MAGNETIC TOPOLOGY OF A NAKED SUNSPOT: IS IT REALLY NAKED?

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ABSTRACT

The high spatial, temporal, and spectral resolution achieved by Hinode instruments gives much better understanding of the behavior of some elusive solar features, such as pores and naked sunspots. Their fast evolution and, in some cases, their small sizes have made their study difficult. The moving magnetic features (MMFs) have been studied during the last 40 years. They have been always associated with sunspots, especially with the penumbra. However, a recent observation of a naked sunspot (one with no penumbra) has shown MMF activity. The authors of this reported observation expressed their reservations about the explanation given to the bipolar MMF activity as an extension of the penumbral filaments into the moat. How can this type of MMF exist when a penumbra does not? In this Letter, we study the full magnetic and (horizontal) velocity topology of the same naked sunspot, showing how the existence of a magnetic field topology similar to that observed in sunspots can explain these MMFs, even when the intensity map of the naked sunspot does not show a penumbra.

Key words: Sun: magnetic topology – sunspots

1. INTRODUCTION

The so-called Moving Magnetic Features (hereafter MMFs) were discovered by Sheeley (1969) and Vrabc (1971) and described in detail by Harvey & Harvey (1973) and Vrabc (1974). From the early observations, they were associated with the moat (Vrabc 1974; Meyer et al 1974; Brickhouse & Labonte 1988), an annular region surrounding the sunspot where the MMFs run away from the penumbra toward the network. MMFs have been explained by a horizontal velocity field in the moat that drags the more horizontal, detached magnetic field lines from the bundle that forms the sunspot. Recently, MMFs have been observed coming from the mid-penumbra and entering the moat region, which is dominated by large outflows (Sainz Dalda & Martínez Pillet 2005; Ravindra 2006; Kubo et al. 2007). Sainz Dalda & Martínez Pillet (2005) averaged a temporal sequence of Solar and Heliospheric Observatory/Michelson Doppler Imager high-resolution magnetograms that revealed a transverse component of the magnetic field beyond the penumbra outer edge as an extension of the most horizontal penumbral filaments in the moat. High spatial resolution data have revealed a sea-serpent behavior of the more horizontal penumbral filaments as responsible for the bipolar magnetic structures in the mid-penumbra that become MMFs when they reach the moat (Sainz Dalda & Bellot Rubio 2008). All these results establish a link between MMF activity and the horizontal magnetic field component in the penumbra with the Evershed flow, as was suggested early on by Vrabc (1974).

One of the open questions about the moat is whether it exists or not around pores and naked sunspots. Vargas Domínguez et al. (2007, 2008) observed sunspots with different penumbral configurations and using local correlation tracking techniques (hereafter LCT) pointed out that the horizontal velocity flow is present in the part of the sunspot where a penumbra exists.

2. DATA AS VIEWED FROM THE MAGNETIC FIELD

The AR NOAA 10977 was observed in the FeI 6301 and 6302 Å lines from 16:25 to 16:47 UT on 2007 December 5 with the Solar Optical Telescope Spectropolarimeter (SOT/SP) (Tsuneta et al. 2008) on the Hinode satellite (Kosugi et al. 2007). This is the closest available in time to the data studied by ZETAL09 (14:06–15:48 UT). The spatial and spectral samplings were 0'32 and 22 mÅ, respectively. At

5 We consider a pore and a naked sunspot to be different solar features. We understand a naked sunspot to be a solar feature that does not show a penumbra when it is observed, but that had or will have a penumbra during its life. A pore never develops a penumbra during its whole lifetime.
the observation time, the naked sunspot was located at heliographic coordinates \((-12^\circ, -5^\circ)\). To obtain the most accurate values of the physical parameters we have applied the SIR inversion code (Ruiz Cobo & del Toro Iniesta 1992) to the Stokes profiles. The calibrated profiles are easily obtained thanks to the data reduction tools mainly developed by B. Lites and available in the SOT SolarSoft package. Several inversions with different initializations were done. Here, we present one that represents a trade-off between the accuracy in inferred values (i.e., with smallest errors) and the degrees of freedom allowed in the inversion. Therefore, we have chosen a combination of degrees of freedom that shows the best fit between the observed and the inverted profiles and is compatible with a reliable atmosphere model. We have used a simple model with a magnetic component occupying the whole pixel (i.e., filling factor is 1.0) and a fixed stray light contribution of 15\%. We have verified that an inversion with stray light as a free parameter does not introduce significant improvement in the output model; therefore, we selected a high mean value in the studied region, and kept it fixed in the inversion presented here.

Figure 1 shows maps of the naked sunspot belonging to the AR NOAA 10977 after the calibration of the Stokes parameters (first row) and their inversion (second and third rows). In the top row, we present the Stokes intensity (with respect to the continuum intensity) map, the Mean Circular Polarization Degree map (hereafter MCPD map), and the Mean Linear Polarization Degree map (hereafter MLPD map). The MCPD and MLPD maps were respectively calculated as 
\[
\text{MCPD} = \frac{\int_{\lambda_0}^{\lambda_1} |V(\lambda)|/I(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} I(\lambda) d\lambda},
\]
and 
\[
\text{MLPD} = \frac{\int_{\lambda_0}^{\lambda_1} (\sqrt{Q_2(\lambda)^2 + U_2(\lambda)^2})/I(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} I(\lambda) d\lambda},
\]
where \(\lambda_0 = 6302.27 \pm 0.02 \text{Å} \) and \(\lambda_1 = 6302.70 \pm 0.02 \text{Å} \), respectively, i.e., a spectral range including the line Fe I 6302 Å. The MCPD is a good proxy for the unsigned vertical component of the vector magnetic field, while the MLPD is good for the transverse component of the vector magnetic field. In these maps, we have overlaid the contours corresponding to the displayed magnitude. Thus, the intensity contour at level \(I/I_c = 0.8\) delineates the naked sunspot from the granulation. In this Letter, we shall refer to this region as photometric naked sunspot, in the sense that its nature is uniquely described by the intensity...
The contour at the MCPD map encloses the area where MCPD > 3.5\%. Similarly, the contours at MLPD map delimit the area where MLPD > 1\%. In these maps, the intensity contour is displayed (black) as reference. Note that in the MLPD maps there is a contour inside the region delimited by the intensity contour, which belongs to the MLPD contour. These three maps simply retrieved from the Stokes profiles offer us valuable information at a glance. The most obvious is the existence of an extended magnetic field beyond the photometric naked sunspot edge. Both the longitudinal and the transverse components of the magnetic field are present inside the photometric naked sunspot and beyond its intensity contour. However, although valuable, these maps are a rough approximation to the magnetic naked sunspot edge. Both the longitudinal and the transverse components of the magnetic field vector. In the magnetic field strength map there are five overlapping contours. From the inner to the outer parts of the naked sunspot the first three contours correspond to the data studied in this Letter: the continuum intensity (black), and contours for values where $B_{\text{vert}} > 0.25 \text{ kG}$ (white) and where $B_{\text{hor}} > 0.10 \text{ kG}$ (white). These contours are also shown in the corresponding $B_{\text{vert}}$ and $B_{\text{hor}}$ maps. The green and red contours are the same to those shown in the Figure 4 of ZETAL09 (black and white there), and correspond to a magnetic flux density of $-25 \text{ Mx cm}^{-2}$ and $+25 \text{ Mx cm}^{-2}$, respectively. The $B_{\text{vert}}$ values drop from roughly $1.10 \pm 0.07 \text{ kG}$ at the edge of the photometric naked sunspot to $0.25 \pm 0.03 \text{ kG}$ at the position of the $B_{\text{vert}}$ contour, which is roughly located $1''$ outside of the intensity contour of the naked sunspot. $B_{\text{hor}}$ values go from $0.80 \pm 0.05 \text{ kG}$ at the outer part of the photometric naked sunspot to $0.12 \pm 0.03 \text{ kG}$ at $1.5''$ outside of the intensity contour where the $B_{\text{hor}}$ contour is located on average.

A comparison between the magnetogram (line-of-sight, hereafter LOS, component of $B$) used by ZETAL09 and the MCPD map used in this work shows that the vertical component is not really so much different, but the levels used by ZETAL09 for defining the contours are very low, therefore they considered an area larger than is shown by the $B_{\text{vert}}$ map used in this study. Consequently, they were able to identify the MMFs, but the low temporal resolution used here does not allow us to identify the MMFs. We have encircled the MMFs observed by ZETAL09 (see Figure 5 there), so that their relation to the magnetic field is more evident. Additionally, we remind the reader that the data shown by ZETAL09 were observed one hour ahead of the data used in our study. In the $B_{\text{hor}}$ figure, we have indicated the positions of the MMFs observed by ZETAL09. In three of the four cases marked by ZETAL09, we can find features with a non-negligible horizontal component of the magnetic field. This is especially clear in case B, where a finger-like structure or spoke seems to poke out of the naked sunspot. In cases C and D, there are some isolated features with a horizontal field between them and the naked sunspot. Unfortunately, the next Hinode-SOT/SP scan is one hour later, and the next is one day later, so we cannot study the evolution of MMFs.

Finally, the third row shows the inclination in the LRF (left), LOS component of the velocity (center), and temperature (right). In this row, all maps have been overlaid with the three contours (continuum intensity, $B_{\text{vert}}$, and $B_{\text{hor}}$). At the center of the naked sunspot the inclination is $180^\circ$, i.e., the magnetic field is directed inward to the solar surface. The inclination of the magnetic field in the LRF roughly drops from $140^\circ \pm 4^\circ$ ($50^\circ \pm 4^\circ$ with respect to the local horizontal) to $110^\circ \pm 4^\circ$ ($20^\circ \pm 4^\circ$) out to the photometric naked sunspot. The LOS velocity is upward or close to zero everywhere both in the photometric naked sunspot and in its surroundings: there is not any trace of Evershed flow, even though the position of the naked sunspot is far off the center of the solar disc. The temperature map shows a hot ring just between the intensity contour and $B_{\text{vert}}$ contour. The temperature of this ring is roughly $5.50 \pm 0.08 \text{ kK}$. It is hotter than the temperature of the photometric naked sunspot ($4.00 \pm 0.03$ to $5.00 \pm 0.05 \text{ kK}$) but cooler than the most prominent granules in the studied area. We can see one granule located at map coordinates (9,19) with a temperature of $5.50 \pm 0.03 \text{ kK}$. The other granule is located at map coordinates (17,10), and it shows a temperature similar to the former one but in this case the error is $\pm 0.10 \text{ kK}$. On average, the temperature of this ring is slightly higher than the granulation, but it is still lower than the hotter granules shown in the map.

The values of both components of the magnetic field are higher than the noise level, and the errors of the components and inclination of the vector magnetic field presented in this Letter are only slightly higher than the maximum errors obtained by Gosain et al. ($2010$). They calculated an error value for the vector magnetic field of a sunspot observed by Hinode-SOT/SP using both a Monte Carlo approach and a Milne–Eddington inversion. The maximum values that they obtained were $\pm 50 \text{ G}$ for the field strength and $\pm 3^\circ$ for the inclination. Therefore, our results look as reliable and consistent as other observations and inferences (see also result and errors in Bellot Rubio et al. $2008$). To summarize, the topology of the (full) vector magnetic field of the observed naked sunspot has been revealed. We refer to this new vision of the naked sunspot as the magnetic naked sunspot.

3. DATA AS VIEWED FROM THE VELOCITY FIELD

In order to analyze the proper motions around the (naked) sunspot, we have selected the same SOT/Broadband Filter Imager data used by ZETAL09 for using LCT to compute the flow map of horizontal velocities. A total of 51 $G$-band images from 14:06 to 15:48 UT ($\sim 2$ minute cadence) were processed with standard SolarSoft routines and co-aligned at a sub-pixel level by cross-correlation over the entire field of view (FOV) between subsequent pairs of images. A subsonic filter (velocity threshold of $4 \text{ km s}^{-1}$) was used to eliminate $p$-modes resulting in a final time series of 46 images after apodization. The LCT procedure was then applied by using a correlation tracking window of FWHM $1''/0$. Two cases (Cases 1 and 2) of maps of horizontal velocities were generated. In the computed map for Case 1 (obtained using a procedure analogous to the one used by ZETAL09) the velocity vectors have a predominant trend to the right, and the velocities closer to the right edge of the FOV are generally larger in magnitude. Figure 2 (top left panel) shows a clipped region of the FOV in the vicinity of the (naked) sunspot. In Case 2, the time series were first aligned with respect to a window enclosing the (naked) sunspot. By doing this, we neglect the proper (inherent) motion of the sunspot through the surrounding granulation, thus focusing on the plasma motions around the anchored sunspot. We detected shifts with respect to Case 1 of up to 26 and 10 pixels in the $x$ and $y$ directions,

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6 Whereas the terms longitudinal and transverse are used for the projection of the magnetic field vector on the observation reference frame, the terms vertical and horizontal are used for the projection on the local reference frame (hereafter LRF).
Figure 2. Distribution of horizontal proper motions around the naked sunspot. Top panels: maps of horizontal velocities for the Hinode (G-band) time series (92 minute average) for Case 1 (left) and Case 2 (right). The background images represent the average image of the series. The length of the black bar at coordinates (0,0) corresponds to 2 km s\(^{-1}\). The circles mark the position of the MMFs as in Figure 5 of ZETAL09. Bottom panels: binary maps of inward (white) and outward (black) radial velocity components for Case 1 (left) and Case 2 (right). The gray area corresponds to the photometric area of the (averaged) naked sunspot.

respectively. Figure 2 (top right panel) shows the resulting map for Case 2 for comparison with Case 1 (left). We follow the same procedure as used by Vargas Domínguez et al. (2010) to establish the direction of velocity vectors around the (naked) sunspot. Figure 2 (bottom panels) shows binary maps displaying the distinction between the inward (white) and outward (black) radial components of the velocity vectors for Case 1 (left) and Case 2 (right), respectively. Our results agree with previous results for pore-like structures (Vargas Domínguez et al. 2010) showing that motions toward the pore are dominant in the closest vicinity. For Case 2 this behavior is even more evident and symmetric around the (naked) sunspot, showing the differential proper motions of plasma around the anchored spot. Motions at the periphery of the structure are significantly influenced by external plasma flows caused by exploding events as observed in previous works (e.g., Sobotka et al. 1999).

4. DISCUSSION, CRITICISM, AND CONCLUSIONS

We remark that a moat and MMF activity could be considered as observed magnetic features, while the umbra and penumbra are observed intensity (or photometric) features. However, we should not forget that this classification is based on the primary technique used for their identification, and several additional aspects of their nature should also be considered.

Figure 1 clearly shows a prominent horizontal magnetic component around the photometric naked sunspot. This horizontal component is cospatial with the vertical component of the
magnetic field in the outermost part of the photometric naked sunspot, and it persists as a horizontal magnetic structure beyond. This magnetic field configuration is very similar to that of a standard sunspot, at least from the magnetic point of view. That is, if we understand a sunspot as an intensity structure, the sunspot studied by ZETAL09 can be classified as a so-called naked sunspot. On the other hand, the configuration of the magnetic field resembles that of a sunspot with an extended magnetic field beyond the penumbra (Sainz Dalda & Martínez Pillet 2005) and that of a naked sunspot during the decay of a sunspot (Bellot Rubio et al. 2008). Sainz Dalda & Bellot Rubio (2008) using Pillet 2005) and that of a naked sunspot during the decay of the magnetic field resembles that of a sunspot with an extended magnetic field beyond the moat. Both observations related the more horizontal magnetic field component of the sunspot with the MMF activity, in agreement with several observational and theoretical proposals (Harvey & Harvey 1973; Schlichenmaier 2002). In the data presented here, we observe a very similar magnetic field configuration to that in a sunspot, although the naked sunspot does not have a photometric penumbra.

It has a very similar magnetic structure surrounding it, although without a (photometric) filamentary distribution at the spatial resolution in these observations. Because sunspots and naked sunspots possess similar magnetic topologies we expect that MMFs behave in the same way in both cases, even those related to the horizontal extension of the magnetic field, i.e., type I and III (see classification in Shine et al. 2000 and Figure 5 of Thomas et al. 2002). ZETAL09 reported—probably for the first time—that MMF activity around a naked sunspot. However, their suggested revision of the relationship between MMF activity and the extension of the more horizontal penumbral filaments on the moat can be questioned if one considers the true (vector) magnetic field of the naked sunspot. Does it mean that all MMF activity can be explained uniquely by the extension of the horizontal penumbral filaments in the moat or even by a horizontal component of the magnetic field around the naked sunspot? It does not, but the absence of a (photometric) penumbra does not imply a lack of a horizontal field around naked sunspot, and therefore some MMF activity can still be explained by the current interpretation. The main conclusion presented by ZETAL09 was based on the observational evidence that the selected sunspot is a naked sunspot. That is true but is only part of the story, as it only takes into account the intensity, the LOS component of B, and applying LCT without correcting for the inherent proper motion of the (naked) sunspot and focusing only on the proper motions of the surrounding granulation. In our analysis, we have shown that the apparent outflows from the naked spot are not actually moat flows (as suggested by ZETAL09), but rather the contribution from outward flows originating in the regular mesh of divergence centers around the pore, in agreement with previous results (e.g., Vargas Domínguez et al. 2010). The inflow and outflow were studied during the decay of a sunspot by Deng et al. (2007). The authors observed that the inflow and outflow do not disappear when the penumbra does. It means that inflow and outflow exist in a naked sunspot. Therefore, both flows are compatible with the MMF activity around the naked sunspot as in the sunspot.

We have shown how a (photometric) naked sunspot has associated vertical and horizontal magnetic components slightly outside of its intensity edge and a horizontal magnetic component extending much further beyond its intensity edge. In this sense, the (magnetic) naked sunspot is as chaste as a sunspot, and the MMF activity around the former can be explained in the same way it is done around the latter.

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