Magnetic Field Rearrangement in the Photosphere Driven by an M5.0 Solar Flare

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Abstract

Sunspot structures can be significantly affected by major flares. In this study, we reported a large penumbral area experiencing two kinds of transformations during the flare SOL2013-11-03T05:22 (M5.0). One penumbral segment decayed and transformed into a small pore when swept by the flare ribbon. At the same time, an adjacent penumbral segment expanded, permeating the granular area along the flaring magnetic polarity inversion line. EUV and X-ray observations indicated that the penumbral enhancement area was close to the flare center, while the penumbral decay area was on the relatively outer side. By tracking the magnetic motions and local magnetic field changes, we found that the magnetic transformations within two regions were totally different during the flare. The central penumbral enhancement area was accompanied by the field collapsing down, whereas the outer penumbral decay area was associated with the field lifting up toward the upper flare center. Particularly, following the uplift motion of the magnetic fields in the outer region, the magnetic flux in the decaying penumbra decreased and that in the forming pore subsequently increased. These results implied that the rearrangement of the magnetic field during the flare would be the action that resulted in the variations of sunspot structures.

Key words: Sun: activity – Sun: flares – Sun: photosphere

Supporting material: animation

1. Introduction

Sunspots are dark features on the solar surface and their magnetic nature has been investigated for more than a century (Hale 1908). Typically, a well-developed sunspot consists of a dark core (umbra) with strong and vertical magnetic fields and a surrounding alternating bright and dark filamentary structure (penumbra) with weaker and more inclined field (Solanki 2003; Borrero & Ichimoto 2011). The birth of sunspots is associated with successive emergence of magnetic flux, and it often initially appeared as naked umbra (also refers to pore) when the flux just rises through the convection zone to the solar surface (Leka & Skumanich 1998). When the pore has grown to sufficient total magnetic flux, the magnetic field at its outer edge becomes more inclined to the vertical, further interacts with the surrounding granular convection, and eventually leads to the production of penumbra (Leka & Skumanich 1998; Watanabe et al. 2014). Jurčáč et al. (2017) also reported a case in which, when the vertical magnetic field was not strong enough, a small pore could completely transform to an orphan penumbra due to the predominantly vertical field becoming horizontal.

Besides natural evolutions, sudden flare-induced variations on the sunspots structure have also been reported recently (see the review by Wang & Liu 2015). For example, the penumbral fibrils could grow up or become darker close to the flaring magnetic polarity inversion lines (PILs; Wang et al. 2004, 2013, 2018; Xu et al. 2017), while they usually decayed in the relatively peripheral region (Deng et al. 2005; Liu et al. 2005; Wang et al. 2012; Li et al. 2016; Xu et al. 2016; Sarkar & Srivastava 2018).

It might also cause the sunspot motion, such as the rapid proper movement (Anwar et al. 1993; Wang et al. 2005; Wang 2006; Xu et al. 2017), sudden acceleration of rotational motion (Wang et al. 2014; Liu et al. 2016), or even reversal of rotational motion during the flare (Bi et al. 2016). These variations were strongly related to the local magnetic field changes. Many researches have revealed that after flares, the fields often became more horizontal in the central PIL regions, and contrarily more vertical in relative outside regions (Wang & Liu 2010; Petrie 2016; Gömöry et al. 2017; Sun et al. 2017). In addition, sudden magnetic vortex flows can also be found in the rotational sunspots cases (Bi et al. 2017). As suggested by the magnetic implosion idea (Hudson 2000; Hudson et al. 2008; Fisher et al. 2012), the flare eruptions in the corona could impact the solar surface and interior, and the authors also predicted that the decrease in coronal magnetic energy should lead the contraction of coronal fields and the field in the photosphere should become more horizontal. The scenario of magnetic implosion was subsequently confirmed by many observations in the corona (Liu et al. 2009; Shen et al. 2012; Yan et al. 2013; Wang et al. 2016). Wang et al. (2012) further discussed that the energy release could also make a negative pressure core above the flaring PIL, then the ambient fields would lift up to fill the void. As a result, the sunspot structures would be affected due to their local magnetic changes.

In this paper, we investigated the flare SOL2013-11-03T05:22 (M5.0) accompanied by both growth and decay of penumbra structures. It is worthwhile to analyze this region because growth and decay of penumbra are adjacent events taking place within an apparent common penumbral area before the flare occurs. Particularly, the penumbral decay finally resulted in the formation of a small pore. It seems to be the reverse procedure of a pore transformed to an orphan penumbra as reported by...
Jurčák et al. (2017). Therefore, such a distinctive event motivated us to investigate how the magnetic fields transformed and further reformed the sunspot structures during the major flare.

2. Observations and Data Processing

The target flare under study here is an M5.0 flare according to the GOES soft X-ray (SXR) observations. It occurred near the central solar disk in the NOAA active region (AR) 11884 (S12W16) on 2013 November 3. Figure 1 shows the general information of the AR and the M5.0 flare. Clearly, the flare occurred at the PIL of the AR marked by the dashed yellow circle in panel (c). The flaring region presented a magnetic delta structure where the positive and negative spots were locked together and separated by a distinct PIL. In panel (a), it can be seen that an S-shape filament (pointed by the white arrow) lays above the PIL. This filament subsequently erupted and the eruption led to an M5.0 flare. Based on the GOES 1–8 Å SXR flux (panel (d)), this flare started at 05:16 UT, peaked around 05:22 UT, and decayed slowly until 06:29 UT. In the decay phase of the flare, the SXR flux had another two small peaks at the time of 05:58 UT and 06:17 UT, respectively. Moreover, the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) hard X-ray (HXR) flux from 05:32 UT to 06:38 UT were also available, which covered the two peaks in the flare decay phase. It thus allowed us to track the X-ray emission by the reconstructed images from RHESSI.

The observational data we used were mainly from the 1 m New Vacuum Solar Telescope (NVST; Liu et al. 2014; Xu et al. 2014; Xiang et al. 2016) located at the Fuxian Solar Observatory, as well as the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). NVST provided the high-resolution observations of the chromosphere and photosphere via Hα and TiO bands, respectively. The Hα observations have a field of view (FOV) of 180° × 180°, with a pixel size of 0.163 and a cadence of 12 s. Whereas the TiO images have an observing FOV of 100″ × 80″, with a pixel size of 0.04 and a cadence of 12 s. The images in each sequence were co-aligned by the subpixel registration algorithm (Feng et al. 2012). As shown in Figures 1(a) and (b), the NVST Hα and TiO images are then registered to the heliographic coordinates by cross-correlation with Global Oscillation Network Group Hα and HMI intensity images (Liu et al. 2018). The information of magnetic field was obtained by adopting the HMI vector magnetograms, which were inverted through the Very Fast Inversion of the Stokes Vector algorithm (Borrero et al. 2011), and the remaining 180° azimuth ambiguity was resolved with the Minimum Energy code (Metcalf 1994; Leka et al. 2011).
The cadence of the vector magnetograms is 12 minutes and the accuracy is \(\sim 10 \text{ G}/\sim 100 \text{ G}\) for the vertical/transverse component. These vector magnetograms were remapped using a Lambert equal area projection and then transformed into the heliographic coordinates with projection effect removed. The \(SDO/AIA 94\) and 171 Å images were also investigated, with a pixel size of \(0^\circ 6\) and a cadence of 12 s. All of the above data were differentially rotated to a reference time close to the flare maximum.

The vector velocity fields of the photosphere were measured by applying the Differential Affine Velocity Estimator for Vector Magnetograms (DAVE4VM; Schuck 2008) based on the difference between two sets of HMI vector field data, and further corrected by removing the irrelevant field-aligned plasma flow using

\[
V_\perp = V - \frac{V \cdot B}{B^2} B,
\]

where \(V\) is the velocity derived by DAVE4VM and \(V_\perp\) is the velocity perpendicular to the magnetic field line. The corrected velocity \(V_\perp\) can denote the transport velocity of the magnetic flux in the photosphere (Kusano et al. 2002; Liu & Schuck 2012). As described by Liu & Schuck (2012), \(V_\perp\) can be decomposed into \(V_{\perp,n}\) and \(V_{\perp,r}\), which are in the directions of normal and tangential to the solar surface, respectively. The \(V_{\perp,n}\) term is related to the emergence or the submergence, and the \(V_{\perp,r}\) is related to the shear motion on the surface.

3. Results

On 2013 November 3, when AR 11884 just passed the central meridian of the solar disk, the flare SOL2013-11-03T05:22 (M5.0) occurred at the PIL of the AR, with start, peak, and end times at around 05:16, 05:22, and 06:29 UT, respectively. As shown in Figure 2, the sunspots at the PIL had a magnetic delta configuration and exhibited an extended penumbra and a relatively poor umbra. In accordance with previous studies (Wang et al. 2004; Deng et al. 2005; Liu et al. 2005), the major flare resulted in a series of significant variations on this delta sunspot structure (an animation of these data is available in Figure 3 to depict more dynamic details). By comparing the TiO images before and after the flare (panels (a1)–(a2)), it is obvious that penumbral area around \(272\arcsec\), \(-263\arcsec\) was reformed after the major flare. The right partial penumbra was strengthened and expanded into the granular area (pointed out by the blue arrow). While the left partial penumbra (pointed by the green arrow) decayed within 80 minutes during the flare and shrank toward the vaguely visible umbra where the penumbra seemed to be rooted. Following the penumbral decay, the umbra became darker and eventually turned into a small pore (pointed by the red arrow) after the penumbra completely decayed.

Based on the vector magnetograms (panels (b1)–(b2)), the expanding penumbra was located bordering the central PIL, while the decaying penumbra was in the relatively peripheral side. Moreover, the horizontal fields \(B_h\) shown by the colorful arrows) in the central region became stronger and more parallel to the PIL. However, in the penumbral decay area, the arrows nearly disappeared in panel (b2), meaning that \(|B_h|\) in this region dropped down to below 300 G after the flare. For better recognition, the TiO difference image (panel (c)) and the strength change of \(B_h\) (\(\delta|B_h|\), panel (d)) were also adopted to highlight the variations of the penumbra and their horizontal fields. Here, the region of interest was focused on the center and left side of the PIL where the major penumbral transformations happened. Clearly in panel (c), the large penumbral area was divided into three different regions, i.e., penumbral decay, penumbral enhancement, and pore formation areas, denoted by green, blue, and red contours, respectively. The contour levels were set as 1500, −2500, and −10,000 (in units of DN s, here, DN s refers to data numbers) after careful examinations. The boundary between the regions of penumbral enhancement and decay is outlined by the blue-dotted curve, with a contour level of 0 DN s in the TiO difference image. Intriguingly, this boundary was also effective in the map of \(\delta|B_h|\). In panel (d), it is quite obvious that the \(|B_h|\) decreased in the left side but increased in the right side of this boundary.

However, the question is what caused such a clear boundary to divide the large penumbral area into two different regions? To answer this question, observations of the chromosphere and corona layer are provided in Figure 4 to investigate the spatial relation between the flare eruption and the photospheric variations. As shown in the Hα images (panel (a) and the online animated Figure 3), this flare was associated with the eruption of a filament bordered by the two typical flare ribbons on both sides. Particularly, a part of the left-side flare ribbon was just coincided with the boundary (blue-dotted curve) mentioned before. The penumbral enhancement area (blue contour) was located in the right side of this ribbon and close to the flaring PIL, whereas the penumbral decay area (green contour) was partially covered by this ribbon and partially located in the left side away from the PIL. In the AIA 94 Å image at the peak time of the flare (panel (b)), it can be seen that the coronal flaring region was located close to the large penumbral area and covered a part of the penumbral enhancement region. However, most of the penumbral decay area was adjacent to but did not coincide with the flaring region. To further study the coronal HXR emission source in detail, we constructed the \(RHESSI\) X-ray map (using the CLEAN algorithm) in the energy range of 6–12 keV. The integration time was set from 05:55:34 UT to 05:58:34 UT around the second peak of the flare when the large penumbral area was under transformation as seen from the animated Figure 3. As shown in panel (c), a bright HXR emission source can be found bordered by the penumbra enhancement area. Compared with the penumbral enhancement area, the penumbral decay area was located more peripheral away from the HXR source. Moreover, the closed-up views of 171 Å images (panels (d)–(f)) show the appearance of the post-flare loops and further compare with the outlines of the sunspots. As shown in panels (e) and (f), the newly appearing post-flare loops crossed over the flaring PIL and rooted in the region around the umbras on the opposite sides of the PIL. By comparing the penumbral outer boundary between three images, it can be seen that the penumbra outside the left footprint of the loops almost decayed, while the penumbra between two footpoints still remained and expanded along the PIL. Consequently, the observations indicated that the penumbral enhancement area was close to the flare center, while the decay part was located in the relatively outer region.

As previously described, magnetic fields suffer transformations during the observed penumbra enhancement and decay.
Much of the research has reported that the flare-induced transformation of magnetic fields can be observed as sudden motions of magnetic fields in the photosphere (Wang et al. 2014; Bi et al. 2017). In Figure 5, the velocity field of magnetic motions was provided by using the DAVE4VM method. The horizontal term was indicated by the orange arrows overplotted on the sunspot structure, with the length denoting the size of velocity, and the vertical term was plotted as the velocity diagram, with the red (blue) patches referring to the down (up) motions. At 05:00 UT before the flare, both the horizontal and vertical motions cannot be clearly detected. However, at 05:24 UT around the peak time of the flare, an obvious horizontal motion (maximum velocity of $\sim 1.4 \text{ km s}^{-1}$) suddenly appeared in the large penumbral area, moving from the left to the right part. At the same time, there was a significant upward motion (maximum velocity of $\sim 1.3 \text{ km s}^{-1}$) at the location of the penumbral decay, in which the magnetic fields were transported rightward during their uplift. On the contrary, at the location of penumbral enhancement, the magnetic fields suffered a downward motion (maximum velocity of $0.6 \text{ km s}^{-1}$) while shifted rightward. Then, at 06:00 UT, in the decay phase of the flare, the magnetic motions were gradually reduced, but it still had some horizontal component from the left partial penumbra toward the umbra where they rooted. During the steadily converging motions of the magnetic field, an umbra developed and became prominent. Finally, at 06:36 UT, after the flare, the magnetic motions almost stopped except for a swirl motion around the pore, and the sunspot structure stayed unaltered. As a result, the right part of the penumbra enhanced and expanded into the granular area, while the left part decayed and possibly transformed into a small pore after the major flare.

The entire process of the penumbral transformations can be comprehensively reflected more clearly by the time slices made from NVST TiO images along two slits, S1 and S2. As shown in Figure 5, the blue slit (S1) was set roughly along the fibrils in the right part of the penumbra to investigate the penumbral enhancement and growth. The other green slit (S2) was set along the fibrils in the left part of the penumbra to track the penumbral decay and pore formation. Moreover, three integral areas, D, E, and F, which covered the penumbral decay, penumbral enhancement, and pore formation regions, were also selected to track their local magnetic field’s changes. The results are given in Figure 6 and compare with the GOES 1–8 Å

**Figure 2.** Comparison of the NVST TiO images (panels (a1)–(a2)) and the HMI vector magnetograms (panels (b1)–(b2)) before and after the flare. In the magnetograms, the vertical fields ($B_z$) are plotted as grayscale background and isogauss contours with levels of $\pm500, 1000,$ and $1500 \text{ G}$. The horizontal components ($B_h$) are denoted by the short arrows aligned to the field direction with color indicating the field strength (see the color bar), and the arrows with $|B_h|$ less than $300 \text{ G}$ are not overplotted. Panels (c) and (d) show the TiO different image and the strength change of $B_h$ ($\delta |B_h|$) between the pre- and post-flare states. In panel (c), green, blue, and red contours outline the penumbral decay, enhancement, and pore formation areas, with levels of $1500, −2500, \text{ and } −10000 \text{ DNs}$, respectively. The blue-dotted curve with level of 0 DNs showing the boundary between the penumbral decay and enhancement areas. The magnetic PIL is overplotted as the dashed yellow curves in panels (b1), (b2), and (c).
Clearly, both the left and right parts of the penumbra had obvious evolutions during the flare eruption as indicated by the time slices (panels (a) and (b)). The right part (panel (a)) enhanced obviously and expanded into the granular area around the first peak of the eruption, with a mean velocity of \( \sim 0.98 \text{ km s}^{-1} \). Then the velocity reduced to \( \sim 0.24 \text{ km s}^{-1} \) during the following two small peaks of the flare. While in the left part (panel (b)), the penumbral decay and the pore formation mainly happened in the flare decay phase, which was slightly delayed relative to the rapid expanding in the right part. The mean velocity of the penumbral decay was on the order of \( \sim 1.07 \text{ km s}^{-1} \). Particularly, following the penumbral decay, the formed pore can be clearly seen after the flare as pointed out by the red arrow in panel (b). Moreover, this pore formation was associated with the concentration of the magnetic flux during the flare. As shown in panel (c), the magnetic flux in the penumbral decay area (D flux) significantly reduced from \( \sim 7.72 \times 10^{19} \) to \( \sim 3.49 \times 10^{19} \) Mx, and the magnetic flux in the pore formation area (F flux) subsequently increased from \( \sim 2.57 \times 10^{19} \) to \( \sim 2.80 \times 10^{19} \) Mx after the onset of the flare. Combined with the magnetic motions in Figure 5, it can be speculated that part of the magnetic flux in region D transformed to the flux in region F, which resulted in the penumbral decay and the pore formation.

As for the concrete information of the local magnetic field changes, the right column in Figure 6 shows the time profiles of the mean inclination angle (panel (d)), the mean horizontal field’s strength (panel (e)), and the mean vertical field’s strength (panel (f)), with the green, blue, and red curves in each panel representing the corresponding results calculated from regions D, E, and F, respectively. In panel (d), the inclination angle is defined with respect to the photospheric surface, i.e., 0° is horizontal, while 90° is vertical. It is clear that the mean inclination angles in regions D, E, and F were similar before the flare eruption, but they became different when the flare erupted. In region E, the inclination angle suddenly reduced by \( \sim 9.4° \), while in regions D and F, the inclination angle significantly increased by \( \sim 15.0° \) and \( \sim 17.9° \), respectively. It means that the magnetic fields became more horizontal in the penumbral enhancement area, and contrarily they became more vertical in the penumbral decay and pore formation areas. In addition, the magnetic field strength also showed sudden
variations as indicated by the time profiles of the mean $|B_h|$ and $|B_r|$ in panels (e) and (f). Consistent with previous observations (Xu et al. 2016, 2017), the penumbral enhancement and decay was associated with the $|B_h|$ increasing and decreasing, with an order of $\sim 464$ G and $\sim 491$ G, respectively. Meanwhile, their $|B_r|$ had no obvious changes. However, meaningfully in this event, $|B_r|$ in the pore formation area significantly increased by $\sim 348$ G during the flare, while its $|B_h|$ only slightly decreased by $\sim 68$ G. This confirms the previous speculation that the magnetic flux converged in the pore formation area when the magnetic fields lifted up in the outer region.

4. Discussion and Conclusion

In this paper, we have presented a clear observation of the sudden variations on a large penumbral area during the flare SOL2013-11-03T05:22 (M5.0). By means of the NVST-SDO joint observational data, the main flaring region was under careful analysis through the multiwavelength imaging ranged from the photosphere to the chromosphere and corona layers. Additionally, the DAVE4VM photospheric velocity field and the HMI vector magnetic magnetograms were also adopted to investigate the magnetic motion and the evolution of the local magnetic field associated with the penumbral transformations. The main results and our interpretations are summarized as follows.

1. Observationally, the large penumbral area experienced two different transformations which were bordered by the left flare ribbon. The right partial penumbra expanded permeating into the granular area between the two flare ribbons and bordering the PIL, while the left partial penumbra was decaying and transforming to a small pore when swept by the left flare ribbon. Moreover, the RHESSI X-ray and AIA EUV images indicated that the flaring center was close to the penumbral enhancement region, whereas the penumbral decay region was on the relatively outer side.

2. The rearrangement of magnetic field can be found associated with the penumbral transformations during the flare. In the outer penumbral decay area, the magnetic fields were transported upward and rightward, meaning that the magnetic fields were lifted up toward the upper flare center. Contrarily in the central penumbral enhancement area, the magnetic motions were downward while shifted rightwards, meaning that the magnetic fields were collapsing down to the solar surface. These results were consistent with the magnetic implosion scenario.

Figure 4. NVST Hα image (panel (a)) showing the two-ribbon flare in the chromosphere associated with the filament eruption. AIA 94 Å image (panel (b)) showing the main flaring region in the corona at the peak time of the flare. The RHESSI CLEAN-reconstructed map (panel (c)) showing the X-ray emission in 6–12 keV between 05:55 and 05:58 UT, when the large penumbral area was under transformation. The green, blue, and red contours in panels (a)–(c) outline the penumbral decay, enhancement, and pore formation regions as described in Figure 2. Close-up views of AIA 171 Å images (panels (d)–(f)) showing the appearance of the post-flare loops. The black and gray contours correspond to the outer boundaries of umbra and penumbra, respectively, with levels of 65% and 87% of the mean quite-Sun intensity in the NVST TiO images. The magnetic PIL is overplotted as the dashed yellow curves in panels (a), (e), and (f).
Figure 5. Selected TiO images (panels (a1)-(a4)) from 05:00 UT to 06:36 UT showing the evolution during the penumbra transformation, with the orange arrows indicating the mean $V_{\perp}$ in the next 12 minutes. The corresponding $V_{\perp}$ diagrams are shown in the right column (panels (b1)-(b4)), with the red/blue patches referring to the downward/upward motions (see the color bar). In panel (b2), the magnetic motions are compared with the outer boundary of penumbra (gray contour). Green, blue, and red boxes show the integral areas of penumbral decay (region D), penumbral enhancement (region E), and pore formation (region F). The blue and green arrows (S1 and S2) mark the positions of time slices in Figure 6.
illustrated by Wang et al. (2012) and this scenario was also confirmed by the local magnetic field’s changes. During the flare eruption, the magnetic fields in the central penumbral enhancement area became more horizontal and their $|B_h|$ were significantly enhanced. While the magnetic fields in the outer penumbral decay area became more vertical and their $|B_h|$ were drastically decreased.

3. Following the uplift motion of the magnetic fields in the outer region, magnetic convergent motions can be observed along with the decaying penumbra. Consequently, partial magnetic flux of the penumbral decay region transformed to that of the pore formation region. The concentration of magnetic fields significantly enhanced the $|B_h|$ in the pore formation region and further suppressed the local convective heat transportation. As a result, a darker pore formed in this compact region. Moreover, the time slices indicated that the penumbral decay and pore formation appeared slightly later than the penumbral enhancement. We thus infer that the uplift of the field in the outer region appeared after the collapse of the field in the central region. However, this delay cannot be very clearly observed in the inclination angle changes with a cadence of 12 minutes. Therefore, more observations and further analysis would be needed with high cadence vector magnetic field data.

Clearly, the present work confirms the magnetic implosion idea that the flare eruption in the upper corona could have the back reaction to the solar surface, and the sunspots structure could be affected by the rearrangement of the local magnetic fields. In this event, the variations mainly occurred in the penumbral part of the sunspots. Recently, Deng et al. (2017) also reported that the fine structures in the umbra, such as the umbral dots, could show rapid evolution during a major flare. It can be expected that, with the aid of high-resolution observations, more details about the flare-induced transformations of sunspots would be observed and studied in the future work.

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