HEMISPHERIC HELICITY TREND FOR SOLAR CYCLE 24

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Received 2011 March 19; accepted 2011 April 22; published 2011 May 6

ABSTRACT

Using vector magnetograms obtained with the Spectro-polarimeter (SP) on board Hinode satellite, we studied two helicity parameters (local twist and current helicity) of 64 active regions that occurred in the descending phase of solar cycle 23 and the ascending phase of solar cycle 24. Our analysis gives the following results. (1) The 34 active regions of the solar cycle 24 follow the so-called hemispheric helicity rule, whereas the 30 active regions of the solar cycle 23 do not. (2) When combining all 64 active regions as one sample, they follow the hemispheric helicity sign rule as in most other observations. (3) Despite the so-far most accurate measurement of vector magnetic field given by SP/Hinode, the rule is still weak with large scatters. (4) The data show evidence of different helicity signs between strong and weak fields, confirming previous result from a large sample of ground-based observations. (5) With two example sunspots we show that the helicity parameters change sign from the inner umbra to the outer penumbra, where the sign of penumbra agrees with the sign of the active region as a whole. From these results, we speculate that both the \( \Sigma \)-effect (turbulent convection) and the dynamo have contributed in the generation of helicity, whereas in both cases turbulence in the convection zone has played a significant role.

Key words: magnetic fields – Sun: activity – sunspots

1. INTRODUCTION

The concept of magnetic helicity was introduced to solar physics in the 1980s (Heyvaerts & Priest 1984; Berger & Field 1984) and has attracted great attentions since then. It is a physical quantity that measures the topological complexity of magnetic field such as the degree of linkage or twistedness in the field (Moffatt 1985; Berger & Field 1984) and has been considered important in modeling many solar phenomena such as coronal mass ejections (Zhang & Low 2005; Zhang et al. 2006; Zhang & Flyer 2008). The helicity of magnetic fields may be characterized by several different parameters (Moffatt 1978) such as magnetic helicity \( H_m \) and current helicity \( H_c \). However, only the vertical component of current helicity density \( h_c \) (and the local twist \( \alpha \), etc.) can be practically computed by using vector magnetograms.

Seehafer (1990) was the first to statistically study the sign of magnetic helicity of solar active regions (ARs) using magnetograms. He estimated current helicity \( h_c \) of 16 ARs by using extrapolation of measured photospheric magnetic fields and concluded that in ARs the current helicity is predominantly negative in the northern hemisphere and positive in the southern hemisphere. This tendency is the so-called hemispheric helicity sign rule. In the following two decades, many researchers (Pevtsov et al. 1995, 2001, 2008; Abramenko et al. 1997; Bao & Zhang 1998; Hagino & Sakurai 2004; Zhang 2006) have studied and confirmed this rule by using data sets obtained with different instruments located in different places of the world, e.g., the University of Hawaii Haleakala Stokes Polarimeter and The Marshall Space Flight Center Vector Magnetograph in the US, the Solar Magnetic Field Telescope (SMFT) in China, and the Mitaka Solar Flare Telescope and The Okayama Astrophysical Observatory Solar Telescope in Japan. It is believed that the usual hemispheric helicity sign rule holds for all three solar cycles observed (that is, solar cycles 21, 22, 23).

However, there is also some debate about this rule. For instance, Bao et al. (2000) found that \( h_c \) in their data showed an opposite hemispheric preference at the beginning of solar cycle 23. Hagino & Sakurai (2005) also reported that the hemispheric helicity sign rule may not be satisfied in the solar minimum phase. Choudhuri et al. (2004) developed a model that predicts deviations from the usual hemispheric rule at the beginning of a solar cycle. However, Pevtsov et al. (2001) argued that the usual heliographic helicity sign rule still holds for the first four years of solar cycle 23, although by nature it is a weak rule with significant scatter. Pevtsov et al. (2008, p. 722) further compared data from four different instruments and concluded that "the notion that the heliographic helicity rule changes sign in some phases of solar cycle is not supported at a high level of significance."

Apart from these arguments, Zhang (2006) did a statistical study using 17,200 vector magnetograms obtained by SMFT. She separated her data into two parts, the weak fields (100 G < \( |B_z| < 500 \) G) and the strong fields (\( |B_z| > 1000 \) G). She calculated \( \alpha \) and \( h_c \) of weak and strong fields separately and found that the weak magnetic fields follow the usual hemispheric helicity sign rule but strong fields do not. She interpreted this as the reason why Bao et al. (2000) found that \( h_c \) in their data violates the usual hemispheric helicity sign rule whereas \( \alpha \) not.

Since its launch in 2006 September, Hinode has provided us with high spatial resolution vector magnetograms for both the descending phase of solar cycle 23 and the ascending phase of solar cycle 24. This gives us a unique chance in this Letter to use these so-far most accurate vector magnetic field measurements to shed light on the above arguments. We organize our Letter as follows. In Section 2, we describe the observations and data reduction. In Section 3, we present our analysis and results. We conclude with a discussion in the last section.

2. OBSERVATION AND DATA REDUCTION

We used vector magnetograms obtained by the Spectro-polarimeter (SP) on board Hinode (Kosugi et al. 2007). SP/Hinode obtains line profiles of two magnetically sensitive Fe lines at 630.15 and 630.25 nm and nearby continuum, using a \( 0\prime.16 \times 164'' \) slit. There are four mapping modes of operation:
normal map, fast map, dynamics, and deep magnetogram (Tsuneta et al. 2008). In this study, we only use the normal maps and fast maps. The resolution of these magnetograms is about 0.32 pixel$^{-1}$ for fast maps and 0.16 pixel$^{-1}$ for normal maps.

For the period we studied, that is, from 2006 November to 2010 September, in total 190 ARs appeared on the Sun; that is, from NOAA 10921 to NOAA 11110. However, not every AR has been observed by SP/Hinode. We searched those ARs observed by SP/Hinode using following criteria. (1) If more than one magnetograms have been obtained for the same AR, then we only use the one that is closest to the disk center. (2) Both the averaging and integral are done over the whole magnetogram. The definition here gives the parameter $\alpha_{hc}$ the same units of $\alpha_z$ and is the same as the $\alpha_p$ parameter discussed in Tiwari et al. (2009). In our calculation we have only used points whose total wavelength-integrated polarization is larger than $10^{-2}$, which is about three times of the polarization noise level (Lites et al. 2008). This is a criterion applied to all helicity parameter calculations, in addition to all other criteria we apply in following analysis.

In calculating $\alpha_z$ and $\alpha_{hc}$, we have used two different representations of magnetic field measurement. One is related to “flux density,” where the longitudinal magnetic field $B_z = f \cdot B \cos(\gamma)$ and the transverse magnetic field $B_t = \sqrt{f^2 \cdot B^2 \sin^2(\gamma)}$. The other is the “field strength” where $B_z = B \cos(\gamma)$ and $B_t = B \sin(\gamma)$. Hereafter, we present the first type as $B_z^1, B_t^1$ and the second type as $B_z^2, B_t^2$. Correspondingly helicity parameters are also hereafter presented as $\alpha_z^1, \alpha_{hc}^1$ and $\alpha_z^2, \alpha_{hc}^2$, respectively. In most previous studies researchers used the helicity parameters of the first type, that is, based on the flux density measurement of magnetic field. Due to the precise measurement of SP on board Hinode, an accurate measurement of filling factor and hence of field strength becomes possible. Thus, in this Letter we calculate the helicity parameter of the second type too, in order to check whether our results depend on the type of magnetic field measurement or not.

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### 3. ANALYSIS AND RESULTS

Figure 1 presents the variation of $\alpha_z^1$ (left panels) and $\alpha_z^2$ (right panels) with the solar latitude for the 30 ARs in the descending phase of solar cycle 23 (top panels), the 34 ARs in the ascending phase of solar cycle 24 (middle panels), and the total 64 ARs (bottom panels). Here, $\alpha_z^1$ and $\alpha_z^2$ are calculated only using points with $|B_z| > 100$ G or $|B_t^1| > 100$ G. The solid lines indicate the results of least-square linear fits.

![Figure 1](image_url)
Similarly, Figure 2 gives the variation of $\alpha_{hc}^1$ (left panels) and $\alpha_{hc}^2$ (right panels) with the solar latitude for the 30 ARs in solar cycle 23 (top panels), the 34 ARs in solar cycle 24 (middle panels), and the total 64 ARs (bottom panels). The $\alpha_{hc}^1$ and $\alpha_{hc}^2$ are also calculated using points with $|B_z^1| > 100$ G or $|B_z^2| > 100$ G.

Values of $d\alpha/d\theta$ from the linear fittings are also shown in Figures 1 and 2, in the unit of $10^{-6}$ m$^{-1}$ deg$^{-1}$. Here we see that for the 30 ARs of solar cycle 23, $d\alpha/d\theta$ for $\alpha_{hc}^1$, $\alpha_{hc}^2$, $\alpha_{hc}^3$, and $\alpha_{hc}^4$ are all positive. Out of these 30 ARs, only 8 (27%) ARs of $\alpha_{hc}^1$ and 14 (47%) ARs of $\alpha_{hc}^2$ obey the usual hemisphere sign rule. This means that ARs in the descending phase of solar cycle 23 do not follow the usual hemispheric helicity sign rule. This is consistent with Tiwari et al. (2009) who made a similar conclusion from a sample combining data from three instruments.

Contrary to that in solar cycle 23, for the 34 ARs of solar cycle 24, 20 (59%) ARs of the $\alpha_{hc}^1$ and 20 (59%) ARs of the $\alpha_{hc}^2$ obey the usual hemisphere sign rule. $d\alpha/d\theta$ for $\alpha_{hc}^1$, $\alpha_{hc}^2$, $\alpha_{hc}^3$, and $\alpha_{hc}^4$ are all negative. This means that ARs in the ascending phase of solar cycle 24 follow the usual hemispheric helicity sign rule, contrary to the prediction made in Choudhuri et al. (2004). Note that ARs in the descending phase of solar cycle 23 do show a deviation from the usual hemispheric helicity sign rule. We speculate that the physical process described in Choudhuri et al. (2004), that is, poloidal flux lines getting wrapped around a toroidal flux tube rising through the convection zone to give rise to the helicity, may still apply, but a phase shift may be required in the dynamo model.

For all of the 64 ARs, 28 (44%) ARs of $\alpha_{hc}^1$ and 34 (53%) ARs of $\alpha_{hc}^2$ follow the usual hemisphere sign rule. As a whole, these 64 ARs still follow the usual hemispheric helicity sign rule, with $d\alpha/d\theta$ for $\alpha_{hc}^1$, $\alpha_{hc}^2$, $\alpha_{hc}^3$, and $\alpha_{hc}^4$ all negative. This is consistent with the results from most previous studies, that is, most ARs follow the usual hemispheric helicity sign rule.

An interesting observation is that, despite for the fact that we have used the so-far most accurate measurement of vector magnetic field given by SP/Hinode, the hemispheric helicity sign rule, either indicated by the 34 ARs in solar cycle 24 or by the 64 ARs as a whole, is still weak with large scatters. As evidence, we see from Figures 1 and 2 that the magnitudes of the correlation coefficients between the latitude and the helicity parameters are all low, with the maximum magnitude only being 0.21. This seems to indicate that the large scatter is an inherent property of the rule, not caused by the measurement errors. This is consistent with the prediction in Longcope et al. (1998), where helicity is considered to be produced in the process of magnetic flux tubes rising through the solar convection zone and being buffeted by turbulence with a non-vanishing kinetic helicity ($\Sigma$-effect).

When calculating $\alpha_{hc}^1$, $\alpha_{hc}^2$, $\alpha_{hc}^3$, and $\alpha_{hc}^4$ in Figures 1 and 2 we have only used points with $|B_z^1| > 100$ G or $|B_z^2| > 100$ G. Next, we progressed further to calculating $\alpha_{hc}^1$, $\alpha_{hc}^2$, $\alpha_{hc}^3$, and $\alpha_{hc}^4$ for $|B_z^1| > 200$, $300$, $400$ G, and so on until for $|B_z^1| > 2000$ G. This not only allows us to check whether our results depend on the selection of the $|B_z|$ threshold, but also gives us a chance to examine how the hemispheric helicity sign rule might vary with the increase of field strength.

Results of the obtained $d\alpha/d\theta$ with different $|B_z|$ thresholds are plotted in Figure 3 for all four helicity parameters. We see here that when changing the $|B_z|$ threshold from 100 G to 200 G or even to 500 G, the sign of $d\alpha/d\theta$ does not change. This suggests that our above conclusion, that is, ARs in the descending phase of solar cycle 23 do not follow the usual hemispheric helicity sign rule and the ARs in the ascending phase of solar cycle 24 do, is not very sensitive to the $|B_z|$ threshold we selected.

At the same time, we see from the middle and bottom panels of Figure 3 that, when the $|B_z|$ threshold goes to high values such as 1200 G for $\alpha_{hc}^1$ and $\alpha_{hc}^2$, or 1800 G for $\alpha_{hc}^3$ and $\alpha_{hc}^4$, the sign of $d\alpha/d\theta$ becomes opposite to those with low $|B_z|$. This suggests that the weak and strong fields have opposite helicity signs, as first pointed out in Zhang (2006) and later confirmed by Su et al. (2009).
Figure 3. Variation of the latitudinal gradient \( \frac{d\alpha}{d\theta} \) with different \(|B_z|\) thresholds (see the text for details). The cross symbols indicate the \( \frac{d\alpha}{d\theta} \) values for \( \alpha_{z1} \) or \( \alpha_{cz} \), and the circles for \( \alpha_{z2} \) or \( \alpha_{cz2} \).

Figure 4. The top left panel shows the continuum image of the NOAA 10940 sunspot observed on 2007 February 1, belonging to the solar cycle 23. The X and Y spatial resolution of the image is 0\(\text{"}2971\) pixel\(^{-1}\) and 0\(\text{"}3199\) pixel\(^{-1}\), respectively. The top right panel shows the corresponding electric current distribution. Circles in these two panels show where the distances to the sunspot center \(r\) are 5\(\text{"}, 10\text{"}, 15\text{"}, and 20\text{"}, respectively. The middle left panel shows the variation of \(B_{z1}\) with \(r\). The dots show the values of \(B_{z1}\) and the double-shelled curve shows the mean value of \(B_{z1}\) with a bin of 1\(\text{"}\) in \(r\). The middle right, bottom left, and bottom right panels are similar to the middle left one, but for the values of electric current, \(h_{1c}\) and \(\alpha\), respectively.

that this actually indicates that on average sunspot umbra and penumbra show opposite helicity sign. In Figure 4 we show the

continuum image (top left panel) and the electric current map (top right panel) of NOAA 10940, which appeared on 2007
February 1 of the solar cycle 23. Circles in these two images show where the distances to the sunspot center \( r \) are \( 5'' \), \( 10'' \), \( 15'' \), and \( 20'' \), respectively. The middle right panel shows the variation of electric current \( J_z = \mu_0 (\nabla \times B_z) \) with \( r \), where the dots give the values of \( J_z \) and the double-shelled curve shows the mean value of \( J_z \) with a bin of \( 1'' \) in \( r \). Similarly, the bottom left and right panels, respectively, show the \( h_z = J_z B_z \) and \( \alpha_z \) values and their averages with a bin of \( 1'' \) in \( r \). We see clearly here that the inner most fields (where \( r < 5'' \)) have a positive average value of \( h_z \) or \( \alpha_z \) and the average value becomes negative when \( r > 5'' \).

The mean value of \( |B_z| \) in the central umbra \( (r \leq 5'') \) is \( 2976 \) G and is \( 970 \) G for fields in \( 5'' < r \leq 20'' \). The mean value of \( \alpha_z \) in \( r \leq 5'' \) is \( 5.033 \times 10^{-8} \) m\(^{-1}\) and is \( -0.717 \times 10^{-8} \) m\(^{-1}\) for regions in \( 5'' < r \leq 20'' \). The mean value of \( h_z \) in \( r \leq 5'' \) is \( 3.942 \times 10^{-2} \) G m\(^{-1}\) and is \( -0.543 \times 10^{-2} \) G m\(^{-1}\) for regions in \( 5'' < r \leq 20'' \). For the whole AR, with \( |B_z| > 100 \) G, \( \alpha_z = -3.274 \times 10^{-9} \) m\(^{-1}\) and \( \alpha_{zc} = -1.332 \times 10^{-8} \) m\(^{-1}\). This means that the sign of the whole AR is dominated by the sign of weak field (penumbra), as also pointed out in Zhang (2006).

Figure 5 gives another example, NOAA 11084, observed on 2010 July 2 of the solar cycle 24. As in Figure 4, the top two panels present the continuum image of the sunspot and the corresponding electric current distribution. Here the circles represent where \( r \) is \( 5'' \), \( 10'' \), and \( 15'' \), respectively. Similar trend as that in Figure 4 can be seen from the bottom panels of \( h_z \) and \( \alpha_z \). Here the average \( h_z \) or \( \alpha_z \) values change their sign at about \( 4'' \). The mean value of \( |B_z| \) in \( r \leq 5'' \) is \( 2382 \) G and is \( 713 \) G in \( 5'' < r \leq 20'' \) region. The mean value of \( \alpha_z \) in \( r \leq 5'' \) is \( -1.300 \times 10^{-8} \) m\(^{-1}\) and is \( 2.950 \times 10^{-8} \) m\(^{-1}\) in \( 5'' < r \leq 20'' \) region. The mean value of \( h_z \) in \( r \leq 5'' \) is \( -0.901 \times 10^{-2} \) G m\(^{-1}\) and is \( 0.315 \times 10^{-2} \) G m\(^{-1}\) in \( 5'' < r \leq 20'' \). For the whole AR, \( \alpha_z = 3.599 \times 10^{-3} \) m\(^{-1}\) and \( \alpha_{zc} = 1.910 \times 10^{-8} \) m\(^{-1}\) with \( |B_z| > 100 \) G. We see here again that the inner umbra and outer penumbra has the opposite helicity sign and the helicity sign of the whole AR is dominated by the sign in penumbra.

Note that Chatterjee et al. (2006) modeled the penetration of a poloidal field into a toroidal rising flux tube through turbulence diffusion. One important prediction of their model is the existence of a ring of reverse current helicity on the periphery of ARs. Our observations seem consistent with their prediction.

4. CONCLUSION AND DISCUSSION

Using high-quality magnetograms taken with SP/Hinode, we examined the hemispheric helicity sign rule in the descending phase of solar cycle 23 and the ascending phase of solar cycle 24. We studied two helicity parameters, \( \alpha_z \) and \( \alpha_{zc} \), of 64 ARs, 30 belonging to solar cycle 23 and 34 belonging to solar cycle 24. We also examined how the hemispheric helicity sign rule depends on the selection of field points and whether strong and weak fields have opposite helicity signs, as previously reported.

Our analysis gives following results. (1) The 34 ARs in the ascending phase of the solar cycle 24 follow the so-called hemispheric helicity sign rule. (2) The 30 ARs in the descending phase of the solar cycle 23 do not follow the usual hemispheric helicity sign rule. (3) When combining all 64 ARs as one sample, the usual hemispheric helicity rule is indicated as in most other observations. (4) Even though we have used the
so-far most accurate measurement of vector magnetic field given by SP/Hinode, the observed hemispheric helicity sign rule is still weak with large scatters. (5) The data show evidence of opposite helicity signs between strong and weak fields, and this indicates that the helicity parameters change sign from the inner umbra to the outer penumbra.

We argue that results (1), (3), and (4) are consistent with the model by Longcope et al. (1998), and result no. (5) is consistent with the model by Chatterjee et al. (2006). Results nos. (1) and (2) seem to suggest that the result of Choudhuri et al. (2004) has merit in its physical picture, but it may need to be modified based on which phase of the solar cycle the deviations from the hemispheric rule take place. From our observations we speculate that both the $\Sigma$-effect (Longcope et al. 1998) and the dynamo (Choudhuri et al. 2004; Chatterjee et al. 2006) have contributed in the generation of helicity, and in both models turbulence in the convection zone has played an important role.

We thank the referee for helpful comments and suggestions. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in cooperation with ESA and NSC (Norway). Hinode SOT/SP Inversions were conducted at NCAR under the framework of the Community Spectro-polarimetric Analysis Center (CSAC, http://www.csac.hao.ucar.edu/). This work was partly supported by the National Natural Science Foundation of China (grant no. 10921303), Knowledge Innovation Program of Chinese Academy of Sciences (grant no. KJCX2-EW-T07), and National Basic Research Program of MOST (grant no. 2011CB811401).

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