Magnetic Correspondence between Moving Magnetic Features and Penumbral Magnetic Fields

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Abstract. We investigate vector magnetic fields of moving magnetic features (MMFs) around a mature sunspot with the Advanced Stokes Polarimeter and SOHO/MDI. In addition to the classical isolated MMFs identified by visually inspecting the time sequence of MDI magnetograms, we focus on any diffuse moving magnetic features that are not recognized as classical MMFs. This feature is called non-isolated MMFs. The non-isolated MMFs occupy most of the moat region surrounding the sunspot, and have nearly horizontal magnetic fields with both polarities. We find that the isolated MMFs located on the lines extrapolated from the horizontal component of the penumbral uncombed structure have magnetic fields similar to the non-isolated MMFs. This suggests that such MMFs are part of horizontal fields extended from the penumbra. The isolated MMFs located on the lines extrapolated from the vertical component of the uncombed structure have vertical fields with polarity same as the sunspot. Our observation shows that such MMFs are detached from the vertical component of the penumbra. Their flux transport rate is estimated to be 1-3 times larger than a flux loss rate of the sunspot. The isolated vertical MMFs alone can be responsible for decaying the sunspot.

1. Introduction

Moving magnetic features (MMFs) are small magnetic elements moving outward in a zone called moat region surrounding the sunspot (Sheeley 1969; Vrabec 1971; Harvey & Harvey 1973). Most of previous works have used longitudinal magnetograms to derive properties of MMFs such as size, motion, and lifetime (e.g., Harvey & Harvey 1973; Ryutova et al. 1998; Zhang et al. 2003). Magnetic field structure of MMFs still remains an open issue. We investigate vector magnetic fields of MMFs from an observation with the Advanced Stokes Polarimeter (ASP, Elmore et al. 1992) and the Michelson Doppler Imager (MDI, Scherrer et al. 1995) to understand the magnetic field structure of MMFs.

MMFs are important for the understanding of the decaying process of sunspots. Time sequences of longitudinal magnetograms give an impression that MMFs carry away magnetic flux from sunspots. Total magnetic flux of MMFs with the polarity same as sunspots is 3-8 times larger than flux loss of sunspots (Martínez Pillet 2002). This result indicates that only limited part of the MMFs contribute to the flux loss of sunspots. In order to understand which MMFs are responsible for decaying a sunspot, we compare magnetic field properties of MMFs to those of sunspot penumbral fields. We estimate how much magnetic flux is carried away from sunspot by MMFs.
2. Observations and Data Analysis

We carried out observations of a well-developed sunspot in an active region NOAA 0306 with the ASP and MDI during 2003 March 11 to 17. We used an ASP data set taken in 17:13–17:35 UT on 2003 March 12 (Figure 1). The sunspot was located near the disk center (N6°, E10°) and rather simple in circular shape. A seeing condition of this map was better than those of the other maps simultaneously observed with MDI longitudinal magnetogram in high resolution mode on March 12.

The ASP is a spectro-polarimeter with capability of precisely measuring the full Stokes profiles of Zeeman sensitive Fe I 6301.5 Å and Fe I 6302.5 Å lines. The slit width was 0′′.525 with the field of view along the slit of 90′′. The mapping to cover the sunspot required 20 minutes. The spatial resolution was about 1′′–3′′, depending on the atmospheric seeing, although the pixel size is 0′′.37. Magnetic field vector and thermodynamic parameters were derived from the ASP full Stokes profiles by using a non-linear least-squares fitting code (called a Stokes inversion) developed by the HAO (Skumanich & Lites 1987; Lites & Skumanich 1990). The HAO inversion code assumes the Milne-Eddington atmosphere and a two-component model atmosphere, which is composed of magnetized and non-magnetized atmospheres. More detailed descriptions for the routine data analysis can be found in Kubo et al. (2003).

MDI longitudinal magnetograms in high resolution mode have one minute cadence and 640′′ × 320′′ field of view with pixel sampling of 0′′.625. Horizontal velocity of magnetic features was obtained by applying a local correlation tracking method (November & Simon 1988) to MDI magnetograms (Chae et al. 2001b; Sakamoto 2004). The two images were made by averaging 5 sequential MDI longitudinal magnetograms (5 minutes) obtained around 17:29 and 17:39 on 2003 March 12 in order to reduce noise. The 1σ noise for the averaged MDI magnetogram was typically 8.9 G (Krivova & Solanki 2004). When a pixel of the averaged MDI magnetogram had magnetic flux less than 10 G or cross-correlation coefficient was less than 0.9, the horizontal velocity for the pixel was not computed. A FWHM of an apodization window was set to be 4 arcsec when we computed the horizontal velocity.

3. Results

3.1. Isolated MMFs and Non-Isolated MMFs

We identify moving magnetic elements isolated from their surroundings in the moat region by visually inspecting the time sequence of the MDI magnetograms. Such MMFs are called isolated MMFs in this study, and these MMFs are referred to as MMFs by previous authors. The moat region is defined to have the width of 15 arcsec (dash-dotted line in Figure 1 (a)) from the outer boundary of the sunspot penumbra (dashed line in Figure 1 (a)). This boundary is given by a continuum intensity level at a local minimum in between two intensity peaks of the quiet area and the penumbra. The selected MMFs (21 MMFs with positive polarity and 21 MMFs with negative polarity) are marked by boxes in Figure 1.

Most of the moat region surrounding the isolated MMFs also have polarization signal higher than the threshold (0.4%), allowing us to perform the Stokes
Figure 1. A sunspot in the active region NOAA 0306 on 2003 March 12. (a) Continuum intensity, (b) magnetic flux, and (c) magnetic field inclination map derived from the ASP data. The magnetic flux map shows the quantity \( F = f |\mathbf{B}| \cos \gamma \) for each pixel, where \( f \), \( |\mathbf{B}| \), and \( \gamma \) are the filling factor (the areal percentage of each pixel occupied by magnetic atmosphere), the field strength, and the inclination respectively. White (black) is for positive (negative) polarity in panel (b). The inclination of 0° and 180° represent that magnetic fields are vertical to the solar surface and 0° corresponds to the direction away from the surface. When magnetic fields are parallel to the solar surface, the inclination is 90°. The dashed line represents the outer boundary of the penumbra. The dash-dotted line represents the position of 15 arcsec in the radial distance from the penumbral outer boundary. Position angle, which is measured counterclockwise around an azimuth center (cross symbol of panel (a)) of the sunspot from the solar west, is used to produce Figures 3. The boxes show the isolated MMFs. Degree of polarization is less than 0.4% for the hatched areas in panel (c). Panel (d) shows horizontal velocity map derived from the MDI magnetograms in high resolution mode with the local cross-correlation technique. White areas represent invalid MDI data areas, which have magnetic flux less than 10 G or the maximum correlation coefficient less than 0.9. Positions are given with respect to the center of the solar disk.
inversion. Horizontal velocity map obtained with the MDI magnetograms shows that magnetic features other than the isolated MMFs also move outward (Figure 1 (d)). Such magnetic features are called non-isolated MMFs in this paper.

Magnetic fields of the non-isolated MMFs are nearly horizontal to the solar surface (γ = 60° − 105°) as shown by Figure 2 (a). The peak in the histogram of inclination is shifted about 10° to positive polarity, which is same as the polarity of the sunspot. Magnetic elements can be identified as the isolated MMFs either when they have polarity opposite to the ambient magnetic fields or when they have magnetic fields > 15° more inclined from that of the ambient magnetic fields (Figure 2 (b)).

3.2. Magnetic Relation between MMFs and Penumbra

We find magnetic correspondence between the isolated MMFs and the penumbral magnetic field structure. Significant azimuthal fluctuations in the inclination and strength of magnetic field vector are observed around the outer boundary of the penumbra as shown in Figure 3 (a) on the assumption that each pixel contains one magnetized atmosphere (Degenhardt & Wiehr 1991; Title et al. 1993; Lites et al. 1993; Stanchfield et al. 1997; Westendorp Plaza et al. 2001a,b; Mathew et al. 2003). These azimuthal fluctuations are mainly due to fluctuations in the filling factors of two magnetic components, which are horizontal fields and relatively vertical fields in the penumbra (Bellot Rubio et al. 2004). Such penumbral magnetic field structure is called uncombed structure (Solanki & Montavon 1993), fluted structure (Title et al. 1993), spine/intra-spine structure (Lites et al. 1993) or interlocking-comb structure (Thomas & Weiss 1992). Magnetic fields of the isolated MMFs located on the lines extrapolated from the relatively vertical component of the penumbral uncombed structure are more vertical to the solar surface than the surroundings. These MMFs have polarity same as the sunspot. The isolated MMFs with nearly horizontal magnetic fields are located on the lines extrapolated from the horizontal component of the penumbral uncombed structure. They have both polarities.
3.3. Flux Transport by MMFs and Flux Loss of Sunspot

MMFs are completely separated from the penumbral uncombed structure around the middle of the moat region \((d_p = 7\) arcsec), according to the time sequence of MDI magnetograms. Thus, the radial outward flux transport rate at \(d_p = 7\) arcsec corresponds to magnetic flux carried away from the sunspot. Most of the MMFs have positive polarity around \(d_p = 7\) arcsec.

The flux transport rate of the positive-polarity MMFs \((5.0 \times 10^{21} \text{ Mx day}^{-1})\) is much larger than that of the negative-polarity MMFs \((0.1 \times 10^{21} \text{ Mx day}^{-1})\) mainly due to difference between the number of positive and negative polarities. The difference between their flux transport rates is about 7 times larger than the flux loss rate of the sunspot \((0.7 - 0.8 \times 10^{21} \text{ Mx day}^{-1})\). The flux loss rate of the sunspot is determined from day-by-day change of total flux of the sunspot during March 12 to 14. Our result is consistent with an estimate of Martínez Pillet (2002), which gave the rate of flux generation by appearance of MMFs with polarity same as the sunspots 3–8 times larger than the flux loss rate of the sunspots. The observations presented here suggest that a part of the MMFs could account for the disintegration of the sunspot. The flux transport rate of the positive-polarity MMFs with vertical magnetic fields is 1–3 times larger than the flux loss rate of the sunspot in the moat region outside the penumbral uncombed structure \((d_p = 7 - 15\) arcsec). Thus, the vertical MMFs can carry away sufficient magnetic flux for the flux loss of the sunspot.

4. Discussions and Conclusions

We extend the definition of MMFs to cover not only the classical MMFs (isolated MMFs) but also any moving magnetic fields in the moat (non-isolated MMFs).
Figure 4. Variations in a radial transport rate ($\Phi_r$) of MMFs in position angle $\psi_p$ of $60^\circ - 180^\circ$ as a function of a distance ($d_p$) from the penumbral edge. We estimate the radial transport rate of MMFs by calculating $\Phi_r = \int_{\psi_p=60^\circ}^{\psi_p=180^\circ} (f|B|\cos\gamma)v_r d\psi_p$, where $f$ is filling factor, $|B|$ is field strength, $\gamma$ is inclination of magnetic fields to the local vertical, $v_r$ is radial component of horizontal velocity, and $\psi_p$ is the position angle. The magnetic parameters ($|B|$, $f$, and $\gamma$) are obtained with the ASP, and the horizontal velocity ($v_r$) is obtained with the local correlation technique for the MDI line-of-sight magnetic signal. The size of one ASP pixel (0.37 arcsec) is used for $dl = rd\psi_p$. The black and gray solid lines represent the flux transport rate of the MMFs with positive and negative polarities respectively. The black dashed-dotted line and gray dotted line represent pixels having vertical magnetic fields with positive ($0^\circ < \gamma < 45^\circ$) and negative ($135^\circ < \gamma < 180^\circ$) polarities respectively. Outward transport is positive.
Our finding of the magnetic correspondence between the isolated MMFs and the penumbral magnetic fields supports the magnetic field structure proposed by Thomas et al. (2002) and Weiss et al. (2004): The vertical component of the penumbral uncombed structure are detached from sunspots, forming unipolar MMFs with polarity same as the sunspot (Figure 5 (a)). Such MMFs contribute to the disintegration of the sunspot. On the other hand, the bipolar MMFs and unipolar MMFs with polarity opposite to the sunspot correspond to intersections of the horizontal fields extended from the penumbra (Figure 5 (b)). Our finding also suggests that a magnetic field structure on the lines extrapolated from the horizontal component of the uncombed structure can be interpreted as the shape of a sea serpent (Harvey & Harvey 1973; Schlichenmaier 2002).

We estimate that flux transport rate of the isolated vertical MMFs with polarity same as the sunspot is about 1–3 times larger than the flux loss rate of the sunspot. If any other MMFs excepting such MMFs contribute to the flux loss of the sunspot, the flux transport rate due to the MMFs becomes much larger than the flux loss rate of the sunspot. Therefore, we conclude that the isolated vertical MMFs with polarity same as the sunspot alone can be responsible for decaying the sunspot.

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