Reconfiguration of the coronal magnetic field by means of reconnection driven by photospheric magnetic flux convergence

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ABSTRACT

Context. Magnetic reconnection is commonly believed to be responsible for flare-like events and plasma ejections in the solar atmosphere, but the field-line reconfiguration observed in association with magnetic reconnection has rarely been observed before.

Aims. We attempt to reconstruct the configuration of the magnetic field during a magnetic reconnection event, estimate the reconnection rate, and analyze the resulting X-ray burst and plasma ejection.

Methods. We use the local-correlation-tracking (LCT) method to track the convergence of magnetic fields with opposite polarities using photospheric observations from SOT/Hinode. The magnetic field lines are then extrapolated from the tracked footpoint positions into the corona, and the changes in field-line connections are marked. We estimate the reconnection rate by calculating the convective electric field in the photosphere, which is normalized to the product of the plasma jet speed and the coronal magnetic field strength inside the inflow region. The observed X-ray burst and plasma ejection are analysed with data from XRT/Hinode and TRACE, respectively.

Results. We find that in this reconnection event the two sets of approaching closed loops were reconfigured to a set of superimposed large-scale closed loops and another set of small-scale closed loops. Enhanced soft X-ray emission was seen to rapidly fill the reconnected loop after the micro-flare occurred at the reconnection site. Plasma was ejected from that site with a speed between 27 and 40 km s⁻¹. The reconnection rate is estimated to range between 0.03 and 0.09.

Conclusions. Our work presents a study of the magnetic field reconfiguration owing to magnetic reconnection driven by flux convergence in the photosphere. This observation of the magnetic structure change is helpful for future diagnosis of magnetic reconnection. The results obtained for the reconnection rate, the X-ray emission burst, and the plasma ejection provides new observational evidence, and places constraints on future theoretical study of magnetic reconnection in the Sun.

Key words. Sun: flares – Sun: activity – magnetic fields – Sun: corona – Sun: photosphere

1. Introduction

It is now widely believed that magnetic reconnection plays a crucial role in the energy conversion occurring in a solar flare, solar jet, coronal bright point (CBP), or transverse wave excitation. Thus, these dynamic emission phenomena are often used to identify and diagnose magnetic reconnection in the solar atmosphere. For the solar flare, typical signatures of magnetic reconnection are identified on the basis of loop observations, e.g., the cusp-shaped loop after a flare (Tsuneta et al. 1992) or the hard X-ray sources visible at the loop apex (Masuda et al. 1994). The ubiquity of small-scale magnetic reconnection is suggested by various observations, e.g., of chromospheric anemone jets (Shibata et al. 2007) and of bi-directional plasma jets seen in Si IV, which are indicative of magnetic reconnection in the transition region (Innes et al. 1997), or of CBPs for which the coronal field topologies were reconstructed from potential-field extrapolation and seem to suggest that magnetic reconnection plays an important role in powering the BP emission (Longcope 1998; Brown et al. 2001; Tian et al. 2008; Pérez-Suárez et al. 2008). Magnetic reconnection is also found to be responsible for the excitation of transverse waves, e.g., Alfvén or kink waves (He et al. 2009).

To study the evolution of magnetic fields in the photosphere is another way of diagnosing the magnetic reconnection process, in addition to analyzing emission phenomena above the photosphere. Magnetic reconnection in the solar atmosphere can be

driven by three different types of motion in the photosphere. The first is the convergence of two magnetic flux tubes approaching each other with opposite polarities (Priest et al. 1994), the second is the shearing of two flux tubes, which may also trigger magnetic reconnection (Moore et al. 2001), and the third is the interaction between an emerging bipolar flux tube and a pre-existing flux tube (Yokoyama & Shibata 1995). Cancellation of separate magnetic features (CMF) in the photosphere is considered to be evidence of magnetic reconnection driven by flux convergence (Priest et al. 1994). However, we may also expect convergence and the apparent cancellation of magnetic fields for a sinking closed loop, which just submerges itself beneath the photosphere and does not require magnetic reconnection above it. Therefore, one needs to study the topological changes of magnetic structures to distinguish magnetic reconnection from other possibilities. The force-free-field extrapolation method seems appropriate for the reconstruction of the magnetic field outside the small reconnection region (Demoulin et al. 1994). The reconstructed three-dimensional (3D) magnetic reconnection structures in the geo-magnetosphere, together with the *in-situ* measurements, have also helped us to identify some physical processes at the heart of reconnection, e.g., electron trapping around the magnetic null (He et al. 2008a,b).

The reconnection rate is a critical parameter for magnetic reconnection, since it determines the speed at which magnetic

flux is transported to the reconnection site and the consequent energy release rate. The magnetic reconnection rate has been estimated well for reconnection events occurring in the Earth's magnetosphere owing to in-situ measurements of the inflow and outflow speeds (He et al. 2008a). However, the reconnection rate in the solar atmosphere has rarely been addressed, because of the difficulty in determining inflow and outflow speeds from remote-sensing observation. Nevertheless, the presence of reconnection inflow in the solar atmosphere was inferred from the two approaching legs of a cusp-shaped structure by some authors (Yokoyama et al. 2001; Lin et al. 2005). However, approaching legs may be caused by the relaxation of the reconnected closed loop rather than a reconnection inflow, if the observation slit is not placed exactly across the x-point. Isobe et al. (2005) assumed that the convective electric field in the photosphere is equal to the electric field in the reconnection current sheet, and thus estimated the reconnection rate. However, the outflow speed in Isobe et al. (2005) was estimated roughly on the basis of the magnetic field strength and the plasma number density in the corona.

In this paper, we investigate the reconfiguration of the coronal magnetic field due to magnetic reconnection. As a result of magnetic reconnection, an X-ray emission burst (micro-flare event) and a plasma ejection were produced. The X-ray emission enhancement in the reconnected loop occurred immediately after the micro-flare event. A jet launch was observed. We also estimate the reconnection rate in two alternative ways, which are based on the observations of the inflow speed of the convex segments on the approaching field lines, the outflow speed of the jet, the converging motion of the magnetic fields in the photosphere, and the coronal magnetic field in the inflow region.

2. Data calibration and alignment

The data analysed here were obtained from XRT/Hinode, TRACE, and SOT/Hinode on February 21, 2007. We used the standard programs “XRT_prep.pro” and “XRT_jitter.pro” to calibrate the XRT data set. The program “TRACE_prep.pro” was adopted to calibrate the TRACE observational data. The SOT Stokes *IV* data was initially calibrated with “FG_prep.pro”. This type of *V* image has been used to analyse the dynamic motions of magnetic elements in the photosphere (Otsuji et al. 2007). In a way similar to Chae et al. (2007) and Chifor et al. (2008), we use the ratio V/I to calculate the line-of-sight magnetic field B_{LOS} in a sub-area around the reconnection site. This B_{LOS} magnetogram is found to be consistent with the scaled *V* image, which is scaled to the MDI magnetogram, assuming that the magnetic flux observed by MDI is equal to that observed by SOT. The reason for this consistency is that the sub-area of the *I* image around the reconnection site is quiet and does not contain any sunspot. Because the edge of the *I* image is of poor quality, we adopt the scaled *V* image to represent the B_{LOS} magnetogram of the whole area. We thus obtain the magnetogram of B_z , which is perpendicular to the solar surface, and assume that magnetic field in the photosphere is vertical everywhere. The edge of the *I* image was blemished by an air bubble in the tunable filter. We improved the *I* image by using a median-filtering method to filter out the blemish background, producing a new *I* image with clear granule patterns. The entire area of the B_{LOS} magnetogram, which is recalculated based on the ratio V/I in the whole area, appears similar to the scaled *V* image. Hence, we can use the scaled *V* image for magnetic field extrapolation in this case study.

To coalign the images from different instruments, all images are first rotated to a common time selected to be 02:00 UT, and the XRT-images and the TRACE-images are then shifted to

match their emission feature with the magnetic feature in SOT-images by applying a cross-correlation technique.

3. Analysis results

3.1. X-ray burst and plasma ejection

In Fig. 1, we show the X-ray burst (micro-flare) and the plasma ejection, both of which are interpreted as evidence of magnetic reconnection. The panels in the left column of Fig. 1 illustrate the evolution of the micro-flare event observed by XRT with the Al-mesh filter. Because of the high count rates at the micro-flare site, the corresponding part on the CCD is saturated. Magnetic reconnection is believed to be responsible for this micro-flare. At 06:41:22 UT, the loop on the left side of the micro-flare site has an emission enhancement, which indicates that many X-ray emitting thermal electrons fill the loop. The wavelength of the soft X-rays recorded by XRT falls in the range of [6, 60] Å, which corresponds to an energy range of [0.2, 2] keV. In the literature, the X-ray emission of energy higher than 10 keV is interpreted as non-thermal emission, and the emission below 10 keV as being thermal (Landini et al. 1972). We therefore consider the X-ray emitting electrons observed by XRT to be thermal electrons. This brightening might be powered by heat conduction released from the reconnection site, local dissipation in the elongated current sheet, or evaporation of the heated chromospheric plasma.

The plasma ejection observed by TRACE in Fe IX/x (171 Å) is illustrated in the right panels of Fig. 1. The jet-head motions are identified from the nose-appearances at the intensity contours, as indicated by the blue arrows in Fig. 1. The ejection initiated at 06:36:11 UT on the left side of the reconnection site (see the small noses at the black and blue contours, indicated by the blue arrow in the figure). The apparent speeds of the jet head in the projected plane during three time periods, [06:34:30, 06:36:11], [06:36:11, 06:37:52], and [06:37:52, 06:41:57] are thus estimated to be 26, 33, and 30 km s⁻¹, respectively, based on the observed jet-head positions at different times. The true speed of the jet head will be given after matching the emission pattern with the reconstructed magnetic field.

3.2. Connectivity reconfiguration of magnetic field structures

The coronal magnetic field of the reconnection event can be constructed by using the force-free-field extrapolation method (e.g., Demoulin et al. 1994; Jing et al. 2009). Here we use the linear force-free-field extrapolation method proposed by Seehafer (1978), which was adopted by Marsch et al. (2004) and Marsch et al. (2008) to reconstruct the closed loops in solar active regions. We set the force-free-field parameter α to be $-9.4 \times 10^{-3} \text{ Mm}^{-1}$ by comparing by eye the projection of the extrapolated magnetic field structure and the TRACE emission pattern during observations. To reconstruct the magnetic field structure so that it approximates the observed coronal loops more accurately, stereoscopic observations of coronal loops would be needed prior to the implementation of the loop-distance optimization method to determining a α (Wiegmann & Neukirch 2002). Figures 2a and b show the extrapolated magnetic field lines with the SOT-magnetogram and TRACE-image as the background, respectively.

To study the connectivity variation in the magnetic field lines, we track the motion of their footpoints by using the local-correlation-tracking (LCT) method (November & Simon 1988).

Fig. 1. *Left:* soft X-ray burst observed by XRT with the Al-mesh filter. The large area with white pixels in every panel is a sign of saturation of the CCD-pixels due to strong radiation. The different levels of radiation intensity ranging from weak to strong are outlined in green, red, and blue colour. *Right:* the launch of a jet observed by TRACE in the Fe IX/X (171 Å) line. The green, red, blue, and black contours mark the different levels of radiation intensity from weak to strong. The blue arrows point at the rising noses of the contours, indicating the jet-head positions.

Figure 3a shows the positions of the footpoints at the beginning of the motion tracking (05:00:40 UT) period. The footpoints were chosen based on the criteria that the local correlation coefficients of all of these footpoints are at all time steps larger than 0.6. Figure 2b shows the footpoint positions at 07:07:42 UT, after a two-hour period of motion.

We then extrapolated the magnetic field lines starting from the tracked footpoints. This is illustrated in the six panels of Fig. 4. The magnetic field lines in green and white emphasize the changes in the field-line connectivity and indicate the field reconfiguration. The reconnection scenario, in which two sets of approaching closed loops are reconnected to form a set of superimposed field lines and another set of closed loops beneath, is thus directly apparent in these observations. Our results are consistent with the theoretical models of reconnection driven by magnetic flux convergence (Priest et al. 1994; von Rekowski et al. 2006). From the evolution of the pair of white-colored field lines shown in Fig. 4, we can infer in detail how the magnetic field lines become reconnected. Their footpoints in the photosphere converge slowly toward the magnetic neutral line, and consequently move their convex segments in the corona, which convect relatively quickly toward the reconnection region through the convective electric field mapped from the

photosphere. The convected convex segments are then reconnected after being pushed into the weak-magnetic-field reconnection region.

3.3. Reconnection rate

In a way similar to Isobe et al. (2005), we estimate the reconnection rate by means of the electric field, E_{cs} , in the reconnecting current sheet, which can be approximated by the convective electric field corresponding to the converging motion in the photosphere. This approximation is appropriate based on the assumption that the electric potential drop in the coronal inflow region can be mapped from the photosphere along the equal-electric-potential magnetic field lines. Since the converging motion occurs mainly in x -direction (see Fig. 3), E_{cs} is mainly in y -direction, and can be written as

$$E_{cs} = V_{in} B_{cr} \simeq V_{foot,x} B_{foot,z}, \quad (1)$$

where V_{in} is the inflow speed, B_{cr} is the coronal magnetic field strength in the inflow region, $V_{foot,x}$ is the x -component of flow speed for the footpoint, and $B_{foot,z}$ is the z -component of magnetic field strength for the footpoint.

Fig. 2. *Top:* map of B_z at 06:39:41 UT superimposed with extrapolated magnetic field lines, which are denoted in blue or red to represent the field lines reaching the height of 60 Mm or not. The end point of a blue line is cut at the height of 60 Mm, which makes the blue lines appear to be cut off randomly in the projection plane. *Bottom:* the background image is observed by TRACE at 06:37:52 UT. The red and blue lines are the same as those in the top panel. Green and blue contours surround the areas with strong positive and negative magnetic fields, respectively.

Fig. 3. *Top:* sub-area of a magnetogram around the micro-flare (reconnection) site at 05:00:40 UT. Red crosses are placed at the positions of footpoints, from which field lines are to be traced. *Bottom:* sub-area of a magnetogram around the reconnection site at 07:07:42 UT. Red crosses represent the positions of footpoints after a two-hour period of motion starting from 05:00:40 UT.

The non-dimensional reconnection rate is thus estimated by the electric field ratio to be

$$M_A = \frac{E_{cs}}{V_A B_{cr}} \simeq \frac{V_{foot,x} B_{foot,z}}{V_A B_{cr}}, \quad (2)$$

where V_A is the Alfvén speed outside the reconnection region. Here we assign V_A to be the jet flow speed. To obtain the true jet flow speed in 3D space, we estimate the jet height positions by matching the jet structure with the extrapolated magnetic field structure. The true jet flow speeds during the three time periods [06:34:30, 06:36:11], [06:36:11, 06:37:52], and [06:37:52, 06:41:57], are thus estimated to be 27, 40, and 32 km s⁻¹, respectively. Here we define V_A to be the mean value of these jet flow speeds, which is 33 km s⁻¹, and B_{cr} is taken to be 16 Gauss according to the extrapolation results. We can calculate the value of $V_{foot,x} B_{foot,z}$ at every pixel affected by converging motion, and then average these values to obtain the representative mean value.

We estimate the non-dimensional reconnection rate at every time step, and plot the profile in Fig. 5a. The non-dimensional reconnection rate is in the range [0.03, 0.09]. Figure 5b shows the time variation of the total X-ray radiation in the area previously shown in Fig. 1. The jet travelling distance is plotted as a function of time in Fig. 5c.

We also directly calculate the reconnection rate based on V_{in}/V_A , since V_{in} can be estimated from the motion of the convex segments on the white-colored field lines in Fig. 4. The convex segment is found to travel a distance of about 6000 km in a period of about 1 h, thus yielding a V_{in} of 1.7 km s⁻¹. The reconnection rate is calculated to be about 0.05 using this second method (dashed line in Fig. 5a), which is compatible with the value derived using the first. In theoretical studies, the magnetic topology, i.e., the separatrix surface or the separator field line,

Fig. 4. Variations of the extrapolated magnetic field lines in a time period from 05:07:42 to 06:39:41 UT (a)–(f)). These field lines are traced from the footpoint positions, which are shown in Fig. 3a at 05:00:40 UT. A set of green lines and a pair of white lines represent the magnetic field lines as they are reconfigured due to magnetic reconnection. Yellow and blue arrows around the position at $[x = 18, z = 8]$ Mm represent the plasma inflow and outflow direction just outside the reconnection region.

has also been used to calculate the reconnection rate in complex 3D magnetic fields related to the possibility of recursive reconnection (Parnell et al. 2008).

4. Summary and discussion

We have directly confirmed the occurrence of coronal magnetic field reconnection that is driven by photospheric flux convergence. Our empirical evidence is based on the analysis of the magnetic field connectivity and its reconfiguration during reconnection. According to our field reconstruction results, two sets of closed loops approach each other and then reconnect, thereby forming a set of large-scale closed loops superimposed on the reconnection region and another set of small-scale closed loops beneath that region. By involving coronal field extrapolation and reconstruction, this approach reduces the uncertainty caused by merely using observations of flux convergence and cancellation in the photosphere.

We have also discovered some plasma properties related to magnetic reconnection that are driven by flux convergence. A soft X-ray burst ($T > 3.0 \times 10^6$ K) was emitted from energized electrons occurring at the reconnection site, where however no obvious emission blink in Fe IX/X ($T \sim 1.0 \times 10^6$ K) occurred. This difference between X-ray and EUV emission suggests that the magnetic reconnection heated the plasma to a temperature higher than 3.0×10^6 K. There was a rapid X-ray emission enhancement in the reconnected loop on the left side of the reconnection site, which might be indicative of a heating of the loop by thermal conduction, a dissipation in the current sheet along the loop, or an evaporation of heated chromospheric plasma. Plasma ejection along the left reconnected loop is also observed in Fe IX/X. The jet speed in 3D space is calculated. A left-right asymmetry of X-ray emission and jet launch around the reconnection site is found, which may be related to an asymmetry in the sizes of the closed loops approaching from two sides.

The reconnection rate has been estimated in two ways. The first way is based on the following three observational

Fig. 5. *Top:* temporal evolution of the reconnection rate as estimated by means of the photospheric convection electric field, the outflow speed, and the coronal magnetic field strength in the inflow region. The level of reconnection rate estimated directly based on V_{in}/V_A is labelled with a dashed line. *Middle:* time variation of the total X-ray radiation in the area shown in Fig. 1. *Bottom:* travelling distance of the jet head as a function of time.

parameters: the convective electric field in the photosphere, the outflow speed, and the coronal magnetic field strength in the inflow region. The reconnection rate is found to reach its maximum value (~ 0.09) about 10 min ahead of the X-ray burst and the jet launch. There may be a time lag between the release of magnetic energy in the outflow region and the piling up of magnetic energy in the inflow region. The second way, $M_A = V_{in}/V_A$, yields a consistent value of about 0.05. In our case studied, the X-ray burst and jet eruption are isolated events. Since we cannot diagnose the micro-physics in the inner reconnection region, the detailed trigger mechanism remains unclear. The creation of anomalous resistivity, which occurs when an enhanced current density reaches instability threshold, might be the triggering cause (Büchner et al. 2004). We speculate that the peak in the reconnection rate 10 min ahead of the X-ray burst is not statistically significant, since this peak is insignificant compared to others in the profile of the reconnection rate.

This work sheds new light on and will alleviate future observational diagnosis of magnetic reconnection in the Sun, and provides deeper theoretical insight into magnetic reconnection in the solar atmosphere. In the future, we will require magnetograms with higher cadence to study the highly dynamic reconfiguration of coronal magnetic field structures. The density and temperature around the reconnection site are also certainly needed to diagnose the plasma via multi-wavelength observations, and to estimate quantitatively the energy transferred during magnetic reconnection.

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