:55 UT, the magnetic fields, especially the negative polarity, had significantly disappeared due to cancellation (see panel (a3)). The temporal evolution of the negative magnetic flux in the cancellation area is shown by the red curve in panel (a3). We can see that, from 00:13:55 UT to 02:28:55, the unsigned negative flux persistently decreased by 26% from 3.5 × 1019 Mx to 2.6 × 1019 Mx. During the cancellation process, the filament was activated, exhibiting as rising and expanding (panels (b1)–(b3)). At 02:29:19 UT, the fine structures of the filament can be easily identified and delineated by the dashed curves in panel (b3). The crossed threads indicate that the filament was twisted. The bottom panels are the simultaneous AIA 304 Å images corresponding to the Hα observations. At 02:20:19 UT, there was a dark feature (denoted by the black arrow in panel (c1)) at the filament location. Only about seven minutes later, a jet-like brightening appeared (denoted by the black arrow in panel (c2)). The brightening feature

Figure 1. NVST Hα image (left panel) and HMI line-of-sight magnetogram (right panel). Square “1” outlines the FOV of Figures 2(b1)–(c3), and rectangle “2” delineates the FOV of Figures 3 and 4. The blue curve in panel (b) is the contour of the filament during activation.

(A color version of this figure is available in the online journal.)
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expanding significantly in size, as shown in panel (c3). The jet-like brightening is commonly considered to be a signature of magnetic reconnection.

3.2. Filament Material Flow Tracking Out the Twisted Flux Rope

After activation, filament material flowed to the southwest direction and tracked pre-existing helical threads (see the left column of Figure 3 and Movie 1). At 02:35:22 UT, the filament material was mainly located near the northeast end (denoted by the arrow in panel (a)). About seven minutes later, the material moved farther (denoted by the arrow in panel (b)). At that moment, the twisted structure outlined by the dark material was more pronounced compared with that seven minutes previously. This part of the flux rope is outlined by the blue and red curves in panel (b). The material kept on flowing and reached the place denoted by the arrow (see panel (c)) at 02:55:57 UT. Another section of the flux rope was consequently tracked by the filament material, and is outlined by the blue and red curves. In order to show the entire flux rope whose different sections were filled with dark material at different moments, a composite Hα image is presented in panel (d). In panel (d), the sub-regions outlined by the two green quadrangles were observed at 02:39:12 UT and 02:42:50 UT, respectively. The rest of the background image was observed at 02:55:57 UT. The entire flux rope exhibits as a twisted structure formed by the dark filament material and connects the positive fields at the northeast and the negative fields at the southwest (the red and the blue contours in panel (d)). The approximate length of the twisted flux rope is 75 Mm. Combined with the observations at different times, the twist configuration of the flux rope tracked by the material flow along the helical threads is roughly sketched out and overlaid on the magnetogram obtained at 02:55:55 UT (see the blue and red thick curves in panel (e)). The left part of the flux rope was tracked at 02:42:50 UT, and the right part was tracked at 02:55:57 UT. Moreover, the right section of the flux rope can be well identified in the AIA 304 Å line (see the blue and green curves in Figure 4(b2)). We estimate that the twist of the flux rope is about $\pi$. To show the material flow clearly, a space–time plot along curve “A–B” marked in panel (b) is shown in panel (f). The plot reveals that the filament material moved from “A” to “B” and the mean velocity is 31.1 km $s^{-1}$.

3.3. Appearance in Multi-wavelength Images

We also examine the multi-wavelength images obtained by AIA and display the 304 Å, 171 Å, and 131 Å images before...
Figure 3. Panels (a)–(c): Hα images showing the process of filament activation. Panel (d) is a composite Hα image showing the whole flux rope tracked by the filament material, and panel (e) is the corresponding photospheric magnetogram. Panel (f) is the space–time plot showing the dark filament material flow along curve “A–B” marked in panel (b). The arrows in panels (a)–(c) denote the filament locations at different stages. The thin red and blue curves in panels (b) and (c) outline the left part and right part of the flux rope, respectively, while the thick curves in panel (e) display the whole twist configuration of the flux rope. The thin red and blue curves in panels (d) and (e) indicate the flux rope footpoints with positive and negative polarities, respectively.

(An animation of this figure is available in the online journal.)

and during the filament activation in Figure 4 (see also Movies 2, 3, and 4). At 02:20 UT, before the activation, the filament appeared as a thin dark structure in the Hα image (panel (a1)). In the 304 Å image (panel (b1)), there was a faint dark channel corresponding to the Hα filament, while there was no distinct dark or bright structure in the 171 Å (panel (c1)) and 131 Å (panel (d1)) images. At 02:46 UT, during the activation, the Hα filament expanded and contained many dark threads. In the 304 Å image, the flux rope shows up as a partial bright and partial dark structure, while in the 171 Å and 131 Å images there were bright structures at the Hα filament location.

The multi-wavelength cuts along slice “A–B” marked in Figure 4 are presented in the upper panels of Figure 5. The gray shadows mark the filament width identified in the Hα images. Panel (a) shows the cuts at 02:20 UT. In the 304 Å cut, the section corresponding to the filament, i.e., the gray section in the Hα cut, only shows a slightly lower emission while in the 171 Å and 131 Å cuts, there is no distinct high or low emission at the corresponding section. Panel (b) shows the cuts at 02:46 UT. The Hα cut shows that there are many dark structures (see the gray section). The cuts of 304 Å, 171 Å, and 131 Å show much higher emissions. Panel (b) shows a striking anti-correlation between the Hα and EUV lines, i.e., peaks of the former correspond to maxima of the latter and vice versa. As revealed by the Hα cut (black curve in panel (b)), four threads of the flux rope are well-resolved. In order to measure their width, we fit the sections of the four threads using Gaussian fitting. Their widths are 1.19 Mm, 0.62 Mm, 1.63 Mm, and 1.00 Mm. The average width of the individual threads is about 1.11 Mm.

As shown in panels (c1) and (c2) of Figure 4, there are many bright coronal loops overlying the filament location. To examine the influence of the filament activation on the coronal loops, a space–time plot along curve “C–D” (marked in Figure 4) is displayed in panel (c) of Figure 5. We can see that, from 02:00 UT to 03:30 UT, the coronal loops (bright structures) were quite steady.

4. CONCLUSIONS AND DISCUSSION

Based on the NVST Hα observations, we study in detail for the first time a flux rope which was tracked by filament activation. The filament material was initially located at one end of the flux rope, and the filament was activated due to magnetic field cancellation. The activated filament then rose and flowed along the flux rope, tracking the twisted structure.
The length of the flux rope is about 75 Mm, the average width of its individual threads is 1.11 Mm, and the estimated twist is $1\pi$. The tracked flux rope appeared as a dark structure in H$\alpha$ images, a partial dark and partial bright structure in 304 Å, and as bright structures in the 171 Å and 131 Å images. During this process, the overlying coronal loops were quite steady since the filament was confined within the flux rope and did not erupt successfully.

The bright core of a CME is thought to be cool filament matter that is suspended in the dips of the magnetic flux (e.g., Xia et al. 2012; Zhang et al. 2012b). As revealed by the event in the present study, the filament is closely related with the flux rope. It seems that the steady filament is only located at one section of the flux rope. However, instead of being suspended in the dips of the twisted magnetic flux, the filament material is confined within the helical threads. Only when the filament is activated can the filament material then flow easily along the threads and thus track the twisted structure of the flux rope. We support a picture of a pre-existing flux rope that was tracked by filament material activated by magnetic flux cancellation. However, since the observation duration of the present event is very short and the FOV is not large enough, we cannot exclude the formation of new flux rope due to flux cancellation, which is a popular mechanism for flux rope formation (e.g., van Ballegooijen & Martens 1989).

As studied by Zhang et al. (2012a) and Cheng et al. (2012), flux ropes could be clearly observed before and during eruptions and were only detected in hot temperature passbands. However, in this study, the flux rope was only observed during the filament activation instead of before the activation, which is similar to the study of Li & Zhang (2013b). The flux rope was tracked by the filament material and detected in both low temperature (e.g., 304 Å) and high temperature (e.g., 131 Å) lines, consistent with the results of Li & Zhang (2013a, 2013b). Moreover, our results show that there exists a striking anti-correlation between the H$\alpha$ and EUV lines (see Figure 5(b)). This could imply some mild heating of cool filament material to coronal temperatures during the filament activation (e.g., Landi et al. 2010). The heating should not be flare-like, reaching temperatures of 10 MK or more. This can be demonstrated by the almost identical cuts in the AIA 171 Å and 131 Å channels (the 131 Å channel bandpass, aside from containing a flare peak at around 10 MK).
also contains a “warm” peak at several 0.1 MK, similar to the main peak of the 171 Å channel).

In some previous studies (Li & Zhang 2013a, 2013b) and also this study, flux ropes were observed in different EUV lines and appeared as bright structures (see Figures 4(c2) and (d2)) or partial bright structures (see Figure 4(b2)), indicating the coexistence of hot and cool components in flux ropes. In contrast, the twisted flux rope in the Hα images consists of dark threads, which is different from its appearance in EUV images. For the flux ropes studied by Li & Zhang (2013b), the approximate length is 570 Mm. They measured the width of the individual threads of the flux ropes and found that the average width is 1.16 Mm. However, the length of the flux rope in the present study is only 75 Mm, much shorter than those studied by Li & Zhang (2013b). In the Hα images, the fine-scale threads can be generally resolved, and their mean width is determined to be 1.11 Mm, consistent with the result of Li & Zhang (2013b).

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Figure 5. Panels (a) and (b): relative brightness of the multi-wavelength cuts along slice “A–B” (see Figure 4) at 02:20 UT and at 02:46 UT, respectively. Panel (c): space–time plot along curve “C–D” marked in Figure 4. The red and blue curves overlaid on the black curve in panel (b) are Gaussian fits of four flux rope threads. (A color version of this figure is available in the online journal.)

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