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. We find that MMFs are not randomly oriented. To wit, in 21 out of 28 (75%) MMF pairs, the magnetic element having the polarity of the sunspot was located farther from the sunspot. Furthermore, there is a correlation between the orientation of the bipole and that of the twist in a sunspot. For the two nearly round sunpots we studied, we found that the bipoles were rotated counterclockwise in the case of a clockwise twisted sunspot and clockwise for a spot with counterclockwise twist. We also found a correlation between the orientation of MMF bipole 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.

Subject headings: 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 that 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). There are two kinds of MMFs: unipolar and mixed polarity, i.e. bipolar (Harvey and Harvey 1973; Zhang et al. 1992). A complete list of all known properties of MMFs was compiled by Ryutova et al. (1998).

Meyer 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 1*a*). This would produce pairs of MMFs in which magnetic elements of polarity opposite to that of the sunspot tend to be formed farther out. An alternative possibility, depicted in Figure 1 *b*, was suggested by Wilson (1973). In this 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, which then are seen as MMFs. Significantly, the orientation of the MMF 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. However, Meyer (1974) and Ryutova et al. (1998) showed some evidence that the inner footpoint of the MMF bipoles share the sunspot's polarity, which supports the model of Harvey and Harvey (1973).

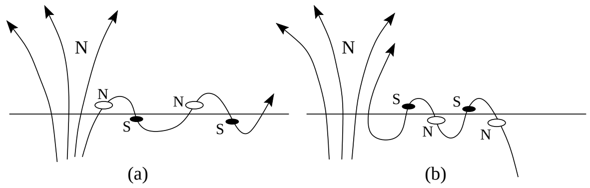


Fig. 1.— Proposed models for the MMFs. (a) the detached field line at the photospheric level (Harvey and Harvey, 1973); (b) the detached field line at deep photospheric levels (Wilson 1973).

Another possibility was demonstrated by Wilson (1986): new magnetic flux may be generated in the form of loops by the action of oscillatory velocity fields. Later, Spruit, Title and Ballegooijen (1987) assumed that a large loop rises from the convection zone and breaks into many small loops as it crosses the surface. There are at least two obstacles to these models. First, as noted by Lee (1992), the models will generate MMFs everywhere in the moat, which does not agree with the earlier studies (Vrabec 1971; Sheely 1972; Harvey and Harvey 1973). Second, the models will produce randomly oriented pairs of MMFs, which also contradicts the result on non-random (radial) orientation of MMFs. However, using Big Bear measurements of the longitudinal magnetic fields, Lee (1992) reached the conclusion, that MMFs are oriented randomly and the data favors Wilson's model.

We use here the Big Bear videomagnetograms and we focus on several observational facts that are relevant to the theoretical models of MMFs. Our study is concerned only with the bipolar MMFs. In Section 2, we describe the data and the method of investigation. We also present here new information on the orientation of MMFs and compare

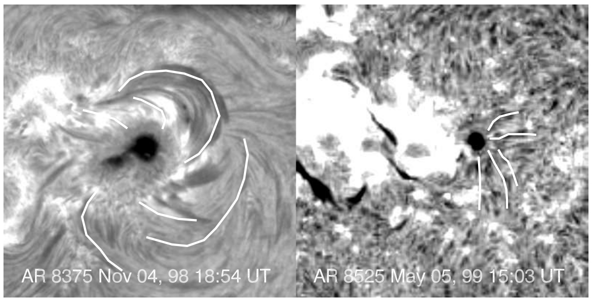


Fig. 2.— Two chromospheric Hα images of AR NOAA 8375 and AR NOAA 8525 taken at Big Bear Solar Observatory. Left frame is a high resolution image and right frame is an enlarged part of a full-disk Hα image. The solid white lines show the approximate direction of the horizontal magnetic field as derived using chromospheric dark filaments.

our findings to existing theoretical models. In Section 3, a discussion and a short summary is presented.

2. Observations 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 – N18W06 and AR NOAA 8525 – N18E02). Line-of-sight magnetograms were obtained using the 25-cm refractor with a pixel size of $0''.6$. Both sunspots were surrounded by intense, nearly radial moat flows. The diameters of the moat annuli were about $70''$, in the north-south direction. These diameters are twice that of the penumbra. Clockwise twist of Hα filaments around a sunspot in AR NOAA 8375 implies positive helicity, while dark filaments and fibrils in an AR NOAA 8525 indicate

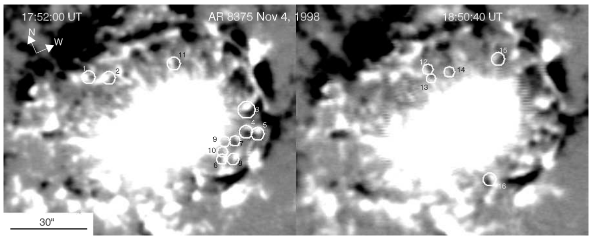
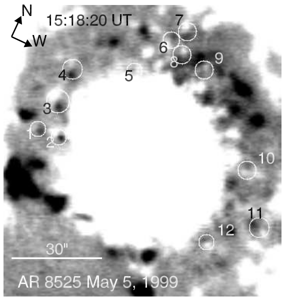


Fig. 3.— Two longitudinal magnetic field images of AR NOAA 8375 taken on 1998 November 4 at Big Bear Solar Observatory. North polarity is white. Clearly defined pairs of MMFs are marked with circles and numbered.



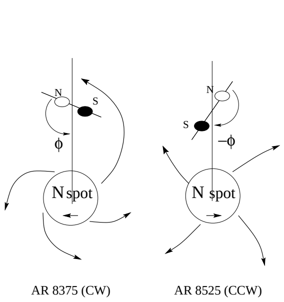


Fig. 4.— Image of longitudinal magnetic field of AR NOAA 8525 taken on 1999 May 5.

Fig. 5.— Definition of an ϕ.

that the sunspot had a weak, but noticeable counterclockwise 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 elements from the sunspot to the moat boundary. Figure 4 shows the N polarity sunspot surrounded by the moat flow observed on 1999 May 5. A 6-hour movie made of the longitudinal magnetograms clearly illustrated that the moving magnetic features originated at the penumbral boundary and migrate to the outside through the moat. 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 did the second magnetic element of the opposite polarity appear on the scene. Frequently, magnetic elements in a pair were not equally visible: the opposite (to the sunspot) polarity element was often observed as a loose and weak magnetic structure.

Our way to study orientation of MMF pairs was similar to that of Lee (1992). In Figures 3 and 4 a total of 28 MMF pairs are encircled and enumerated. Each pair was reliably defined by two successive magnetograms. To avoid an ambiguity in the measurements of the orientation of MMF bipole, we selected only well isolated MMF pairs. Table 1 shows angles ϕ of axes of MMF bipoles with respect to the radial direction from the sunspot center. ϕ is defined as a smallest angle measured in the direction from the 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). In case of AR 8375, all values of ϕ were positive with a mean $<\phi_{8375}>= 95°$. In AR 8525 there were 8 bipoles with negative angles ($<\phi_{8525}>= -129°$) and 4 pairs with positive ϕ.

First, we find no strong evidence that the inner footpoint of the MMF pair shares the sunspot polarity, as was observed earlier (Meyer et al. 1974, Ryutova et al. 1998). In fact, in 21 out of 28 MMF pairs (75%), the magnetic element with the sunspot's polarity was located farther from the sunspot ($|\phi|$ is greater than 90°). Only in 6 out of 28 MMFs the inner footpoint of MMF pair shares the sunspot polarity. For a sake of simplicity, we will call them *normal* oriented MMFs, whereas we will call *reverse* oriented MMFs those bipoles with the outer footpoint having the sunspot's polarity.

Second, MMF bipoles do not seem to be randomly oriented, as suggested by Lee (1992). Orientation of the MMF bipole is related to the large-scale twist of the sunspot. In each MMF 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, $\beta = 180° - <\phi>$ (angle β measured in counterclockwise direction is positive), of bipole axes from the radial direction is correlated with the amount of helicity (twist) in the sunspot. The helicity can be estimated by calculation $2D$ helicity maps (Pevtsov et al. 1994; Abramenko et al. 1996) or by computing the α parameter of linear force-free field (Seehafer 1990; Pevtsov et al. 1995). Unfortunately, we were not able to use these methods, for we lack BBSO vector magnetograms for the active regions under study. However, reliable qualitative estimations of the amount of current helicity can be done using the Hα images of the active regions. BBSO Hα images of AR 8375 revealed that the leading sunspot had strong positive helicity and deviation β_{8375} was 85° (see also Figure 2). At the same time, the sunspot in AR 8525 showed a very weak, but noticeable amount of negative helicity[1] (counter-clockwise twist) and $\beta_{8525} = -51°$. This might imply that a sunspot without large-scale twist would have all its MMF bipoles oriented along the sunspot radius.

3. Conclusions and Discussion

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

1. MMF bipoles are not randomly oriented. In 21 out of 28 (75%) MMF 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 have positive helicity, and vice versa.

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

3. The magnetic element with the same polarity as the sunspot comes out first, and then the magnetic element of the opposite polarity appears second, forming the MMF bipolar pair.

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

Lee (1992) argued that the bipolar MMF pairs are randomly oriented. Figure 1 in Lee (1992) shows two BBSO videomagnetograms of NOAA AR 5612 where a total of 9 MMF pairs are indicated. However, in the figure we can see that the magnetic polarity of the inner footpoint of all MMF pairs is opposite to that of the sunspot's polarity (reverse oriented MMFs), which implies that the observed MMFs are not randomly oriented. Furthermore, in 6 out of 9 bipoles the magnetic element with the sunspot's polarity is located on the left side, if we look at a bipole from the center of the sunspot. The Hα images from the Crimean Coronograph show that the sunspot had a very complicated structure. It can not be described by one sign of the α parameter. The N-W part of the sunspot shows a clockwise twist or positive helicity (this also can be seen in the Figure 1 of Lee (1992) paper), while the southern part was twisted counter-clockwise. The relation between the helicity sign and the orientation of MMFs for NOAA AR 5612 is the same as for NOAA AR 8375 that we studied here. Thus, Lee's data fully support our conclusion on the non-random orientation of MMFs.

The 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, may be randomly oriented. This model is in-

[1] Calculations of linear force-free field for AR 8375 showed that the active region magnetic field can be described with positive α parameter (Yurchyshyn et al. 2000). Moreover, as pointed by referee, Haleakala Stokes Polarimeter magnetograms give positive helicity for both regions, although for NOAA AR 8525 the helicity is very small, near zero.

consistent with the observed preferred orientation of the MMF 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). It is assumed that near the surface the granules can twist the flux tube into loops which can be observed as moving magnetic features. MMFs would appear in pairs with the magnetic polarity of the sunspot being located closer to the sunspot. Wilson (1986) argued that the magnetic energy density is of order 10^5 erg cm^{-3}, whereas the energy density of the granular motions is two orders of magnitude smaller, which implies that the granular motion can not deform a flux tube. Later, Ryutova et al. (1998) showed that non-linear coupling of flux and plasma flows in the presence of gravitational field can form a stable soliton-like kink along the magnetic flux. Numerical simulations show that 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 MMFs, 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 MMF pairs. According to the model, in the case of strong positive helicity, a soliton-like kink would be seen at the photospheric level as MMF pairs in which, the inner footpoint of MMF pair, located on the left side, shares the sunspot's magnetic polarity, which replicates the Harvey and Harvey (1993) model (see also Figure 1). Thus, the Harvey and Harvey configuration can successfully explain generation of normal oriented MMFs, with the trailing footpoint having the same polarity as the main sunspot (see MMFs 4, 13, 15 and 16 in Figure 3 and MMFs 6 and 10 in Figure 4).

On the other hand, if the kink occurs in the configuration suggested by Wilson (1973), then the inner footpoint in the model has polarity opposite to that of the main sunspot, however the orientation of MMF bipole differs from what we observe. (see Figure 1). The Wilson model seems to fail to explain the kinds of MMFs we observe here.

To conclude, none of existing theoretical model can completely explain the MMF phenomena we observe here. However, the Harvey and Harvey (1973) model successfully explains the origin of normal oriented MMFs (approximately 25% of all observed MMFs). New theoretical efforts are needed to understand the MMF phenomenon. The new results on MMFs, revealed here, pose new questions on the generation of MMFs. Are the two types of orientation of MMFs generated by two different mechanisms acting simultaneously or, does only one mechanism do the job? If there is only one mechanism, what defines the orientation of MMFs? All these are important questions, since the mechanisms of the generation of MMFs are defined by the subsurface structure of the solar spot and the structure of ambient subsurface plasma flow, as well.

4. Acknoledgement

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Table 1: Orientation of MMF pairs

Bipole, #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
ϕ_{8375}, deg	138	138	135	78	102	102	95	92	93	93	90	93	30	99	78	55
ϕ_{8525}, deg	-135	-135	-130	-130	-112	30	160	-155	168	-70	-165	150				