Formation of Moving Magnetic Features and Penumbral Magnetic Fields with Hinode/SOT

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Abstract

Vector magnetic fields of moving magnetic features (MMFs) were well observed with the Solar Optical Telescope (SOT) aboard the Hinode satellite. We focused on the evolution of three MMFs with the SOT in this study. We found that an MMF having relatively vertical fields with the same polarity as the sunspot was detached from the penumbra around the granules appearing in the outer penumbra. This suggests that granular motions in the outer penumbra are responsible for disintegration of the sunspot. Two MMFs with polarity opposite to the sunspot are located around the outer edge of horizontal fields extending from the penumbra. This is evidence that the MMFs with polarity opposite to the sunspot are the prolongation of penumbral horizontal fields. Redshifts larger than the sonic velocity in the photosphere are detected for some of the MMFs with polarity opposite to the sunspot.

Key words: Sun: magnetic fields — Sun: photosphere — Sun: sunspots

1. Introduction

A lot of small magnetic features moving outward are observed in moat regions surrounding mature sunspots. Such magnetic features, called moving magnetic features (MMFs: Harvey & Harvey 1973), have been studied for about 40 years after their discovery by Sheeley (1969), but their formation process and magnetic field structure are still open issues due to a difficulty of tracking the evolution of such tiny magnetic features using vector magnetograms with high spatial resolution.

The relationship between MMFs and penumbral fields is important for understanding the formation of MMFs and the decaying process of sunspots. The penumbral outer boundary has at least two magnetic components (horizontal fields and relatively vertical fields), called an uncombed structure (Solanki & Montavon 1993), and Evershed flows are observed in the horizontal component of the penumbra (Degenhardt & Wiehr 1991; Title et al. 1993; Lites et al. 1993; Rimmele 1995; Stanchfield et al. 1997; Westendorp Plaza et al. 2001a, 2001b; Mathew et al. 2003; Bellot Rubio et al. 2003, 2004; Ichimoto et al. 2007a). Some authors have suggested that such Evershed flows drive outward motions of MMFs (Ryutova et al. 1998; Martínez Pillet 2002; Thomas et al. 2002; Schlichenmaier 2002; Zhang et al. 2003). Sainz Dalda and Martínez Pillet (2005) observed that several bipolar MMFs crossed the penumbral outer boundary to enter the moat region along the penumbral horizontal fields. Cabrera Solana et al. (2006) discovered that at least some MMFs were the continuation of penumbral Evershed flows into the moat region. Kubo et al. (2007) found that MMFs had a significant magnetic correspondence with a penumbral uncombed structure from the observation of vector magnetic fields with the Advanced Stokes Polarimeter (Elmore et al. 1992): MMFs having horizontal fields with both polarities were located on a line extrapolated from the horizontal component, while MMFs having relatively vertical fields with the same polarity as the sunspot were located on the line extrapolated from the vertical component (spine). Unipolar MMFs with the same polarity as the sunspot have been less studied so far, but they would be more important in terms of sunspot decay.

In this study, we investigated the temporal change of the magnetic field vector for MMFs with the Solar Optical Telescope (SOT: Tsuneta et al. 2007; Suematsu et al. 2007; Ichimoto et al. 2007b; Shimizu et al. 2007a) aboard Hinode (Kosugi et al. 2007). The Hinode/SOT provides a time series of vector magnetic fields with the finest resolution (0.3") ever achieved with uniform data quality.

* Movies for figures 2 and 3 are available in the electronic version (http://pasj.asj.or.jp/v59/s3/v59s306/).
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used a data set obtained with the Spectro-Polarimeter (SP) of the SOT/SP repeatedly scanned the same region with a cadence of 21.6 m˚A. Based on the result of Kubo et al. (2007), we investigate the evolution of MMFs located on the lines extrapolated from the vertical and horizontal components of the penumbra separately.

3.1. MMF Detached from the Penumbral Spine

The penumbral spine is a radial filamentary structure with more vertical magnetic fields than the surroundings (Lites et al. 1993), as shown by the black arrow in figure 2b. We find that the penumbral spine branches off at their outer edge (two green arrows in the first panel of figure 2b). The right branch of the spine is connected to a large magnetic feature with vertical fields in the first frame; this large magnetic feature also branches off at its outer edge. Then, this large magnetic feature is detached from the penumbral spine in the later frames. We have confirmed that the detached magnetic feature moves through the moat region as the MMF after the SP observation using longitudinal magnetograms with the Narrow band Filter Imager (NFI) of the SOT. There is no magnetic feature connected to the left branch of the spine in the first frame. The left branch elongates and a tiny magnetic feature (the green arrow at 22:41 frame in figure 2b) subsequently appears at the outer edge of the elongated branch. Such a tiny magnetic feature is also formed for the right branch immediately after the large magnetic feature is detached (the green arrow in the last frame of figure 2b).

We found that the branch of penumbral spine is formed along the edge of bright features in the penumbra (the horizontal arrow in figure 2a). The bright features are located around the penumbral spine, but the penumbral spine itself is not bright. Such bright features gradually connect to the granular cells outside the penumbra, and then the dark penumbral area between them completely disappears. Another large bright feature (the vertical arrow in figure 2a at 22:15) appears at the right side of the right branch, while the large magnetic feature with more vertical fields is separating from the spine. The bright features in the penumbra have upward motions and weaker field strength for both longitudinal and transverse components, compared with the surrounding penumbral fields. These properties are similar to granular cells outside the penumbra. The difference in the magnetic and velocity fields from the surrounding penumbra is less clear for the bright features in the inner penumbra.

We can see many velocity features other than upward motions of the bright features, but there is no systematic flow related to the formation of a penumbral spine and MMFs detached from the spine.

3.2. MMFs Located on the Lines Extrapolated from the Horizontal Component of the Penumbra

Only MMFs with negative polarity, which is polarity opposite to the sunspot, are described here in detail, because they are clearly identified from their surroundings. We discovered that two MMFs with polarity opposite to the sunspot appear at the outer edge of horizontal fields extending from the penumbra, and move outward with the extending horizontal fields. The areas with stronger transverse field are extended to the moat region from the penumbra, as shown by the red and green arrows in figure 3c. The outer edge of extending horizontal fields clearly corresponds to the positions

Fig. 1. G-band image with Hinode/SOT for a sunspot in the active region NOAA 10933 on 2007 January 4. The field of view of the Spectro-Polarimeter of the SOT is shown by the dotted box. Two white solid boxes indicate the field of view for figures 2(lower) and 3(upper) respectively.
Fig. 2. Time series of (a) continuum intensity, (b) longitudinal magnetic field, (c) transverse magnetic field, and (d) Doppler velocity for a MMF having relatively vertical fields with the same polarity as the sunspot. The continuum intensity was normalized to the quiet area intensity. The contours represent the continuum intensity of 0.87, which corresponds to the boundary between the quiet area and the penumbra. White (black) is positive (negative) polarity in panel b and a positive velocity corresponds to a redshift. See the text for arrows in the panels. Panels a, b, c, and d are also shown as movie 1.

Figures 3b and 3d show that the negative-polarity MMFs have large redshifts. This result has already been mentioned of the two MMFs with negative polarity. The fuzzy and elongated MMF with positive polarity is observed inside the extending horizontal fields (the black arrow in figure 3b). These horizontal fields extending from the penumbra have been observed around the outer boundary of the penumbra in other data sets.
Fig. 3. Same as figure 2, but for MMFs with polarity opposite to that of the sunspot. The red and green arrows in panels b and c represent the outer edges of horizontal fields extending from the penumbra, and the black arrow represents the position of the MMF with positive polarity. The cross symbol indicates the position for which the Stokes profiles are displayed in figure 5. The center of the boxes in panel b are manually determined to track the center of a MMF with negative polarity. The first box is located at the same position as the second one because the MMF appears from the second box. Panels a, b, c, and d are also shown as movie 2.∗

in previous papers (Westendorp Plaza et al. 2001a; Cabrera Solana et al. 2006). One example of evolution in Stokes profiles is shown in figure 4. We find that the shift of linear polarization profiles ($Q$ and $U$) are much different from that of circular polarization ($V$); a major component of the linear polarization has a blueshift of about $-1$ km s$^{-1}$, while a major component of the circular polarization has a redshift of about $+5$ km s$^{-1}$ when the negative MMF appears. Note that the large downward component is seen not only in the Stokes $V$ profile, but also in the Stokes $Q$ and $U$ profiles: the Stokes $Q$ and $U$ have an extended wing that reaches the range of 5–10 km s$^{-1}$. The major component of the linear polarization does not significantly change with time, while the redshifted circular polarization decreases. The duration of the large redshift is more than 10 minutes for the two cases in figure 3, and Shimizu et al. (2007b) showed that a typical duration of such a large redshift around the penumbrae is 5–20 minutes.

Redshifts larger than the sonic velocity ($\sim 7$ km s$^{-1}$) in the photosphere have been detected for some of the MMFs with negative polarity in this study, as shown in figure 5. The zero-cross position of the Stokes $V$ profile is estimated to be about $+9$ km s$^{-1}$. In this case, significant linear polarization
Fig. 4. Time series of Stokes profiles at the center of the boxes in figure 3. Stokes $Q$, $U$, and $V$ are shown with the same vertical scale, and the scale of Stokes $I$ is 10 times larger than the other profiles. Zero velocity of horizontal axis corresponds to the averaged velocity over the quiet area. The MMF appeared at 22:30.

Fig. 5. Example of Stokes profiles for the negative polarity MMF (the cross symbol in figure 3). The vertical axis is normalized by a continuum intensity. The zero velocity of the horizontal axis corresponds to the averaged velocity over the quiet area.

signals ($Q$ and $U$) are not observed, but linear polarization is often observed in MMFs with negative polarity, as well as the circular polarization, as shown in figure 4.

4. Discussion

Our observational result of the MMF detached from the penumbral spine shows that the branching and elongating of the spine are the basic process in the formation of the vertical MMF. Such vertical MMFs can carry away sufficient magnetic flux, causing a loss of the sunspot magnetic fields (Kubo et al. 2007). Therefore, we suggest that the granules appearing in the outer penumbra remove the vertical MMF from the penumbra, and that such granules are responsible for the decay of the sunspot (figure 6a). We believe that the observed MMF is a representative case of vertical MMFs with the same polarity as the sunspot, but the branches of the penumbral spines and the granules in the outer penumbra are not observed for all of the spines. Many small spines, themselves, seem to be elongating rather than branching. Whether the granules appear in the outer penumbra...
penumbra may depend on the size and amount of field-free gas under the photospheric surface. It is necessary to confirm that the nature of the observed MMF is common to other vertical MMFs.

The fact that the MMFs with polarity opposite to that of the sunspot are located at the outer edge of horizontal fields extending from the penumbra is evidence that such MMFs are continuations of the penumbral fields. This result supports the idea that such MMFs and the extending horizontal fields have the shape of a sea serpent (Harvey & Harvey 1973; Schlichenmaier 2002). The MMFs with both polarities located at the outer edge and the inside of the extending horizontal fields are intersections with the photospheric surface (formation layer of Fe I lines). The extending horizontal fields correspond to diffuse and ubiquitous moving moat fields in previous observations (Sainz Dalda & Martínez Pillet 2005; Kubo et al. 2007). The SOT, for the first time, clearly resolves the diffuse structure in the moat region observed with a lower spatial resolution in the past, and reveals that the moving moat fields extending from the penumbra are dynamical phenomena.

The complicated Stokes profiles for the MMFs with opposite polarities to that of the sunspot are reported in Cabrera Solana et al. (2006), and the complication of profiles seems to increase in the SOT data due to the resolution of magnetic fields with large velocity from ambient fields without any motion. The assumption of a Milne–Eddington atmosphere is too simple for a quantitative discussion on the MMFs having the Stokes V profile with more than two lobes. However, the MMFs with polarity opposite to the sunspot apparently have a larger circular polarization signal than the linear polarization in the red wing. This means that such MMFs are more vertical than the horizontal fields extending from the penumbra and have large downward motion in the deep layer of photosphere. The inclination of extending horizontal fields drastically change at the patchy area of MMFs with polarity opposite to that of the sunspot (figure 6b).

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