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Tilt and $\alpha_{\rm best}$ of major flare-producing active regions

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Abstract.
We surveyed 86 active regions in the years from 1996 to 2002 in the 23rd solar cycle that produced more than three major flares. We studied the systematic tilt angle with respect to the solar equator and the force-free parameter $\alpha_{\rm best}$ of the magnetic field of the active regions, and we obtained the following results. (1) Only 46 (54%) of the active regions follow Joy's law. (2) 43 (50%) active regions obey the hemispheric helicity rule. (3) 56 (65%) have the same sign for the tilt and the $\alpha_{\rm best}$, and the tilt and the $\alpha_{\rm best}$ of all 86 regions are positively correlated. (4) 33 (60%) of the 55 active regions which have an $\beta\gamma\delta$ magnetic configuration show the same sign for the tilt and $\alpha_{\rm best}$.
It is commonly believed that the sign of the tilt and $\alpha_{\rm best}$ obtained in the photosphere can describe the sign of the twist and writhe of the flux tube rising from the convection zone. Therefore, the results above appear to support the kink hypothesis for active regions that the sign of the twist and writhe should be the same where a kink instability has developed (Linton, et al. 1999).

Key words. Sun: twist and writhe–Sun: major flares–Sun: active regions

1. Introduction

Magnetic twist is an important parameter to describe magnetic complexity, a measure of the turning of the field lines around the axis of the flux tube. Various observations show that the twist is predominantly left/right handed in the northern/southern hemisphere (Bieber et al. 1987; Burlaga 1988; Seehafer 1990; Martin et al. 1994; Pevtsov et al. 1995; Rust & Kumar 1996; Abramenko et al. 1996; Bao & Zhang 1998). Although the solar photospheric magnetic field is not likely to be force-free, the value of the force-free field parameter α ($\bigtriangledown \times \mathbf{B} = \alpha \mathbf{B}$) may still be used to describe the twist of magnetic fields (Pevtsov et al. 1995). Although maps of $\alpha = \mu J_z/B_z$ show significant variations, both in magnitude and sign, within an individual active region, there is often a pronounced overall twist for a given region (see, e. g. Pevtsov et al. 1995; Bao, et al., 1998) and $\alpha_{\rm best}$, the best-fit single value for a whole active region (Pevtsov et al. 1995), may be taken as a measure of this overall twist. A negative/positive value denotes left/right handed twist in the northern/southern hemisphere.

On the other hand, the average orientation of the bipolar active region magnetic field has been observed to tilt slightly away from the azimuthal direction (the direction of solar rotation) towards the solar equator. The tilt is defined by the line joining the opposite main polarities with respect to the equator; it is predominantly positive/negative in the northern/southern hemisphere, obeying the Hale-Nicholson Law (Hale, 1919) and Joy's Law (Zirin 1988). Positive/negative value in the northern/southern hemisphere denotes right/left handed writhe, which is a measure of the turning of the axis of the flux tube, (see, e. g. Tian et al. 2001).

Canfield & Pevtsov (1998), Tian et al. (2001), and López Fuentes et al. (2003) have analyzed the relationship between the writhe and the twist of active regions. Though these authors used different parameters to characterize the twist and writhe of the field, the results all showed a predominantly right/left handed writhe and left/right handed twist in the northern/southern hemisphere. Canfield & Pevtsov (1998) showed a positive correlation between the writhe and the twist, while Tian et al. (2001) and López Fuentes et al. (2003) showed a negative correlation (62−65%) between them. On the basis of Moffatt & Ricca (1992), the total magnetic helicity is the sum of the writhe and twist, $H = W_r + T_w$, where W_r is the writhe determined by the turning of the axis of the flux tube, and T_w is the twist contributed by the turning of the field lines around the axis. Since the magnetic helicity H is a conserved quantity, the total helicity is minimized when the twist and writhe are negatively correlated, and maximized when they are positively correlated.

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Recently Linton et al. (1999) performed a three-dimensional MHD simulation which showed that in a flux tube where the kink instability has developed the sign of the twist and writhe should be the same. Based on this, a kink hypothesis was proposed for the formation of the δ-spot active regions, and this model predicts that the twist and writhe in δ-spot active regions should have the same sign (see Fisher et al. 2000, and references therein). It is well-known that δ-sunspots have a high flare productivity, implying the presence of considerable amount of free energy in the active region. Thus it is interesting to ask whether highly flare-productive active regions have a higher incidence of like-signed twist and writhe, since kink instability occurs only in the presence of high magnetic twist, implying strong electric currents. In this work, we will address this question using a sample of 86 active regions in the 23rd cycle that produced 3 or more major flares. In Section 2, We will describe the data used and the calculations made. The results will be given in Section 3. Then we summarize the results and present a discussion in Section 4.

2. Observations

Vector magnetograms from Huairou Solar Observing Station (HSOS) of National Astronomical Observatory are used to compute the force-free parameter, $\alpha_{\rm best}$, as defined in the previous section. A detailed description of the instrument and calibration can be found in Wang et al. (1996). The 180° ambiguity for the transverse component of the magnetic field is resolved using a linear force-free field method (Wang & Abramenko, 2000). The vertical electric current density, J_z, is derived from the vector magnetic field by $J_z = \frac{1}{\mu_0}(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y})$. Since the transverse field has a noise level of 100 Gauss (Wang et al., 1996), the data we used for computing $\alpha_{\rm best}$ are from the areas where the transverse component of magnetic field is greater than 300 Gauss ($3\sigma_B$).

Full disk magnetograms of MDI/SOHO were used to calculate the tilts of the active regions. Considering that MDI has a noise level of 20 Gauss (Scherrer, et al., 1995), we only use data greater than 20 Gauss for this computation. For an active region with two major N and S polarities, the magnetic flux-weighted center of each polarity was determined, then the systematic tilt was defined as the angle of the line joining the opposite polarity centers to the solar equator. The tilt (ψ) was computed from the Cartesian coordinate differences (δy and δx) in the heliographic plane between the two polarities, $\tan(\psi)=\delta y/\delta x=\delta\theta\ /(\delta L * cos\theta)$, where δL and $\delta\theta$ are the differences in the Carrington longitude and latitude and θ is the mean latitude (Tian et al, 1999, 2001). Most $\beta\gamma\delta$ active regions in this work have two obvious opposite polarities, and their tilt angles were calculated as described above. We omitted two active regions from our sample because they have magnetic configurations so complex that we were unable to locate the predominant polarities or the direction of the tilt angle. We define the tilt as positive (negative) when the active region is tilted clockwise (counter-clockwise) from the E-W direction. We also compare the computed tilt with that of the two main polarities to ensure they have the same sign.

From July 1996 to December 2002, there are 91 active regions that produced more than three major flares and whose X-ray flare indexes are larger than 0.5. HSOS had no data for three of the active regions and two of the active regions were omitted due to the reason described above. Thus, 86 active regions (5 β, 26 $\beta\gamma$, and 55 $\beta\gamma\delta$) are used in this study. Generally, for each active region, three vector magnetograms taken in the same day were used for our analysis when the active region was near the central meridian (from -35° to 35°). We compute $\alpha_{\rm best}$ and tilt angle for each magnetogram, and then average them to obtain a mean value for every active region. But six of the 86 active regions have only one vector magnetogram near the central meridian, and the $\alpha_{\rm best}$ and tilt were derived solely from this data.

Each active region had a predominant sign for the $\alpha_{\rm best}$, though the field evolved in time and the map of $\alpha = \mu J_z/B_z$ showed much variation within an individual active region. It is worth noting that the sign of the predominant $\alpha_{\rm best}$ for most of the active regions did not change during the days of the central meridian pass. We omitted active regions for which we are unable to determine their predominant sign of $\alpha_{\rm best}$ in our sample.

Other data, such as magnetic class and X-ray flare index (XRI), are from the weekly reports at web-site (http://www.sec.noaa.gov/weekly). The index XRI is the sum of the numerical multipliers of the X-ray flare classes M and X for the disk transit of the active regions with M1 flares counting 0.1, M2 as 0.2; X1 flares as 1.0 and so on (see, e. g. McIntosh, 1992).

3. Results

Figure 1 shows the tilt and the $\alpha_{\rm best}$ as functions of the latitude for our sample. Only 54% (29.2% for negative tilts in the southern hemisphere and 24.7% for positive tilts in the northern) of the ARs follow Joy's law. A least-square fit for all the 86 active regions shows a very weak anti-correlation between the tilt and the latitude, implying a slight, general tendency of violating Joy's law (Figure 1a). 50% (22.1% for negative $\alpha_{\rm best}$ in the northern hemisphere and 27.9% for positive $\alpha_{\rm best}$ in the southern) obey the hemispheric helicity rule, and the overall tendency of all 86 regions weakly follows the hemispheric helicity rule (Figure 1b), with a correlation coefficient of 0.165, (the correlation coefficient at 95% confidence level is 0.205 for a sample size of 90, and 0.217 for a sample size of 80).

The relationship of the tilts and the $\alpha_{\rm best}$ for these active regions is shown in Figure 2. 65% (33.7% with positive tilt and $\alpha_{\rm best}$ and 31.4% with negative tilt and $\alpha_{\rm best}$) of the active regions have the same signs for the tilt and the $\alpha_{\rm best}$, and a least-square fit for all 86 active regions gives a positive correlation between them at the 95% confidence level. For 55 active regions with $\beta\gamma\delta$ magnetic configu-

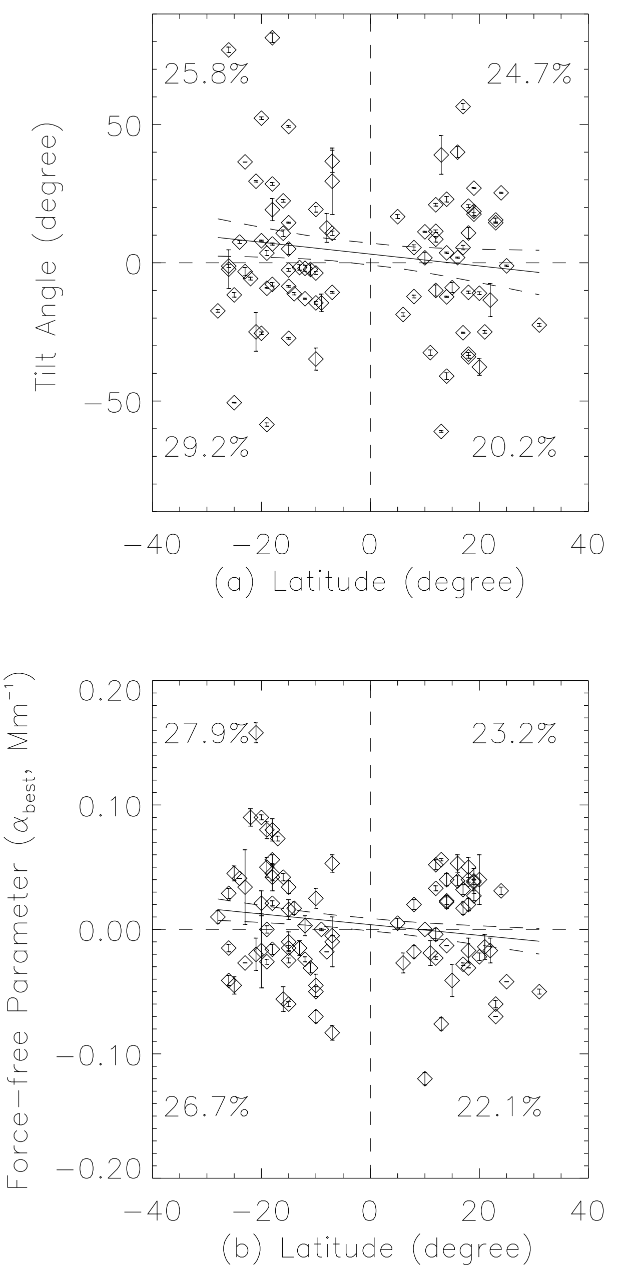

Fig. 1. The tilt and $\alpha_{\rm best}$ versus the latitude for 86 active regions. The percentage is the number ratio of active regions with positive (negative) tilts and $\alpha_{\rm best}$ in the two hemispheres and all regions. The error bars represent mean measuring errors. The lines are the least-square fits.

rations in this sample (the stars in Figure 2), 33 regions (60%) show the same sign for the tilt and the $\alpha_{\rm best}$, a tendency to support the kink instability for formation of δ-spot active regions (see Fisher et al. 2000, and references therein). Among the 14 active regions with XRI greater than 4.0, 10 (71 %) have the same sign for the $\alpha_{\rm best}$ and the tilt, a greater percentage than for all 86 active regions (65%). It seems to suggest that the active regions with like-signed $\alpha_{\rm best}$ and tilts are more likely to produce strong flare activities.

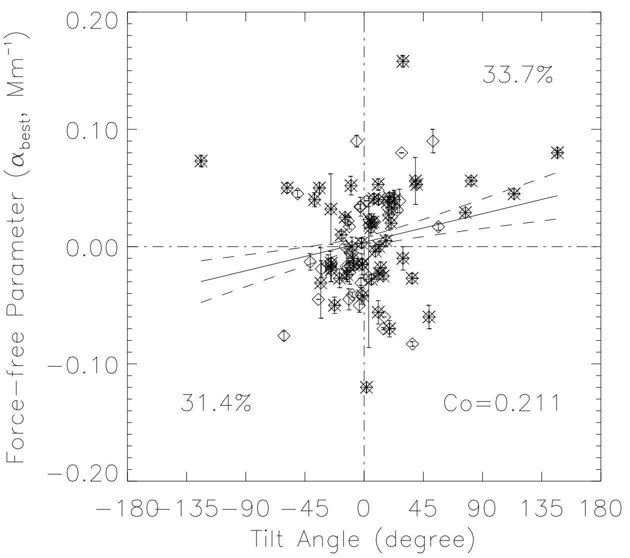

Fig. 2. Correlation of the $\alpha_{\rm best}$ and the tilt for the 86 active regions. 'Co' is the correlation coefficient between the $\alpha_{\rm best}$ and the tilt. Percentage is the ratio of active regions with same (positive/negative) signs for $\alpha_{\rm best}$ and tilt and the total active regions. '$\diamond$' with '$\star$' denotes active regions with a $\beta\gamma\delta$ magnetic configuration. The error bars represent mean error measured. The line denotes a least-square fit to the data.

4. Discussions and Conclusions

In this paper we have analyzed 86 active regions in the years from 1996 to 2002, which produced more than three X-ray major flares and whose XRI was greater than 0.5. We measured their systematic tilt angles with respect to the solar equator and the force-free parameter $\alpha_{\rm best}$, and found (1) that only 46 active regions (54%) follow Hale's law; (2) that 43 active regions (50%) obey the hemispheric helicity rule; (3) that 56 active regions (65%) have the same sign for the tilt and the $\alpha_{\rm best}$, and that a least-square fitting of the tilt-$\alpha_{\rm best}$ plot for all 86 regions gives a positive correlation; and (4) that 33 (60%) of the 55 active regions in this sample that have the $\beta\gamma\delta$ magnetic configuration show the same sign for the tilt and the $\alpha_{\rm best}$.

The $\alpha_{\rm best}$, obtained from the observed vector magnetic field of the photosphere, is considered as a measure of the twist of the magnetic fields in the flux tubes emerging from the convection zone (see, e.g. Pevtsov, Canfield, and Metcalf, 1995). It is not, of course, the twist itself though, its sign can be used as a proxy for the sign of the twist. The sign of the systematic tilt of an active region, on the other hand, can be used as a proxy for the sign of the writhe of the tube. A positive/negative $\alpha_{\rm best}$ (tilt), therefore, indicates right/left handed twist (writhe) of the magnetic field.

It is still controversial whether there is a predominantly positive or negative correlation between the magnetic twist and writhe in solar active regions. Based on a sample of 99 active regions observed by the Haleakala Stokes Polarimeter (HSP) at Mees Solar Observatory (MSO), Canfield and Pevtsov (1998) found a weak positive correlation. On the other hand, however, Tian et al. (2001) found that for 62% of 286 active regions taken at HSOS the twist and the writhe have opposite signs; López Fuentes et al. (2003) also obtained opposite signs for 65% of 22 active regions with vector magnetic field measurements, again, by the HSP at MSO.

There are apparent differences in these samples studied. In Tian et al's work most of the active regions (about 70%) have a simple bipolar magnetic configuration; in López Fuentes et al.'s sample of 22 long-lived active regions, 13 (59%) produced no major flares and 6 (27%) produced more than 3 major flares. Thus, most of the regions studied by Tian et al. and López Fuentes et al. are regions with no or lower activities. The present study, on the other hand, makes an attempt, through studying a sample of 86 major flare-producing active regions, to relate the twist and the writhe in order to investigate whether or not these active regions are subjected to kink instability. The present sample shows a positive correlation between the twist and the writhe. It thus seems that whether the twist and the writhe have the same or opposite signs is linked to the activity level of the active region.

If, before the emergence of an Ω-formed flux tube from the bottom of the convection zone, the dynamo produces a very small (or zero) initial twist (T_{w0}) in the tube, then the Coriolis force acting on external flows would importantly deform the flux tube rising through the convection zone. Helicity conservation, $T_w + W_r \simeq 0$, implies that the twist (T_w) and the writhe (W_r) should have opposite signs. On the other hand, if the initial twist helicity (T_{w0}) is very large before the tube emerges, where the kink instability has developed, the sign of the twist and the writhe should be the same, because as the instability grows, part of the twist is transferred into writhe (Linton, et al, 1999). The higher percentage (71%) of the same signs of twist and writhe for active regions with XRI greater than 4.0 shown in this study suggests that kink instability may play a key role in strong flares-producing active regions.

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