A Magnetic Reconnection Event in the Solar Atmosphere Driven by Relaxation of a Twisted Arch Filament System

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Abstract

We present high-resolution observations of a magnetic reconnection event in the solar atmosphere taken with the New Vacuum Solar Telescope, Atmospheric Imaging Assembly (AIA), and Helioseismic and Magnetic Imager (HMI). The reconnection event occurred between the threads of a twisted arch filament system (AFS) and coronal loops. Our observations reveal that the relaxation of the twisted AFS drives some of its threads to encounter the coronal loops, providing inflows of the reconnection. The reconnection is evidenced by flared X-shape features in the AIA images, a current-sheet-like feature apparently connecting post-reconnection loops in the Hα + 1 Å images, small-scale magnetic cancelation in the HMI magnetograms and flows with speeds of 40–80 km s\(^{-1}\) along the coronal loops. The post-reconnection coronal loops seen in the AIA 94 Å passband appear to remain bright for a relatively long time, suggesting that they have been heated and/or filled up by dense plasmas previously stored in the AFS threads. Our observations suggest that the twisted magnetic system could release its free magnetic energy into the upper solar atmosphere through reconnection processes. While the plasma pressure in the reconnecting flux tubes are significantly different, the reconfiguration of field lines could result in transferring of mass among them and induce heating therein.

Key words: Sun: chromosphere – Sun: corona – Sun: filaments – magnetic reconnection

Supporting material: animations

1. Introduction

Magnetic reconnection, which can convert magnetic energy to heat and kinetic energy, is a fundamental process in the conductive plasma. It has been thought to be the major cause of various active phenomena on the Sun, from small-scale explosive events (e.g., Dere et al. 1991; Innes et al. 1997; Huang et al. 2014, 2015, 2017), Ellerman and IRIS bombs (e.g., Nelson et al. 2013; Peter et al. 2014; Tian et al. 2016; Zhao et al. 2017), bright points (e.g., Priest et al. 1994; Huang et al. 2012; Zhang et al. 2012; Mou et al. 2016), and jets (e.g., Antiochos et al. 1999; Tian et al. 2014; Sterling et al. 2015; Tian et al. 2017), to large-scale flares and CMEs (e.g., Lin & Forbes 2000; Chen et al. 2016; Ni et al. 2016; Zheng et al. 2016). In the solar observations, much evidence of magnetic reconnection, including plasma inflows/outflows, current-sheet structures, shocks, and plasma ejections and heatings, has been frequently reported. However, it is impossible to observe the full processes of magnetic reconnection on the Sun directly because of the limitations in the remote-sensing data. In the upper solar atmosphere, where the plasma beta is low, the geometry of magnetic field might be traced via the evolution of plasma structures, and thus allow one to infer the processes of magnetic reconnection. More details of magnetic reconnection and its applications can be found in the textbooks written by Priest & Forbes (2000) and Priest (2014).

Thanks to the high temporal and spatial resolution data obtained in the past decade, it has reported on a few sets of observations that directly verify the pictures of magnetic reconnection in the solar atmosphere. Using Atmospheric Imaging Assembly (AIA) and RHESSI data, Su et al. (2013) present the processes of magnetic reconnection in the corona that occurred during a modest flare. In their case, the magnetic reconnection occurred when a set of coronal loops were moving toward another set of loops and then were creating an X-shape geometry of coronal structures. Newly formed coronal loops and sources of hard X-ray emissions were observed after the disconnection of the X-shape structure, which demonstrated the occurrence of magnetic reconnection. Using Hα images taken by the New Vacuum Solar Telescope (NVST), Yang et al. (2015a) reported observations of magnetic reconnection in the chromosphere between two sets of anti-parallel filament threads, which also show clear responses in AIA EUV images. They observed that the approach of anti-parallel loops to form an X-shape geometry is the overtaking of magnetic reconnection. The plasma inflows/outflows of the reconnection processes were also clearly present in their data. With AIA and the twin spacecraft of STEREO, Sun et al. (2015) imaged an eruptive event in the solar atmosphere at three different viewing angles. They observed that the reconnection processes include a gradual approach of two groups of opposite directed loops, generating a quasi-separator and forming new loops. Their observations are thought to be consistent with the theoretical three-dimensional configuration of magnetic reconnection. In another case, Li et al. (2016) reported AIA observations of a magnetic reconnection event between an eruptive solar filament and nearby coronal loops. In their case, an X-shape structure was observed while the eruptive filaments ran into the coronal loops, and then bright current-sheet-like features were formed and bi-directional plasma ejections were produced. While analyzing a solar filament eruption observed by NVST and Solar Dynamics Observatory (SDO), Xue et al. (2016) observed the processes of magnetic reconnections between the filament and chromospheric fibrils. In their observations,
the filaments and fibrils are approaching (inflows), and then cusp structures and elongated bright structure (current sheet) are forming. The disconnection of the cusp structure forms new loops that are moving bi-directionally (outflows).

Magnetic reconnection in the solar atmosphere has been confirmed by previous observations, but the causes of the inflows that directly drive magnetic reconnection are rarely observed. In the present work, we present observations of small-scale active phenomena in the solar atmosphere that were caused by magnetic reconnection between threads of an arch filament system (AFS) and coronal loops. In this particular case, we will see that the inflows of the magnetic reconnection are driven by relaxation of the twisted AFS, and the reconnecting system has significantly flared up.

2. Observations

Our observing campaign was carried out on 2016 September 25 from 06:32 UT to 07:52 UT with a target of AR12597. The data were obtained by the ground-based NVST (Liu et al. 2014) that is one of the main observing facilities in the Fuxian Lake Solar Observing stations operated by the Yunnan Astronomical Observatories in China and the space-borne AIA (Lemen et al. 2012) and the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the SDO (Pesnell et al. 2012). The NVST data include series of Hα images taken at line center and offband at +1.0 and −1.0 Å with a bandpass of 0.25 Å. The cadence of each series is about 50 s after being reconstructed with Speckle techniques (Xiang et al. 2016 and references therein). The stabilization of image series is carried out by a fast sub-pixel image registration algorithm provided by the instrument team (Feng et al. 2012; Yang et al. 2015b). The spatial sampling of the Hα images is 0′′.17 per pixel. The AIA data primarily presented here include series UV/EUV images taken with the passbands of 1600, 304, 171, 193, 131, and 94 Å. The spatial resolution of the AIA data is 1′′.2, and the cadences are 24 s for the 1600 Å passband and 12 s for the rest. To study the evolution of the magnetic features associated with the active event, the HMI line-of-sight magnetograms with a cadence of 45 s and a spatial resolution of 1′′ are used.

The images from different instruments and passbands have been aligned with a principle of best cross-correlation between images of two passbands with the closest representative temperatures. The Hα images have also been rotated to fit into the Helioprojective-Cartesian coordinate system as used in the AIA and HMI data.

3. Results and Discussions

The general connectivities in the region are shown in Figure 1. In Hα images, we clearly observe a twisted AFS (Bruzek 1967; Frazier 1972; Su et al. 2017). While following the long-term evolution of magnetic features in the region (see the online animation associated with Figure 4), we found that this AFS is possibly formed by flux emergence with rotating motions in the footpoint polarities. The AFS has a serpentine geometry, which is consistent with common emerging flux tubes (see, e.g., Pariat et al. 2004, 2009; Schmieder et al. 2014). The east ends of the AFS threads appear rooted in a large patch of negative polarity, while the west ends are positive polarities at various locations (see the bottom panel of Figure 1). One set of the AFS threads (their west ends) is rooted in a patch of positive polarity at the location of about \( \text{solar}_x = 225'' \) and \( \text{solar}_y = -345'' \). These AFS threads will be lifted by the untwined motion of the system (see Section 3.1). This patch of positive polarity also surrounds a small patch of negative polarity that is the host of the east footpoints of coronal loops seen in the AIA 94 Å passband. The west ends of the coronal loops are situated in a large patch of positive polarity. The magnetic reconnection event appears to occur in this region between raising AFS threads and the coronal loops, and the reconnection processes are given in the following descriptions. Some threads of the coronal loops can be resolved earlier than 06:30 UT and are best visible in the AIA 94 Å passband. However, the threads involved in the active event (purple lines in Figure 1) appear to be obscured in the background emission at the early stage and could be resolved in the AIA 94 Å images only after 07:12 UT (see the animation).
The activities started at ~07:00 UT, while the western portion of the twisted AFS threads was apparently being untwined. The untwisting motion progresses southward, and it results in northward motion in the eastern portion of the AFS. The northward motion forces the AFS threads to move toward the pre-existing coronal loops. The flaring activity is observed around 07:15 UT when the AFS threads encountered the coronal loops. This indicates occurrences of magnetic reconnection between the AFS threads and the coronal loops. The resulting flaring hot loops last for relatively long periods of time in the AIA 94 Å images. The full evolution of the event can be viewed in the animation of Figure 1, and more details of the analyses are given in the following sections.
3.1. Relaxation of the Twisted AFS and Inflows of the Reconnection

In this section, we focus on the untwined activities of the twisted AFS occurring at the early stage of the event. Such untwined motions appear to drive the AFS threads moving toward the pre-existing coronal loops and thus provide the inflows of the magnetic reconnection. The activities of the AFS are shown in Figure 2 and the animation. The high-resolution H\textalpha{} images reveal AFS threads in very fine scale (∼0.5 in width). Well before the beginning of the AFS activity, we can see that the AFS threads are winding each other and forming a twisted AFS (Figure 2(a)).

Starting from about 06:40 UT, threads in the western portion of the AFS were intermittently untwined and moving southward (Figures 2(a)–(c)). The most clear untwined activities start from ∼06:54 UT and can be clearly seen after 06:58 UT. From the time–distance image, we found that this rapid untwined motion has an apparent acceleration of ∼15 m s\(^{-2}\) along the cut (Figure 2(d)). The acceleration could be result of the instability causing the untwining motion and/or the projection effects of the untwining circular motion. The present observations, however, do not allow us to distinguish the two processes.

After ∼07:00 UT, we observe that the threads in the eastern portion of the AFS appear to be lifted and start to move northward (Figures 2(e)–(g)). This northward motion appears to follow the untwined motion of the western portion of the AFS. At ∼07:14 UT, the site where these AFS threads contact the coronal loops (see Figure 1) start to flare up. This suggests that the magnetic reconnection begins. The speed of the northward lifted motion gives 5.5 km s\(^{-1}\) measured from the time–distance image (Figure 2(h)). This could be

Figure 3. Transformations of the connectivities in the region of interest seen in NVST H\textalpha{} line center ((a1)–(a3)), AIA 94 Å ((b1)–(b3)), and NVST H\textalpha{} + 1 Å ((c1)–(c3)). The images show the connectivities just before the reconnection (a1), (b1), (c1), during the reconnection (a2), (b2), (c2), and slightly after (a3), (b3), (c3). In the left column, the AFS threads that are being lifted are denoted by the blue line in panel (a1) (the lifting process is better seen in the animation associated with Figure 1), the coronal loops are marked by the purple line in panel (b1), and both are illustrated in panel (c1) with the black arrow indicating the northward motion of the AFS threads. The remarkable patterns observed during the reconnection are denoted in the images. The region enclosed by the black dashed lines in the AIA 94 Å image at 07:16:48 UT is used to produce light curves in Figure 5. ((d1)–(d3)) A cartoon showing the processes of the magnetic reconnection as observed.
taken as the apparent velocity of the inflows of the magnetic reconnection. The real velocity of the inflows should be larger if the projection effect is taken into account.

3.2. Geometry of the Magnetic Reconnection

While following the evolution of the active event, we observed some clear patterns that are representative of the magnetic reconnection processes. While the lifted AFS threads were clearly seen in Hα line center, this activity can also be observed in Hα offbands (see the animation associated with Figure 1). The evolution of the event is shown in Figure 3 and the animation. In the Hα line center, besides the activity of the AFS, the flaring at the site where the AFS threads encountered the coronal loops is also clearly observed (see Figures 3(a1)–(a3)). This flaring can be seen in all AIA passbands (as the 94 Å images show in Figures 3(b1)–(b3) and a few others show in the animation of Figure 1). The AIA images also reveal the X-shape geometry of the event (Figures 1 and 3). In the Hα line center and all AIA passbands, we can also observe clear flows along the coronal loops, which will be investigated in the next section.

Viewed in Hα + 1 Å, dark features can be clearly seen in the footpoints of the threads (Figures 3(c1)–(c3)). These features show motions toward the solar surface (see the animation of Figure 1), which are possibly the downflows in the AFS threads while they are being lifted. While the reconnection is initiated, the AFS threads remain dark in Hα, suggesting that the cool dense plasma in the AFS threads has not yet evacuated by the downflow. While the inferred reconnection site was flaring (∼07:16 UT), we observed a bright elongated feature in Hα + 1 Å. The size of the feature is about 3.5′ in length and 0.5′ in width. At the two ends of the bright elongated feature we observe a set of very large and a set of very small dark loop-like features (see Figure 3(c3)). These loops are very likely the post-reconnection loops, and thus the bright elongated feature could be representative of a current sheet forming in the reconnection. The set of small loops seen in the Hα + 1 Å images/animations include threads with various sizes shrinking back toward the solar surface, which are downflows and/or submerging loops.

These observations could be simplified as a cartoon shown in Figures 3(d1)–(d3). The small-scale loops that are observed in the Hα + 1 Å images could be produced by the reconnection processes and eventually submerged. The submergence of the small-scale loops could be observed as flux cancellations that are clearly seen in Figure 4. The larger-scale loops produced by the reconnection processes are hotter loops in the corona as viewed by AIA 94 Å channel. In the flux emerging region, large coronal loops could be formed through a series of reconnection above bald patches of the emerging serpentinite flux tubes (e.g., Pariat et al. 2004, 2009; Schmieder et al. 2004; Zhao et al. 2017). While magnetic reconnection above bald patches is assumed to be driven by line-tied motions, the untwisting motion of the AFS observed here could be an alternative mechanism to produce larger coronal loops. A question is whether the reconnecting AFS threads and coronal loops belong to the same emerging serpentinite flux tubes. The question cannot be fully answered with the present data; however, if they belong to the same emerging system, the coronal loops would require heating before the active event.

Because the AFS threads could contain much denser plasma then the coronal loops, the pressure gradient in the newly formed large-scale loops could be important and drive a plasma flow therein. The plasma density of the original coronal loops could increase according to this process and the newly formed loops could be flaring up as observed in AIA 94 Å channel. The newly formed loops could be then heated by the enthalpy carried in such a plasma flow. Furthermore, the magnetized plasma will certainly flow along magnetic field lines (J.-S. He et al. 2017, in preparation), while the component along the magnetic tension force defines the outflow of the magnetic reconnection. In this case, we clearly observe the plasma flow along the newly formed loops and will investigate in the next section.

3.3. Flows and Heating Resulting from the Reconnection

The flows along the coronal loops can be seen in all AIA channels and the Hα line center (see the animation of Figure 1). The flows appear as multiple bright blobs running along the coronal loops. The time–distance plot along the coronal loop taken with the AIA 171 Å channel (Figure 5(b)) presents a few interesting patterns: fast propagating “flows,” slow flows with multiple speeds, and remote brightening. The fast propagating “flows” appear to originate in the reconnection region. Their apparent speeds exceed 1000 km s⁻¹, which cannot be accurately measured with the current data, and it remains puzzling whether these are shock flows or the sudden appearance of coronal loops that were previously obscured by overlying structures. The apparent velocities of the slow flows measured from the three tracks of the multiple blobs give 36, 52, and 81 km s⁻¹. This speed differences could be interpreted as intermittent reconnection in different loop
threads that have different plasma and magnetic environments. The remote brightening away from the reconnection region is found in the tracks of the fast propagating “flows.” This brightening seems to be a secondary activity triggered by the reconnection event, and it also produces a slow flow with a speed of 64 km s\(^{-1}\), comparable to the slow flows produced in the reconnection site. If we understand the fast propagating “flows” as shock flows, the remote brightening could be a response of the exhaust region (Gosling et al. 2005; J.-S. He et al. 2017, in preparation) and the flow could be the result of heating therein. This, however, cannot be confirmed with the present data.

Besides the apparent flows, the reconnection has also flared up the loops that could be seen in all AIA channels. In Figure 5(c), we present the light curves taken from a small region crossing the flaring loops. The peaks in the light curves between 07:12 UT and 07:30 UT are representative of the activities resulting from the reconnection event. Multiple peaks
are clearly present in the light curves of the passbands of 1600, 304, 171, and 193 Å. Between any two passbands, these peaks in their light curves do not show any detectable delay. Why are these light curves well in-phase? One interpretation could be multi-thermal nature of the phenomenon. Alternatively, since the bandwidths of the AIA passbands are relatively large, these peaks could be mainly contributed by the continuum emission because of the density increase resulting from the running blobs. These peaks also correspond to small humps in the AIA 131 Å and 94 Å light curves, which are also contributed by continuum emissions. In this period of time, the AIA 131 Å and 94 Å light curves are closed to be single-peaked, especially the later one. This suggests that the intensity increase from the running blobs might not be the only major contributor and the thermal/heating effect could not be neglected. The major peak in the 94 Å light curve is present at 07:22:24 UT, while a small hump is present in the 131 Å light curve at 07:21:19 UT. Since the 131 Å passband has a large contribution from Fe XVIII (0.4 MK) emission (O’Dwyer et al. 2010), it suggests that this passband is representative of a cooler temperature than that of the 94 Å (Fe XVIII, 6.3 MK). This time delay (65 s) between the emissions in two passbands could be a result of the heating process.

The light curves and the animation of Figure 1 also reveal that the AIA 94 Å brightness of the coronal loops remains at a higher level for a relatively long period of time. It suggests that the post-reconnection loops are relatively stable in temperature around 6.3 MK. This is consistent with the visibility of the coronal loops in the AIA 94 Å channel during the pre-reconnection stage. Most plausibly, the brightening in the post-reconnection loops results from the heated filamentary plasmas that have been filled in the loops. Therefore, such reconnection processes could be a considerable approach for feeding mass and energy into coronal loops.

4. Conclusion

In this study, we present high-resolution observations of a magnetic reconnection event taken with NVST and SDO/AIA/ HMI. The magnetic reconnection occurred between coronal loops and threads of a twisted AFS. The NVST Hα images reveal that the inflows of the reconnections were driven by relaxation of the AFS. The untwined motions of the twisted AFS result in some of its threads encountering the coronal loops and providing inflows of the reconnection. This could be an approach of how random motions in the photosphere drive magnetic reconnection in higher solar atmosphere. The untwined motions of the AFS threads have an apparent acceleration of $\sim 15 \text{ m s}^{-2}$, and an apparent speed of 5.5 km s$^{-1}$ is found for the motions of the AFS threads encountering the coronal loops. Our observations reveal that the twisted magnetic system could release its free energy into the upper solar atmosphere through reconnection processes.

The observations reveal the rearrangement of connectivities in the region due to the reconnection event. An elongated current-sheet-like feature that is $3'5$ in length and $0'5$ in width is also observed with the Hα + 1 Å images. Small-scale magnetic cancelation is present below the inferred reconnection site. The reconnection heats the filamentary plasma and allows them to be released into the coronal loops. The flows along the loops driven by the reconnection appear to have various speeds in a range of about 40–80 km s$^{-1}$, possibly resulting from intermittent reconnection. The emission increase in the coronal loops could be the result of the filling-in filamentary plasma and/or heating. Therefore, these observations also suggest that reconfiguration of field lines in a solar magnetic system could result in transferring of mass between different loops and induce heating therein.

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