Changes of Magnetic Structure in 3-D Associated with the X3.4 Flare of 2006 December 13

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ABSTRACT

Recent observations demonstrated that sunspot structure can change rapidly and irreversibly after flares. One of the most puzzling results is the increase in magnetic shear around flaring magnetic polarity inversion line after flares. However, all these observations were made at the photosphere level. In this letter, we study the altitude variation of the non-potentiality of the magnetic fields associated with the 4B/X3.4 flare of 2006 December 13. The vector magnetograms with unprecedented quality from Hinode before and after the flare are used as the boundary conditions to extrapolate the 3-dimensional non-linear force-free magnetic fields and the potential fields. The former are computed with the optimization algorithm and the later with Green’s function method. At the photosphere boundary, magnetic shear increases after the flare in a local area close to the flaring magnetic polarity inversion line. Two measures of the magnetic non-potentiality, the weighted mean shear $\theta_w$ and the total magnetic shear $\theta_w B$, are calculated in this area at progressively higher altitude. By comparing their altitude variation profiles before and after the flare, we find that the non-potentiality of the local area increases after the flare below $\sim$8 Mm and decreases from that height to $\sim$70 Mm. Beyond 70 Mm, the magnetic fields approach potential for both times.

Subject headings: Sun: magnetic fields — Sun: activity — Sun: flares — Sun: corona
1. Introduction

There is mounting evidence of the rapid and permanent changes of photospheric magnetic fields during major flares (Wang 1992; Wang et al. 1994; Kosovichev & Zharkova 2001; Sudol & Harvey 2005, Wang 2006). In particular, with white-light (WL) observations obtained from Transition Region and Coronal Explorer (TRACE), a consistent pattern of changes in sunspot structures has been identified: part of the penumbral segments in the outer $\delta$ spot decays rapidly during flares, and meanwhile, the umbral cores and/or inner penumbral regions enhance (Wang et al. 2004; Deng et al. 2005; Liu et al. 2005). Chen et al. (2007) extended this work by performing a statistical study consisting of 403 flare events. It is found that over 40% X-class flares are associated with such a sunspot structure change. To explain these observations, Liu et al. (2005) proposed a reconnection picture in which the two components of a $\delta$ spot become strongly connected during the flare. The penumbral fields change from a highly inclined to a more vertical configuration, which leads to the penumbral decay. Wang (2006) favored the model of tether cutting (Moore et al. 2001 and references therein) via magnetic reconnection at or close to the photosphere.

Among these flare-associated changes in the photospheric magnetic field, the most intriguing result is that magnetic shear around flaring magnetic polarity inversion line (PIL) may actually increase after flares (e.g., Ambastha et al. 1993; Chen et al. 1994; Wang et al. 1994), that indicates energy build-up, rather than release. This result poses a difficulty in explaining the contradiction between the observed increase in magnetic shear and the requirement to release magnetic energy to power the flares. However, previous observations were made at the photosphere level that is the only environment for which we can directly observe and measure the solar magnetic field. To better understand the role that the magnetic fields play in powering the flares, it is essential to study the 3-dimensional (3-D) structure of magnetic fields and their evolution associated with flares. The coronal imaging observations and field modelling approaches contribute to the solution to certain degree. For instance, sigmoid coronal loops visible in extreme-ultraviolet (EUV) and X-ray are indicative of the non-potentiality of the magnetic fields. The sigmoid-to-arcade transformation of the coronal loops during flares has been frequently observed, signifying that magnetic fields relax to a more potential state (e.g., Sakurai et al. 1992; Mandrini et al. 2005; Liu et al. 2007; Jing et al. 2007). A comparison of the non-linear force-free (NLFF) fields before and after the eruption shows that magnetic energy and relative helicity decreased after the eruption (Bleybel et al. 2002).

With the aid of high-resolution and high-accuracy vector magnetogram data from the recently launched Hinode satellite (Kosugi et al. 2007) and the advanced non-linear force-free
field modelling techniques (e.g., Wiegelmann 2008), we are presently in a good position to make advances to address this issue. In this Letter, with *Hinode* vector magnetogram data, we investigate the altitude variation of the non-potentiality of the magnetic fields associated with the 4B/X3.4 flare of 2006 December 13. The changes of the sunspot structure during the flare are studied with high-cadence G-band observations from *Hinode*.

2. **Data Sets and Non-linear Force-free Modelling of Coronal Magnetic Fields**

The 4B/X3.4 flare we discuss in this Letter occurred in active region NOAA 10930 and peaked in GOES soft X-ray at 02:40 UT on 2006 December 13. The flare was accompanied by a Halo CME that appeared on the *Large Angle and Spectrometric Coronagraph Experiment (LASCO)* C2 coronagraphs at 02:54 UT. The evolution of the photospheric magnetic field at the flare site was described by Kubo et al. (2007).

The G-band (430 nm) observations were obtained with the Broadband Filter Imager (BFI) of Solar Optical Telescope (SOT; Tsuneta et al. 2007) on board *Hinode* with a 2 minute cadence. Since the active region is not located at the center of the solar disk, the images are warped onto a heliographic grid so that they appear as they would had been at the disk center. The Spectro-Polarimeter (SP) of SOT obtained Stokes profiles of two magnetically sensitive Fe Lines at 630.15 nm and 630.25 nm. Photospheric vector magnetograms were obtained based on the assumption of the Milne-Eddington atmosphere. The vector magnetograms taken at two time bins, 20:30 UT − 21:33 UT on 2006 December 12 and 4:30 UT − 5:36 UT on 2006 December 13, are used as the boundary conditions to extrapolate the coronal magnetic fields before and after the flare. The 180° ambiguity in the vector magnetograms is resolved using the “minimum energy” algorithm that simultaneously minimizes both the electric current density and the field divergence (Metcalf 1994). This “minimum energy” algorithm is the top-performing automated method among present state-of-art algorithms used for resolving the 180° ambiguity (see Metcalf et al. 2006 for details). The magnetograms are rebinned 2 × 2 to 0.63 arcsec per pixel. The dimensions of the simulation box are 320 × 320 × 256 pixel, which correspond to 150 × 150 × 120 Mm. The potential fields were computed with the Green’s function method (Metcalf et al. 2007). The magnetogram data and the potential fields were prepared for the NLFFF-consortium (Schrijver et al. 2008). The details of the data preparation including re-mapping and disambiguation are described by Schrijver et al. (2008).

In order to reduce the effect of the Lorentz force acting in the photosphere and find suitable boundary conditions for the NLFF field extrapolation, the rebinned photospheric vector magnetograms have been pre-processed (including spatial smoothing) using a method devised by Wiegelmann, Inhester & Sakurai (2006). The preprocessing routine minimizes a 2-D functional
of quadratic form $L_{\text{prep}} = \mu_1 L_1 + \mu_2 L_2 + \mu_3 L_3 + \mu_4 L_4$. The $L_1$ and $L_2$ terms contain force-free and torque-free consistency integrals, the $L_3$ term controls how close the preprocessed data are compared to the original magnetogram (noise-level), and the $L_4$ term controls the smoothing. In this case, $\mu_1 = \mu_2 = 1$, $\mu_3 = 0.001$, and $\mu_4 = 0.01$.

The NLFF fields are computed with the Optimization method (Wheatland et al. 2000) as implemented by Wiegelmann (2004). This method involves minimizing a joint measure ($L$) for the normalized Lorentz force and the divergence of the field throughout the volume of interest $V$:

$$L = \frac{1}{V} \int_V \left[ \omega_f(r) B^{-2} |(\nabla \times \mathbf{B}) \times \mathbf{B}|^2 + \omega_d(r) |\nabla \cdot \mathbf{B}|^2 \right] dV$$  \hspace{1cm} (1)

where $B = |\mathbf{B}|$, $\omega_f$ and $\omega_d$ are weighting functions for the force and divergence terms, respectively. The weighting functions have been chosen $\omega_f = \omega_d = 1$ in the volume except for a boundary layer of 32 points towards the lateral and top boundary of the computational domain. In the boundary layers $\omega_f$ and $\omega_d$ drop from 1 to 0 with a cosine profile. (See Wiegelmann 2004 for details). The force-free equations are solved with the magnetic field vector prescribed in the photosphere as boundary condition.

Schrijver et al. (2006) compared six state-of-art algorithms for the NLFF field extrapolation, and concluded that the optimization algorithm is the best-performing and fastest-converging algorithm in modelling the coronal magnetic field, particularly in the strong-field, strong-current regions.

3. Calculation of Magnetic Shear

In this work, the magnetic shear $\theta$ is defined as the azimuth difference between the extrapolated NLFF magnetic field and the potential field. In each pixel $i$,

$$\theta_i = \cos^{-1} \frac{\mathbf{B}^N_i \cdot \mathbf{B}^p_i}{B^N_i B^p_i}$$  \hspace{1cm} (2)

where $B_i = |\mathbf{B}_i|$, and the superscripts $N$ and $p$ represent the NLFF field and the potential field, respectively.

At each altitude, we calculate the weighted mean shear $\theta_w$ (Wang et al. 1994) and the total magnetic shear $\theta_w B$ as follows. Both provide a quantitative description of the non-potentiality of the magnetic field.

$$\theta_w = \frac{\sum (B^N_i \theta_i)}{\sum B^N_i}$$  \hspace{1cm} (3)
\[ \theta_w B = \theta_w \sum B_i^N = \sum (B_i^N \theta_i) \] (4)

where the sum is performed over all the pixels in a region.

4. Results

In Fig. 1, the top row compares the sunspot structure shown in the G-band images taken before (left) and after (middle) the X3.4 flare. The contours show the magnetic PILs from the SP line-of-sight magnetograms. The alignment between the G-band and the SP images is performed by manually aligning the spots and network structures. In their difference image (right), we can identify the dark patches in the central region surrounded by less obvious bright patches. The dark patches corresponds to the areas of the darkening inner penumbra, whereas the bright patches correspond to the areas of the decaying peripheral penumbra. To better illustrate the changes of sunspot structure, the central darkening region (RG1) around the flaring magnetic PIL and a peripheral brightening region (RG2) are marked with the green and yellow boxes, respectively. The bottom panel shows the time variation of total G-band intensities in RG1 (green line) and in RG2 (yellow line) over a period of \( \sim 11 \) hours around the time of the flare. As mentioned, the SOT/SP pre-flare vector magnetograms are obtained between 20:30 UT and 21:33 UT on 2006 December 12 and the post-flare vector magnetograms between 4:30 UT and 5:36 UT on the next day. The blue and red vertical lines refer to the starting times of the SP scanning observations, between which there is a 8-hour time interval. The peak time of the flare non-thermal emission is indicated by the time derivative of GOES X-ray flux (dotted vertical spike). For a direct comparison, all these data are normalized to their maximum value. Evidently, the intensity in RG1 decreases by \( \sim 12\% \) within the interval of two time bins while the intensity in RG2 shows relatively little change, \( \sim 6\% \), over the 8-hour interval. It was observed that, prior to the flare, three emerging flux regions appeared between the two umbrae as well as in the area west of that (Kubo et al. 2007). Parts of the emerging flux merged into the adjacent penumbra enclosed with RG1, which may explain the intensity decrease in this area.

In Fig. 2, the top \( 3 \times 3 \) panels show a sequence of the shear-difference images \( \theta_2 - \theta_1 \) at progressively higher altitude, where the subscripts 1 and 2 refer to two time bins of the SP vector magnetograms before and after the X3.4 flare, respectively. The magnitude of \( \theta_2 - \theta_1 \) in each pixel is indicated by the grey scale bar. Two panels in the bottom row are the pre-flare (left) and post-flare (right) line-of-sight magnetograms, respectively. The contours show the magnetic PILs. The large square boxes are drawn to mark the field-of-view (FOV) of the G-band images shown in Fig. 1. We use blue and red color to distinguish two time bins, that
is also used in Fig. 1. By comparing the line-of-sight magnetograms and the shear-difference image at the photosphere boundary (h=0), we can see an increase in magnetic shear in an area P near the flaring magnetic PIL. This area P is marked by the small rectangles. Since the development of shear around the magnetic PIL is more essential for the flare occurrence, θ_w and θ_wB in the area P at two time bins are specifically calculated for a quantitative comparison, that is shown in Fig. 3.

In Fig. 3, we plot the θ_w (top) and θ_wB (bottom) in the area P as a function of altitude for two time bins (blue: before the flare; red: after the flare). As mentioned, both θ_w and θ_wB can provide a quantitative description of the non-potentiality of the local area. We see that, at the photosphere boundary (h=0 km), the non-potentiality of this area increases after the flare. With the ascending altitude, the non-potentiality decreases both before and after the flare, but at different rates. As a result, 8 Mm appears to be a critical height, below which the non-potentiality increases after the flare and above which to a height of ∼70 Mm the field is relaxed to a more potential state. Beyond 70 Mm, the fields approach potential for both times.

5. Summary

In this Letter, Hinode G-band observations reveal that the sunspot structure undergoes some changes during the X3.4 flare of 2006 December 13. The most conspicuous change is the darkening of the central feature near the flaring magnetic PIL, probably as a result of the continuing flux emergence at this region. The abrupt penumbral decay associated with major flares was first observed by Howard (1963) and recently by Wang et al. (2004), Deng et al. (2005), Liu et al. (2005) and Chen et al. (2007). Compared with the previous observations, the duration of this observation (∼11 hours around the time of the flare) is 2-3 times longer. Therefore, we find that, although the change rate peaks associated with the flare, the trend of change is persistent. I.e., the intensity changes start even several hours prior to the flare, achieve the maximum change rate immediately after the flare, and are complete ∼1 hour after the flare emission ceased. The intensity changes in the peripheral penumbral are not as obvious as that in the central feature. Comprehensive quantitative study of decaying penumbral structure will be presented in a future paper.

We extrapolate the coronal magnetic fields of active region NOAA 10930 before and after the flare, and calculate the shear parameters of the extrapolated fields around the flaring magnetic PIL. By comparing the height variations of the shear parameters calculated in the pre- and post-flare fields, we find that: (1) from the photosphere boundary to an altitude of ∼8 Mm, the magnetic shear in an area around the magnetic PILs increases after the flare; (2) from ∼8 Mm to ∼70 Mm, the shear in this area decreases after the flare; and (3) beyond ∼70
Mm, both pre- and post-flare fields become potential.

As mentioned, previous observations of the photosphere magnetic field show that magnetic shear can increase after the flare (e.g., Ambastha et al. 1993; Chen et al. 1994; Wang et al. 1994; Schmieder et al. 1994). It seems puzzling because shear increase signifies energy build-up, rather than release for energizing flares. This work, based on the shear evaluation in 3-D magnetic field, may resolve the previous observational paradox: the magnetic shear may increase in a local area near flaring magnetic PIL due to the emerging flux regions, but, at higher altitudes, magnetic fields are relaxed. In particular, it appears likely that the energy release process happens at the altitude ranging from ∼8 Mm to ∼70 Mm.

It is worth noticing that the on-going flux emergence not only causes an increase in the magnetic shear at low altitude (<8 Mm), but also causes an increase in free energy by ∼5% from the pre-flare fields to the post-flare fields (Schrijver et al. 2008). Presumably the flare might only release some of the new energy introduced by the flux emergence. NOAA 10930 is a flare-productive active region. Its energy build-up and release process requires magnetic field observations with higher cadence. The 8-hour interval between the SP magnetograms is certainly too long to address this issue.

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Fig. 1.— Top row: *Hinode* G-band images taken before (left) and after (middle) the flare and the difference image (right). The contours show magnetic PILs. The central darkening region (RG1) around the flaring magnetic PIL and a peripheral brightening region (RG2) are marked with the green and yellow boxes, respectively. The field-of-view (FOV) is 90×90 arcsec. Bottom panel: Normalized time variation of the total G-band intensities in area RG1 (green) and RG2 (yellow). The blue and red vertical lines denote the times of the vector magnetograms used for 3-D extrapolation. The dotted vertical curve is the time derivative of GOES X-ray flux.
Fig. 2.— Top three rows: the shear-difference images $\theta_2-\theta_1$ at progressively higher altitude, where the subscripts 1 and 2 refer to two time bins of the SP vector magnetograms taken before and after the flare, respectively. The magnitude of $\theta_2-\theta_1$ in each pixel is indicated by the grey scale bar. Bottom row: the line-of-sight magnetograms taken before (left) and after (right) the flare. The contours show the magnetic PILs. The FOV is 140" $\times$ 140". The area P close to the magnetic PILs is marked with the rectangles. The large square boxes are drawn to mark the FOV of the G-band images shown in Fig. 1.
Fig. 3.— The weighted mean shear $\theta_w$ (top) and the total magnetic shear $\theta_w B$ (bottom) of area P (defined in Fig. 2) as a function of altitude for two time bins. The step size of altitude is $\sim 0.46 \text{ Mm}$. Blue: before the flare; Red: after the flare.