Observational Evidence of Magnetic Reconnection Associated with Magnetic Flux Cancellation

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Abstract

Using high spatial and temporal data from the Solar Dynamics Observatory (SDO) and the Interface Region Imaging Spectrograph (IRIS), several observational signatures of magnetic reconnection in the course of magnetic flux cancellation are presented, including two loop–loop interaction processes, multiple plasma blob ejections, and a sheet-like structure that appeared above the flux cancellation sites with a Y-shaped and an inverted Y-shaped end. The IRIS 1400 Å observations show that the plasma blobs were ejected from the tip of the Y-shaped ends of the sheet-like structure. Obvious photospheric magnetic flux cancellation occurred after the first loop–loop interaction and continued until the end of the observation. Complemented by the nonlinear force-free field extrapolation, we found that two sets of magnetic field lines, which revealed an X-shaped configuration, aligned well with the interacted coronal loops. Moreover, a magnetic null point was found to be situated at about 0.9 Mm height, which was right above the flux cancellation sites and located between the two sets of magnetic field lines. These results suggest that the flux cancellation might be a result of the submergence of magnetic field lines following a magnetic reconnection that occurs in the lower atmosphere of the Sun, and the ejected plasma blobs should be plasmoids created in the sheet-like structure due to the tearing-mode instability. This observation reveals a detailed magnetic field structure and a dynamic process above the flux cancellation sites and will help us to understand magnetic reconnection in the lower atmosphere of the Sun.

Key words: Sun: activity – Sun: atmosphere – Sun: magnetic fields

Supporting material: animations

1. Introduction

Magnetic reconnection is a process by which magnetic field lines with antiparallel components are brought together in a current sheet or at a magnetic null point, where they break up and reconnect to form new magnetic field lines (Priest & Forbes 2000; Yamada et al. 2010). During this process, magnetic energy is thereby converted into plasma kinetic and thermal energy. It is widely accepted that magnetic reconnection is the cause of various types of solar activities, such as solar flares (Shibata 1996a), coronal mass ejections (CMEs; Lin & Forbes 2000), filament eruptions (Chen & Shibata 2000; Shen et al. 2012; Zhou et al. 2017), jets (Shibata et al. 1996b; Jiang et al. 2013), explosive events (Innes et al. 1997), and coronal bright points (Priest et al. 1994). To date, many signatures that are probably related to magnetic reconnection have been reported, including hot cusp-shaped structures (Tsuneta et al. 1992), loop-top hard X-ray sources (Masuda et al. 1994; Sui & Holman 2003), reconnection inflows (Yokoyama et al. 2001; Li & Zhang 2009; Su et al. 2013; Sun et al. 2015; Yang et al. 2015) and outflows (Asai et al. 2004; Savage et al. 2010; Liu et al. 2013; Chen et al. 2016), current sheets (Webb et al. 2003; Lin et al. 2005; Liu et al. 2010; Xue et al. 2016; Yan et al. 2018), plasmoid ejections (Shibata et al. 1995; Nishizuka et al. 2010; Takasao et al. 2012), loop–loop interactions (Sakai & de Jaeger 1996; Li et al. 2014), and drifting pulsating structures observed in radio waves (Kliem et al. 2000; Ning et al. 2007). Through decades of observations, much evidence for the reconnection scenario has been obtained. However, most evidence was indirect and was detected in the solar corona, and direct observational evidence that characterizes the reconnection in the lower atmosphere has been poorly reported.

Magnetic flux cancellation, which observationally describes the mutual disappearance of converging magnetic patches of opposite polarities in the photospheric longitudinal magnetograms (Livi et al. 1985; Martin et al. 1985), is considered to be evidence of magnetic reconnection occurring in the lower atmosphere of the Sun (Priest et al. 1994). A “U-loop emergence” scenario and an “Ω-loop submergence” scenario were proposed by Zwaan (1987) to account for magnetic flux cancellation. Two unconnected magnetic patches of opposite polarities could build up a connection with magnetic reconnection during flux cancellation (Wang & Shi 1993); whether a “U-loop emergence” scenario or an “Ω-loop submergence” scenario could contribute to flux cancellation depends on the height that reconnection is initiated. The “U-loop emergence” will be dominant during the cancellation when magnetic reconnection takes place below the photosphere. On the contrary, the “Ω-loop submergence” will be dominant when magnetic reconnection occurs above the photosphere. By investigating the evolution of the photospheric and chromospheric magnetograms simultaneously, Harvey et al. (1999) proposed strong evidence that suggests an “Ω-loop submergence” scenario at flux cancellation sites. The transverse magnetic field and the Doppler velocity field around flux cancellation sites are usually utilized to study flux cancellation events. During and after flux cancellation, the horizontal field at the flux cancellation sites are usually found to be enhanced significantly (Wang & Shi 1993; Yang et al. 2016).
However, Wang & Shi (1993) implied that the change of the horizontal field at flux cancellation sites could not fit the quite popular view of interpreting flux cancellation mentioned above. They put forward that the association of flares to flux cancellation seems to represent the coupling of a slow reconnection in the lower atmosphere to a fast reconnection in the upper atmosphere. Chae et al. (2004) and Iida et al. (2010) verified that both redshifts and a strong horizontal field at flux cancellation sites support the “U-loop submergence” scenario. Zhang et al. (2009) reported extremely large Doppler blueshifts at flux cancellation sites and interpreted the cancellation as a “U-loop emergence.” Kubo & Shimizu (2007) found that there are both blue and redshifts at flux cancellation sites, indicating that magnetic reconnection between the converging magnetic patches occurs at multiple locations with different heights. Nevertheless, Yang et al. (2009) investigated the emerged dipoles in a coronal hole and found that the submergence of the emerged original loops can also lead to flux cancellation. Therefore, to understand the physical nature of flux cancellation, the detailed magnetic structures above the flux cancellation sites in the upper atmosphere need to be investigated in detail.

In this paper, with high-resolution observations acquired by the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) and the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014), we present clear and direct observational evidence showing magnetic reconnection associated with photospheric magnetic flux cancellation. This is an exemplary event to show in detail the relationship between magnetic reconnection and photospheric magnetic flux cancellation. In Section 2, we describe the detailed observations and methods that we used. The results are shown in Section 3. The conclusion and the discussion are given in Section 4.

2. Observations and Methods

The detailed reconnection process associated with magnetic flux cancellation on 2015 January 9 was captured by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the SDO. The AIA instrument observes full-disk images of the Sun in 10 ultraviolet (UV) and extreme ultraviolet (EUV) wavelengths with a spatial resolution of 1″5 (0′′6 pixel−1) and a high cadence of up to 12 s. In this study, we mainly used the Level 1.5 images observed in 304 Å (Fe x, 0.05 MK), 171 Å (Fe XI, 0.6 MK), 94 Å (Fe XVII, 7 MK), and 1600 Å (C IV + cont., 0.01 MK). The HMI measures the full-disk continuum intensity images and the line-of-sight (LOS) magnetic field for the Fe I absorption line at 6173 Å with a spatial sampling of 0′′5 pixel−1 and a cadence of 45 s. The AIA data used in this study were taken between 2015 January 9 19:30 UT and 21:30 UT, and the HMI data were taken between 2015 January 9 18:00 UT and 22:00 UT. This event was also observed by the IRIS slit-jaw imager (SJI) in 1400 Å during two periods (19:03–20:00 UT; 20:40–21:32 UT). The time cadence and the spatial resolution of the SJIs are 9 s and 0′332 pixel−1, respectively. Using full-disk, soft X-ray (SXR) images from the X-ray Telescope (XRT) on board the Hinode satellite (Kosugi et al. 2007), the associated coronal structures were also examined. All images were then aligned by differentially rotating to a reference time (2015 January 9 20:40 UT).

In addition, the continuous photospheric vector field (Turmon et al. 2010), which has a pixel scale of about 0′′5 pixel−1 and a cadence of 12 minutes, in the so-called HMI Active Region Patches (HARPs) region is also provided by the HMI. The very fast inversion of the Stokes vector algorithm (Borrero et al. 2011) is utilized to compute the vector field data, and the minimum energy method (Metcalfe 1994; Metcalfe et al. 2006; Leka et al. 2009) is used to resolve the remaining 180° azimuth ambiguity. In order to remove the projection effect, the HARPs vector field data are remapped to a Lambert cylindrical equal-area projection and then transformed into standard heliographic spherical coordinates. To obtain the magnetic field topology of the flux cancellation event, we carried out a nonlinear force-free field (NLFFF) extrapolation to reconstruct the coronal fields. To perform the NLFFF extrapolation, the “weighted optimization” method (Wheatland et al. 2000; Wiegelmann 2004) is used. Before the extrapolation, a preprocessing procedure, which drives the observed non-force-free data toward suitable boundary conditions for a force-free extrapolation (Wiegelmann et al. 2006), is applied to the bottom boundary vector data.

3. Results

3.1. Cancellation of the Photospheric Magnetic Field

On 2015 January 9, AR NOAA 12257 was located at about N5° W29° with a β magnetic configuration. As shown in Figure 1(a), the magnetic flux cancellation region of interest is enclosed by a red rectangle, and the detailed magnetic flux cancellation process is shown in the zoomed-in view in panels (b)–(f). The canceling magnetic flux patches “p” and “n1” existed from the beginning of the observations, and a transverse field, which was emanated from p and connected to n1, indicates that there was a connectivity between p and n1 (panel b). Note that flux emergence happened before 20:00 UT (panels b–c). The positive flux patches of the emerged flux were mixed with p, while its negative flux patches were composed of “n2” and “n3.” In particular, during its emerging process, n3 moved toward and merged with n1. As a result, the flux density and the area of p and n1 increased, although the flux cancellation occurred between p and n1. A remarkable decrease in the flux density and the area of n1 was observed from 20:00 UT to 21:40 UT (panels d–g), and the unsigned negative flux dropped by 8.0 × 1019 Mx, corresponding to an approximate flux cancellation rate of 4.8 × 1019 Mx h−1. At the end of the observations, n1 almost disappeared (panel f). Different from many flux cancellation events observed before (Wang & Shi 1993; Yang et al. 2016), the change to the transverse field was not obvious, and the flux cancellation was accompanied by the flux emergence in the same region. Therefore, it is difficult to confirm which mechanism could account for the flux cancellation. Investigating the coronal structures and activities above the flux cancellation sites may shed light on the understanding of the physical nature of the flux cancellation.

3.2. The First Loop–Loop Interaction Process

By scrutinizing the observations from the SDO/AIA and IRIS, two loop–loop interaction processes and two plasma blob ejection processes were found to be closely related to the flux cancellation. The first loop–loop interaction process is displayed in Figure 2 (see also the animation of Figure 2). Just prior to the interaction, at about 19:40 UT, an IRIS 1400 Å image shows the general appearance of the two sets of
interacting loops, “L1” and “L2” (panel (a)). Remarkably, as shown by the contoured HMI magnetogram, L1 connected the positive flux patch “p1” to a negative flux patch n1, whereas L2 connected the positive flux patch p to a negative flux patch n2. Thus, the adjacent endpoints of L1 and L2 were co-spatial with the canceling flux patches, p and n1. By about 19:43 UT, the loop–loop interaction started, and a set of rising loops, “L3,” which connected p1 to n2, was formed (panels (b)–(c)). At the same time, four footpoint brightenings, which were exactly coincident with the footpoints of L1 and L2, appeared (panels (c) and (f)). Note that L1 could not be detected by the AIA observations before the interaction. However, after the interaction, L1 and L3 were clearly presented by the AIA 94 Å and SXR images, implying that L1 and L3 might be heated during the interaction and that the connectivity of L1 was partially changed. Furthermore, a set of loops, “L4,” which connected p to n1, was also observed by the AIA 94 Å and SXR observations. These observations indicate that magnetic reconnection may take place between L1 and L2. The reconnection changed the connectivity of L1 and L2, resulting in the formation of L3 and L4.

3.3. Successive Ejection of Plasma Blobs from the Flux Cancellation Sites

It is widely accepted that plasma blob ejections and magnetic flux cancellation are evidence of magnetic reconnection. Currently, plasma blob ejections are frequently observed in different types of reconnection events; however, successive plasma blob ejections associated with flux cancellation have rarely been observed. In our observations, from 20:25 UT to 20:40 UT—about half an hour after the first loop–loop interaction—we found that a chain of plasma blobs were ejected from the flux cancellation sites successively. The detailed ejection process is displayed by the selected AIA 304 Å images in Figure 3 (see also the animation of Figure 3). Before the initiation of the plasma blob ejection at about 20:21 UT, two adjacent bright streaks were found to be rooted in the flux cancellation patches p and n1, respectively (panel (a)).
Those bright streaks may represent two sets of loops with opposite directions. In particular, the bright streak rooted in n1 had the same connectivity as L1. Hereafter, we call the loops, which connect p1 to n1, L1. As soon as those bright streaks approached each other, the plasma blobs, as indicated by the arrows, were ejected from the flux cancellation sites, propagated along L1, and finally stopped at the far ends of L1 (panels (b)–(d)). The plasma blob ejections observed here are quite similar to those reported by Zhang et al. (2016). Generally, those ejected blobs are believed to be formed by a tearing-mode instability occurring in a current sheet structure (Furth et al. 1963; Shibata & Tanuma 2001). Thus, our observations may also imply that magnetic reconnection and a tearing process may occur in a current sheet between the two bright streaks.

3.4. The Second Loop–Loop Interaction Process

Immediately after the plasma blob ejection, an intense activity occurred (see also the animation of Figure 4). This activity is quite obvious in the AIA 304 Å images in Figures 4 (a)–(c). At about 20:40 UT, when the plasma blob ejections stopped, a compact brightening appeared at the flux cancellation sites (panel (a)). Simultaneously, relatively weak remote brightening appeared at the location corresponding to the negative footpoint of L1. Subsequently, from 20:42 UT to 20:50 UT, mass flows, which originated from the compact brightening region, spread along two arched trajectories in opposite directions (panels (b)–(c)). Careful inspection of the AIA 171 Å difference image (panel (d)) revealed that mass flows moved along the two arched trajectories and traced out the appearance of two sets of loops, L1 and “L5.” Supplemented by the contoured HMI magnetogram, one can see that the adjacent ends of L1 and L5 are rooted in the canceling flux patches p and n1 (panel (d), respectively). Moreover, the negative footpoint of L5 is rooted in a plage region (labeled as “n”). These observational signatures may suggest that the compact brightening and the plasma flows are the results of the interaction occurring between L1 and L5.

3.5. Successive Ejection of Plasma Blobs from a Sheet-like Structure Observed by IRIS

At 21:03 UT, about 13 minutes after the second loop–loop interaction, a particularly remarkable sheet-like structure with a Y-shaped end and an inverted Y-shaped end appeared above the flux cancellation sites (Figure 5(a)). Afterward, multiple plasma blobs likely stemmed from the tip of the Y-shaped end and ejected successively along L1. This is evidenced by the sequential IRIS 1400 Å images in Figures 5(a)–(d) (see also the animation of Figure 5). The zoomed-in view (panel (e)) displays the morphology of the sheet-like structure more clearly. This sheet-like structure, which is similar to the sheet-like structure reported by Singh et al. (2012) and Li et al. (2016), lasted about 8 minutes and finally disappeared at about 21:11 UT. Singh et al. (2012) and Li et al. (2016) suggested that this structure should be a current sheet. In our observations, however, there is no direct evidence to confirm that this sheet-like structure is a current sheet apart from its morphology. Fortunately, the vector field data obtained by the HMI are conducive to extrapolating and reconstructing the coronal magnetic field over the flux cancellation region and are helpful for us to understand the event.

3.6. Magnetic Topology of the Flux Cancellation Region

With the aid of the HMI vector magnetograms, we carried out an NLFFF extrapolation to reconstruct the coronal magnetic field of the flux cancellation region. Figures 5(g)–(f) show the consequence of the NLFFF extrapolation. The red and blue lines, which are traced from photospheric flux patches p and n1, delineate the extrapolated coronal field lines. It is evident that the red and blue field lines reveal an X-shaped configuration. Previous theoretical and observational studies (Priest et al. 1994; Jiang et al. 2017) suggested that such a
configuration should contain a magnetic null point, which is in favor of the reconnection. By employing a trilinear null finding method (Haynes & Parnell 2007) to scan the NLFFF-modeled field, we indeed find that a magnetic null point is located between the red and blue field lines (as indicated by the green arrows in Figures 5(f)–(g)). The magnetic null point is situated at a height of \(\sim 0.9\) Mm right above the flux cancellation sites. It separates the red and blue field lines into two distinct connections: one connects p1-n1, and the other connects p-n. From Figures 4(d) and 5(g), the red and blue field lines were found to match strikingly well with L1 and L5. The magnetic field near an X-type null point would collapse and evolve to a field with a current sheet (Priest & Forbes 2000). In our event, the X-shaped magnetic field configuration may imply that the magnetic null point is an X-type null point. Moreover, the spatial location of the magnetic null point and the observed sheet-like structure is almost overlapping. Thus, our observations strongly suggest that the reconnection occurring between L1 and L5 was triggered at the magnetic null point, and the magnetic field near the null point collapsed during the reconnection, resulting in the formation of a current sheet. Accordingly, we speculate that the sheet-like structure observed by the IRIS may represent a current sheet. Tearing-mode instability (Furth et al. 1963; Priest & Forbes 2000) may further develop in the sheet-like structure, creating multiple plasma blobs.

4. Conclusion and Discussion

In this paper, we present two unambiguous loop–loop interaction processes and two plasma blob ejection processes, which are closely related to magnetic flux cancellation in the same location. The first loop–loop interaction took place between a set of pre-existing loops (L1) and a set of emerging
small loops (L2). Half an hour after the first loop–loop interaction, a chain of plasma blobs were ejected from the flux cancellation sites and spread along L1. Immediately after the plasma blobs ejection, the second loop–loop interaction was initiated. Compact brightening that resided at the flux cancellation region and mass flows that spread in opposite directions were observed. The mass flows traced out the interacting loops (L1) and another set of loops (L5). Following the second loop–loop interaction, IRIS 1400 Å images show that a sheet-like structure with a Y-shaped end and an inverted Y-shaped end appeared above the flux cancellation sites, and a chain of plasma blobs were ejected successively from the tip of the Y-shaped ends and moved along L1. It is evident from HMI vertical magnetograms that obvious flux cancellation occurred after the first loop–loop interaction and continued until the end of the observation. Supplemented by an NLFFF extrapolation, two sets of coronal field lines, which align with L1 and L5 very well, are extrapolated. Moreover, a magnetic null point was found to be located between the two sets of coronal field lines. Based on the observations, we suggest that the first loop–loop interaction may be due to the magnetic reconnection between L1 and L2, while the second loop–loop interaction may be due to the magnetic reconnection between L1 and L5. Furthermore, tearing-mode instability might be further developed during the course of the interaction between L1 and L5 in a current sheet, creating the ejected plasma blobs. Our observations not only provide evidence of a submergence of the \( \Omega \)-loop following magnetic reconnection at the flux cancellation sites, but also shed new light on magnetic reconnection in the lower atmosphere of the Sun.

Previous theoretical models have suggested that there should be a magnetic null point and a current sheet around the flux cancellation sites in the upper atmosphere (Priest et al. 1994; von Rekowski et al. 2006). Numerous observations mainly focused on the change of the velocity field and the transverse field around flux cancellation sites, while a direct observation of the detailed structure and the dynamic process above the flux cancellation sites is extremely rare. In our event, the loop–loop interactions should be the evidence of magnetic reconnection, and the sheet-like structure revealed by the IRIS 1400 Å images...
should be a current sheet that resides above the flux cancellation sites. Moreover, the extrapolated coronal field lines and the detected magnetic null point may be further evidence that magnetic reconnection would occur above the flux cancellation sites. These results are comparable with the theoretical models of Zwaan (1987) and Priest et al. (1994) and reveal the detailed magnetic field structure above the flux cancellation sites. According to the theoretical models of Zwaan (1987) and Priest et al. (1994), we can naturally explain our observations as follows: as L1 contacts L2 or L1 contacts L5 in a magnetic null point, the magnetic field near the null point would collapse and evolve into a field with a current sheet (as shown by the sheet-like structure in Figure 5(e)). Magnetic reconnection between L1 and L2 or between L1 and L5 happened at the null point or inside the current sheet, leading to the formation of a set of long loops that connects their far ends of the interacted loops and a set of short loops (L4) that connects their adjacent ends. Caused by magnetic tension, L4 further submerged and resulted in the flux cancellation. The theoretical models of Zwaan (1987) and Priest et al. (1994) are suitable for interpreting the two loop–loop interactions and the associated flux cancellation. However, the detailed dynamic processes above the flux cancellation sites (for instance, the plasma blob ejections) need further investigation.

An important observational signature in our event is the ejection of plasma blobs. As mentioned above, these plasma blobs were ejected from the tip of the Y-shaped ends of the sheet-like structure, and the extrapolated coronal field lines reveal an X-shaped configuration containing a magnetic null point. Accordingly, we inferred that the ejected plasma blobs should be plasmoids, which are created by the tearing-mode instability occurring in the current sheet (Furth et al. 1963; Bhattacharjee et al. 2009). Previously, plasmoids are frequently observed in the coaxial bright rays that appear in white-light images in the wake of the CMEs (Lin et al. 2005), in the current sheet of solar flares (Takasao et al. 2012; Kumar & Cho 2013), and in some jets (Singh et al. 2012; Zhang et al. 2014, 2016; Shen et al. 2017; Zhang & Zhang 2017). More recently, a detailed formation and evolution process of plasmoids was reported by Li et al. (2016). They found that the plasmoids appeared within the current sheets at the interfaces between an erupting filament and nearby coronal loops and propagate bidirectionally along them and then further along the filament or the loops. In the lower atmosphere, continuous ejections of plasmoids from the flux cancellation sites have seldom been observed directly. Through the numerical simulation method, Ni et al. (2015) simulated a magnetic reconnection process in a partially ionized solar chromosphere and confirmed that fast magnetic reconnection mediated by tearing-mode instability could be indeed triggered. In particular, by analyzing the Si IV line profiles obtained from the flux cancellation sites of some small-scale reconnection events, Innes et al. (2015) suggested that a fast reconnection proceeding via tearing-mode instability may play a central role in those small-scale reconnection events. In the present case, the continuous ejection of plasma blobs above the flux cancellation sites from the tip of the Y-shaped ends of the sheet-like structure are the direct observational evidence that support the idea of Innes et al. (2015). This observation displays the detailed dynamic process above the flux cancellation sites and has a significant physical implication for the magnetic reconnection in the lower atmosphere of the Sun.

Before the first loop–loop interaction, we notice that there is connectivity between the canceling flux patches p and n1, and there is a lack of velocity field information around the flux cancellation sites. Moreover, the new magnetic flux emerged beside the canceling flux patches, and the emerged positive flux patches mixed with p, while parts of its negative flux patches moved and merged with n1. Thus, it is difficult to absolutely rule out the possibility that the submergence of the original loops that connect p to n1 may also contribute to the magnetic flux cancellation. However, it is clear from the time profile of the flux changes (Figure 1(g)) that obvious flux cancellation was observed after the first loop–loop interaction and continued till the end of the observation. This time interval covers the second loop–loop interaction process and the two plasma blob ejection processes (as indicated by the pink shadow in Figure 1(g)). Therefore, our observations support a causal relationship among the loop–loop interactions, the plasma blob ejections, and the flux cancellation.

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