Sideways displacement of penumbral fibrils by the solar flare on 2006 December 13

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ABSTRACT

Flares are known to restructure the magnetic field in the corona and to accelerate the gas between the field lines, but their effect on the photosphere is less well studied. New data of the Solar Optical Telescope (SOT) onboard Hinode provide unprecedented opportunity to uncover the photospheric effect of a solar flare, which associates with an active region NOAA AR 10930 on 2006 December 13. We find a clear lateral displacement of sunspot penumbral regions scanned by two flare ribbons. In the impulsive phase of the flare, the flare ribbons scan the sunspot at a speed of around 18 km s\textsuperscript{−1}, derived from Ca II and G-band images. We find instantaneous horizontal shear of penumbral fibrils, with initial velocities of about 1.6 km s\textsuperscript{−1}, produced when a flare ribbon passes over them. This velocity decreases rapidly at first, then gradually decays, so that about one hour later, the fibrils return to a new equilibrium. During the one hour interval, the total displacement of these fibrils is around 2.0 Mm, with an average shear velocity of 0.55 km s\textsuperscript{−1}. This lateral motion of the penumbral fibrils indicates that the magnetic footpoints of these field lines being rearranged in the corona also move.

Subject headings: Sun: flares — sunspots — Sun: activity — Sun: photosphere

1. INTRODUCTION

Solar flares are one of the most spectacular phenomena in solar physics, and quickly release magnetic energy stored in the corona in a short time. Flare-associated changes in the magnetic field are fundamental, and of importance in the general physics of magnetic energy

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storage and explosive release. These changes in photospheric magnetic fields largely include two topics: long-term changes before the flare and short-term changes during the flare, among which the short-term changes mean magnetic changes that occur on the flare time-scale \cite{Zhao2009}. The rapid short-term magnetic field changes in the course of flares was first reported by \cite{Patterson1981}. However, \cite{Patterson1984} later recognized that the reported magnetic transients were not real changes in the magnetic field but could be explained by transient emission of the Fe I 5324 Å line which was used to produce the magnetograms. \cite{Qiu2003} provided a scenario that the observed transient polarity reversal in MDI magnetograms is likely to be produced by distorted measurements when the Ni I 6768 Å line comes into emission or strong central reversal as a result of non-thermal beam impact on the atmosphere in regions of strong magnetic fields. They called this transient polarity reversal as magnetic “anomaly”.

On the other hand, \cite{Kosovichev1999} detected rapid variations of the photospheric magnetic field during an X-class flare in AR 8210 on 1998 May 2, and \cite{Cameron1999} found a significant change in the longitudinal magnetic fields in NOAA AR 6063 during an X9.3 flare. \cite{Sudol2005} further presented new evidence of longitudinal magnetic field changes accompanying 15 X-class flares. Associated with Bastille Day flare/CME event \cite{Zhang2001}, \cite{Kosovichev2001} detected two types of rapid magnetic changes: irreversible changes and magnetic transients. Recently, \cite{Wang2004} and \cite{Deng2005} found penumbral decay and neighboring umbral core darkening rapidly right after the flares. \cite{Liu2005} further studied this type of short-term evolution of sunspot structure associated with seven major flares, and proposed accordingly a reconnection picture to interpret the findings. Moreover, \cite{Chen2007} found that the rapid and permanent structural changes are evidenced in the time profile of white light mean intensity and are not likely resulted from flare emission. In addition, \cite{Wang2009} and \cite{Zhao2009} discovered rapid, significant and persistent changes and flare induced signals in polarization measurements during flare events.

Here, we report on observations from Hinode spacecraft of sideways displacement of penumbral fibrils driven by a solar flare on Dec. 13, 2006. This displacement carries potentially interesting information about the flare induced variations of the magnetic fields and sunspots.

2. OBSERVATIONS AND ANALYSIS

Active region NOAA AR 10930 displayed the evolution of a complex magnetic structure, surrounded by many small dark pores and bright magnetic faculae \cite{Zhang2007};
Li & Zhang (2009). Images of the X3.4 flare related to the active region on December 13, 2006, were obtained by the Solar Optical Telescope (SOT, Tsuneta et al. 2008) onboard Hinode in two spectral filters: the molecular line G-band and Ca II H. In each filter the images were obtained every 2 minutes, and the pixel size of the 2048×1024 images was 0.11 arcsec.

A first signature of the flare appeared in the Ca II H images at about 2:08 UT between two sunspots with the opposite magnetic polarity (Kosovichev & Sekii 2007). The energy release was probably triggered by strong shearing flows around the following sunspot (Zhang et al. 2007). The flare emission quickly extended during the next 10 min, forming a two-ribbon structure. Figure 1 displays a G-band (top) and a co-temporal Ca II image (bottom) from Hinode/SOT. The three ellipses ‘E1’, ‘E2’ and ‘E3’ outline the flare-affected regions determining from time slice maps, and overplotted on the Ca II image. The dash-dotted curves represent the leading edge of the two ribbons at different times. At 02:22 UT, the two flare ribbons (R1 and R2) first became visible in the G-band images, indicating that the perturbation extends into the photosphere. R1 moved laterally across the penumbra of the sunspot P1 with a velocity of 18 km s\(^{-1}\) in the first 2 minutes, after which its horizontal propagation velocity decreased rapidly. The ribbons on the Ca II images first appeared at 02:16 UT, 6 minutes earlier than on the G-band. From 02:16 to 02:20 UT, the apparent motion velocity of R1 was about 12 km s\(^{-1}\), and from 02:20 to 02:24 UT, R1 scanned across the penumbra with a velocity of 19 km s\(^{-1}\). Then the chromospheric ribbon also quickly slowed down. In the course of the scanning, the two ribbons expanded in length and separated from each other, subsequently they intrude from the penumbrae into the umbrae of the sunspots. The dotted and the dashed lines labeled ‘a’ to ‘g’ and ‘ref1’, ‘ref2’, cut the penumbral fibrils, respectively. The lines ‘a’ to ‘g’ lie in the parts of the penumbra where we see an immediate influence of the flare during the passage of the ribbons (see the accompanying movie), while ‘ref1’ and ‘ref2’ are located in parts of the penumbra that are not crossed by the flare ribbons. Time slices of the measured quantities along these lines are shown in Figs. 2-4.

We display four time-slice maps taken from the G-band images in Fig. 2. From top to bottom, these maps correspond to the four lines ‘ref1’, ‘a’, ‘b’ and ‘c’, respectively. The X-axis is the distance (∼22 Mm) of the lines from left to right, which cut the penumbra of the largest sunspot ‘P1’. The Y-axis of each map denotes time, running from 2006 Dec. 13, 02:00 to 04:00 UT (from bottom to top). Bright horizontal strips on maps (a)-(c) represent the flare ribbon ‘R1’ at the time when it crosses that particular cut, while moving from the neutral area of the active region to the umbra of the largest sunspot ‘P1’. The top map indicates the G-band signals at the position ‘ref1’ where it is not disturbed by the flare ribbon R1, and the others maps (a)-(c), the signals affected by the ribbon. From map (ref1), we find no shear motion of the penumbral fibrils. However, from maps (a)-(c), we
find that there is a rightwards tilt of these fibrils before the arriving of the flare ribbon R1 (see the blue and black arrows in Fig. 2b). The inward motion of bright/dark structures can explain the rightwards tilt in the time-slice maps (a), (b), (c) between 02:00 UT and 02:14 UT (e.g. see the blue arrow). However, the rightwards tilt between 02:14 UT and 02:22 UT (see the black arrow) is due to lateral rightwards displacement of the penumbral fibrils and it is related to the flare. Moreover, we find distinct opposite sideward displacement (see the white arrows) when the flare ribbon first scans the fibril in the photospheric layers. The whole fibril is offset perpendicular to its long direction and not just the part at which the flare ribbon currently resides (see the accompanying movie). Numbers 1-6 mark the positions where the lateral velocities are plotted in the bottom of Fig. 5. The lateral motion lasts for about one hour. This is much longer than the duration of the flare ribbon resides in the penumbra, which is 4-10 minutes, depending on which part of the penumbra we are considering. Although the signals on numbers ‘1’ and ‘2’ still display shear motion one hour after the initial shear, this motion is mainly contributed from the outward movement of bright material along the penumbral fibrils, seen from G-band movie. In the one hour interval from the original shear, the displacements at the six positions 1-6 are 2.1 Mm, 2.1 Mm, 2.0 Mm, 1.9 Mm, 1.8 Mm and 1.4 Mm, respectively. Evidently, the displacement of the penumbral fibrils started immediately after the flare ribbon reached the region.

Figure 3 shows time-slice maps along lines ‘d’ and ‘e’ in the penumbra of the opposite polarity spot during and after the passage of the flare ribbon R2. This flare ribbon looks like a bright horizontal strip on each map, at the time when it crosses that particular cut, while moving from the central area of the active region to the umbra of the smaller sunspot ‘P2’. Figure 3(d) shows that the fibrils along this cut display a lateral motion. This motion lasts for about 50 minutes with a final displacement of 1.6 Mm. Figure 3(e) shows the displacement of a lightbridge which separates the two sunspots (P2 and P3). The lightbridge displays a smaller displacement (0.7 Mm) in the 50 minutes interval.

Figure 4 shows three time-slice maps (corresponding to the three lines ‘ref2’, ‘f’ and ‘g’ in Fig. 1) taken from the G-band images. The top panel of Fig. 4(ref2) confirms that the penumbral fibrils in regions unaffected by the flare ribbon remain at the line ‘ref2’ position, quite stable in the two hour interval. The penumbral fibrils cut by the lines ‘f’ and ‘g’ are parallel to the umbral boundary of sunspot P2. When flare ribbon R2 scans the penumbra, the fibrils displayed in map ‘f’ shear with a velocity of 1.1 km s$^{-1}$ in the first 10 minutes. For map ‘g’, the shear velocity of the penumbral fibrils is 0.8 km s$^{-1}$. The lateral motion last for about 30 minutes, along both cuts, which is shorter than that of the fibrils displayed in Figs. 2 and 3. The top panel of Fig. 5 displays soft X-ray flux (solid curve) of the flare measured by GOES-12 and lateral horizontal speed (dotted curve) at the position of number ‘3’ denoted in Fig. 2. Light gray area represents the period at which the flare is
strongest. The shear appears suddenly at 02:24 UT, with a peak velocity of 1.6 km s\(^{-1}\), then the velocity decreases rapidly, and lasts for about one hour. On the bottom panel, the filled circles represent the peak lateral velocities between 2:24 and 2:28 UT at the six positions showed in Fig. 2, and the empty circles, the mean lateral velocities between 2:24 and 3:24 UT. The peak velocities of all the six positions are around 1.6 km s\(^{-1}\), while the mean velocity, 0.55 km s\(^{-1}\).

3. DISCUSSION AND CONCLUSIONS

The observations of the solar flare of December 13, 2006 from Hinode reveal a flare-induced displacement of penumbral fibrils, as seen in series of G-band images. The displacement was started locally immediately after the passage of a flare ribbon. Fibrils not crossed by the flare ribbon are not seen to move. The passage of the flare ribbon produces a strong acceleration of the fibrils transverse to their elongated direction almost instantaneously. This results in a peak velocity reaching up to 1.6 km s\(^{-1}\). The maximum value of the horizontal displacement reaches 2.0 Mm, although at most locations the displacement is smaller, so that it is perhaps not surprising that the discovery of such photospheric effects of flares had to await the advent of data with consistent high resolution approaching 0.2'' as provided by Hinode.

Wang et al. (2004) studied three X-class flares in the active region NOAA 10486 and found that the penumbral segments decayed rapidly right after the flares; meanwhile, the adjacent umbral cores became darker. The location of such a disappearance of penumbral structure coincides with, or is close to, the flare kernel. Moreover, these changes are permanent, e.g., they remained well after the flares and did not go back to the preflare level. They put forward the interpretation of the results: magnetic fields become more vertical after flares, which cause penumbrae to decay. The umbrae become darker as a result of enhancement of longitudinal magnetic field. However, in this study, we find the sideways displacement of the penumbral fibrils associated with the flare instead of the penumbral decay observed by Wang et al. (2004).

The structure of the magnetic field in the penumbra is complex, with interlaced fibrils of different magnetic inclination (e.g. Lites et al. 1993; Title et al. 1993; Solanki & Montavon 1993; Solanki 2003), which are related to fibril brightness in inner and lateral penumbra. As the cause of the shift, we propose the motion of field lines rearranged by the flares. Zirin (1984) have provided evidence that the coronal magnetic field rearranges itself significantly in the course of a flare. Such a rearrangement also leads to force that attempt to move the photospheric footpoints of the affected fields lines. Since the gas density is 8 orders of
magnitude higher in the photosphere than in the corona and the pressure is $10^5$ times higher, it is generally assumed that the field in the photosphere cannot be moved (line-tying). In a sunspot, however, the plasma $\beta = 1$ (Solanki et al. 1993), so that magnetic field can also move the plasma bodily.

Our results therefore test the line-tying condition often involved in coronal magnetic field studies (Hood 1986; Zweibel & Bruhwiler 1992) and shows that although linetying is not exactly fulfilled, even in the case of an X-class flare and the field lines anchored in the penumbra, their footpoints move by less than 2 Mm. This suggests that the line-tying condition is relatively well fulfilled, e.g. for reconnection work. Furthermore, the sideways displacement occurred simultaneous with the passage of the flare ribbon may be the result of the lower reconnection site during the flare event.

In addition, under some assumptions, we estimate the value of the magnetic energy needed to result in the sideways displacement of the penumbral fibrils. Here, we use $10^8$ km$^2$ to be the area of these penumbral fibrils, and $10^3$ km, the height. As the density of the photosphere is about $10^{-9}$ g cm$^{-2}$, then the mass of these penumbral fibrils is $10^{17}$ g. The maximum velocity of these penumbral fibrils is 1.6 km s$^{-1}$. Therefore, the kinetic energy of these penumbral fibrils are about $10^{27}$ erg. That is to say, more than $10^{27}$ erg magnetic energy will lead to the sideways displacement of the penumbral fibrils. Actually, the magnetic energy of lots of big flares are beyond this value. With higher spatial resolution observations (such as Hinode), we may find more flare events with sideways displacement of the penumbral fibrils. More major flare events need to be examined if the revealed magnetic changes in the course of flare by this study are common.

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REFERENCES

Cameron, R., & Sammis, I. 1999, ApJ, 525, L61

Chen, W. Z., Liu, C., Song, H., et al. 2007, Chin. J. Astron. Astrophys., 7, 5, 733

Deng, N., Liu, C., Yang, G., et al. 2005, ApJ, 623, 1195
Hood, A. W. 1986, Sol. Phys., 105, 307
Kosovichev, A. G., & Zharkova, V. V. 1999, Sol. Phys., 190, 459
Kosovichev, A. G., & Zharkova, V. V. 2001, ApJ, 550, L105
Kosovichev, A. G., & Sekii, T., 2007, ApJ, 670, L147
Li, L. P., & Zhang, J. 2009, ApJ, 706, L17
Lites, B. W., Elmore, D. F., Seagraves, P., et al. 1993, ApJ, 418, 928
Liu, C., Deng, N., Liu, Y., et al. 2005, ApJ, 622, 722
Patterson, A., & Zirin, H. 1981, ApJ, 243, L99
Patterson, A. 1984, ApJ, 280, 884
Qiu, J., & Gary, D. E. 2003, ApJ, 599, 615
Solanki, S. K., & Montavon, C. A. P. 1993, A&A, 275, 283
Solanki, S. K., Walther, U., & Livingston, W. 1993, A&A, 277, 639
Solanki, S. K. 2003, A&A Rev., 11, 153
Sudol, J. J., & Harvey, J. W. 2005, ApJ, 635, 647
Title, A. M., et al. 1993, ApJ, 403, 780
Tsuneta, S. et al. 2008, Sol. Phys., 249, 167
Wang, H. M., Liu, C., Qiu, J., et al. 2004, ApJ, 601, L195
Wang, J. X., Zhao, M., & Zhou, G. P. 2009, ApJ, 690, 862
Zhang, J., Wang, J. X., Deng, Y. Y., Wu, D. J. 2001, ApJ, 548, L99
Zhang, J., Li, L. P., & Song, Q., 2007, ApJ, 662, L35
Zhao, M., et al. 2009, Research in Astron. Astrophys., 9, 7, 812
Zirin, H. 1984, ApJ, 281, 884
Zweibel, E. G., & Bruhwiler, D. L. 1992, ApJ, 399, 318

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Fig. 1.— A G-band (top) and a co-temporal Ca II image (bottom) from Hinode/SOT showing the penumbral structures of sunspots (‘P1’, ‘P2’ and ‘P3’ in the Ca II image) belonging to the active region NOAA AR 10930 on 2006 Dec. 13. The dash-dotted curves represent the leading edges of the two ribbons (marked by ‘R1’ and ‘R2’ in the Ca II image) while they scan these penumbral fibrils (see also the accompanying movie), with different colors indicating the different time. The dotted and the dashed lines cut the penumbral fibrils. Time slices of measured quantities along these lines are shown in Figs. 2-4. The three ellipses ‘E1’, ‘E2’ and ‘E3’ on the G-band outline flare-affected regions determining from the time slice maps, and are overplotted on the Ca II image. The field-of-view of both frames is $55'' \times 55''$. 
Fig. 2.— From top to bottom: four time-slice maps, which correspond to the four lines ‘ref1’, ‘a’, ‘b’ and ‘c’ (see Fig. 1), respectively, taken from the G-band images. The X-axis is the distance (∼22 Mm) of the lines from left to right. Line ‘ref1’ is given for a reference. Lines ‘a’, ‘b’ and ‘c’ cut the penumbra of the largest sunspot ‘P1’. The Y-axis of each map denotes time, running from 2006 Dec. 13, 02:00 to 04:00 UT. Circles numbered by 1-6 show the position of the shear velocities plotted in the bottom of Fig. 5. Bright strips on maps ‘a-c’ represent the flare ribbon ‘R1’ while it moves from the central area of the active region to the umbra of the largest sunspot ‘P1’. The slopes of the arrows indicate the speed of motion in the direction of the cut.
Fig. 3.— Similar to Fig. 2 but for the two horizontal lines ‘d’ and ‘e’ (see Fig. 1), with X-axis representing the distance (∼16 Mm) from left to right. These lines cut the penumbra of the smaller sunspot ‘P2’ from the outer to the inner boundary. The Y-axis of each map denotes time, running from 2006 Dec. 13, 02:00 to 04:00 UT (from bottom to top). A bright strip on each map represents the flare ribbon ‘R2’ while it moves from the central area of the active region to the outer boundary of the smaller sunspot ‘P2’. The slopes of the arrows indicate the speed of motion in the direction of the cut.
Fig. 4.— Similar to Fig. 2 but for the three vertical lines ‘ref2’, ‘f’ and ‘g’ (see Fig. 1). The X-axis of each map denotes time, running from 2006 Dec. 13, 02:00 to 04:00 UT (from left to right). The Y-axis represents the distance (∼16 Mm) of the lines. Line ‘ref2’ is considered for a reference. Lines ‘f’ and ‘g’ cut the penumbra of the smaller sunspot ‘P2’. A bright strip on each map represents the flare ribbon ‘R2’. The slopes of the arrows indicate the speed of motion in the direction of the cut which are on the umbral boundary of ‘P2’.
Fig. 5.— *Top*: Soft X-ray flux (solid curve) measured by GOES-12 and shear velocities (dotted curve) at the position of number ‘3’ denoted in Fig. 2. Light gray area represents the flaring activity period. *Bottom*: Estimates of the peak shear velocities (solid circles) between 2:24 and 2:28 UT, as well as mean shear velocities (hollow circles) between 2:24 and 3:24 UT at the six positions (see Fig. 2) in the penumbra of the largest sunspot.