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Evidence of two-stage magnetic reconnection in the 2005 January 15 X2.6 flare

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ABSTRACT

We analyze in detail the X2.6 flare that occurred on 2005 January 15 in the NOAA AR 10720 using multiwavelength observations. There are several interesting properties of the flare that reveal possible two-stage magnetic reconnection similar to that in the physical picture of tether-cutting, where the magnetic fields of two separate loop systems reconnect at the flare core region, and subsequently a large flux rope forms, erupts, and breaks open the overlying arcade fields. The observed manifestations include: (1) remote Hα brightenings appear minutes before the main phase of the flare; (2) separation of the flare ribbons has a slow and a fast phase, and the flare hard X-ray emission appears in the later fast phase; (3) rapid transverse field enhancement near the magnetic polarity inversion line (PIL) is found to be associated with the flare. We conclude that the flare occurrence fits the tether-cutting reconnection picture in a special way, in which there are three flare ribbons outlining the sigmoid configuration. We also discuss this event in the context of what was predicted by Hudson et al. (2008), where the Lorentz force near the flaring PIL drops after the flare and consequently the magnetic field lines there turn to be more horizontal as we observed.

1. Introduction

There are a number of models that can explain some aspects of observed properties of solar flares. One way or the other, most flare models still contain a key component of Kopp–Pneuman's original theory to explain two-ribbon flares: flare ribbon emissions are due to magnetic reconnection of overlying arcade fields that are opened by the erupting flux ropes, and the ribbons move away from the magnetic polarity inversion line (PIL) as successive reconnections occur at higher and higher latitudes (Kopp and Pneuman, 1976). This and modified models of this kind tend to predict that photospheric magnetic fields do not change after flares. However, more and more evidence demonstrates that photospheric magnetic fields can have permanent changes after flares (Cameron and Sammis, 1999; Kosovichev and Zharkova, 2001; Wang et al., 2002, 2004a,b; Liu et al., 2005; Sudol and Harvey, 2005). It is noticeable that building on Kopp–Pneuman scenario, many recent models of flares/CMEs exhibit signatures of two-stage magnetic reconnection. Taking the well received break-out model (Antiochos et al., 1999) as an example, the flares/CMEs occur in multipolar topologies in which reconnection between a sheared arcade and neighboring flux systems triggers the eruption, and this initial external reconnection could be related to remote brightenings (Liu et al., 2006). Another instance is the tether-cutting model, which was proposed by Moore and Labonte (1980) and further elaborated by Moore et al. (2001). This is one of the very few models that imply that the near-surface magnetic fields could have flare-associated changes, and it also proposes a two-step reconnection leading to flares/CMEs. At the eruption onset, the first stage reconnection near the solar surface produces a low-lying shorter loop across the PIL and a longer twisted flux rope connecting the two far ends of a sigmoid. The second stage reconnection begins when the formed twisted rope subsequently becomes unstable and erupts outward, distending the larger scale envelope field that overarches the sigmoid. The opened legs of the envelope field subsequently reconnect back to form an arcade structure and the ejecting plasmoid escapes as a CME. The tether-cutting model may potentially explain other observational facts including: (1) transverse magnetic fields at flaring PIL increase rapidly following flares (Wang et al., 2004a); (2) penumbral decay occurs in the outer border of δ configuration, indicating that the peripheral field lines turn more vertical after flares (Liu et al., 2005; Wang et al., 2004b); (3) multiwavelength including hard X-ray signatures of preflare activities develop prior to the impulsive phase of flares (Fárník et al., 2003 and references therein); (4) hard X-ray (HXR) images show a change of the source morphology from a confined footpoint structure to an elongated ribbon-like structure after the flare maximum (Liu et al., 2007).

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Recently, the two-stage nature of magnetic reconnection involved in major flares is further evidenced by observational studies. Xu et al. (2010) presented HXR observations of the 2003 October 29 X10 flare obtained with the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) (Lin et al., 2002), and identified two pairs of HXR conjugate footpoints at the flare early impulsive phase that are shown to have different temporal evolutions. By carrying out magnetic sequence analysis, Qiu (2009) made a comprehensive study of the 2004 November 7 X2.0 flare and revealed that the flare ribbons first spread along then separate away from the PIL. Guo et al. (1998) and Cheng et al. (2010) found reconnection and brightening in the core field followed by the final eruption for the 2006 December 13 flare and the 2008 April 26 CME/flare, respectively. All these results strongly suggest that two distinctively separate reconnection processes could occur in succession during a single event. A theoretical progress in the study of magnetic reconnection made by Cassak et al. (2006) shows that slow and collisional reconnection in sheared magnetic fields in the corona can exist for a long time. When the dissipation region becomes thinner and the resistivity drops below a critical value, fast, collisionless reconnection sets in abruptly, increasing the reconnection rate by many orders of magnitude in a very short time. It is possible that the contracting phase of flares, which is observed to be correlated with rapid unshearing and abnormal temperature structures of hard X-ray looptops of a number of flares (e.g., Ji et al., 2006; Shen et al., 2008), corresponds to the first stage, while the ribbon expansion corresponds to the second stage.

However, from the viewpoint that observations and models should yield the same conclusions in all aspects, results reported in the literature thus far have not yet converged especially regarding how the observed changes of photospheric magnetic fields due to flares could reconcile in the two-stage magnetic reconnection scenario, and more importantly, could be understood in the context of coronal magnetic field restructuring. Thus further investigation of individual events should be accumulated to advance our understanding of flaring processes.

In this paper, we study the 2005 January 15 X2.6 flare that was well observed by the Big Bear Solar Observatory (BBSO), with a focus on the flare ribbon dynamics and the flare-related photospheric magnetic field changes. For this event, Liu et al. (2010) reported an asymmetric filament eruption. The asymmetric filament eruption is a kind of eruption with one point fixed and flare brightening propagates along the PIL together with the expansion/separation from the (PIL), as reported by Tripathi et al. (2006). For this event, Liu et al. (2010) found that magnetic reconnection proceeds along the PIL toward the regions where the overlying field decreases with height more rapidly. Our main goal here is to provide further evidence reflecting physical properties of the two-stage magnetic reconnection, especially, the physical mechanisms for initiating the filament eruption. In Section 2 we introduce the data sets used in this study. We present the main results of observations and modeling in Section 3, which are summarized and further discussed in Section 4.

2. Observations and data processing

The source active region, NOAA 10720, produced many X-class flares in 2005 January, and its magnetic configuration and long-term evolution have already received attention in some studies (e.g., Zhao and Wang, 2006; Zhao et al., 2008; Wu et al., 2009; Martinez-Oliveros and Donea, 2009). As BBSO routinely monitors the activity of the solar chromosphere, the X2.6 flare of January 15 that peaked at 23:02 UT in the GOES soft X-ray flux was fully covered by its full-disk Hα observation with a cadence of 1 min and a pixel scale of $\sim$1 arcsec. Moreover, vector magnetograms were obtained by the Digital Vector Magnetograph (DVMG) system at BBSO with a field of view of about $300'' \times 300''$ targeted at this active region. The hardware of DVMG, consisting of a 1/4 Å band pass filter, a 12-bit 1024×1024 CCD camera, and three liquid crystals acting as polarization analyzers, has been described in detail by Spirock et al. (2002). Each complete set of Stokes data has typically a 1 min cadence and comprises four images: 6103 Å filtergram (Stokes I), line-of-sight magnetogram (Stokes V), and the transverse magnetogram (Stokes U and Q) (Wang et al., 2002). For each of Q, U, V, we use about 4 s of integration. The pixel scale of vector data is $\sim$0.6 arcsec after rebinning to increase the sensitivity of the magnetograms, which is approximately 2 and 20 Gauss for the line-of-sight and transverse magnetic fields, respectively (Spirock et al., 2002; Wang et al., 2002). To fully utilize the vector magnetograms, we resolved the 180° azimuthal ambiguity in the transverse

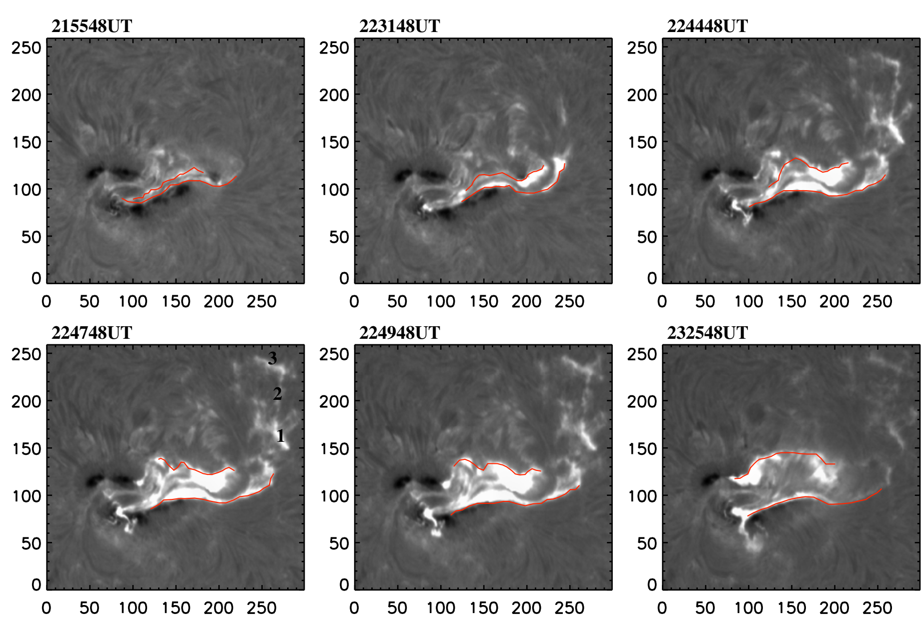

Fig. 1. Time sequence of Hα images of the 2005 January 15 X2.6 flare. Three remote brightenings under discussion are marked as 1, 2 and 3. The images are centered on the point (80 arcsec, 350 arcsec) with solar west to the right and north up. The field of view is $\sim 320 \times \sim 260$ arcsec. The ribbons' moving fronts are marked by the over-plotted lines.