Irreversible rapid changes of magnetic field associated with the 2012 October 23 circular near-limb X1.8 Flare

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Abstract It has been found that photospheric magnetic fields can change in accordance with restructuring of the three-dimensional magnetic field following solar eruptions. Previous studies mainly use vector magnetic field data taken for events near the disk center. In this paper, we analyze the magnetic field evolution associated with the 2012 October 23 X1.8 flare in NOAA AR 11598 that is close to the solar limb, using both the 45 s cadence line-of-sight and 12 min cadence vector magnetograms from the Helioseismic and Magnetic Imager on board Solar Dynamics Observatory. This flare is classified as a circular-ribbon flare with spine-fan type magnetic topology containing a null point. In the line-of-sight magnetograms, there are two apparent polarity inversion lines (PILs). The PIL closer to the limb is affected more by the projection effect. Between these two PILs there lie positive polarity magnetic fields, which are surrounded by negative polarity fields outside the PILs. We find that after the flare, both the apparent limb-ward and disk-ward negative fluxes decrease, while the positive flux in-between increases. We also find that the horizontal magnetic fields have a significant increase along the disk-ward PIL, but in the surrounding area, they decrease. Synthesizing the observed field changes, we conclude that the magnetic fields collapse toward the surface above the disk-ward PIL as depicted in the coronal implosion scenario, while the peripheral field turns to a more vertical configuration after the flare. We also suggest that this event is an asymmetric circular-ribbon flare: a flux rope is likely present above the disk-ward PIL. Its eruption causes instability of the entire fan-spine structure and the implosion near that PIL.

Key words: Sun: flares — Sun: magnetic field

1 INTRODUCTION

The long-term evolution of the photospheric magnetic field can play an important role in solar eruptions like flares, coronal mass ejections (CMEs) and filament eruptions as shown in many previous studies (see the review by Wang & Liu (2015) and Yang et al. (2015)). Because of the much higher gas pressure and density in the photosphere compared to the corona, photospheric magnetic fields do not change significantly during eruptions as usually found in earlier observations. This has been considered to be one of the basic assumptions applied in modeling eruptions.

Using ground-based observations, Wang (1992) and Wang et al. (1994) first found rapid changes of vector magnetic fields associated with some X-class flares. Later, many studies confirmed the earlier results and advanced our knowledge of flare-related photospheric field changes (see the review by Wang & Liu (2015)). Most notably, Wang et al. (2012a) demonstrated that photospheric magnetic fields near the polarity inversion line (PIL) became more horizontal immediately following eruptions. The authors also suggested that the line-of-sight (LOS) magnetograms also provide a useful tool for understanding the topological changes of active region magnetic fields associated with eruptions. Indeed, studies have shown that the disk-ward flux decreases but the limb-ward flux increases right after flares (e.g., Wang et al. 2002; Wang 2006; Wang & Liu 2010). Sudol & Harvey (2005) also found that photospheric magnetic fields changed permanently during eruptions by using GONG magnetograms. They employed a step function to characterize the rapid changes of the magnetic field. Wang et al. (2009) studied an X7.1 flare close to the solar limb, and found clear evidence of weakening in the horizontal magnetic fields in the peripheral area of the δ -sunspot group and strengthening of it in an extended area centralized at the PIL between major sunspots with opposite polarities. This demonstrated the usefulness of the projection effect of near-limb eventsit avoids the complicated analysis of vector magnetograms in deriving the horizontal components of vector magnetic fields.

There has been recent progress in the study of magnetic field changes associated with flares (Wang et al. 2014; Wang & Liu 2012; Petrie 2014). Importantly, such a phenomenon also motivated some modeling efforts. Hudson et al. (2008) presented a model to predict that the photospheric magnetic field would become more horizontal after flares.

In addition, Hudson et al. (2008) and Fisher et al. (2012) used the concept of momentum conservation and assessed the Lorentz-force changes due to the release of energy associated with the rapid evolution of the coronal magnetic field. It is argued that a back-reaction following CME eruptions could push the photospheric magnetic fields to become more horizontal near the flaring PIL. The authors estimated the change of the integrated vertical Lorentz force exerted on the photosphere from the corona to be

$$\delta F_{\rm r} = \frac{1}{8\pi} \int (\delta B_{\rm r}^2 - \delta B_{\rm h}^2) dA, \qquad (1)$$

where B_r is the vertical field strength, B_h is the horizontal field strength and dA is the surface of a vector magnetogram. The integrated area is denoted as the region of interest (ROI) as we discuss below.

The above observational studies and theoretical modeling are mainly based on the classical two-ribbon flare topology. Recently, it has become evident that many flaring regions have a spine-fan magnetic structure and produce so-called circular-ribbon flares (e.g., Wang & Liu 2012; Wang et al. 2014; Liu et al. 2015; Joshi et al. 2015; Wang & Liu 2015). Understanding this type of event requires extending the magnetic topology analysis from 2D to 3D. For the X1.8 flare that occurred on 2012 October 23 considered in the present study, Yang et al. (2015) found that it has many characteristics of circular-ribbon flares. The main topological structures of the flaring region as revealed by the authors include a null point embedded in the fan-spine fields, a flux rope lying below the fan dome and a largescale quasi-separatrix layer induced by the quadrupolarlike magnetic field of the active region. These motivated us to study the rapid 3D magnetic field changes associated with this particular circular-ribbon flare.

Although many previous studies have provided evidence of the relationship between magnetic field changes and solar eruptions, they usually focus on just one component of photospheric magnetic field data. Thus a complete understanding of the field restructuring still has not been achieved. In this study, to examine the magnetic evolution associated with the circular-ribbon flare, we will study both the LOS and vector photospheric magnetic field observations. In Section 2, we introduce the observations and data reduction procedure. In Section 3, we present the results for magnetic field changes. The explanation for the evolution and restructuring of the magnetic field associated with the flare is given in Section 4, and a summary and discussion are also provided.

2 OBSERVATION AND DATA REDUCTION

The X1.8 flare on 2012 October 23 occurred in NOAA Active Region 11598, located close to the east limb (S10°E42°). The flare started at 03:13 UT, peaked at 03:17

UT, and ended at 03:21 UT in GOES 1-8 Å soft X-ray flux. Full-disk, multi-wavelength observations with high resolution have been made available with the Helioseismic and Magnetic Imager (HMI, Schou et al. 2012) and the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). The LOS magnetic field observation from HMI has a pixel resolution of $\sim 0.5''$ and a cadence of 45 s. The noise level of the LOS field measurement is about 10 G. We also analyzed HMI vector magnetic field data (Hoeksema et al. 2014), which have the same pixel scale but a lower cadence (12 min) compared to the LOS observation. As we mentioned earlier, Yang et al. (2015) focused on the same active region in their study. Mainly based on magnetic topology and flare emission morphology as seen in AIA images and magnetic field models, the authors suggested that this event is a circularribbon flare.

Before quantitatively analyzing the data, we first scrutinized movies of HMI intensity, LOS and vector magnetic fields, and AIA extreme ultraviolet images covering the flare. Similar to the event analyzed by Liu et al. (2015), the circular ribbon in this flare is somewhat asymmetric: under part of the dome structure closer to disk center, a filament flux rope is embedded. This is also the core part of the δ configuration of the flaring region under study. Yang et al. (2015) published a nice presentation of the flare ribbons, the dome structure of magnetic fields and magnetic flux rope for this event (see figs. 2, 3 and 5 in their paper). From the HMI intensity movie, we can observe a rapid enhancement (darkening) of the sunspot feature at the central location of this δ structure, together with the decay of penumbrae in the surrounding areas. To pinpoint the location of magnetic field changes, we constructed difference images for both LOS and horizontal field magnetograms, which will be discussed in the next section. From the difference images, we can easily identify ROIs for our analysis, which covers the region with the most obvious magnetic field changes. Our study will focus on the time variation of different parameters at different ROIs, in order to evaluate the rapid/irreversible changes of magnetic fields associated with the flare.

3 RESULTS

3.1 The Change of LOS Magnetic Fields

In Figure 1, we demonstrate the overall structure of this active region and changes related to the flare. The top panels show the LOS magnetograms before and after the flare and their difference image (the postflare image minus the preflare image). The bottom panels show the corresponding intensity images. The red boxes outline the main ROIs, which include three magnetic components: Area I that contains negative flux in the left box (limb-ward negative flux), Area II that contains all positive flux in both red boxes; and Area III that contains all the negative flux in the right box (disk-ward negative flux). Two apparent PILs are observed, and we name them the disk-ward PIL and the limb-



Fig. 1 *Top panels*: HMI magnetograms before and after the X1.8 flare on 2012 October 23, and their difference image, from left to right respectively. *Bottom panels*: HMI intensity images before and after the flare, and their difference image, from left to right respectively. The boxes outline the region of the circular-ribbon flare, featuring double PILs. Three components of magnetic flux are defined. The negative flux in the left box is defined as Area I, the positive flux in both boxes as Area II, and the negative flux in the right box as Area III.



Fig. 2 The *SDO*/HMI LOS flux as a function of time. *Top*: The central positive flux (Area II). *Middle*: The disk-ward negative flux expressed in terms of absolute value (Area II). *Bottom*: The limb-ward negative flux expressed in terms of absolute value (Area I).



Fig. 3 *Top left*: Vertical component of the deprojected HMI vector magnetic field. *Top right*: Horizontal component of vector magnetic field after the flare. *Bottom left*: Horizontal component of vector magnetic field before the flare. *Bottom right*: Difference image of horizontal magnetic field (the postflare image minus the preflare image). The green box outlines the central positive flux region. The disk-ward PIL is next to the right edge of the box, where the horizontal field has an obvious increase after the flare.



Fig. 4 Time profile of horizontal magnetic field at the disk-ward PIL (central white area in Fig. 3). The solid curve shows the *GOES* 1–8 Å soft X-ray flux, indicating the time of the flare.

ward PIL (labeled as PIL 1 and PIL 2 respectively, that will be discussed later in the paper). As Wang et al. (2014) pointed out, this kind of structure that has double PILs may be closely associated with quasi-circular flares. A filament flux rope is found to be present in this flaring region, lying above the disk-ward PIL (Yang et al. 2015). The difference images (the right column) show that changes of the apparent magnetic field and intensity are concentrated in the marked ROIs. Figure 2 plots different components of the LOS magnetic flux as a function of time. The top red curve shows the evolution of the central positive flux (Area II). The absolute value of the disk-ward negative flux, which is in Area III, is shown as the blue curve in the middle panel and that of the limb-ward negative flux in Area I is in the bottom. It is obvious that these are closely associated with the occurrence of the flare that peaked around 03:17 UT, since all these three magnetic flux components exhibit significant changes in a step-like fashion. Specifically, the flux in the



Fig. 5 Time profile of horizontal magnetic field in the area surrounding the disk-ward PIL (surrounding darkened area in Fig. 3).



Fig. 6 A schematic diagram interpreting the observed magnetic field changes associated with the 2012 October 23 X1.8 circular-ribbon flare. The eruption of a flux rope above PIL1 causes coronal implosion and the subsequent enhancement of the horizontal field at PIL1. The surrounding fields collapse toward the center to increase the LOS field strength in the central positive flux region and also to decrease the field in the disk-ward negative flux region. The loops above PIL2 also expand outward, explaining the decrease in the limb-ward negative flux, which also contributes to the increase in central positive flux.

central positive polarity region increases by about 45% after the flare; meanwhile, negative fluxes decrease by about 26% and 20% in the disk-ward and limb-ward negative flux regions, respectively.

3.2 The Change of Vector Magnetic Fields

For vector field analysis, we use vector magnetograms prepared by the HMI team. The 180° azimuthal ambiguity is resolved and the observed fields are also transformed to heliographic coordinates so that the projection effect is removed. We understand the difficulty and uncertainty involved in these data analysis procedures. That is why we also used directly observed LOS fields to provide complementary information to understand 3D magnetic field evolution for this near-limb event. As shown in Figure 3, the surface magnetic field structure typical for circularribbon flares is more obvious: the central parasite positive flux is surrounded by negative flux. Here we focus on the study of evolution of the horizontal field component parallel to the solar surface, which can be calculated as $B_h = \sqrt{B_x^2 + B_y^2}$.

Similar to the analysis of LOS field and intensity, we subtract the horizontal magnetogram after the flare by the horizontal magnetogram before the flare to obtain the difference horizontal field image (bottom right panel of Fig. 3). We can see that the most obvious change is the enhancement of the horizontal field at the location of the disk-ward PIL (right edge of the green box) where the flux rope is embedded. Also, this enhancement is surrounded by regions with decreased horizontal field. The temporal evolutions of the increased and decreased mean field strength are shown in Figures 4 and 5 respectively. The results show that after the flare, the mean horizontal field in the disk-ward PIL region increases by about 190 G, i.e., about 25% of the pre-flare value. The mean horizontal field in the surrounding region decreases by about 130 G, i.e. about 13% of the pre-flare value. Using Equation (1), we derive that associated with the flare, the total Lorentz force change in the vertical direction is about 3.9×10^{22} dyne, comparable with previous studies (Hudson et al. 2008; Fisher et al. 2012; Wang et al. 2012b). The maximum change of Lorentz force per area is 3.4×10^4 dyne cm⁻² and the mean value is 2.8×10^4 dyne cm⁻².

4 SUMMARY AND DISCUSSION

We investigated the rapid changes associated with the flare by using the LOS and horizontal components of magnetic fields associated with the X1.8 flare on 2012 October 23. This is a unique event as it is a circular-ribbon flare located close to the limb. The main results are summarized as follows.

- (1) For the LOS component, we found a rapid increase in the central positive flux and a decrease in the surrounding negative fluxes (both disk-ward and limb-ward) after the flare.
- (2) For the horizontal component, we found a significant enhancement of magnetic field at the disk-ward PIL. This is also the location of an embedded flux rope as suggested by Yang et al. (2015).

All these results support the theory and prediction that were elaborated on by Hudson et al. (2008). As discussed in Wang & Liu (2010), the surrounding magnetic field lines would change to a more vertical state after eruptions, because the pressure in the region where flux rope eruption occurs is released after the flare. In the meantime, the magnetic field lines at the flaring PIL would change to be more horizontal relative to the solar surface due to the backreaction of the upward eruption. In Figure 6, we use a simple schematic diagram to explain our observations. Since this is a circular-ribbon flare, there are two loop systems in the cross section of the fandome as illustrated in this 2D view. As we described above, the most significant changes are associated with the eruption of the flux rope located at the disk-ward PIL (PIL1). The limb-ward system above PIL2 expands outward in response to the flux rope eruption, which can explain why the limb-ward negative flux also decreases. In summary, we believe that this event is similar to the flare studied by Liu et al. (2015): the flux rope eruption destabilizes the fan-spine structure and triggers the null point reconnection. The enhancement of horizontal field at PIL1 is only a consequence of the flux rope eruption, not the null point reconnection.

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