MAGNETIC RECONNECTION BETWEEN SMALL-SCALE LOOPS OBSERVED WITH THE NEW VACUUM SOLAR TELESCOPE

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ABSTRACT

Using the high tempo-spatial resolution \(\text{H}\alpha\) images observed with the New Vacuum Solar Telescope, we report solid observational evidence of magnetic reconnection between two sets of small-scale, anti-parallel loops with an X-shaped topology. The reconnection process contains two steps: a slow step with a duration of more than several tens of minutes, and a rapid step lasting for only about three minutes. During the slow reconnection, two sets of anti-parallel loops gradually reorient, and new loops are formed and stacked together. During the rapid reconnection, the anti-parallel loops approach each other quickly, and then rapid reconnection takes place, resulting in the disappearance of the former loops. In the meantime, new loops are formed and separate. The region between the approaching loops is brightened, and the thickness and length of this region are determined to be about 420 km and 1.4 Mm, respectively. During the rapid reconnection process, obvious brightenings at the reconnection site and apparent material ejections outward along reconnected loops are observed. These observed signatures are consistent with predictions by reconnection models. We suggest that the successive slow reconnection changes the conditions around the reconnection site and triggers instabilities, thus leading to the rapid approach of the anti-parallel loops and resulting in the rapid reconnection.

Key words: magnetic reconnection – Sun: chromosphere – Sun: evolution

Supporting material: animations

1. INTRODUCTION

Magnetic reconnection is a rearrangement of magnetic field topology and it is a fundamental physical process in conductive plasma. Magnetic flux is frozen in the plasma except in the small diffusion region where magnetic reconnection takes place (see Zweibel & Yamada 2009; Yamada et al. 2010). When magnetic field lines reconnect, magnetic energy is converted to the thermal energy and kinetic energy of plasmas. According to most theories, in the magnetic reconnection, there should exist a small dissipation region, topological changes, strong outflows, and other signatures of magnetic energy release, such as sudden brightenings (e.g., Parker 1957; Sweet 1958; Furth et al. 1963; Petschek 1964). Magnetic reconnection is often considered to be the mechanism driving energy release in solar flares, stellar flares, and many types of jets and outbursts (Rosner et al. 1985; Haisch et al. 1991; Yuan et al. 2009).

The evidence of magnetic reconnection has been observed in different types of solar events, such as flares, coronal mass ejections, and solar wind (Masuda et al. 1994; Gosling et al. 2007; Li & Zhang 2009). In particular, as one of the most energetic phenomena on the Sun, solar flares are widely considered to be caused by the successive reconnection of magnetic field lines in the corona. Many signatures of magnetic reconnection during flares have been observed, such as cusp-shaped structures above flare loops (Tsuneta et al. 1992), the transformation of “open” loops to closed post-flare ones (Zhang et al. 2013), and the reconnection inflows and outflows (Yokoyama et al. 2001; Innes et al. 2003; Asai et al. 2004; Lin et al. 2005; Takasao et al. 2012; Su et al. 2013). In situ measurements also revealed the occurrence of magnetic reconnection in the magnetosphere (Mozer et al. 2002; Phan et al. 2007; Xiao et al. 2006, 2007; Dunlop et al. 2011).

When the magnetic fields carried by solar wind travel outward from the Sun and interact with the planetary magnetic fields, current sheets are created and magnetic reconnection occurs. In laboratories, experiments dedicated to magnetic reconnection have been extensively carried out under controlled conditions (Bratenahl & Yeates 1970; Yamada et al. 1997). With intense lasers in the laboratory, Zhong et al. (2010) reconstructed a magnetic reconnection topology which is similar to that in solar flares. In their experiment, loop-top-like X-ray source emission and outflows were successfully reproduced and the diffusion regions were also identified.

As the primary observing facility of the Fuxian Solar Observatory in China, the New Vacuum Solar Telescope (NVST; Liu et al. 2014), a vacuum telescope with a clear aperture of 985 mm, is designed to observe the Sun at high temporal and spatial resolutions. The \(\text{H}\alpha\) line, which is formed in the chromosphere, is quite useful to investigate the fine structures of dynamic events. In this Letter, using the NVST \(\text{H}\alpha\) images, we report a well-observed process of magnetic reconnection with two steps between small-scale loops in the chromosphere, which provides observational evidence of magnetic reconnection, as predicted in theories.

2. OBSERVATIONS AND DATA ANALYSIS

On 2014 February 3, the NVST was pointed to AR 11967 with a field of view (FOV) of 151” × 151”. The NVST data used in this study were obtained in the \(\text{H}\alpha\) 6562.8 Å line from 05:49:52 UT to 09:10:01 UT. The \(\text{H}\alpha\) images have a cadence of 12 s and a pixel size of 0′′.163. The data are calibrated from Level 0 to Level 1 with the dark current subtracted and the flat field corrected, and then the calibrated images are reconstructed to Level 1+ by speckle masking (Weigelt 1977;
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Figure 1. (a and b) HMI line-of-sight magnetogram and AIA 171 Å image displaying the overview of AR 11967. (c1–e1) NVST Hα, AIA 171 Å, and 131 Å images showing the expanded view of the area outlined by the square in panel (a). (c2–e2) Similar to panels (c1)–(e1), but for the area outlined by the square in panel (d1) three minutes later. The red square in panel (c2) outlines the FOV of Figure 2. The black and white curves in panel (c1) are the contours of the positive and negative magnetic fields at levels of 220 G and −220 G, respectively. The red and green dotted curves outline two sets of loops involved in reconnection identified in the Hα image.

Lohmann et al. 1983). In addition, the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) multi-wavelength images and the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012; Schou et al. 2012) line-of-sight magnetograms from the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) are also adopted. We choose the AIA 171 Å and 131 Å images to study the process of magnetic reconnection at different temperatures. The AIA images were obtained from 05:30 UT to 09:30 UT on February 3 with a pixel size of 0.6" and a cadence of 12 s. We use the HMI line-of-sight magnetograms observed from 00:00 UT on February 1 to 00:00 UT on February 5. They have a spatial sampling of 0.5 pixel−1 and a cadence of 45 s. The AIA and HMI data are calibrated to Level 1.5 by using the standard procedure aia_prep.pro, and rotated differentially to a reference time (07:15:00 UT on February 3). Then, we co-align the SDO and NVST images using the cross-correlation method with specific features.

3. RESULTS

Magnetic reconnection took place at the edge of AR 11967 (see Figure 1(a)). At 07:15 UT, there was a small X-shaped structure at the reconnection site in the AIA 171 Å image (outlined by the green square in panel (b)), which can be identified more clearly in the expanded view (panel (d1)). In the AIA 131 Å band, this structure was also conspicuous (panel (e1)). The X-shaped structure observed in the EUV images was located between two set of loops (outlined by the dotted curves) identified in the Hα image (panel (c1)). It should be mentioned that as noted by Yang et al. (2014), magnetic loops
can be indicated by the dark fibrils in Hα images. Here, the reconnection occurred between the loops outlined by the dotted curves. The left loops connected the positive sunspot and the nearby negative fields, and the right loops linked the negative sunspot with the nearby small-scale fields of positive polarity. Three minutes later, the brightness of the X-shaped structure increased significantly in the 171 Å and 131 Å images (see panels (d2) and (e2)), and there were also some brightenings and changes of the Hα fibrils (panel (c2)). The reconnection process can be divided into two steps: a slow step followed by a rapid one.

### 3.1. Step One: Slow Reconnection

In the area outlined by the red square in Figure 1(c2), slow reconnection was observed for several tens of minutes, and part of the reconnection is shown in the accompanying animation. Figures 2(a)–(c) display the formation of a small loop during the slow reconnection process. In our observations, the high-density and low-temperature plasmas may not be sufficiently heated, i.e., some plasmas are heated to high temperatures while others are still at low temperatures. Therefore, newly formed loops can be outlined by either bright or dark features in the outflow regions. In the ellipse region (panel (a)), a loop being formed could be identified at 06:45:10 UT (denoted by the red arrow in panel (b)). At 06:46:23 UT, the newly formed loop was much more clear and reached to a lower site (denoted by the red arrow in panel (c)). In the difference image (panel (d)) between 06:44:10 UT and 06:46:23 UT, there exists a dark structure as outlined by the ellipse, indicating the formation of a dark loop.

Along slices “A–B,” “C–D,” and “E–F” marked in panel (c), we make three space–time plots and display them in panels (e)–(g), respectively. We can see that there are many bright features which seem to be the heated blob-like plasmas, moving from “B” to “A” and from “D” to “C” (as indicated by the dotted lines in panels (e) and (f)). The average velocity of the apparent motion of bright features both along “B–A” and “D–C” is about 17 km s\(^{-1}\). In panel (g), the line denoted by arrow “M” indicates the quick downward motion of the newly formed loop shown in panel (b). After the quick motion, the new loop continued to move downward slowly, as denoted by arrow “N.” As the reconnection went on, more and more new loops were formed and stacked together (see the other blue and red dotted lines in panel (g)). The boundaries of the loop stack are marked by the dashed lines.

### 3.2. Step Two: Rapid Reconnection

Figure 3 shows the process of the rapid reconnection (see also the accompanying animation). The loops involved into the reconnection are labeled “L1” and “L2,” as denoted by the arrows in panels (a) and (b). Before the occurrence of the rapid
reconnection, the two sets of loops were approaching each other. At 07:17:03 UT, the distance between loops “L1” and “L2” was much shorter than that at 07:13:50 UT. Then loops “L1” and “L2” continued to move toward each other and eventually interacted. At 07:18:04 UT, an obvious brightening (denoted by the arrow in panel (c)) can be observed. The two short parallel lines mark the reconnection region of the interacting loops. The inserted blue curve shows the brightness along slice “M–N,” and the overlaid red curve is the Gaussian fit of the brightness profile. The width of the bright interaction region is given by the width of the Gaussian, which is found to be 420 km. The length (presented by the length of the parallel lines) of the interaction region is about 1.4 Mm. At 07:18:52 UT, both loops “L1” and “L2” apparently broke (as denoted by the two arrows in panel (d)). Only 13 s later, a new loop had formed, as denoted by the arrow in panel (e). At 07:20:05 UT, the new loop was more conspicuous (indicated by the lower arrow in panel (f)) and another new loop (denoted by the higher arrow) can also be observed. Then the two new loops retracted and moved away from each other (panels (g) and (h)). The difference image between 07:17:03 UT and 07:23:31 UT is displayed in panel (i). In the difference image, the locations of the former loops “L1” and “L2” are white structures, which is caused by the disappearance of loops “L1” and “L2,” while the black structures coincided with the locations of loops “L3” and “L4,” indicating the formation of new Hα loops.

During the rapid reconnection process, the most remarkable changes are the disappearance of loops “L1” and “L2” and the formation of loops “L3” and “L4.” To clearly display these changes with time, we make two space–time plots along slices “A–B” and “C–D” which are marked in Figure 3, and display them in Figures 4(b) and (c). When the reconnection began, we can find apparent ejections of bright features outward along “E1–F1,” “F3–E3,” and “F4–E4,” and dark features along “E2–F2” (marked in Figure 3) from the reconnection site. It should be noted that, as displayed in Figure 3(f), the background of slice “E2–F2” is so bright that the expected bright moving features could not be distinguished, while some dark features can be identified. Then we derive four space–time plots along the four slices and display them in Figures (d)–(g). We also measure the brightness variations of the Hα, 171 Å, and 131 Å images in the region outlined by the rectangle in Figure 3(h), and the corresponding light curves are shown in Figure 4(a). Before 07:16:27 UT (t1, indicated by the leftmost vertical line...
in Figure 4), loop “L1” approached loop “L2” slowly with an average velocity of 1.9 km s$^{-1}$ (see panel (b)). While after $t_1$, loop “L1” moved toward loop “L2” quickly with a velocity of 15.4 km s$^{-1}$, and they contacted each other at 07:17:28 UT ($t_2$, the second vertical line). Before $t_2$, there was no obvious variation for the brightness in each wavelength (panel (a)), and no significant moving feature along different directions (panels (d)–(g)). After $t_2$, when loop “L1” began to interact with loop “L2” (panel (b)), the brightness in each wavelength increased rapidly (see panel (a)). At and around the reconnection region, the brightenings in the Hα, 171 Å, and 131 Å lines can be found in panels (a) and (c) and in the animation accompanying Figure 3. All three light curves reach the maximum at the same time, i.e., 07:18:52 UT ($t_3$ in panel (a)). Also at that time, loops “L1” and “L2” disappeared (see panel (b)) and loops “L3” and “L4” began to form (panel (c)). From $t_3$, the light curves exhibit a decreasing trend (panel (a)), and the newly formed loops separated quickly with a separation velocity of 42 km s$^{-1}$ (panel (c)). When the reconnection ended at around 07:20:54 UT ($t_4$), the brightenings in multi-wavelengths almost disappeared (see panels (a) and (c) and the animation accompanying Figure 3). The separation velocity also slowed down to about 5.2 km s$^{-1}$ (as indicated by the dotted curves in panel (c)). In panels (d)–(g), moving features only can be identified after $t_2$, i.e., the start time of the rapid reconnection. The apparent motions of small features along all of the four directions can be observed, and they have a comparable velocity of about 50 km s$^{-1}$.

4. CONCLUSIONS AND DISCUSSION

Using the NVST Hα images with high tempo-spatial resolutions, we have observed signatures of magnetic reconnection between two sets of small-scale loops. The reconnection process can be divided into two steps: a slow reconnection with a duration of several tens of minutes and a rapid reconnection lasting for only about three minutes. During the slow reconnection process, two sets of anti-parallel loops gradually reconnected, and new loops were formed and stacked together. During the rapid reconnection, the anti-parallel loops moved toward each other quickly, and then the rapid reconnection took place, resulting in the disappearance of the former loops. In the meantime, new loops were formed and separated. During the rapid reconnection process, we have observed obvious brightenings at the reconnection site and apparent ejections of bright or dark features outward along the newly formed loops with an average velocity of about 50 km s$^{-1}$.

According to the observational results, we sketch a series of illustrations (see Figure 5) to demonstrate the reconnection process. Loops “L1” and “L2,” which will be reconnected, move toward each other to a very close distance, as shown in panels (a) and (b). When the loops are close enough (about 420 km determined in this study), magnetic reconnection between them takes place. At the reconnection site, brightenings are observed and, along different directions, apparent ejections of small features outward from the reconnection site can be observed (see panel (c)). Then, two new loops (“L3” and “L4”) are formed while the former loops (“L1” and “L2”) have disappeared, and the newly formed loops begin to separate (panels (d) and (e)). The common features of most reconnection theories include the changes of magnetic topologies and the release of magnetic energy (Parker 1957; Sweet 1958; Petschek 1964; see the review by Yamada et al. 2010). The topology changes are mainly the break of inflowing anti-parallel loops.
and the formation of new loops. When the loops reconnect in the diffusion region, magnetic energy is released, thus heating the plasmas. The plasma pressure is raised, and a great deal of energy is converted to the kinetic energy. Therefore, the plasmas are brightened and expelled. All the above features, which should appear in the magnetic reconnection, have been observed in the present study. Our results are highly consistent with the common models of magnetic reconnection.

Until now, much evidence of magnetic reconnection on the Sun has been reported by many authors (Tsuneta et al. 1992; Yokoyama & Shibata 1995; Yang et al. 2011; Takasao et al. 2012; Cirtain et al. 2013). However, most of these observational signatures of magnetic reconnection have been found in solar eruptive events. According to the popular flare model, a rising flux rope in the corona stretches the overlying magnetic fields, and a current is created between the anti-parallel field lines, and a current is created between the anti-parallel field lines and magnetic reconnection occurs (Shibata et al. 1995; Tsuneta 1996; Lin & Forbes 2000). In the present study, the magnetic reconnection is observed in a relatively stable X-shaped structure in the chromosphere compared with that observed during the flares in the corona. Previous observations have revealed that the current sheets have a thickness $>10^4$ km and a length of more than several hundreds of millimeters (Ciavarella & Raymond 2008; Lin et al. 2009). In the present study, the thickness and length of the brightening region between the approaching loops are only about 420 km and 1.4 Mm, respectively. It is likely that a current sheet is embedded inside this structure of the enhanced emission. If so, the current sheet determined in this study is much smaller than those previously reported.

In our observations, the reconnection process includes two steps, i.e., a slow reconnection followed by a rapid reconnection. The slow reconnection lasted for several tens of minutes, while the rapid step only took about three minutes. We suggest that the continual slow reconnection changed the conditions around the reconnection region which triggered instabilities and led to rapid approaching of the anti-parallel loops, thus resulting in the rapid reconnection. A similar scenario was also proposed in the flare events by Wang & Shi (1993). They suggested that there is a slow reconnection between two topologically separated loops in the lower atmosphere and the slow reconnection triggers the fast reconnection in the corona which is responsible for large solar activities.

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