THE EVOLUTION OF THE TWIST SHEAR AND DIP SHEAR DURING X-CLASS FLARE OF 2006 DECEMBER 13: HINODE OBSERVATIONS

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ABSTRACT

The non-potentiality of solar magnetic fields is traditionally measured in terms of a magnetic shear angle, i.e., the angle between the observed and potential field azimuths. Here, we introduce another measure of the shear that has not been previously studied in solar active regions, i.e., the one that is associated with the inclination angle of the magnetic field. This form of the shear, which we call “dip shear,” can be calculated by taking the difference between the observed and the potential field inclination. In this Letter, we study the evolution of the dip shear as well as the conventional twist shear in a δ-sunspot using high-resolution vector magnetograms from the Hinode space mission. We monitor these shears in a penumbral region located close to a flaring site during 2006 December 12 and 13. It is found that (1) the penumbral area close to the flaring site shows a high value of the twist shear and dip shear as compared with other parts of the penumbra, (2) after the flare, the value of the dip shear drops in this region while the twist shear tends to increase, (3) the dip shear and twist shear are correlated such that pixels with a large twist shear also tend to exhibit a large dip shear, and (4) the correlation between the twist shear and dip shear is tighter after the flare. The present study suggests that monitoring the twist shear alone during the flare is not sufficient, but we need to monitor it together with the dip shear.

Key words: Sun: flares – Sun: magnetic topology – sunspots

1. INTRODUCTION

The deviation of an active region (AR) magnetic field from its potential configuration can arise due to photospheric footpoint motions and/or during flux emergence. However, studies of high-quality data from space- and ground-based observatories over the last decade suggest that the latter is a more dominant mechanism (Wheatland 2000; Démoulin et al. 2002; Falconer et al. 2002; Leka & Barnes 2003; Schrijver et al. 2005; Jing et al. 2006; Schrijver 2007). The deviation of the magnetic field from a potential configuration is called non-potentiality (NP) of the field. The magnetic energy of an AR in excess of the potential magnetic energy is called free magnetic energy (Low 1982). The free magnetic energy of an AR, or a portion of it, is released when the flare and/or coronal mass ejections (CMEs) are triggered due to the instability or non-equilibrium (Priest & Forbes 2002). The energy released in the flare is then limited by the amount of free energy or magnetic NP of the AR. Therefore, it is important to characterize the NP of the AR magnetic field in order to predict the intensity of the flare and/or CME.

Traditionally, the so-called magnetic shear, i.e., the angle between the observed (ψ_o) and potential (ψ_p) field azimuths, is used to characterize the NP of the AR magnetic field and is measured as

\[ Δψ = \arccos \left( \frac{\mathbf{B}_o \cdot \mathbf{B}_p}{|\mathbf{B}_o||\mathbf{B}_p|} \right), \]

where \( \mathbf{B}_o \) and \( \mathbf{B}_p \) are the observed and potential transverse field vectors. The term “magnetic shear,” used here and in similar studies on solar magnetism, really refers to “observational shear,” which is not to be confused with the actual “shear”—a microscopic property in fluid dynamics. In what follows, we use the term magnetic shear for traditional reasons and by this term we would always mean the observational shear. Various forms of this parameter are used, namely, the mean shear (Hagyard et al. 1984), weighted mean shear (Wang 1992), spatially averaged signed shear (Tiwari et al. 2009), most probable shear (Moon et al. 2003), etc. It is well known that the polarity inversion line (PIL) in ARs bearing highly sheared magnetic fields is the potential site for flares (Hagyard et al. 1984, 1990). These PILs are generally characterized by dark filaments in the images taken in the chromospheric hydrogen alpha line (Zirin & Tanaka 1973).

It may be noted that all of the shear parameters mentioned above measure the twist-shear component of the shear, which is measured in the horizontal plane. However, one can also measure the shear of a magnetic field in the vertical plane. This type of the shear can be called “dip shear” (we choose the term “dip” because it is synonymous to the dip angle measured in geomagnetism) and can be measured by taking the difference between the observed (ψ_o) and the potential field inclination angle (ψ_p), i.e., Δψ = (ψ_o - ψ_p).

Physically, the dip shear can be understood in terms of azimuthal currents, in the same way as the twist shear is understood in terms of axial currents. To our knowledge, the dip shear has not been studied earlier in solar ARs. Henceforth, we call the parameters Δψ and Δψ the twist shear and dip shear, respectively. The larger the value of these angles the larger will be the NP of the AR. It may be noticed that, unlike the twist shear, the dip shear is not affected by the 180° azimuth ambiguity, provided that the AR is observed close to the disk center. This is because the dip shear depends upon the inclination angle of the magnetic field which can be measured without ambiguity (Metcalf et al. 2006).

In this Letter, we study the evolution of the twist shear and dip shear in a penumbral region located close to the flaring site in AR NOAA 10930. We use a sequence of high-quality vector magnetograms observed by the Hinode space mission. This AR was in a δ-sunspot configuration which led to a X3.4 flare and a large CME during 02:20 UT on 2006 December 13. The flare was quite powerful and the white light flare ribbons...
Figure 1. Panels (from top to bottom) show a continuum intensity map of the $\delta$-sunspot in NOAA 10930 during the times mentioned at the top. The transverse magnetic field vectors are shown by arrows overlaid upon these maps. The black rectangle, as shown in all panels, is the region where we monitor the evolution of the twist shear and dip shear.

The evolution of the twist shear and dip shear together shows interesting patterns which can be distinguished in the pre-flare and post-flare stages. In general, we find that (1) the regions with a high twist shear also exhibit a high dip shear, (2) the penumbral region close to the flaring site shows a high twist shear and a high dip shear, and (3) the twist shear and dip shear studied together can be used to analyze the flare-related changes in ARs.

The Letter is organized as follows. The observational data and the methods of analysis are described in Section 2. The results are presented in Section 3, and the discussions and conclusions are given in Section 4.

2. OBSERVATIONAL DATA AND METHODS OF ANALYSIS

2.1. Hinode Observations

A sunspot with a $\delta$ configuration was observed in AR NOAA 10930 during 2006 December 12 and 13 by the Spectro-Polarimeter (SP) instrument (Lites et al. 2007; Ichimoto et al. 2008) with the Solar Optical Telescope (SOT; Tsuneta et al. 2008) on board the Hinode satellite (Kosugi et al. 2007). The SP obtains the Stokes profiles, simultaneously in the FeI 6301.5 Å and 6302.5 Å line pair. The spectro-polarimetric maps of the AR are made by scanning the slit across the field of view. This takes about an hour to complete one scan. We choose a sequence of six SP scans from 2006 December 12 03:50 UT along with impulsive lateral motion of the penumbral filaments were observed (Gosain et al. 2009).
to 2006 December 13 16:21 UT when the sunspot was located close to the disk center with heliocentric distances ($\mu$) of 0.99 and 0.97, respectively. The scans were taken in “Fast Map” observing mode with the following characteristics: (1) field of view (FOV) $295 \times 162$ arcsec, (2) the integration time of 1.8 s, and (3) the pixel width across and along the slit of 0.32 and 0.29 arcsec, respectively. The Stokes profiles were then fitted to an analytic solution of Unno–Rachkovsky equations (Unno 1956; Rachkovsky 1973) under the assumptions of the fitted to an analytic solution of Unno–Rachkovsky equations and 0.29 arcsec, respectively. The Stokes profiles were then fitted to an analytic solution of Unno–Rachkovsky equations (Unno 1956; Rachkovsky 1973) under the assumptions of the local thermodynamic equilibrium (LTE) and Milne–Eddington model atmosphere (Landolfi & Landi Degl’Innocenti 1982) with a nonlinear least-squares fitting code called Helix (Lagg et al. 2004). The physical parameters of the model atmosphere retrieved after inversion are the magnetic field strength, its inclination and azimuth, the line-of-sight velocity, the Doppler width, the damping constant, the ratio of the line center to the continuum opacity, the slope of the source function, and the source function at $\tau = 0$. We fit a single-component model atmosphere along with a stray light component. The inversion code Helix is based upon a reliable genetic algorithm (Charbonneau 1995). This algorithm, although more robust than the classical Levenberg–Marquardt algorithm in the sense that the global minimum of the merit function is reached with higher reliability (Lagg et al. 2004).

The vector magnetograms obtained after inversion were first solved for the 180° azimuth ambiguity by using the acute angle method (Harvey 1969) and were then transformed from the observed frame (image plane) to the local solar frame (heliographic plane) using the procedure described in Venkatakrishnan et al. (1988). The potential field was computed from the line-of-sight field component by using the Fourier transform method (Alissandrakis 1981; Gary 1989). The IDL routine used for the potential field computation is fff.pro which is available in the NLFFF (nonlinear force-free field) package of the SolarSoft library. The continuum intensity images of the sunspot, corresponding to the sequence of scans used, are shown in Figure 1, with the transverse field vectors overlaid on it. The two magnetograms were aligned using the cross-correlation technique applied to the continuum image of the sunspot. A black rectangle is overlaid on these images to show the location of the region where we study the evolution of the twist shear and dip shear. The location of this black rectangle is chosen with the help of a co-aligned G-band filtergram observed from the Hinode Filtergraph instrument during the flare. This G-band image is shown in the left panel of Figure 2. The flare ribbon is marked by “+” symbols and the black rectangle of Figure 1 is also shown here. The flare ribbons sweep across the rectangular box during 02:20 to 02:26 UT. This indicates that the rectangle is chosen such that it samples the penumbra which is very close to the flaring site. The right panel of Figure 2 shows the longitudinal magnetogram in order to indicate the location of the rectangle (shown here with white color) with respect to the PIL. The maps of the dip shear $\Delta \gamma$ and the twist shear $\Delta \psi$ for the sequence of vector magnetograms are shown in Figure 3 and 4, respectively. In Figure 5, we show the distribution of the dip shear $\Delta \gamma$ and the twist shear $\Delta \psi$ inside the black rectangle and its evolution with time.

3. RESULTS

3.1. Distribution and Evolution of Non-potentiality in NOAA 10930

3.1.1. Dip Shear

The maps of the dip shear $\Delta \gamma$ for the entire sequence of vector magnetograms covering the pre-flare (panels (a)–(c)) and post-flare (panels (d)–(f)) phases are shown in Figure 3. The value of the field inclination $\gamma$ is measured with respect to a local solar vertical direction and ranges from $0^\circ$ to $180^\circ$. For a purely vertical positive (negative) polarity field the value of $\gamma$ corresponds to $0^\circ$ ($180^\circ$). The black rectangle in Figure 3 corresponds to a negative polarity field. Therefore, the positive value of the dip shear $\Delta \gamma$ inside this rectangle means that the observed field is more vertical than the potential field. The magnitude of the dip shear $\Delta \gamma$ can be judged with the aid of a color bar at the bottom of Figure 3.

It may be noticed that (1) the value of the dip shear $\Delta \gamma$ is large inside the rectangle as compared with other penumbral locations. (2) In the pre-flare phase (panels (a)–(c)) the dip

Figure 2. Left panel shows the G-band filtergram of the $\delta$-sunspot in NOAA AR 10930 during 2006 December 12 02:30 UT, with the location of the flare ribbon marked by “+” symbols. The flare ribbons sweep across the rectangular box during 02:20 to 02:26 UT. The right panel shows the map of the longitudinal field component for this sunspot. The black (white) rectangle in the left (right) panel marks the region where we monitor the evolution of the twist shear and dip shear.
shear $\Delta \gamma$ consistently has a large magnitude which decreases in the post-flare phase (panels (d)–(f)).

### 3.1.2. Twist Shear

The field azimuth has been solved for the 180° azimuth ambiguity by using the acute angle method (Harvey 1969), and the projection effects have been removed by the application of vector transformation (Venkatakrishnan et al. 1988). This azimuth ambiguity resolution method works well in the regions where the angle $\Delta \psi$ is less or greater than 90°. For regions where $\Delta \psi$ reaches value close to 90° such as along parts of PIL in flaring ARs, the accuracy of the method is poor. This is why we choose a rectangular box for studying the evolution of the twist shear and dip shear to sample the penumbra close to the flaring site and at the same time stay away from the PIL where the acute angle method may have problems in resolving the azimuth ambiguity.

The maps of the twist shear $\Delta \psi$ for the entire sequence of vector magnetograms covering the pre-flare (panels (a)–(c)) and post-flare (panels (d)–(f)) phases are shown in Figure 4. The value of the field azimuth $\psi$ is measured with respect to

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**Figure 3.** Panels (from top to bottom) show the maps of the dip shear, $\Delta \gamma = \gamma_o - \gamma_p$, for NOAA AR 10930 at different times. The black rectangle marks the region where we monitor the evolution of the twist shear and dip shear.
the positive X-axis and is positive in the anticlockwise direction. The magnitude of the twist shear $\Delta \psi$ can be judged with the aid of a color bar at the bottom of Figure 4. However, for the present study the sign of the shear angle is not important, so we focus on its magnitude. It may be noticed that the value of the twist shear $\Delta \psi$ is large inside the rectangle and adjacent PIL as compared to other penumbral locations. However, the flare-related changes are not so discernable to the eyes as compared to the dip shear in Figure 3.

3.1.3. Evolution of the Dip Shear and Twist Shear

In Figure 5, we show the scatter between the dip shear $\Delta \gamma$ and the twist shear $\Delta \psi$ for the pixels within the black rectangle shown in previous figures. The panels (a)–(c) correspond to the pre-flare phase while the panels (d)–(f) correspond to the post-flare phase.

It may be noticed that

1. The distribution of the dip shear $\Delta \gamma$ and the twist shear $\Delta \psi$ in panels (a)–(c) is different from the distribution in panels (d)–(f).
2. The dip shear increases before the flare (panels (a)–(c)) but the twist shear tends to decrease at the same time.
3. The dip shear and twist shear are in general correlated; i.e., the pixels with a large dip shear also have a large twist shear.
4. The most important change can be noticed after the flare, i.e., between panels (c) and (d). After the flare (panel (d)), the dip shear decreases significantly while the twist shear increases. However, now both shear components show less dispersion, i.e., follow a tight correlation.
5. In panels (d)–(f), the two shears maintain smaller dispersion but the dip shear starts to increase once again. This increase suggests that the NP was building up again in the AR. It may be noted that the flaring activity continued in this region on the next day, i.e., 2006 December 14 also, with another X-class flare occurring at about 22:00 UT.

4. DISCUSSION AND CONCLUSION

Hudson (2000) conjectured that the free energy is stored in non-potential magnetic loops that are stretched upward and that the free-energy release during the flare must be accompanied by a sudden shrinkage or implosion in the field. Also, it is predicted that after the flare the field should become more horizontal (Hudson et al. 2008). Using coronal images during flares, there are observational reports about the detection of the loop contraction during flares (Liu et al. 2009).

Further, it was described by Venkatakrishnan (1990) that in force-free fields a high NP implies a weaker magnetic tension, which in turn implies a larger vertical extension of the field due to a lower magnetic pressure gradient. Conversely, the release of the free magnetic energy during the flare implies loss of magnetic NP leading to a decrease in the vertical extension of the field or shrinkage (Forbes & Acton 1996).

The NLFFF extrapolations of the NOAA 10930 AR by Schrijver et al. (2008) show the NP of this AR in the form of a twisted flux rope structure. As suggested by Venkatakrishnan (1990) and Hudson (2000), such a structure will have a larger vertical extension in the pre-flare as compared to the post-flare configuration. The closer the post-flare field approaches the potential field configuration, the smaller is the value of the inclination difference $\Delta \gamma$ expected. This may give an explanation for the decrease in the dip shear $\Delta \gamma$ after the flare.

However, in contrast, the increase in the twist shear $\Delta \psi$ after the flare also needs an explanation. The opposite behavior of the twist shear and dip shear in relation to the flare can be understood in the following way. The twist shear is dependent on sub-photospheric/photospheric forces, so the twist shear will continue to increase independent of coronal processes such as flares. However, the plasma $\beta$ decreases rapidly above the photosphere, and thus there is no non-magnetic force or shear that is strong enough to change the inclination of the field lines. Hence, inclination will be more responsive to coronal processes. This may explain why inclination became more potential after the flare. Hence, the dip shear could be a better diagnostic of NP above the photosphere.

In summary, we studied the evolution of the twist shear and dip shear in a flaring $\delta$-sunspot using a sequence of high-quality vector magnetograms spanning the pre-flare and post-flare phases and found that (1) the penumbra located close to the flaring site has a high twist shear and a high dip shear as compared to other parts of the penumbra, (2) the twist shear increases after the flare which was also reported by Jing et al. (2008), (3) the dip shear however shows a decrease after the flare,
The twist shear and dip shear are correlated, i.e., pixels with a high twist shear exhibit a high dip shear, and this correlation is much tighter after the flare, and (5) the distribution of the twist shear and dip shear and its evolution (in Figure 5) clearly show different patterns before and after the flare.

This type of behavior in the twist shear and dip shear parameters needs to be evaluated further in more flares before it can be understood physically. We plan to carry out a more extensive study of the dip shear and twist shear in the existing Hinode data sets. However, a high-cadence study of these shear parameters would be possible only with the upcoming observations from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO; Scherrer & SDO/HMI Team 2002). The present study is important in the sense that it points the way to a vector-field follow-up to the results of Sudol & Harvey (2005), which established the line-of-sight field changes during powerful flares.

In the context of the present study, one should keep in mind that the vector magnetograms derived from the Hinode SOT/SP scans, although polarimetrically very precise, are very noisy geometrically. An unwanted consequence of the geometric noise could be that the flows, especially on long time scales, would tend to create an appearance of NP, even if there was none. This is an important issue which needs to be addressed sooner than later considering the widespread use of SOT/SP magnetic maps as the “vector magnetograms.” We plan to carry out a detailed study of this effect using the simultaneously observed SP scan from the Hinode SOT and vector magnetograms from the HMI on board the SDO.

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REFERENCES

Alessandrakis, C. E. 1981, A&A, 100, 197
Charbonneau, P. 1995, ApJS, 101, 309
Démoulin, P., Mandrini, C. H., Van Driel-Gesztelyi, L., Lopez Fuentes, M. C., & Aulanier, G. 2002, Sol. Phys., 207, 87
Falconer, D. A., Moore, R. L., & Gary, G. A. 2002, ApJ, 569, 1016
Forbes, T. G., & Acton, L. W. 1996, ApJ, 459, 330
Gary, G. A. 1989, ApJS, 69, 323
Gosain, S., Venkatakrishnan, P., & Tiwari, S. K. 2009, ApJ, 706, L240
Hagyard, M. J., Teuber, D., West, E. A., & Smith, J. B. 1984, Sol. Phys., 91, 115
Hagyard, M. J., Venkatakrishnan, P., & Smith, J. B., Jr. 1990, ApJS, 73, 159
Harvey, J. W. 1969, PhD thesis, Univ. Colorado at Boulder
Hudson, H. S. 2000, ApJ, 531, L75
Hudson, H. S., Fisher, G. H., & Welsch, B. T. 2008, in ASP Conf. Ser. 383, Subsurface and Atmospheric Influences on Solar Activity, ed. R. Howe et al. (San Francisco, CA: ASP), 221
Ichimoto, K., et al. 2008, Sol. Phys., 249, 233
Jing, J., Song, H., Abramenko, V., Tan, C., & Wang, H. 2006, ApJ, 644, 1273
Jing, J., Wiegelmann, T., Suematsu, Y., Kubo, M., & Wang, H. 2008, ApJ, 676, L81
Kosugi, T., et al. 2007, Sol. Phys., 243, 3
Lagg, A., Woch, J., Krupp, N., & Solanki, S. K. 2004, A&A, 414, 1109
Landolfi, M., & Landi Degl’Innocenti, E. 1982, Sol. Phys., 78, 355
Leka, K. D., & Barnes, G. 2003, ApJ, 595, 1296
Lites, B. W., et al. 2007, in ASP Conf. Ser. 369, New Solar Physics with Solar-B Mission, ed. K. Shibata, S. Nagata, & T. Sakurai (San Francisco, CA: ASP), 55
Liu, R., Wang, H., & Alexander, D. 2009, ApJ, 696, 121
Low, B. C. 1982, Sol. Phys., 77, 43
Metcalf, T. R., et al. 2006, Sol. Phys., 237, 267
Moon, Y.-J., Wang, H., Spirock, T. J., Goode, P. R., & Park, Y. D. 2003, Sol. Phys., 217, 79
Priest, E. R., & Forbes, T. G. 2002, A&AR, 10, 313
Rachkovsky, D. N. 1973, Izvestiya Ordiena Trudovogo Krasnogo Znameni Krymskoj Astrofizicheskoi Observatorii, 47, 3
Scherrer, P. H., & SDO/HMI Team, 2002, BAAS, 34, 735
Schrijver, C. J. 2007, ApJ, 655, L117
Schrijver, C. J., De Rosa, M. L., Title, A. M., & Metcalf, T. R. 2005, ApJ, 628, 501
Schrijver, C. J., et al. 2008, ApJ, 675, 1637
Sudol, J. J., & Harvey, J. W. 2005, ApJ, 635, 647
Tiwari, S. K., Venkatakrishnan, P., & Sankarasubramanian, K. 2009, ApJ, 702, L133
Tsuneta, S., et al. 2008, Sol. Phys., 249, 167
Unno, W. 1956, PASJ, 8, 108
Venkatakrishnan, P. 1990, Sol. Phys., 128, 371
Venkatakrishnan, P., Hagyard, M. J., & Hathaway, D. H. 1988, Sol. Phys., 115, 125
Wang, H. 1992, Sol. Phys., 140, 85
Wheatland, M. S. 2000, ApJ, 532, 616
Zirin, H., & Tanaka, K. 1973, Sol. Phys., 32, 173