

ON THE SOLAR CYCLE VARIATION OF THE HEMISPHERIC HELICITY RULE

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ABSTRACT

We study the statistical significance of observed temporal variations of the solar active-region hemispheric helicity rule, as measured by the latitudinal gradient of the best-fit linear force-free-field parameter, $d\alpha/d\varphi$. Using data from four different vector magnetographs, we compute and compare average annual $d\alpha/d\varphi$ values for these instruments for 19 years from solar cycles 21, 22, and 23. We find that although every instrument shows the "wrong" sign for the hemispheric rule in some years, there is no agreement among the instruments on which years are abnormal. None of the four data sets shows annual values of $d\alpha/d\varphi$ departing from the hemispheric helicity rule by more than 3σ . We conclude that because the hemispheric helicity rule is a weak tendency with significant scatter, an annual subset of active regions is likely to produce statistically unreliable results.

Subject headings: Sun: activity— Sun: magnetic fields

1. INTRODUCTION

The concept of magnetic/current helicity, introduced to solar physics more than 20 years ago (Berger & Field 1984) has now successfully been used to study solar phenomena from the dynamo to flares and coronal mass ejections. Earlier studies led to the discovery that the Sun’s magnetic fields exhibit certain patterns of helicity (for reviews, see Brown, Canfield, & Pevtsov 1999; Pevtsov & Balasubramaniam 2003). In particular, manifestations of such patterns are suggested for solar active regions where the fields are associated with specific, recurring patterns, e.g., the spiral shapes of sunspot fibrils (Hale 1927), helical filaments (Martin, Bilimoria, & Tracadas 1994; Pevtsov, Balasubramaniam, & Rogers 2003; Bernasconi, Rust, & Hakim 2005), interplanetary magnetic clouds (Rust 1994), sigmoidal-shaped coronal X-ray emissions (Rust & Kumar 1996; Pevtsov 2002), and network magnetic fields (Pevtsov & Longcope 2001; 2007). Interpretations of the sense of helicity of the fields in these observed structures have revealed the so-called ‘hemispheric helicity rule’ whereby patterns of negative helicity occur predominantly in the northern solar hemisphere, and those of positive helicity in the south. The rule may be attributed to several different processes including differential rotation (Demoulin et al 2002), action of the Coriolis force on a flux tube rising through the convection zone (Holder et al. 2004), subsurface dynamo (Gilman & Charbonneau 1999) and the interaction of flux tubes rising through the convection zone with helical convective turbulence, i.e., the so-called Σ -effect (Longcope et al. 1999). The Σ -effect presently seems to explain various observational properties of the hemispheric helicity rule better than any other mechanism (Longcope et al. 1999; Nandy 2006)

Mathematically, helicity is defined as the dot product of a vector and its curl, integrated over a closed volume. Thus, for example, magnetic helicity, $H_m = \int \mathbf{A} \cdot \nabla \times \mathbf{A} dD$, where D is closed volume, and \mathbf{A} is the vector potential of the magnetic induction $\mathbf{B} = \nabla \times \mathbf{A}$. Similarly, one can define the current helicity, $H_c = \int \mathbf{B} \cdot \nabla \times \mathbf{B} dD$, and kinetic helicity, $H_k = \int \mathbf{V} \cdot \nabla \times \mathbf{V} dD$, where \mathbf{V} is the velocity of flows. In the restrictive case of linear force-free fields, $\nabla \times \mathbf{B} = \alpha \mathbf{B}$, $\alpha = \text{const}$, the magnetic vector potential \mathbf{A} can be expressed as $\mathbf{A} = \alpha^{-1} \mathbf{B} + \nabla \psi$, where ψ is an arbitrary scalar function. Then, the magnetic helicity can be written as

$$H_m = \int \mathbf{A} \cdot \mathbf{B} = \int (\alpha^{-1} \mathbf{B} + \nabla \psi) \mathbf{B} dD = \int \alpha^{-1} B^2 dD + \int \nabla \psi \mathbf{B} dD. \quad (1)$$

For a closed volume, magnetic field does not cross the volume boundary, which results in the additional condition $\mathbf{n} \cdot \mathbf{B} = 0$. Under this condition, the second integral goes to zero, and magnetic helicity can be expressed in terms of the α -coefficient, and the magnetic energy, E_m :

$$H_m = 2\mu\alpha^{-1}E_m, \quad (2)$$

where μ is the magnetic permeability in vacuum. Magnetic helicity has several properties that make it an important parameter. For example, the discovery of the hemispheric helicity rule led to the modification of early mean-field dynamo models (e.g. Seehafer 1996). As another example, Pevtsov & Longcope (2007) suggested how helicity can be used to constrain the origin of network magnetic fields. In the mid-90's, observations with the University of Hawaii Haleakala Stokes Polarimeter were used to infer the helicity of the magnetic fields of individual active regions using as a proxy the force-free parameter α . In the framework of the force free field model, the α coefficient has the same sign as magnetic helicity (see Eq. 2). This sign correlation encouraged use of α , a measure of magnetic field twist, as a helicity proxy (e.g. Pevtsov, Canfield, and Metcalf 1995). More recently, Pevtsov (2007) used Eq. 2 formulation to determine true magnetic helicity of 67 active regions. Using vector magnetic observations in a single level in solar atmosphere, one can determine α either by determining the best fit of a linear force free field to the observed transverse component of the field (called, α_{best} , Pevtsov, Canfield, and Metcalf 1995), or by computing the vertical (z) component of α for each pixel in magnetogram and averaging it ($\langle \alpha_z \rangle$). Burnette, Canfield, and Pevtsov (2004) found a reasonably good correlation between α_{best} and $\langle \alpha_z \rangle$. Alternatively, one can also compute z-component of current helicity density, $h_c = (B \cdot J)_z = \mu B_z \cdot J_z$, where \mathbf{J} is electric current density. Although current helicity is not a conserved quantity (unlike magnetic helicity), it has the same sign as H_m . Two different helicity proxies based on current helicity have been used: the fractional imbalance of h_c (percentage of pixels of one sign of h_c in a given magnetogram) and area-averaged h_c ($\langle h_c \rangle$, e.g. Abramenko et al, 1996; Bao and Zhang, 1998). It is widely recognized that the $\alpha(lff)$ proxy for helicity is only an approximation. As discussed in Hagyard & Pevtsov (1999), it is only in the case of linear force-free fields (where $\alpha = \alpha(lff) = \text{constant}$) that the density of magnetic helicity h_m can be calculated from observations of the vector magnetic field:

$$h_m = B^2/\alpha(lff). \quad (3)$$

However, the Hawaii results indicate that h_m as represented by $\alpha(lff)$ does exhibit a hemispheric preference. From observations of 69 different active regions (245 magnetograms) during the period 1988 to 1994 in solar cycle 22, Pevtsov, Canfield, & Metcalf (1995) found that 76% of the regions in the northern hemisphere had negative helicity and 69% in the south had the opposite helicity. Using a much larger data base of 203 active regions, Longcope, Fisher, & Pevtsov (1998) confirmed this hemispheric rule. Subsequent to these studies,

other solar groups have used their vector magnetograph observations to infer the helicity of active region fields. From observations with the Huairou Solar Magnetic Field Telescope Abramenko, Wang, and Yurchishin (1996) and later Bao & Zhang (1998) found a similar tendency. These authors used the ‘current helicity’ parameter in their study. As Hagyard & Pevtsov (1999) show, this parameter has the same sign as the magnetic helicity under the condition of linear force-free fields, the condition assumed in the analysis of the Hawaii data. More recently, in a study by Hagino & Sakurai (2005), vector magnetograms obtained by two vector magnetographs in the years 1983-2000 were analyzed, and the results agreed with the hemispheric rule.

With one exception, all existing dynamo models predict that the hemispheric helicity rule should be independent of phase of the solar cycle. Choudhuri, Chatterjee & Nandy (2004) have considered helicity creation in a kinematic dynamo model. In their model, toroidal field is generated in overshoot region at the base of the convection zone, and poloidal field is created at the photosphere via decay of tilted active regions. Helicity is produced when poloidal field wraps around a toroidal field rising through the convective zone. On the basis of this model they proposed that during certain phases of the solar cycle, magnetic helicity can deviate from the hemispheric rule. Typically, mutual orientation of poloidal and toroidal fields in this model results in negative/positive helicity in northern/southern hemisphere. However, early in a cycle, when new cycle active regions interact with previous-cycle large scale field, the model predicts reversal in the hemispheric helicity rule. Hagino & Sakurai (2005) used observations taken with the Okayama Observatory Solar Telescope (OAO) and the Mitaka Solar Flare Telescope (SFT) to calculate α for active regions from 1983 through 2000. In their papers the authors found evidence of a time variability in the gradient (slope) $d\alpha/d\varphi$ of the linear fit of α versus latitude (φ); this gradient should always be negative for the hemispheric rule to hold. Recently, Zhang (2006) reported that penumbral and umbral magnetic fields may have opposite sign of helicity, and the hemispheric helicity rule may reverse its sign as a result of sign-reversal of helicity of umbral fields. On the other hand, several researchers maintain that the hemispheric helicity rule is independent of solar cycle (e.g. Hale 1927; Pevtsov, Canfield, and Latushko 2001). Establishing that the hemispheric helicity rule may indeed reverse its sign during some periods of solar activity would have important consequences. If confirmed, reversals of the hemispheric helicity rule could require modifying dynamo models. On the other hand, knowing that the hemispheric helicity rule is independent of the solar cycle will help to interpret the observations. It is the primary purpose of the present study to assess the validity of several recent reports of the time variability of the hemispheric helicity rule. We do it by comparing observations from several different magnetographs for the time interval 1980 to 2000. In the following sections of this paper, we describe the observational data and their analyses. Next, we present our

results from these analyses and discuss their implications.

2. DATA

This study employs data from four vector magnetographs: Marshall Space Flight Center (MSFC, Hagyard et al. 1982; Hagyard & Kineke 1992), the University of Hawaii Haleakala Stokes Polarimeter (HSP, Mickey 1985), the Okayama Astrophysical Observatory Solar Telescope (OAO, Makita et al. 1985), and the Mitaka Solar Flare Telescope (SFT, Sakurai et al., 1995). The details on observations and data reduction for each individual instrument can be found in the corresponding referenced publications.

2.1. Hemispheric Helicity Rule in Various Individual Years

Several previously published articles indicate that all of the four data sets, each taken as a whole, exhibit the hemispheric helicity rule: the majority of active regions in the northern/southern hemisphere have negative/positive helicity. The strength of the rule, measured by the value of $d\alpha/d\varphi$ for the whole data set, varies slightly between different data sets. We see such variation of the strength of the rule as the result of differences in AR selection, data set size, and data analysis methodology. Using magnetograms from the four instruments, we have determined the hemispheric helicity rule on annual basis for selected years shown in Table 1. We determined average values $\langle \alpha(lff) \rangle$ from all available magnetograms of each of the number of active regions indicated in parentheses in the table. We then plotted $\langle \alpha(lff) \rangle$ versus the average latitude of each active region and performed a linear fit to the data. The negative slope is a signature of the normal hemispheric helicity rule, and positive slopes indicate the larger positive deviations from the rule. The results from all 4 observatories are shown in Figure 1 and Table 1.

One should note that each instrument does not have a 100% coverage: due to weather, instrument status, etc., the coverage for a given instrument may vary from one year to the next. In that respect, the observations in Table 1 may be considered different incomplete samples of all the active regions that were present.

3. RESULTS AND CONCLUSIONS

Year to year variations such as those shown in Figure 1 have led other researchers to suggest that $d\alpha/d\varphi$ values vary quasi-periodically with time. Bao & Zhang (1998) reported

variations in current helicity density $h_c = B \cdot (\nabla \times B)$ with a period of about 2 years. To explain such periodicity, Benevolenskaya (2000) proposed a model of a double magnetic cycle with magnetic fields generated in two separate regions: at the base of the convection zone and in a shear layer beneath the photosphere. On the other hand, since the amplitude of h_c depends on field strength,¹ h_c variations may be attributed to a quasi-periodic increase in production of strong fields, not the change in magnetic helicity. For example, every two years the Sun might produce a “pulse” or long-lived activity complex with stronger-than-usual magnetic fields. The presence of such “pulses” of activity was reported by several researchers (e.g., Pevtsov & Acton 2001, Benevolenskaya 2003). Nevertheless, below we argue that the data in Figure 1 are dominated by statistical fluctuations, and hence, this figure does not compellingly show the presence or absence of quasi-periodic variations of magnetic helicity. The data shown in Figure 1 indicate the occurrence of temporal variation in sign of the gradient for observations with a given instrument, but there is no consistency among the 4 instruments. For example, MSFC data give the same sign of $d\alpha/d\varphi$ as OAO in only 3 (50%) out of 6 overlapping years. OAO and HSP show the same sign in only 3 (38%) out of 8 years, and for SFT – HSP data only 5 (56%) out of 9 years. Such inconsistencies may be attributed to a basic property of the hemispheric rule – it is a weak tendency with significant scatter – combined with insufficient sampling. To test this hypothesis we used the Mees (Haleakala Stokes Polarimeter) data as a ‘parent population’ and analyzed the hemispheric helicity rule in random samples of active regions drawn from this data set. Figure 2 shows averaged $d\alpha/d\varphi$ values computed using a random sampling of the HSP data set. For each N (number of active regions in a sample) the data set was randomly sampled 200 times, α versus latitude dependencies were fitted by a straight line, and the resulting slopes were averaged. Figure 2 demonstrates that for $N < 20$ a random sample has significant probability to show the hemispheric helicity rule of “incorrect sign.” On this Figure, mean value of $d\alpha/d\varphi$ is shown by a thick line and two thinner lines show 67%-probability range for deviations from this mean value. Thus, in approximately 16% of cases, a random sample with $N < 20$ may show positive $d\alpha/d\varphi$ slope deviation from the hemispheric helicity in disagreement with the hemispheric rule. Only when N is sufficiently large ($N > 50$) do the samples systematically give negative $d\alpha/d\varphi$ values at the 67% significance level. In addition to $d\alpha/d\varphi$ slopes, we also computed the fraction of cases (out of 200) when a random sample exhibits a negative Kendall coefficient τ for the correlation between α and φ , and the significance of this correlation. For small N, the number of cases with $\tau < 0$ is comparable to the number of cases with $\tau > 0$. For $N=30$, $\tau < 0$ in about 90% of all cases. The number of cases with $\tau > 0$ steadily decreases from 5 to 2% as N approaches 100. On the other hand, for N between 30 and

¹Unlike h_c , α does not depend on magnetic field strength.

100 the correlation is statistically significant at $> 95\%$ significance level in approximately 25–65% of the cases. Thus, even when the number of active regions in random sample is relatively large ($N > 50$), the sample may still show the “wrong” sign for the hemispheric rule in approximately 10% of cases. Furthermore, even for $N \approx 100$, such an “incorrect” sign for the hemispheric helicity rule should be expected in about 2-5% cases. For these large N , in about 35% of all cases, the fitted $d\alpha/d\varphi$ values will not be statistically significant at the 95% significance level even if the derived hemispheric rule has the correct sign. In Table 1, entries with small numbers of active regions in an annual sample show large variations in $d\alpha/d\varphi$ values. As N increases, the annual values became more consistent with each other. Fifteen entries in Table 1 have a number of active regions larger than 30. In only 2 (13%) out of the 15 cases is the $d\alpha/d\varphi$ value positive, in disagreement with the hemispheric helicity rule. This is consistent with our statistical experiment (Figure 2). Hence, we conclude that the results (sign-reversals in $d\alpha/d\varphi$) in Table 1 can be explained on the basis of purely statistical terms; the notion that the hemispheric helicity rule changes sign in some phases of solar cycle is not supported by these results at a high level of significance. It is clear that given the nature of the hemispheric helicity rule – a weak tendency with significant scatter – claims about its solar cycle dependence need to be substantiated by significant statistics. As it is demonstrated by our statistical experiment, all “reversals” in the hemispheric helicity rule based on the data from the four observatories studied here, in the period 1980 – 2000, can be explained on purely statistical grounds, without any underlying temporal variation at all. The declining number of active regions at around the time of solar minimum makes it even more difficult to substantiate helicity-rule reversals during years of low sunspot activity. Unfortunately, reversals in the hemispheric helicity rule reported by some researchers (e.g. Bao, Ai, & Zhang, 2000; Hagino & Sakurai 2005) fall into years of low sunspot activity as well, which calls into question validity of these claims.

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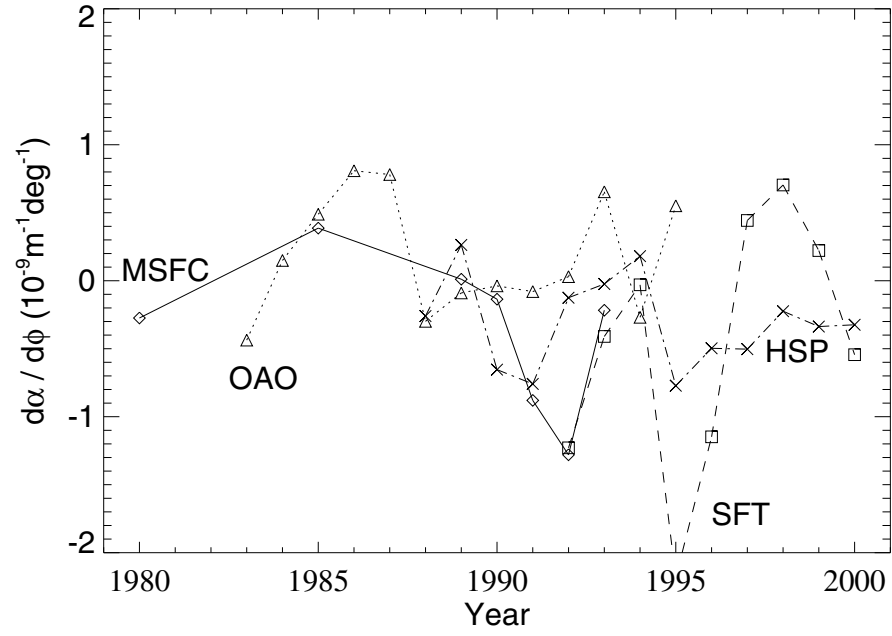


Fig. 1.— Annual values of the latitudinal gradient of α in years observed by the four magnetographs studied in this work.

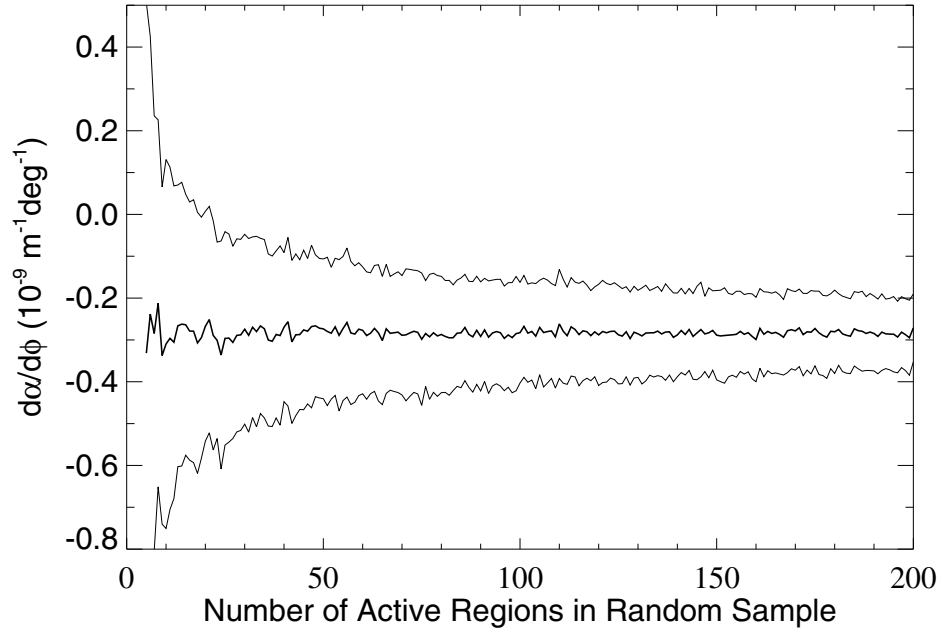


Fig. 2.— Latitudinal gradient $d\alpha/d\varphi$ computed using a random sampling of active regions in the HSP data set, as a function of sample size. The averaged $d\alpha/d\varphi$ values are shown by the thick solid line. The upper and lower thin lines show \pm one standard deviation of the average.

Table 1. Annual values of $d\alpha/d\varphi^a$ and number of active regions

Year	MSFC	OAD	SFT	HSP
1980	-0.274 (60)	...	...	...
1983	...	-0.437 (11)	...	...
1984	...	0.149 (48)	...	...
1985	0.387 (3)	0.489 (27)	...	...
1986	...	0.809 (25)	...	...
1987	...	0.781 (5)	...	...
1988	...	-0.299 (24)	...	-0.260 (6)
1989	0.011 (4)	-0.090 (39)	...	0.263 (17)
1990	-0.136 (8)	-0.038 (39)	...	-0.654 (12)
1991	-0.880 (5)	-0.080 (89)	...	-0.759 (20)
1992	-1.280 (6)	0.030 (65)	-1.229 (62)	-0.125 (42)
1993	-0.217 (2)	0.654 (30)	-0.410 (26)	-0.024 (69)
1994	...	-0.269 (9)	-0.030 (15)	0.181 (20)
1995	...	0.551 (19)	-2.184 (9)	-0.772 (32)
1996	...	...	-1.148 (7)	-0.497 (4)
1997	...	...	0.443 (12)	-0.503 (33)
1998	...	...	0.704 (6)	-0.224 (91)
1999	...	...	0.222 (23)	-0.337 (96)
2000	...	...	-0.544 (40)	-0.324 (43)

^ain units of $10^{-9} \text{ m}^{-1} \text{ deg}^{-1}$