Statistical properties of Moving-Magnetic-Feature pairs

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Abstract. Employing data recorded by the Michelson Doppler Imager (MDI) instrument on the Solar and Heliospheric Observatory (SOHO), we have identified 144 pairs of opposite magnetic polarity moving magnetic features (MMFs) in two active regions (NOAA ARs 8375 and 9236). The statistical results are uncovered: (1) The majority of MMF pairs first appears at a distance of 1000 to 5000 km to the outer boundary of sunspot penumbra; (2) The mean lifetime of elements belonging to 144 MMF pairs is about 4 hour; (3) Separation between two polarities of MMFs falls in the range of 1100–1700 km, and the separation decreases slightly while the MMF pairs move outwards; (4) MMF bipoles are not randomly oriented. Their orientations are associated with the twist of the sunspot superpenumbra; (5) MMF pairs move approximately radially outward from sunspots at an average speed 0.45 km s\textsuperscript{-1}. The distance travelled by MMF pairs is about 6000 km; (6) Around the periphery of the parent sunspot of AR 8375, MMFs tend to cluster at particular azimuths around the parent sunspot. Their motion is directed towards magnetic flux of opposite polarity to that of the parent sunspot.

Key words: Sun: chromosphere – Sun: magnetic fields – Sunspots

1. Introduction

Moving magnetic features (MMFs) are small magnetic features that move away from a sunspot to the periphery of the surrounding moat (Vrabec 1971; Harvey & Harvey 1973; Muller & Mena 1987; Brickhouse & Labonta 1988; Lee 1992). There are two kinds of MMFs: unipolar and mixed polarity (Harvey & Harvey 1973; Ryutova et al. 1998; Yurchyshyn, Wang, & Goode 2001). Harvey & Harvey (1973) proposed a model in which magnetic flux is removed from the sunspot at the photospheric level. This produces pairs of MMFs in which magnetic elements of the same polarity as the sunspot tend to lie farther in as the opposite polarity elements, in agreement with their observations. An alternative possibility was suggested by Wilson (1973, 1986). In his case, a magnetic flux tube is detached from the main bundle of tubes well below the surface. The detached tube floats turbulently to the surface developing twists and kinks, which then are seen as MMFs. Spruit, Title, & van Ballegooijen (1987) assumed that a large loop rises from the convection zone and breaks into many small loops as it crosses the surface. According to the proposals of Wilson and of Spruit et al. the relative distribution of the MMFs with the two polarities is random.

In this paper we study 144 pairs of opposite magnetic polarity MMFs. For each pair of MMFs we determined a set of parameters. These included the total magnetic flux, the net magnetic flux, the separation between the two polarities, the azimuthal angle relative to the centre of the sunspot, the orientation of the MMF pair (i.e. of the line connecting the two polarities) relative to the radial direction measured from the centre-of-gravity of the sunspot, the lifetime of magnetic elements of MMF pairs, the speed of propagation, the distance from the edge of the penumbra at which the MMF was first seen, etc. The method used to study orientation of MMF pairs was similar to that of Yurchyshyn et al. (2001). Angle $\alpha$ represents the angle of the axis of an MMF bipole with respect to the radial direction from the sunspot center. It is positive when the measurement is made in the counterclockwise direction. Angle $\beta$ is defined as the angle between the line connecting center-of-gravity of an MMF pair with the sunspot center and the line from sunspot center to the north. $\beta$ increases in counter-clockwise direction from 0 to 180°; in clockwise direction, $\beta$ runs from 0 to –180°.

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2. Observations and analysis

We use magnetic field observations carried out by the Michelson Doppler Imager, MDI (Scherrer et al. 1995) on the Solar and Heliospheric Observatory (SOHO). MDI was employed in the high-resolution mode (0.625 arcsec per CCD pixel and a 1 minute cadence). Observation of two active regions, AR 8375 and AR 9236, are analyzed. We determined 93 MMF pairs from the 40 hour (from 1998 November 23 18:53 UT to 25 10:51 UT) magnetograms of AR 8375, 51 MMF pairs from the 48 hour (from the beginning of 2000 November 23 to the end of November 24) time sequence of magnetograms of AR 9236. During the observations, the two active regions were located near the central meridian (AR 8375: N18W06; AR 9236: N23W05). The two active regions have a similar magnetic structure: a relatively large compact leading sunspot of positive polarity and an extended negative polarity region. MMFs emerge successively around the leading sunspots. Here we concentrate on the MMF pairs. Each MMF pair was reliably defined by tens of successive magnetograms. We selected only well-isolated MMF pairs.

Fig. 1 shows two BBSO Hα images (left) of AR 8375 and AR 9236, respectively, two corresponding MDI line-of-sight magnetogram (middle), and two corresponding MDI continuum images (right). The two dotted curves in the continuum images outline the boundary of the penumbra. The counterclockwise twist of Hα filaments around the sunspot in AR 8375 implies a positive helicity, while the clockwise twist of filaments in AR 9236 indicates a negative helicity.

3. Statistical properties of MMFs

We identify 144 MMF pairs, 93 of them are from AR 8375, and the remainder, from AR 9236. In AR 8375, the flux appearing in the form of MMF pairs is \(6.8 \times 10^{20}\) Mx, with a net flux of \(1.2 \times 10^{20}\) Mx. In AR 9236, about \(4.2 \times 10^{20}\) Mx appears in the form of MMF pairs, the net flux is \(1.4 \times 10^{20}\) Mx. We also find that in both active regions the net flux of MMFs has the same polarity as the parent sunspots. Unfortunately, we cannot compare the net flux carried by the MMFs with a possible flux loss by the parent sunspots, since the MDI field strength and flux measurements are unreliable in sunspot umbrae (R. Bush, private communication). The average flux of an MMF element of either polarity ranges from \(3 \times 10^{17}\) Mx to \(10^{19}\) Mx, with a mean value of \(3.6 \times 10^{18}\) Mx. The detailed properties of MMFs are described below.

1. Distance from penumbra of parent sunspots: The majority of MMF pairs first appears at 2–6 arcsec from the penumbral boundary. Note that this distance is measured from the centre-of-gravity of the MMF, so that the polarity nearer to the sunspot started 500–1000 km closer to the penumbral boundary. (2) Lifetime: The lifetime ranges from 0.25 to 9 hour with the peak of the distribution lying at 3 hour. The average lifetime is 3.9 hour. MMFs travel about 6000 km during their lifetime. (3) Separation between polarities of MMF pairs: Another parameter of MMF pairs is the separation between the opposite polarity elements. The separation between two polarities of MMF pairs is about 500–2000 km. At beginning, the mean separation is 1500 km, while at end, 1380 km. During the process that the MMF pairs are moving outward, the separation decreases slightly, by 120 km on average. (4) Motion: In general, all MMF pairs move roughly radially away from center of the parent sunspot. The velocity of 288 elements belonging to 144 MMF pairs falls in the range from 0.05 to 0.9 km s\(^{-1}\) with the peak of the distribution lying at 0.4 km s\(^{-1}\). The average velocity is 0.45 km s\(^{-1}\) (irrespective of the polarity). We have noticed that at least some MMFs initially move quite fast, but later slow down to the typical speed of supergranule outflow. (5) Orientation of MMF bipoles: A central property of MMFs with respect to deciding their nature is the orientation of MMF bipoles. We find that the magnetic element of MMF pairs with the polarity of the parent sunspots is further away from the sunspot in 85% (±12%) of the cases in AR 8375 and in 87% (±7%) in AR 9236. One surprising result is that for AR 8375 the number of MMF pairs is not evenly distributed all around the sunspot, instead they are most common at azimuths \(\beta\) between 0 and 90°, with a peak in the distribution at \(\beta = 40°\). We notice that the line with \(\beta\) equals 40° presents the line connecting N-polarity and S-polarity spots (see the continuum image in Fig. 1 of AR 8375). Hence the largest number of MMFs are found in the region between the two opposite polarity spots, travelling from the larger spot towards the smaller. Some of the MMFs disappear before reaching the smaller spot, other merge/cancel with it. The MMFs lying between \(\beta = 10°\) and 65° do not travel on a straight line, but are focussed onto the smaller sunspot.

4. Discussion

The Evershed flow represents a nearly horizontal flow of matter directed radially outward in sunspot penumbra. Shine et al. (1994) have argued on the basis of filament movies that the flow is not steady but intermittent. Consider now a packet of dense outward flowing gas. Within the penumbra this packet, which cools as it flows along a horizontal flux tube in the penumbra (Schlichenmaier and Schmidt 2000), is prevented from sinking by magnetic forces. Plasma \(\beta < 1\) in the penumbra and the substantial vertical field strength gradient of 1–2 G/km provides a force that resists the gravitational force. At the edge of the penumbra this supporting force disappears and a sufficiently dense and massive packet of Evershed gas cannot be supported by the flux tube field any more. This gas will then sink, taking the magnetic field with it. In this way an U-loop is created near the penumbral edge. The outer arm of the U-loop has the same polarity as the sunspot. This agrees with our findings and those of Yurchyshyn et al. (2001). Submergence of field and a downflow near the penumbral boundary has been observed by Westendorp Plaza et al. (1997).

The ensuing U-loop is driven outward initially due to its inertia, partly by the moat flow. The intersections of this U-loop with the solar surface are visible as the two polarities of a bipolar MMF. Note that the MMF speeds are similar to those of intranetwork magnetic elements (Zhang et al. 1998), which are thought to be dragged along by the supergranular
flow. The Evershed flow in the magnetic canopy of 1–2 km/s is faster, however, than the MMFs, so that fresh material from the sunspot keeps catching up with the MMF. Presumably this material will flow down the leg of the MMF and its inertia will keep providing fresh impetus to keep the MMF moving against the drag of the surrounding gas. It has been shown that less than half of the mass flux seen in the penumbra continues in the magnetic canopy (Solanki et al. 1994, 1999). We suggest that the remainder is transported by the MMFs. The field lines found to submerge by Westendorp Plaza (1997) eventually rejoin the magnetic canopy. The forces acting on the U-loop are buoyancy (or rather gravity), which pulls the dense material downwards, and the magnetic tension (curvature forces) which pulls the field lines upwards. Superficially at least the situation is similar to the eruption of magnetic flux from the overshoot layer below the convection zone, with an inverted geometry and the flux tube now being dense.

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