On the Origin of Helicity in Solar Active-Region Magnetic Fields

Alexei A. Pevtsov and Richard C. Canfield

Physics Department, Montana State University

P.O. Box 173840, Bozeman, MT 59717-3840, U.S.A.

Received ____________________; accepted ____________________

ABSTRACT

In this paper we use vector magnetic field observations to test a simple model of the formation of the overall twist that is present in solar active-region magnetic fields. In this model magnetic flux bundles that form active regions start as axisymmetric toroids, without intrinsic twist, and rise in Ω-shaped loops through the convection zone, acquiring writhe through the effect of the Coriolis force on the large-scale flows within them. The tilt of active regions with respect to the equator is an observable manifestation of such writhe, at photospheric levels. If magnetic helicity is conserved, we should expect rising flux bundles to acquire equal and opposite amounts of twist and writhe.

Using a dataset of Mees Solar Observatory vector magnetograms for 99 active regions, we have measured both the tilt and twist of their magnetic fields, on active-region scales. This dataset clearly shows two well-known phenomena, Joy's law and the hemispheric dependence of twist. However, twist and tilt are not related as expected in the simple model. We conclude that the overall twist seen in active-region magnetic fields is not generated by the Coriolis force on large-scale flows occurring within them during their buoyant rise through the convection zone.

Subject headings: Sun:Magnetic Fields Sun:X-rays

1. INTRODUCTION

Observations of the coronal structure of solar active regions with the Soft X-ray Telescope (SXT: Tsuneta *et al.* 1991) on the YOHKOH mission commonly show S and inverse-S structures (Acton *et al.*1992, Canfield, Pevtsov & Acton 1995, Rust & Kumar 1996). Such structures can readily be modeled from observed magnetic fields using non-zero values of the constant α in the linear force-free-field equation $\nabla \times \mathbf{B} = \alpha \mathbf{B}$ (Pevtsov, Canfield & McClymont 1997), indicating the presence of significant twist in the large-scale magnetic fields of these regions. It is known that that there is a significant hemispheric preference in the handedness (chirality) of such twist. Inverse-S structures dominate in the northern hemisphere, forward-S in the southern.

Photospheric vector magnetograms made with the Haleakala Stokes Polarimeter (Mickey 1985) at Mees Solar Observatory and similar instruments elsewhere (Hagyard, Cumings & West 1984, Elmore *et al.* 1992) also commonly show twist in active-region magnetic fields. Although photospheric magnetic fields are not plausibly force-free, the value of α that best fits the fields observed in the vector magnetograms is a convenient way of characterizing their twist. Hemispheric preferences are well known in these data. Negative α values dominate in the North, and positive in the South (Seehafer 1990, Pevtsov, Canfield & Metcalf 1995).

2. HELICITY OF MAGNETIC FLUX TUBES

Consider a magnetic field $\mathbf{B}(\mathbf{x}) = \nabla \times \mathbf{A}(\mathbf{x})$ in a domain $\mathcal{D}$ on whose surface $\mathbf{n} \cdot \mathbf{B} = \mathbf{0}$. The magnetic helicity $\mathcal{H}$ of this flux system is then

$$\mathcal{H} = \int_{\mathcal{D}} \mathbf{A} \cdot \mathbf{B} \; \mathrm{dV}. \tag{1}$$

Consider a thin tube T with local $\mathbf{B}(\mathbf{r}, \theta, \mathbf{z})$ defined by its axial component $\mathbf{B}_{\mathrm{a}} = (0, 0, \mathrm{B_z(r)})$ and meridional component $\mathbf{B}_{\mathrm{m}} = (0, \mathrm{B}_\theta(\mathrm{r}), 0)$. Moffatt & Ricca 1992 showed that the total magnetic helicity $\mathcal{H}$ is given by

$$\mathcal{H} = \int_{\mathrm{T}} \mathbf{A}_{\mathrm{a}} \cdot \mathbf{B}_{\mathrm{a}} \, \mathrm{dV} + 2 \int_{\mathrm{T}} \mathbf{A}_{\mathrm{m}} \cdot \mathbf{B}_{\mathrm{m}} \, \mathrm{dV}. \tag{2}$$

The axial term gives the *writhe* contribution $\mathcal{W}$

$$\mathcal{W} = \mathcal{H}_{\mathrm{a}} = \int_{\mathrm{T}} \mathbf{A}_{\mathrm{a}} \cdot \mathbf{B}_{\mathrm{a}} \, \mathrm{dV}. \tag{3}$$

The meridional term gives the *twist* contribution $\mathcal{T}$

$$\mathcal{T} = \mathcal{H}_{\mathrm{m}} = 2 \int_{\mathrm{T}} \mathbf{A}_{\mathrm{m}} \cdot \mathbf{B}_{\mathrm{m}} \, \mathrm{dV}, \tag{4}$$

where $\mathbf{B}_{\mathrm{a}} = \nabla \times \mathbf{A}_{\mathrm{a}}$ and $\mathbf{B}_{\mathrm{m}} = \nabla \times \mathbf{A}_{\mathrm{m}}$.

The thin flux tube approximation (Spruit 1981) has been used by many investigators to understand the rise of magnetic flux tubes through the convection zone (Moreno-Insertis 1986, Choudhuri & Gilman 1987, Chou & Fisher 1989, D'Silva & Choudhuri 1993, Fan, Fisher, & DeLuca 1993). Such simulations successfully model observations of proper motions of emerging magnetic features (Caligari, Moreno-Insertis, & Schüssler 1995) and the morphology of leading and following polarities (Fan, Fisher, & DeLuca 1993). They also succeed in explaining observations of the dependence of tilt angles of active regions on latitude (D'Silva & Choudhuri 1993), total flux (Fan, Fisher, & McClymont 1994, Fisher, Fan, & Howard 1995), and statistical scatter (Longcope & Fisher 1996).

In these models, the tilt of active regions reflects the writhe of the flux tube, which arises due to the Coriolis force on material flowing away from the apex of the rising Ω-shaped flux tube. For total helicity to be conserved (Taylor 1974), twist must be generated of sign opposite to, and magnitude equal to, this writhe. To guide the analysis of our data, we use a simple nonlinear force-free field – a uniformly twisted cylindrical flux tube (Priest 1984). It is straightforward to show that for this field, which has no writhe,

$$\alpha = \mathcal{T}/L \tag{5}$$

.

3. OBSERVATIONS AND DISCUSSION

The dataset for this study consists of 249 vector magnetograms of 99 active regions obtained with the Haleakala Stokes Polarimeter (Mickey 1985) in 1988 - 1994, gathered and reduced in the standard manner described by Canfield *et al.* 1993. For each vector magnetogram we determined α_{best}, the best-fit single value of α; θ, the tilt of the active region axis with respect to the solar equator (positive in the counter-clockwise direction); L, the separation of the centroid of the N and S polarities; λ, the helio-latitude of the active region. When more than one magnetogram was available for an active region, we computed the mean and its uncertainty.

It is well known that solar active regions show a hemispheric relationship in the tilt of active regions with respect to the solar equator, called Joy's law (Hale *et al.* 1919). This hemispheric relationship, in our dataset, is shown in Figure 1. The simple model therefore leads us to expect a hemispheric dependence of twist, with $\alpha < 0$ in the Northern hemisphere because of helicity conservation and $\mathcal{W} > 0$ ($\theta < 0$) there. Observations of active region α values (Seehafer 1990, Pevtsov, Canfield & Metcalf 1995) show such a relationship.

Various authors (e.g., Tanaka 1991) have appealed to kinked flux tubes as an explanation of regions that do not obey the Hale-Nicholson polarity law (Hale *et al.* 1925, Hale & Nicholson 1938). If this explanation has merit, the measured tilt has an 180-degree ambiguity. To avoid this potential difficulty, we eliminate from our dataset those regions that disobey the Hale-Nicholson law. Of the 99 regions in our dataset, 91 obey the Hale-Nicholson law.

The relationship between α_{best} and tilt (per unit length) for those regions is shown in Figure 2, for two datasets. On the left, all 91 regions that obey the Hale-Nicholson law are plotted. On the right, only those of these regions that depart by more than $\pm\, 6\sigma$ from Joy's law are shown. In both, the slope of the relationship between α_{best} and $\frac{\theta}{L}$ is essentially -1, and the functional form resembles equation (5). The scatter is very large. For the regions that obey the Hale-Nicholson polarity law, the correlation coefficient is -0.350; for those that depart by more than $\pm\, 6\sigma$ from Joy's law, it is -0.558.

It is instructive to consider a simple model in which, at the base of the convection zone, flux tubes are simple axisymmetric toroids, without intrinsic twist. When they rise through the convection zone the Coriolis force on the flow in the rising tube produces right-handed writhe ($\mathcal{W} > 0$, corresponding to $\theta < 0$) in the Northern hemisphere. From helicity conservation, we then expect the production of left-handed twist ($\mathcal{T} < 0$, corresponding to $\alpha < 0$) in the Northern Hemisphere. We also then expect $\alpha < 0$ ($\mathcal{T} < 0$) when $\theta < 0$ ($\mathcal{W} > 0$). However, the observations do not conform to this relationship; the sign of their slope is opposite that of this simple model.

The dynamics of a thin magnetic flux tube, including the interaction between twisting and writhing, has been studied by Longcope & Klapper 1997. They estimate values of $\alpha \sim 2 \times 10^{-9} m^{-1}$, significantly smaller than those we typically observe ($\alpha \sim 10^{-8} m^{-1}$). Their study does not include the temporal evolution of twist, which means that the redistribution of twist throughout the entire domain of the flux tube is not included. Hence, we should expect α values from this mechanism to be even smaller.

In summary, we call attention to three features of the observations. First, the observed relationship between twist and tilt has sign opposite what the simple model predicts.

Second, there is a great deal of scatter in the relationship. Finally, the characteristic amplitude of the twist is much larger than studies of the dynamics of thin magnetic flux tubes predict. We therefore conclude that the twist observed in active region magnetic fields is not the consequence of large-scale flows that occur along them during their rise through the convection zone.

Acknowledgments

We thank Dana Longcope, Isaac Klapper, and Fausto Cattaneo for helpful discussions. This research has been supported by NASA, through Supporting Research and Technology Grants NAGW-5072 and NAG5-5043 and Yohkoh Soft X-ray Telescope contract NAS8-40801.

REFERENCES

Acton, L. W., *et al.*1992, Science, 258, 618.

Caligari, P., Moreno-Insertis, F., & Schüssler, M. 1995, ApJ, 441, 886.

Canfield, R. C., de La Beaujardiere, J.-F., Fan, Y., Leka, K. D., McClymont, A. N., Metcalf, T. R., Mickey, D. L., Wuelser, J.-P., & Lites, B. W. 1993, Astrophysical Journal, 411, 362.

Canfield, R. C., Pevtsov, A. A., & Acton, L. W. 1995, EOS Trans. AGU, 76(17), Spring Meet Suppl., S235.

Chou, D.-Y., & Fisher, G. H. 1989, A&A, 341, 533.

Choudhuri, A. R., & Gilman, P. A. 1987, ApJ, 316, 788.

D'Silva, S., & Choudhuri, A. R. 1993, A&A, 272, 621.

Elmore, D. F. *et al.* 1992, in Polarization Analysis and Measurement (SPIE Proc. v. 1746), 22.

Fan, Y., Fisher, G. H., & DeLuca, E. E. 1993, ApJ, 405, 390.

Fan, Y., Fisher, G. H., & McClymont, A. N. 1994, ApJ, 436, 907.

Fisher, G. H., Fan, Y., & Howard, R. F. 1995, ApJ, 438, 463.

Hagyard, M. J., Cumings, N. P., & West, E. A. 1984, Solar Physics and Interplanetary Travelling Phenomena, Eds.: C. de Jager & Chen Biao, Kunming, People's Republic of China, 179.

Hale, G. E. *et al.* 1925, ApJ, 62, 270.

Hale, G. E., & Nicholson, S. B., 1938, Carnegie Inst. Wash. Publ., 49, 8.

Hale, G. E., Ellerman, F., Nicholson, S. B., & Joy, A. H. 1919, ApJ, 49, 153.

Longcope, D. W., & Fisher, G. H. 1996, ApJ, 458, 380.

Longcope, D. W. & Klapper, I. 1997, ApJ, 488, in press.

Mickey, D. L., 1985, Sol. Phys., 97, 223.

Moffatt, H.K., & Ricca, R.L., 1992, Proc. R. Soc. Lond. A, 439, 411.

Moreno-Insertis, F. 1986, A&A, 166, 291.

Pevtsov, A. A., Canfield, R. C., and McClymont, A. N. 1997, ApJ, 481, 973.

Pevtsov, A. A., Canfield, R. C., and Metcalf, T. R. 1995, ApJ, 440, L109.

Priest, E. R. 1984, Solar Magnetohydrodynamics (Dordrecht: Reidel), p. 125.

Rust, D. M. & Kumar, A. 1996, Astrophysical Journal, 464, L199.

Taylor, J. B., 1974, Phys. Rev. Lett., 33, 1139.

Seehafer, N., 1990, Solar Phys., 125, 219.

Spruit, H. C. 1981, A&A, 98, 155.

Tanaka, K. 1991, Solar Phys., 136, 133.

Tsuneta, S., Acton, L. W., Bruner, M., Lemen, J. R., Brown, W., Caravalho, R., Catura, R., Freeland, S., Jurcevich, B., Morrison, M., Ogawara, Y., Hirayama, T., and Owens, J., 1991, Sol. Phys., 136, 37.

This manuscript was prepared with the AAS LaTeX macros v4.0.

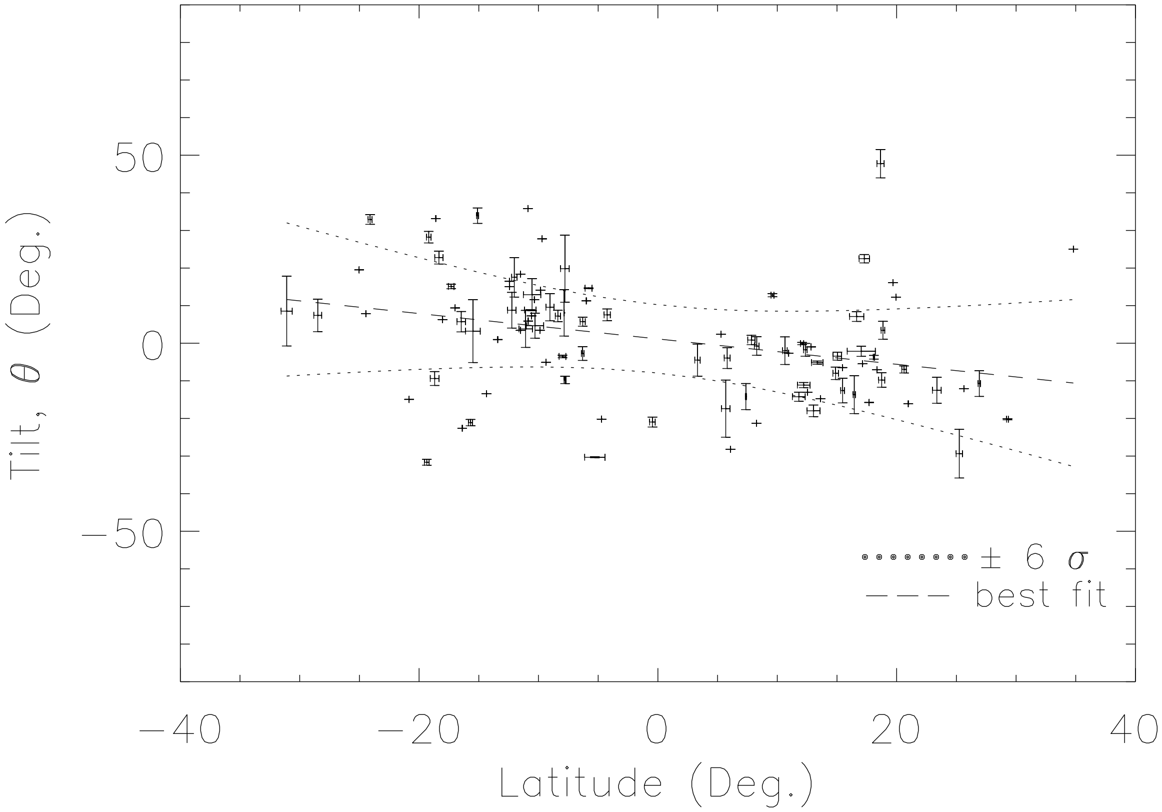

Fig. 1.— The dependence of the active region tilt on latitude for all 99 active regions. Error bars are given when there is more than one magnetogram per region. The long-dashed line shows the best least-squares fit. The short-dashed lines define the ± 6σ error band of the fit.

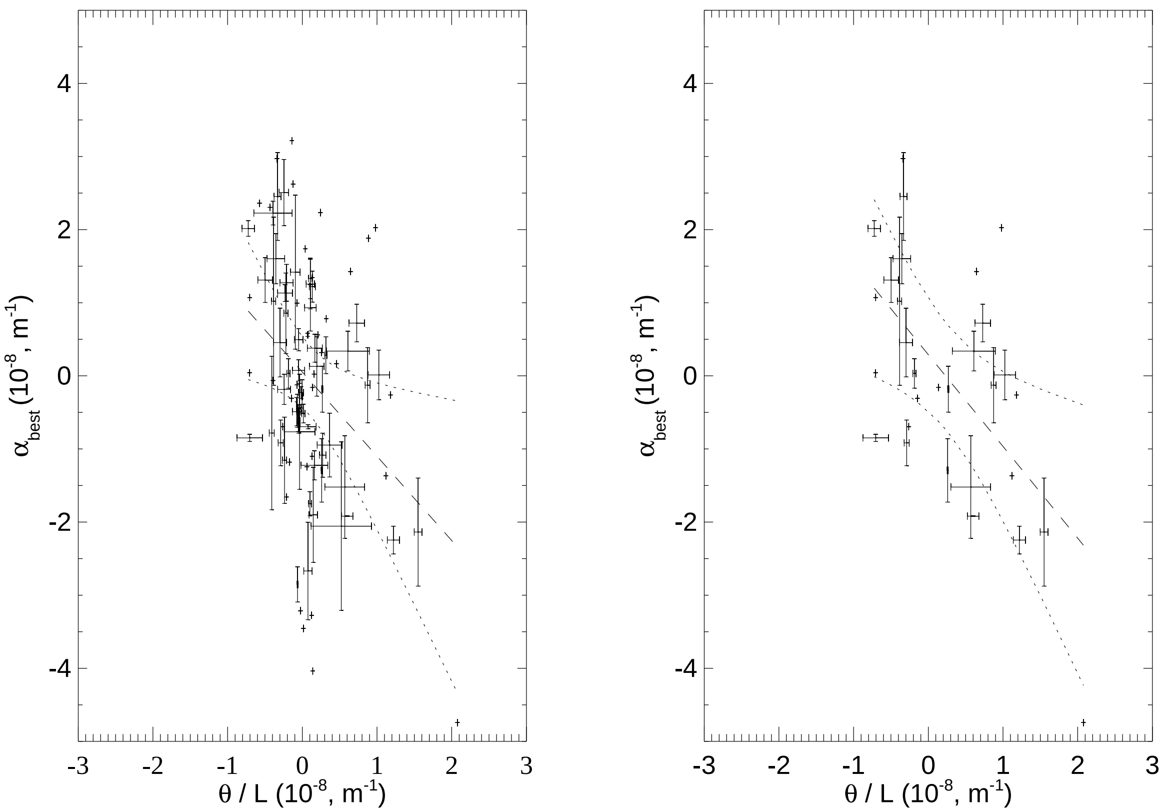

Fig. 2.— The dependence of observed active region α_{best} on the ratio of tilt to characteristic length. Left: All 91 regions that obey the Hale-Nicholson polarity law. Right: Only those regions that depart from Joy's law by more than $\pm$ 6σ (see Fig. 1). The long-dashed lines are linear least-squares fits; the short-dashed curves define the $\pm$ 3σ error bands.