GLOBAL TWIST OF SUNSPOT MAGNETIC FIELDS OBTAINED FROM HIGH-RESOLUTION VECTOR MAGNETOGRAMS

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ABSTRACT

The presence of fine structures in sunspot vector magnetic fields has been confirmed from Hinode as well as other earlier observations. We studied 43 sunspots based on the data sets taken from ASP/DLSP, Hinode (SOT/SP), and SVM (USO). In this Letter, (1) we introduce the concept of signed shear angle (SSA) for sunspots and establish its importance for non-force-free fields. (2) We find that the sign of global $\alpha$ (force-free parameter) is well correlated with that of the global SSA and the photospheric chirality of sunspots. (3) Local $\alpha$ patches of opposite signs are present in the umbra of each sunspot. The amplitude of the spatial variation of local $\alpha$ in the umbra is typically of the order of the global $\alpha$ of the sunspot. (4) We find that the local $\alpha$ is distributed as alternately positive and negative filaments in the penumbra. The amplitude of azimuthal variation of the local $\alpha$ in the penumbra is approximately an order of magnitude larger than that in the umbra. The contributions of the local positive and negative currents and $\alpha$ in the penumbra cancel each other giving almost no contribution for their global values for the whole sunspot. (5) Arc-like structures (partial rings) with a sign opposite to that of the dominant sign of $\alpha$ of the umbral region are seen at the umbral–penumbral boundaries of some sunspots. (6) Most of the sunspots studied belong to the minimum epoch of the 23rd solar cycle and do not follow the so-called hemispheric helicity rule.

Key words: Sun: magnetic fields – Sun: photosphere – sunspots

1. INTRODUCTION

Helical patterns in sunspots and associated features have been observed for a long time (Hale 1925, 1927; Richardson 1941) with a hemispheric preference of their chirality, which is independent of the solar cycle. Since the 1990s, the subject has been intensively revisited and the similar behavior of hemispheric patterns for various solar features has been reported by many researchers (Hagino & Sakurai 2004; Nandy 2006; Bernasconi et al. 2005; Pevtsov & Longcope 2001, 2007 and references therein). However, this hemispheric behavior needs further investigation due to some inconsistencies reported for different phases of a solar cycle and also for data sets obtained from different magnetographs (Hagino & Sakurai 2004; Pevtsov et al. 2008).

For a force-free field, the global twist per unit axial length is given by the force-free parameter $\alpha$ (see Appendix A of Tiwari et al. 2009a). Some recent studies (Tiwari et al. 2008, 2009b; S. K. Tiwari et al. 2009, in preparation) have shown that the global $\alpha$ of an active region bears the same sign as its associated features/structures observed at chromospheric and coronal heights. The chromospheric and coronal sign of twist is inferred from the topological chirality sign of the observed features. This leads us to believe that some form of the photospheric global twist exists on the scale of sunspots. However, the structures in the sunspot fields revealed by modern vector magnetographs with high spatial and spectral resolution compels us to make a careful revaluation of global $\alpha$ and its physical meaning.

Since the photospheric field is not force-free (Metcalf et al. 1995), we need an alternative measure of the twist other than $\alpha$. We introduce the concept of the signed shear angle (SSA) for sunspot magnetic fields in this Letter and show how the SSA is directly related to vertical current ($J_z$) and $\alpha$, irrespective of the force-free nature of the sunspot fields.

The presence of oppositely directed currents in a single unipolar sunspot was first shown by Severnyi (1965). For a detailed investigation of local $\alpha$ distribution in three sunspots using 46 vector magnetograms, see Pevtsov et al. (1994). Recently, Su et al. (2009) reported an interesting pattern of fine structures in the $\alpha$ distribution within one active region (AR) using Hinode data with higher resolution. We present a comprehensive study of 43 sunspots with high resolution and establish the contribution of such fine structures to the global twist. For this purpose we will rely on $J_z$ and $\alpha$ values.

The helicity hemispheric rule or, more precisely, twist hemispheric rule is claimed to be established by many researchers (Seehafer 1990; Pevtsov et al. 1995; Abramenko et al. 1996; Bao & Zhang 1998; Longcope et al. 1998; Hagino & Sakurai 2005) and has recently been a matter of some debate (Hagino & Sakurai 2005; Pevtsov et al. 2008). A model developed by Choudhuri et al. (2004) predicts deviation from the twist hemispheric rule in the beginning of the solar cycle. However, some observers claim that this deviation from the hemispheric rule may be present in different phases of different solar cycles (Pevtsov et al. 2008). We have studied 43 ARs (as shown in Table 1) mostly observed during the declining phase of solar cycle 23. None but five follow the twist hemispheric rule.

In the following section (Section 2), we discuss the data sets used. Section 3 describes the analysis and results obtained. Finally, in Section 4 we present our conclusions.

2. DATA SETS USED

We have used the vector magnetograms obtained from the Solar Optical Telescope/Spectro-polarimeter (SOT/SP; Tsuneta et al. 2008; Suematsu et al. 2008; Ichimoto et al. 2008) onboard Hinode (Kosugi et al. 2007) and the Advanced Stokes Polarimeter (ASP; Elmore et al. 1992) as well as the Diffraction Limited Spectro-polarimeter (DLSP; Sankarasubramanian et al. 2004, 2006) of the Dunn Solar Telescope (DST). A standard and well-established calibration procedure was adopted for ASP/DLSP data. The procedure for obtaining the vector fields...
from the ASP/DLSP data is described elsewhere (Elmore et al. 1992; Sankarasubramanian et al. 2004, 2006). The Hinode (SOT/SP) data have been calibrated by the standard “sp_prep” routine available in the Solar-Soft packages. The prepared polarization spectra have been inverted to obtain vector magnetic field components using an Unno–Rachkovsky (Unno 1956; Rachkovsky 1967) inversion under the assumption of a Milne–Eddington (ME) atmosphere (Landolfi & Landi Degl’Innocenti 1982; Skumanich & Lites 1987). The 180° azimuthal ambiguity in the data sets are removed by using an acute angle method (Harvey 1969; Sakurai et al. 1985; Cuperman et al. 1992). All the data sets used have high spatial sampling. For example, ASP ∼0.3 arcsec pixel⁻¹, DLSP ∼0.1 arcsec pixel⁻¹, and Hinode (SOT/SP) ∼0.3 arcsec pixel⁻¹. However, a few observations are seeing limited to about an arcsec.

To minimize noise, pixels having transverse ($B_t$) and longitudinal magnetic field ($B_z$) greater than a certain level are only analyzed. A quiet-Sun region is selected for each sunspot and $\sigma$ deviations in the three vector field components $B_x$, $B_y$, and $B_z$ are evaluated separately. The resultant deviations in $B_x$ and $B_y$ are then taken as the $\sigma$ noise level for transverse field components. Only those pixels where longitudinal and transverse fields are simultaneously greater than twice the above mentioned noise levels are analyzed.

The data sets with their observation details are given in Table 1. The data sets observed from 2001 August to 2005 April are obtained with the ASP and those observed from 2005 June to 2005 December are from the DLSP. Two vector magnetograms observed on 2007 January 9 and 2007 February 6 from the Solar Vector Magnetograph at the Udaipur Solar Observatory from the ASP/DLSP data is described elsewhere (Elmore et al. 1992; Sankarasubramanian et al. 2004, 2006).

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(SVM-USO: Gosain et al. 2004, 2006), and reported in Tiwari et al. (2008), also have been included to improve the statistics. All the other data sets obtained since 2006 November onward are taken from Hinode (SOT/SP).

3. DATA ANALYSIS AND RESULTS

We have used the following formula to compute the local $\alpha$ values

$$\alpha = \frac{(\nabla \times \mathbf{B})_z}{B_z}. \quad (1)$$

The global $\alpha$ value of the active regions is estimated from the following formula as described in Tiwari et al. (2009a):

$$\alpha_g = \frac{\sum (\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}) B_z}{\sum B_z^2}. \quad (2)$$

This estimate was shown to be not seriously affected by the polarimetric noise (Tiwari et al. 2009a). Moreover, since $\alpha_g$ is weighted by strong field values (Hagino & Sakurai 2004) and not affected by singularities at polarity inversion lines (Tiwari et al. 2009a), this parameter is more accurate than a simple average of local $\alpha$.

Hagyard et al. (1984) introduced the shear angle $\Delta \Phi = \Phi_{\text{obs}} - \Phi_{\text{pot}}$, where $\Phi_{\text{obs}}$ and $\Phi_{\text{pot}}$ are the azimuthal angles of the observed and potential fields, respectively. The amplitude of this angle was studied at the polarity inversion lines to investigate the flare related changes (Hagyard et al. 1990; Ambastha et al. 1993; Hagyard et al. 1999). To emphasize the sign of shear angle we wish to introduce the SSA for the sunspots as follows: we choose an initial reference azimuth for a current-free field (obtained from observed line-of-sight field). Then we move to the observed field azimuth from the reference azimuth through an acute angle. If this rotation is counter-clockwise, then we assign a positive sign for the SSA. A negative sign is given for clockwise rotation. This sign convention will be consistent with the sense of azimuthal field produced by a vertical current. This sign convention is also consistent with the sense of chirality (for details, see Appendix A). The potential field has been computed using the method of Sakurai (1989). The mean of the SSA obtained for a whole sunspot is taken as the global value of the SSA for that sunspot.

The force-free parameter $\alpha$ involves three dimensions since it basically represents the rate of change of rotation per unit axial length. The SSA is the rotational deviation of the projection of the field onto the photosphere from that of a reference current-free field. The $\alpha$ parameter is a gradient of angle per unit length, while the SSA is just an angle. We therefore cannot expect a strong correlation between the amplitudes of both the quantities, the SSA and the $\alpha$ parameter. But we do find a good correlation between their signs as evident from Table 1.

The SSA provides the sign of twist irrespective of whether the photospheric magnetic field is force-free or not. Table 1 shows that the sign of $\alpha$ is the same as the sign of SSA. Thus, we conclude that even if the photosphere is non force-free, the sign of global $\alpha$ will empirically give the sign of global SSA and therefore the sign of global twist (chirality) of the sunspots.

To avoid any kind of projection effect we have transformed the data sets to the disk center (Venkatakrishnan & Gary 1989) if the observed sunspot is equal to more than $10^\circ$ away from the disk center. In some active regions both the polarities are compact enough to be studied separately. We have treated each pole of those active regions as an individual sunspot and this is denoted in Table 1 after the NOAA no. of sunspots by plus or minus sign.

Two examples of the local $\alpha$ distribution for the data sets obtained from Hinode (SOT/SP) are shown in Figure 1. The positive/negative contours are shown in red/blue colors. The local $\alpha$ patches are seen in the umbra and filamentary distribution of $\alpha$ is observed in the penumbral region. We find that the inclination angles oscillate between $\sim 30^\circ$ and $80^\circ$ when we go along the azimuthal direction in the filamentary penumbral structures. This is consistent with the interlocking-comb penumbral structure (Ichimoto et al. 2007) of the penumbral magnetic fields. The vertical current $J_z$ has two components, viz. $-\frac{1}{r} \frac{\partial B_y}{\partial r}$ and $\frac{1}{r} \frac{\partial (r B_z)}{\partial r}$. If we approximate the observed transverse field ($B_y$) to be mostly radial ($B_y \sim B_r$) then we can interpret the azimuthal variation of $J_z$ to result from the term $-\frac{1}{r} \frac{\partial B_y}{\partial r}$. This term is not expected to contribute to global twist. However, $\frac{1}{r} \frac{\partial (r B_z)}{\partial r}$ could be an important contributor to the global twist. A detailed investigation of this interesting possibility is deferred to another paper. For the present, we obtain positive and negative values of current side by side in the penumbra. Because the $\alpha$ parameter depends on the current, this oscillation in the filamentary structure across the penumbral filaments is expected for the $\alpha$ values too.

The distribution of vertical current and local $\alpha$ in the penumbral cross section is high than that in the umbra regions. An arc and a straight line, selected respectively in the penumbra and umbra of AR NOAA 10933, have been over plotted as shown in the left panel of Figure 1. The corresponding values of vertical current and $\alpha$ along the arc and the line are shown in Figures 2(a) and (b), respectively. We can see that both the positive and negative vertical current as well as $\alpha$ are equally distributed in the penumbra along the azimuthal direction. This gives a negligible contribution to the global current and global $\alpha$ values, thereby indicating that the contribution of $-\frac{1}{r} \frac{\partial B_y}{\partial r}$ is indeed small. We have selected an arc rather than the complete circle because many times sunspots are not circular and therefore selecting a proper penumbral region is not possible by a full circle. Similar arcs have been selected in the other sunspots and all the time it is seen that both the positive and the negative vertical current as well as $\alpha$ are distributed equally in the penumbra giving negligible contribution to their global values. While current and $\alpha$ variations are correlated for positive $B_z$, they will be anti-correlated for negative $B_z$.

Figure 1(b) shows a typical profile of spatial variations of current and $\alpha$ across the umbra (along the line) in the AR NOAA 10933 shown in the left panel of Figure 1. We see that the amplitude of variation of $\alpha$ in the umbra is smaller than that in the penumbra by approximately an order of the magnitude and is of the same order as that of the global $\alpha$ value of the whole sunspot. The variation of $J_z$ in the umbra is of the same order as the penumbral $J_z$ variation. The mean umbra $J_z$ is much larger than the mean penumbral $J_z$.

In the right panel of Figure 1 an arc-like structure (partial ring) with a bunch of red contours (positive $\alpha$) can be observed. This is opposite to that of the dominant negative global $\alpha$ of the sunspot. Such partial rings with opposite signs of the global $\alpha$ are observed in 10 of the sunspots from our sample. In the rest of the sunspots mixed current and $\alpha$ are present in the umbra with one dominant sign and no such specific structures are seen at the umbra–penumbral boundaries.

A few sunspots in our data sets studied are small and have no penumbra. Some ASP data do not show fine structures in the penumbra due to lack of spatial resolution. We have included
Figure 1. Two examples of local $\alpha$ distribution observed in Hinode (SOT/SP) data. The background is the continuum image. Red and blue contours represent positive and negative values of $\alpha$, respectively. The contour levels are $\pm 1 \times 10^{-8}$ m$^{-1}$, $\pm 5 \times 10^{-8}$ m$^{-1}$, and $\pm 10 \times 10^{-8}$ m$^{-1}$. The values of vertical current and $\alpha$ along the arc shown in the penumbra of the image in the left panel are plotted in Figure 2(a) and those along the straight line in the umbra are plotted in Figure 2(b).

Figure 2. Plots of vertical current and $\alpha$ values along (a) the arc and (b) the straight line shown in the penumbra and umbra of AR NOAA 10933 (the left panel of Figure 1) respectively. Black and red colors represent the current and $\alpha$ values, respectively. The mean values of both the vertical current and the $\alpha$ values with their $1\sigma$ standard deviations in the arc and the line are printed on the plots in their respective colors.

4. DISCUSSION AND CONCLUSIONS

We have introduced the concept of SSA for sunspots and further find that the SSA and the global $\alpha$ value of sunspots have the same sign. Thus, $\alpha$ gives the same sign as the SSA and therefore the same sign of the photospheric chirality of the sunspots, irrespective of the force-freeness of the sunspot fields.

Most of the data sets we studied are observed during the declining minimum phase of solar cycle 23. All except five of the sunspots observed do not follow the twist hemispheric rule.

As can be observed from Table 1, the magnitudes of SSA and $\alpha_g$ are not well correlated. This lack of correlation could be due to a variety of reasons: (1) departure from the force-free nature, (2) even for the force-free fields, $\alpha$ is the gradient of twist variation whereas the SSA is purely an angle. The missing link is the scale length of variation of twist. The magnitude of the global SSA, therefore, holds promise for characterizing global twist of the sunspot magnetic fields, irrespective of its force-free nature.

Patches of vertical current and $\alpha$ with opposite signs are present in the umbra of each sunspot studied. Since opposite currents repel, the existence of a dominant current may be a useful binding force for the umbra (cf. Parker 1979). This will be examined in detail in further studies of evolution of twist in decaying sunspots. One sign of $\alpha$ dominates in the umbra which is also seen to be the sign of the global $\alpha$ of the sunspot. Similarly, the magnitude of the global $\alpha$ is of the same order as the amplitude of the local $\alpha$ in the umbra.

The filamentary structures of vertical current and local $\alpha$ are observed in the penumbra of the sunspots and are, as discussed above, due to oscillatory behavior in the inclination values and therefore gradients of the transverse field in the azimuthal direction. We find that the contributions of both positive and negative values of vertical current and $\alpha$ to their global values cancel each other in the penumbra of the sunspot. Thus the penumbral fine structures provide a negligible contribution to the global $\alpha$ and current values of sunspots. The mutual repulsion of opposite currents also seems to balance out in the azimuthal direction. It is to be seen whether disruption of this balance leads to sunspot rotation and change in global twist. At any rate, the observed balancing of the filamentary currents in the azimuthal direction may be an important contribution to the force-free nature of the sunspot fields. The amplitude of $\alpha$ variation is approximately an order of magnitude smaller in the umbral regions than that in the penumbral regions and is of the order of the global $\alpha$ of the whole sunspot.
Partial rings with opposite signs to that of dominant sign of umbral $\alpha$ are observed at sunspot umbral—penumbral boundaries in 10 out of 43 sunspots studied. However, even in these few cases, the rings are never complete in any sunspot. Most of the ARs observed do not follow the twist hemispheric rule. This issue of the hemispheric rule needs to be reinvestigated over a longer period as well as with improved data. Some researchers have tried to predict flare activity from local distribution of $\alpha$ as well as global $\alpha$ values of sunspots (Nandy 2008; Hahn et al. 2005 and references therein). Nandy (2008) concluded from a study of AR 6982 that the global twist present in a sunspot does not influence the flaring activity. It is, rather, governed by the spatial distribution and evolution of twisted substructures present in the sunspot. This conclusion indeed needs more study. We plan to address, in our forthcoming study, the question of relation between flaring activity and the role of global as well as the local twist present in a large number of sunspots.

For the present, we demonstrate that the sign of the SSA provides the sign of the photospheric chirality irrespective of its force-free nature. The sign of the global $\alpha$ of a sunspot is determined by the dominant sign of umbral $\alpha$ values without much contribution from the penumbral $\alpha$ values.

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APPENDIX

RELATION BETWEEN THE SIGN OF SSA AND THE SENSE OF CHIRALITY

The definition of the SSA is introduced in Section 3. Figure 3 shows four structures, the first two having positive chirality and the next two having negative chirality. The sign of $B_{\text{pot}}$ and $B_{\text{obs}}$ point inward for negative $B_z$ and outward for positive $B_z$. The rotation from $B_{\text{pot}}$ to $B_{\text{obs}}$ through an acute angle is counterclockwise for cases of positive chirality and clockwise for negative chirality. This is consistent with positive and negative SSA, respectively, by definition. Thus, the sign of SSA will bear the same sign of the chirality.

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