Spectro-polarimetric Observations of Moving Magnetic Features around a Pore

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Abstract. Moving Magnetic Features (MMFs) are small-size magnetic elements that are seen to stream-out from sunspots. Although several observations suggest that MMFs are closely related to the existence and presence of penumbral filaments, there are some very few observations that report MMFs streaming from pores and sunspots after the penumbra has disappeared. Here we report on the first high spectral, spatial and temporal resolution observations of type II and III MMFs streaming out from a small pore and compare our results with previous observations of features streaming out from penumbrae. We analyzed spectro-polarimetric observations of NOAA 11005 acquired with the IBIS instrument at the Dunn Solar Telescope in the Fe i 617.3 nm and the Ca ii 854.2 nm spectral lines, and in the G-band. We show that the characteristics of the investigated MMFs agree with those reported in the literature for MMFs which stream out from spots with penumbrae. We believe that our results provide new information that might be helpful in the future development and upgrade of numerical modeling of the generation of MMFs in the lack of a penumbra.

1. Introduction

In this paper we investigate the role played by moving magnetic features (MMF) in the process of diffusion and re-distribution of the magnetic field during the decay phase of active regions, in order to give a contribution to the comprehension of the role that diffused magnetic fields can have in the global dynamo mechanism.

MMFs have been classified into the following types (see e.g., Shine et al. 2000): (a) Type I MMFs are bipolar structures, of typical velocities ~ 0.5−1 km s⁻¹, which can be further divided into two classes: Ω-shaped, having an inner footpoint of the same polarity as the sunspot, and U-shaped, characterized by an inner footpoint of opposite polarity with respect to the parent sunspot; (b) Type II MMFs are single magnetic elements having the same polarity as the parent sunspot, characterized by velocities of ~ 0.5 − 1 km s⁻¹; (c) type III MMFs are single magnetic elements of opposite polarity...
with respect to the sunspot from which they stream out, and have velocities in the range \(\sim 2 - 3\ \text{km s}^{-1}\).

In a previous study, based on high resolution data provided by the Hinode satellite, we could evidence the presence of bipolar MMFs in a naked sunspot without a visible penumbra, observed in NOAA 10977. The characteristics of the observed MMFs allowed us to classify them as type I (U-shaped) MMFs. Moreover, we deduced that these MMFs were co-spatial with sites of increased brightness both in the photosphere and the chromosphere (Zuccarello et al. 2009). Taking into account the absence of a visible penumbra in the parent naked spot, we concluded that the results obtained could not be explained by models of sunspot structure which assume that the MMFs can be considered as extensions of the filaments forming the penumbra (Schlichenmaier 2002; Zhang et al. 2003; Sainz Dalda & Bellot Rubio 2008). We also outlined that this result could have consequences on our understanding of the way in which magnetic fields diffuse in a plasma. In this context it is worthwhile to mention recent self-consistent realistic full 3D radiative MHD simulations developed by Rempel (2011), which investigate also the decay process of a sunspot, giving a description of the magnetic field evolution and separation in this phase.

Therefore, in order to clarify the role played by the moving magnetic features in the process of decay and diffusion of the magnetic fields in the solar atmosphere, we carried on a new analysis on data acquired during another observing campaign with high resolution instruments, in order to determine the magnetic and dynamic characteristics of these structures and to characterize how their appearance and successive disappearance might be related with the flux tubes that form the umbra and penumbra of the spots.

2. Dataset

We observed the active region NOAA11005 close to disk center [25.2 N, 10.0 W] on October 15th 2008 with the Interferometric BIdimensional Spectrometer (IBIS, Cavallini 2006) at the National Solar Observatory’s (NSO) Dunn Solar Telescope (DST) during its decay phase. During the acquisition, the high-order Adaptive Optics system of the NSO/DST (Rimmele 2004) tracked the pore present in the Field-of-View (FOV) providing good performance and stability.

The analyzed dataset consists of 80 scans, each lasting 52 s, along the Fe i (617.3 nm) and Ca ii (854.2 nm) lines. Both lines were sampled at 21 spectral points. The following six modulation states were acquired: \(I \pm Q, I \pm V,\) and \(I \pm U\) at each wavelength of the Fe i line. The FOV is \(\sim 40'' \times 80''\) and the pixel scale is \(0''.167\) pixel\(^{-1}\). White Light (WL) and G-band images of approximately the same field of view were acquired. The pixel scales of the WL images and G-band images are \(0''.083\) pixel\(^{-1}\) and \(0''.051\) pixel\(^{-1}\), respectively. We applied the standard reduction pipeline on the spectro-polarimetric data (e.g. Judge et al. 2010; Viticchié et al. 2010), which allowed us to correct for the instrumental blue-shift and for the instrument and telescope induced polarization. Examples of reduced data are shown in Figure 1. The FOV includes a small pore that had developed a partial penumbra in days previous our observations.

Standard calibration was applied. Atmospheric aberrations were compensated for through Multi Frame Blind Deconvolution technique (van Noort et al. 2005). Horizontal velocity fields were estimated through Local-Correlation-Tracking (LCT, November & Simon 1988) technique. Line-of-Sight (LOS) magnetic flux was estimated applying
the center of gravity method (COG, Rees & Semel 1979) to left and right circular polarization signals. This method has been proved to reasonably estimate the magnetic flux for field strengths up to approximately 1 kG (Uitenbroek 2003) in the case of some Fe i lines. The magnetic field inclination along the LOS was derived by the intense field approximation (Landi Degl’Innocenti & Landolfi 2004). This method has been proved to provide good estimates of the inclination, at least for moderate inclination angles, in the case of the Fe i 630.2 nm line (Beck et al. 2007). As this line has the same Landé factor as the Fe i 617.3 nm line and forms in similar photospheric conditions, we expect this method to provide good estimates of the inclination also when applied to our data.

LOS velocities in the photosphere were computed by the zero-crossing shift of Stokes V profiles. LOS velocities in the chromosphere were computed by the Doppler shifts of Stokes I profiles.

3. Results

From the visual inspection of the COG magnetograms we could identify several moving magnetic features streaming out from the pore. The investigation of the properties of a selected number of those features, chosen among the most evident and longest living, allowed us to determine that they were not bipolar structures and that they did not all show the same magnetic polarity: some of them presented a polarity opposite to the pore (characterized by negative polarity) and were therefore labeled as P MMFs, while the others, showing the negative polarity as the pore, were labeled as N MMFs. As the N features have the same polarity as the pore, they can be classified as type II MMFs, while P features, having opposite polarity with respect to the pore, are of type III. The N MMFs are found very close to where the pore shows high circular polarization signal.
and they migrate toward the plage region nearby (which has also the same polarity as the pore); the P MMFs are located to the north of the pore, where we inferred a higher linear polarization signal, and are seen to migrate preferentially in the opposite direction with respect to the plage region (see also Figure 4 in Del Moro et al., this volume).

In the following we describe the evolution of one sample of each type MMF (namely, those labeled as P1 and N1 in Figure 4 of Del Moro et al., this volume), in order to highlight the differences that were evidenced from our analysis.

### 3.1. MMF Type III (P)

The type III MMF, characterized by positive polarity, originates in a region of polarity gradients (see 1st col., Figure 2, that shows the physical conditions of part of the FOV few minutes before the formation of the MMF) and high Total Linear Polarization (TLP). It shows an increase in size as it evolves (4th col., Figure 2) and slowly dissolves (6th col), while a new MMF of type III streams out from the same location and follows a similar trajectory (7th col., Figure 2). The analysis of the corresponding G-band images shows bright features to form in the same location of this MMF ~ 15 min after the MMF formation (6th col., Figure 2). We note that these also correspond to the formation of plasma downflows within the MMF. Conversely, we did not observe any associated chromospheric brightening. The LOS velocities appear to be lower than 2 km s$^{-1}$ (in absolute value) and mostly upward (1st col., Figure 2).
Figure 3. Sub-fields of the available data centered on an exemplar type II (N) feature at different most significant times along the sequence. Legend as in Figure 2. This MMF detached from the field of the pore at 16:42:29 UT.

from the LCT analysis, we could infer a horizontal speed of $\sim 1 \text{ km s}^{-1}$. Concerning the magnetic behavior, it results that in this MMF the initial magnetic flux is $\sim 200 \text{ G}$, while the magnetic field strength is $\sim 1 \text{ kG}$ and that both values decrease with time. The inclination of the field also slowly decreases from 60 to 45 degrees with respect to the Line of Sight as the MMF moves away from the pore.

3.2. MMF Type II (N)

The characteristics retrieved from the analysis of the type II MMF show that this feature, having negative polarity, originates in a region of low TLP and later flows toward and merges with the same polarity plage region nearby. In this case, brightening in G-band occur before (1st col., Figure 3) the detachment of the MMF, having associated chromospheric brightening. The LOS velocities, again lower than $2 \text{ km s}^{-1}$ (in absolute value) are mostly downward (Figure 3), while the horizontal speed results to be $\sim 500 \text{ m s}^{-1}$. This MMF shows a LOS magnetic flux $\sim 200 \text{ G}$ and a magnetic field strength of $\sim 1.3 \text{ kG}$. Both values vary with time as the MMF merge with other features of the same polarity. Similarly to the case of the type III MMF, the inclination of the magnetic field slowly decreases with time.

4. Conclusions

The two types of MMFs investigated are characterized by quite different observational characteristics. Type III MMFs are bigger, less compact, and travel at higher horizontal
speeds than the observed type II. The horizontal speeds that we found for type II features are in agreement with the typical values reported in the Shine et al. (2000) classification, while the velocities we found for type III features are lower and are closer to the values typical for type I features. Using the G-band, Fe i core, Ca ii wing images we can confirm that both types have associated bright features in the photosphere, which are often very close to the location of highest magnetic flux of the MMF. Chromospheric brightness counterparts are observed only for type II features. As, in agreement with Zuccarello et al. (2009), we do not observe any visible penumbra, these observations indicate that numerical models have to go a step forward to explain the generation of all observed MMFs. More details about the results presented in this contribution are given in Criscuoli et al. (2012), where results from spectro-polarimetric inversions are also illustrated.

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References

Schlichenmaier, R. 2002, Astronomische Nachrichten, 323, 303