ON THE CORRELATION BETWEEN THE ORIENTATION OF MOVING MAGNETIC FEATURES
AND THE LARGE-SCALE TWIST OF SUNSPOTS

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ABSTRACT

We present new results on the nature of moving magnetic features (MMFs) deduced from Big Bear Solar Observatory observations of the longitudinal magnetic fields of two large solar spots. MMFs are small magnetic bipoles that move outward, across the moat, of an eroding sunspot. Distinct from previous studies, we find that MMFs are not randomly oriented. To wit, in 23 out of 28 (82%) MMF pairs, the magnetic element with the polarity of the sunspot was located farther from the sunspot. Furthermore, there is a correlation between the orientation of the bipoles and that of the twist in a sunspot. For the two nearly round spots we studied, we find that the bipoles are rotated counterclockwise in the case of a clockwise twisted sunspot and clockwise for a spot with counterclockwise twist. We also find a correlation between the orientation of MMFs bipoles and the amount of twist in the spot. The MMF bipoles around the highly twisted sunspot are oriented nearly tangential to the edge of the sunspot; while in the slightly twisted sunspot the bipoles are oriented nearly radially, so that they point back to the spot.

Key words: Sun: magnetic fields, moving magnetic features, moat flow

1. INTRODUCTION

The magnetic fields outside a sunspot appear discontinuous, while the large area around the spot displays a variety of mass flows. Moving Magnetic Features (MMFs) are regarded as small magnetic elements which are carried away from the sunspot to the periphery by plasma flows (Vrabec 1971; Harvey and Harvey 1973; Muller and Mena 1987; Brickhouse and LaBonte 1988; Lee 1992). A complete list of all known properties of MMFs was compiled by Ryutova et al. (1997).

Mayer et al. (1974) reviewed the possible orientations in which a magnetic tube can be taken away from a sunspot. The model by Harvey and Harvey (1973) suggests that magnetic flux is removed from the sunspot at the photospheric level (Figure 1a). This would produce pairs of MMFs in which magnetic elements of opposite polarity to the sunspot tend to be formed farther out. An alternative possibility, depicted in Figure 1 b, was suggested by Wilson (1973). In latter case, the magnetic flux tube is detached from the main bundle of tubes well below the surface (at depths of about 12,000km). The detached tubes turbulently float to the surface developing twists and kinks (Ryutova et al. 1997) which then are seen as MMFs. Significantly, orientation of the MMFs bipoles in Wilson’s model is exactly the opposite: magnetic elements of opposite polarity to the sunspot will tend to be formed close to the sunspot. Therefore, high resolution observations of longitudinal magnetic field can easily delineate between the models. At present, there is no solid observational evidence on MMF bipoles orientation that would favor one or another model. However, Mayer (1974) and Ryutova et al. (1997) showed some evidence that the inner footpoint of the MMF bipoles share the sunspot’s polarity, which marginally supports the model of Harvey and Harvey (1973).

To distinguish between existing models, one needs to know exactly how MMFs appear on the solar disk and their subsequent evolution, as well. We focus here on several observational facts which are relevant to the theoretical models of MMFs. In Section 2, we present new information on MMFs derived from Big Bear Solar Observatory (BBSO) videomagnetograms and compare our findings to existing theoretical models. In Section 3, discussion and a short summary is presented.

2. OBSERVATION AND RESULTS

The data are observations of the longitudinal magnetic field of two large sunspots (AR NOAA 8375 and AR NOAA 8525) which were obtained at BBSO on 1998 November 4 and 1999 May 05, respectively. During the observations, the sunspots were located near the central meridian (AR NOAA 8375
Figure 1. Proposed models for the MMFs. (a) the detached field line at the photospheric level (Harvey and Harvey, 1973); (b) the detached field line at deep photospheric levels (Wilson 1973).

Figure 2. Two chromospheric Hα images of AR NOAA 8375 and AR 8525 taken at Big Bear Solar Observatory. Left frame is a high resolution image and right frame is an enlarged part of a full-disk Hα image. The solid white lines in both panels re-inforce the apparent direction of the field.

- N18W06 and AR NOAA 8525 (N18E02). Line-of-sight magnetograms were obtained by the 25-cm refractor with a pixel resolution of 0.′′6. Both sunspots were surrounded by intense, nearly radial moat flows. Diameters of the moat annuli were about 70′′, in the south-north direction, which is twice as large as the diameter of the penumbra. Hα images indicate that the sunspot in AR NOAA 8375 was rotated in a clockwise direction (positive helicity), while dark filaments and fibrils in an AR NOAA 8525 indicate that the sunspot had a weak, but noticeable counter-clockwise twist (negative helicity, Figure 2). Figure 3 shows two magnetograms taken on 1998 November 4 with a time interval of approximately one hour. The magnetic configuration includes three different structures: the N polarity sunspot, the moat boundary circumscribing the sunspot on the west and the moat flow transporting magnetic flux from the sunspot to the moat boundary. Figure 4 shows the N polarity sunspot surrounded by the moat flow observed on May 5, 1999. We observed the origination of the MMFs pairs at the penumbral boundary. Most of the MMFs appeared in closely spaced pairs of opposite-polarity magnetic elements. Usually, the magnetic element of sunspot polarity came out first and only then, the second magnetic element of the opposite polarity appeared on the scene. Frequently magnetic elements in a pair were not equally visible: opposite (to the sunspot) polarity element was often observed as a loose and weak magnetic structure. A 6-hour movie made of the longitudinal magnetograms clearly illustrated that the moving magnetic features originated at the penumbral boundary and migrate outside through the moat.

In Figures 3 and 4 a total of 28 MMF pairs are encircled and numerated. Each pair was reliably defined by two successive magnetograms. To avoid an ambiguity in the measurements of the orientation of MMF’s dipole, we selected only well-isolated MMF pairs. Table 1 shows angles φ of axes of MMF’s bipoles in reference to the radial direction. φ is defined as a smallest angle measured in direction from N polarity element to the sunspot radius and is a positive number when the measurement is made in the counter-clockwise direction (see Figure 5 for definition of φ).

First, we find no evidence that the inner footpoint of the MMFs pair shares the sunspot polarity as it was guessed earlier (Meyer et al. 1974, Ryutova et al. 1997). In fact, in 23 out of 28 MMFs' pairs (82%), the magnetic element with the sunspot's polarity was located farther from the sunspot (|φ| is greater than 90°).
Figure 3. Two longitudinal magnetic field images of AR NOAA 8375 taken on November 4, 1998 at Big Bear Solar Observatory. White is north polarity magnetic field. Clearly defined pairs of MMFs are marked with circles and numbered.

Table 1. Orientation of MMFs pairs

<table>
<thead>
<tr>
<th>Bipole</th>
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<td>125</td>
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<tr>
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<td>-130</td>
<td>-130</td>
<td>-112</td>
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<td>168</td>
<td>-70</td>
<td>-165</td>
<td>150</td>
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Figure 4. Image of longitudinal magnetic field of AR NOAA 8525 taken on May 5, 1999.

Second, MMFs bipoles do not seem to be randomly oriented. Orientation of the MMFs bipole is related to the large-scale twist of the sunspot. In each MMFs pair, the magnetic element of the sunspot-polarity has a preferable position in the pair: it is located on the left side, if we look at the pair from the center of the sunspot with clockwise twist, and on the right side in the case of counterclockwise twist (see also Figure 5). A careful study of the sequence of magnetograms showed that the orientation of bipoles remains the same throughout the lifetime of the bipoles. The only notable and significant changes in orientation were related to the break-up of the bipoles. The picture we deduce from the date is shown in Figure 5.

Third, we find that the deviation $\beta = 180^\circ - < \phi >$ (angle $\beta$ measured in counter-clockwise direction is positive) of bipole axes from the radial direction is correlated with the amount of helicity (twist) in the sunspot. The amount of helicity can be estimated by calculation of 2D current helicity maps (Abra menko et al. 1996) or by comparison of parameter $\alpha$ of linear force-free field with Hα pattern around the sunspot (Seehafer 1990; Pevtsov et al. 1995). Unfortunately, we were not able to use these methods, for we lack vector magnetograms for the ARs under study. However, reliable qualitative estimations of the amount of current helicity can be done using the Hα images of the active regions. Penumbral filaments and chromospheric fibrils in the vicinity of sunspots show a hemisphere-dependent predominant sense of curvature. The degree of the curvature is related to the amount of helicity in the sunspot. Thus, clockwise rotational motions of the N polarity spot would generate a vortex structure with a positive helicity. In our case, BBSO Hα images of AR 8375 revealed that the leading sunspot had strong positive helicity and deviation $\beta_{8375}$ was $81^\circ$ (see also Figure 2).
3. CONCLUSIONS AND DISCUSSION

We presented high resolution observations of the longitudinal magnetic field in a sunspot area. We learned new specific properties of MMFs in the sunspot moat.

1. MMF bipoles are not randomly oriented. In 23 out of 28 (82%) MMFs pairs, the magnetic element with the sunspot's polarity has a preferred position in the pair: it is located farther from the sunspot and a bipole is rotated counter-clockwise when the sunspot is twisted clockwise, and vice versa.

2. There seems to be a link between amount of rotation of the MMFs bipole, and amount of twist in the sunspot. Bipoles around the sunspot with strong twist oriented nearly perpendicular to the sunspot radius, while bipoles of slightly twisted sunspot are oriented mostly parallel to the radius.

3. The magnetic element of the same polarity as the sunspot comes out first, and the magnetic element of the opposite polarity appears second to form the MMFs bipolar pair. We found no evidence that the inner foot of a MMFs pair shares the sunspot polarity.

4. The majority of MMFs pairs consist of a stronger and compact magnetic element with the polarity of the sunspot, and a weaker and diffuse magnetic element of opposite polarity.

Loop models proposed by Wilson (1986) and Spruit, Title and Ballegooijen (1987) assume that MMFs are formed by closed detached loops which are separated and, hence, are randomly oriented. This model is inconsistent with the observed preferred orientation of the MMFs pairs.

Another possibility is that the magnetic flux is detached from the main flux bundle at the surface as suggested in the model of Harvey and Harvey (1973). MMFs would appear in pairs with the magnetic polarity of the sunspot being located closer to the sunspot, which contradicts our data.

Ryutova et al. (1997) proposed that non-linear coupling of flux and plasma flows leads to formation of a stable soliton-like kink along the magnetic flux. Numerical simulations show that the kink travels with a precisely defined speed and it has precisely defined width and amplitude. The orientation of the kink soliton is uniquely defined by the sign and the amount of helicity in the magnetic flux tube. Applying their results to the observed properties of MMF they found a reasonable qualitative and quantitative agreement, however, the model seems to fail to explain the diffuse structure of the second magnetic element in a MMFs pair. According to Ryutova et al. (1997) both elements in MMFs pair are clearly seen in the simulations.

In the case of strong positive helicity, a soliton-like kink would be seen at the photospheric level as MMFs pairs in which, the magnetic element to the left shares the sunspot magnetic polarity. If we assume that the kink occurs in the configuration suggested by Wilson (1973), then the closest magnetic element in the model will have the same polarity as the closest element in an observed MMFs pair, but it will be positioned to the left of the radius of a sunspot, which does not correspond to the observed result (see Fig. 1). We suggest, that strong subsurface outflow outside of a sunspot (Hulburt and Rucklidge 1999) can rotate a detached magnetic flux and, thus, affect the orientation of a MMFs pair as well as its asymmetry.

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