Helicity Transport and Generation in the Solar Convection Zone

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ABSTRACT

Magnetic helicity provides a theoretical tool for characterizing the solar dynamo and the evolution of the coronal field. The magnetic helicity may be inferred from several types of observation including vector magnetograms of the photospheric magnetic fields. The helicity of an active region reflects, to some degree, the twist in the magnetic field below it. Photospheric observations reveal a tendency for left-handed chirality in the Northern hemisphere, although one-quarter to one-third of the active regions twist in the opposite sense. This means that coronal magnetic field has negative helicity in the North. Sub-photospheric fields will have left-handed twist in the North, although the net helicity also depends on the writhe of the flux tube axes. We show that buffeting by turbulence, the so-called Σ-effect, can explain the handedness and level of intrinsic variation of observed twist. This mechanism does not generate helicity, rather it produces twist and writhe of opposite signs. In this scenario, helicity of one sign propagates into the corona, while opposing helicity propagates downward in the form of torsional Alfvén waves.

CHALLENGES FROM OBSERVATIONS

There is overwhelming observational evidence that the solar magnetic field has a net relative helicity in each hemisphere. There are clear indications that the magnetic fields of sunspots, active regions, prominences and heliopsheric magnetic clouds are all twisted. These fields are generally twisted in left-handed screws in the Northern hemisphere and in right-handed screws in the Southern hemisphere (see the review by Zirker et al., 1997). This sense of twist indicates a negative (positive) relative helicity in the North (South). Furthermore, the advection of these helical structures through the heliosphere would result in a net helicity flux of the same sign in each hemisphere. There is good evidence for this helicity flux at 1 AU (Bieber and Rust, 1995).

The observed helicity segregation has significance for models of the solar dynamo, and possibly for models of magnetic activity (Boozer, 1993; Berger and Ruzmaikin, 2000). A complete accounting of the solar helicity budget must also account for the helicity flux through the solar photosphere. Here we consider what the observations can say about this.

The photosphere and chromosphere are the layers from which most of the solar radiation originates, thus it is this location which is easiest to characterize by remote sensing. The first observational suggestions of a hemispheric trend in magnetic twist were found by Hale (1927) and then by Richardson (1941) both of whom noted that sunspot super-penumbrae had a preference (3:1 in Richardson's larger survey) for clockwise spirals in the North, and a similar preference for counter-clockwise spirals in the South. Seehafer (1990) found a similar trend in the current-helicity of active region fields: 3:1 preference for $H_c < 0$ in the North.

Pevtsov et al. (1995) developed a technique to quantify the twist within an entire active region as $\alpha_{\rm best}$, from vector magnetograms. They then applied this to a survey of active regions, finding a clear anti-correlation with heliographic latitude. This ongoing survey presently includes 466 active regions observed by the Haleakela Stokes Polarimeter during the period 1987–2000, spanning two solar cycles (Fig. 1). The correlation with latitude is indisputable, since its Spearman coefficient, $\rho = -0.23$, has a significance over

99.999%. Nevertheless, the hemispheric segregation is far from perfect: only 63%(68%) of the Northern (Southern) regions adhere to the trend $\alpha_{\rm best} < 0$ ($\alpha_{\rm best} > 0$).

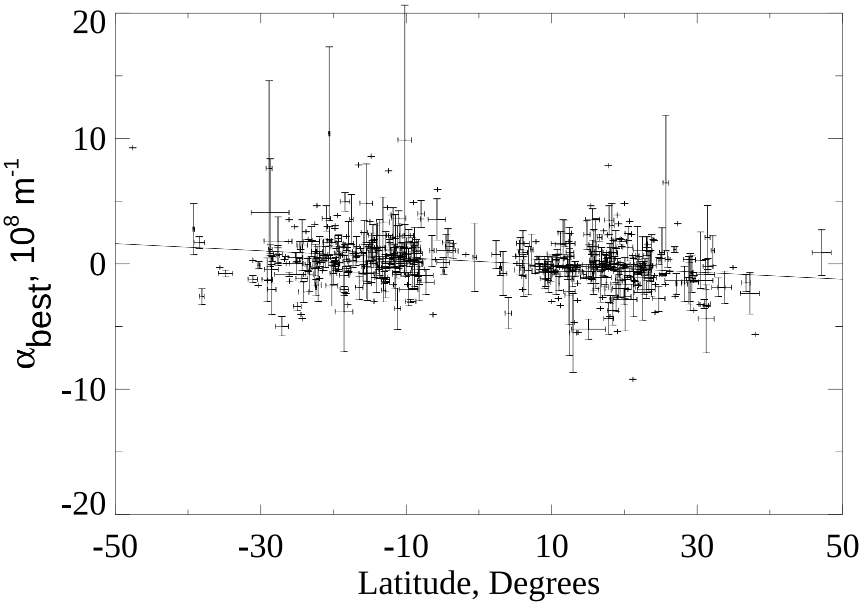

Fig. 1. Latitudinal dependence of $\alpha_{\rm best}$ for 466 active regions observed by Haleakala Stokes Polarimeter during 1987–2000 (solar cycles 22 and 23). In this data set 63%(68%) of the regions in the Northern (Southern) hemisphere have Negative (Positive) $\alpha_{\rm best}$. The Spearman correlation is $\rho = -0.23$, which could occur in the absence of correlation with a likelihood of 2.5×10^{-7}.

This work reviews theoretical models of coronal and sub-photospheric helicity and seeks the cause of this hemispheric preference. We show that the photospheric twist is due to twist within the emerging active region flux tubes. We show that the observed twist *does not* necessarily indicate a transport of net helicity from the dynamo layer, instead it might indicate a segregation of helicity between convection zone (CZ) and corona. We demonstrate exactly such a scenario in the helicity-conserving deformation of rising flux tube by helical turbulence. In this process, called the Σ-effect (Longcope et al., 1998; Longcope et al., 1999), the flux tube develops an internal twist due to an opposing writhe caused by turbulent buffeting during the tube's rise. We show that the coronal and photospheric fields inherit helicity from the twist of the flux tube, rather than its net helicity. This proposed mechanism explains the magnitude, sign and degree of fluctuation of the observations. It does, however, raise other questions concerning the Sun's overall helicity budget.

TWIST IN FLUX TUBES

Active regions are presently believed to form when isolated strands of magnetic field, called *flux tubes*, emerge from a layer at the base of the convection zone. A portion of the tube becomes buoyant relative to its surroundings and rises through the CZ deforming the tube into an "Ω" shape. Upon reaching the surface the two "legs" of the Ω-loop form the two magnetic polarities of the active region.

The dynamical evolution of the rising magnetic flux tube has been modeled using *thin flux tube equations*, proposed by Spruit (1981) and refined by subsequent investigators (Choudhuri and Gilman, 1987; Chou and Fisher, 1989). A tube of flux Φ is assumed to be sufficiently thin[1] that it may be represented as a space-curve $\mathbf{r}(s)$ parameterized by axial-length coordinate s. Sectioned at coordinate s the tube has magnetic field

[1]Specifically, its cross sectional radius is assumed to be much smaller than either the ambient pressure scale height or its radius of curvature.

strength $B(s)$ confined to an area $A(s) = \Phi/B(s)$ by an imbalance between the external and internal plasma pressure. The tube is characterized by a very large plasma β, (it can exceed $\beta = 10^5$), so that confinement is achieved with a tiny relative pressure deficit. The plasma surrounding the flux tube is assumed to be unmagnetized.

The thin flux tube equations describe the time-evolution of the axis $\mathbf{r}(s,t)$ and its local field strength $B(s,t)$. These follow from the effects of buoyancy, magnetic tension and aerodynamic drag on each tube-segment, combined with the requirement of total pressure balance across its surface. Under typical circumstances the tube's inertia is negligible and it moves at "terminal velocity" where drag balances all other forces

$$\mathbf{v}_\perp \;=\; \mathbf{v}^{\rm e}_\perp \;+\; \frac{\Phi^{1/4}}{B^{1/4}}\,|v_{\rm A}^2\mathbf{k} + \frac{\delta\rho}{\rho}\mathbf{g}_\perp|^{-1/2}\,(v_{\rm A}^2\mathbf{k} + \frac{\delta\rho}{\rho}\mathbf{g}_\perp) \quad , \tag{1}$$

where $\mathbf{v}^{\rm e}$ is the velocity of the unmagnetized, external medium, $\delta\rho \equiv \rho - \rho^{\rm e}$ is the over-density of the flux tube (it is negative for a buoyant tube, and typically $\ll \rho$), $v_{\rm A}(s) = B(s)/\sqrt{4\pi\rho}$ is the Alfvén speed within the flux tube, and $\mathbf{k}$ is the curvature vector of the axis. The $\perp$ subscripts indicate components perpendicular to the axis's tangent vector $\hat{\mathbf{s}} \equiv \partial\mathbf{r}/\partial s$.

In a stationary external medium, $\mathbf{v}^{\rm e} = 0$, the tube rises at approximately its free-fall speed, where upward buoyancy balances downward drag. The leading coefficient $\Phi^{1/4}/B^{1/4}$ is the square-root of the tube's diameter, arising from the classical formula for aerodynamic drag (Parker, 1979; Choudhuri and Gilman, 1987). Therefore, among tubes of equal field strengths, those with larger flux raise to the surface more quickly. Solutions of time-dependent equations, including inertia, have shown behaviors in quantitative agreement with numerous observed properties of bipolar active regions (see Fisher et al. 1999 for a review.)

The observation of twist in the field of an active region implies that current is crossing the photosphere from the flux tube below. There are, broadly speaking, two ways that this current might have been generated: the active region field might have been sheared by photospheric flows *after* its emergence, or the flux tube might have emerged in a twisted state. In a pioneering series of papers, Leka et al. (1994, 1996) showed that the second explanation applied to at least one active region: AR7260 was born twisted. They observed, over a period of seven days beginning 14-August 1992, this particular active region ($\Phi \simeq 10^{22}$ Mx) emerge through a series of 50 separate bipolar events, each typically adding 10^{20} Mx to the active region flux. A sequences of vector magnetograms of three bipolar events showed that in each case, the vertical current increased in direct proportion to the magnetic flux. The constant of proportionality was negative (consistent with the preferred handedness of Northern hemisphere active regions).

Dynamics of Twist

A model for the evolution of a twisted flux tube has been proposed (Longcope and Klapper, 1997) which generalizes the tube of Spruit (1981) to incorporate a magnetic twist, $q(s,t)$, and spin rate $\omega(s,t)$. Were the tube's axis perfectly straight, $\mathbf{r}(s,t) = s\hat{\mathbf{z}}$, then these quantities would correspond to $q = B_\phi/\varpi B_z$ and $\omega = v_\phi/\varpi$ where (ϖ,ϕ) are the cylindrical radius and angle coordinates. The model applies to tubes of arbitrary axes undergoing arbitrary time-evolution $\mathbf{r}(s,t)$. The twisted tube carries a current $I(s) = 2q(s)\Phi$ distributed over its cross section. Since the tube is by assumption embedded in field-free external plasma, it carries no net current. Thus there is an opposing axial return current distributed over its surface, joining the larger azimuthal surface current present even in the untwisted flux tube.

A dynamical equation for spin follows from the conservation of angular momentum of any tube segment (Longcope and Klapper, 1997). While the external medium couples to the axis dynamics through aerodynamic drag, it is not evident how such a coupling could exert significant torque on the tube. At high Reynold's number, the aerodynamic drag quantifies the momentum carried away by the tube's wake, a well-studies process in hydrodynamics. There is no analog of a wake for carrying away angular momentum at high Reynold's number, so the effect of the external medium will be ignored in the twist dynamics. The resulting equation for the evolution of spin is

$$\frac{d\omega}{dt} \;=\; B^{-1}\dot{B}\omega \;+\; v_{\rm A}^2\frac{\partial q}{\partial s} \quad , \tag{2}$$

which includes the effect of a changing moment of inertia (the first term on the right-hand side) and varying axial magnetic torque (the second term). The magnetic torque term attempts to equalize the twist everywhere along the tube[2] in order that the distributed current not be shunted radially to the return current, which would produce $\partial I/\partial s \neq 0$.

The final piece of the model is a kinematic equation for the evolution of twist on an evolving axis of arbitrary shape

$$\frac{dq}{dt} = -\left(\hat{\mathbf{s}}\cdot\frac{\partial \mathbf{v}}{\partial s}\right) q + \frac{\partial \omega}{\partial s} + \underbrace{(\hat{\mathbf{s}}\times\mathbf{k})\cdot\frac{\partial \mathbf{v}}{\partial s}}_{\Sigma(s,t)} \quad . \tag{3}$$

The first and second terms on the right-hand side change the twist in a tube segment by stretching it or by by spinning its ends at different rates (or in opposite directions). The third term, denoted Σ, corresponds to the change in twist resulting from changing the writhe of its axis. The relative helicity of on isolated flux tube may be written as a sum of twist and writhe (Berger and Field, 1984; Moffatt and Ricca, 1992) and will be conserved. The writhe contribution involves the tube's axis $\mathbf{r}(s,t)$ while the twist is merely the integral $\int q(s,t)ds$. In order that the sum of these contributions remain constant there must be a coupling between the dynamics of the axis and the dynamics of the twist. This coupling is given by the Σ-term and follows from kinematic considerations alone (Longcope and Klapper, 1997).

Equations (2) and (3) describe undamped torsional Alfvén waves propagating at the Alfvén speed $v_{\rm A}$. For the simplified case of a stationary axis with uniform Alfvén speed solutions may be written

$$q(s,t) = w_L(t+s/v_{\rm A}) + w_R(t-s/v_{\rm A}) \tag{4}$$

$$\omega(s,t) = v_{\rm A}\left[w_L(t+s/v_{\rm A}) - w_R(t-s/v_{\rm A})\right] \ , \tag{5}$$

for arbitrary rightward and leftward wave-forms $w_R(t)$ and $w_L(t)$. The absence of damping is a direct consequence of the conclusion that a spinning tube does not couple to the external medium.

COUPLING TWIST ACROSS THE PHOTOSPHERE

In the layer which includes the photosphere, chromosphere and transition region, fundamental radiative, thermodynamic and MHD parameters vary dramitically over very small scales. From the standpoint of an entire active region flux tube, however, the layer, hereafter collectively called the "photosphere", represents a thin interface between the high-β and low-β regimes of the convection zone and corona respectively. Below it the field is confined to narrow flux tubes across which pressure balance obtains. Above the photosphere the magnetic field expands to fill the coronal volume, evolving mostly through force-free equilibria (see Fig. 2). This field may contain a net current I_c flowing from the positive to negative polarity (i.e. $I_c < 0$ in regions with lefthanded twist).

Requiring torque balance across the photospheric interface is equivalent to demaning continuity of the current flowing along the magnetic field lines (Longcope and Welsch, 2000). This means that the distributed current within the tube, $I = 2q\Phi$, must match the coronal current I_c at each of the interfaces.[3] This boundary condition reflects waves incident on the photosphere from below. The leftward reflection from the positive pole located at $s = s_+$ is

$$w_L^+(t) = \frac{I_c(t)}{2\Phi} - w_R^+(t) \ , \tag{6}$$

where the wave-forms w_R^+ and w_L^+ are defined as in expressions (4) and (5) but using a shifted length coordinate $\Delta s_+ = s - s_+$. A similar expression gives the rightward reflection, $w_R^-(t)$, from the negative pole using length coordinate $\Delta s_- = s - s_-$.

The coronal field evolves on time scales of the coronal Afvén transit time, typically less than a minute. This is so much shorter than the time-scale of the flux tube evolution (days) that we will treat the corona as evolving quasi-statically through a sequence of force-free equilibria. In our model of the entire active region we characterize each equilibrium only by its net coronal current I_c. The spinning of the flux tube's two

[2] This contradicts a common assertion that twist will propagate toward wider portions of the tube.

[3] The return current flowing on the tube's surface will join the general surface current defining the magnetic layer called the canopy or merging layer (Longcope and Welsch, 2000).

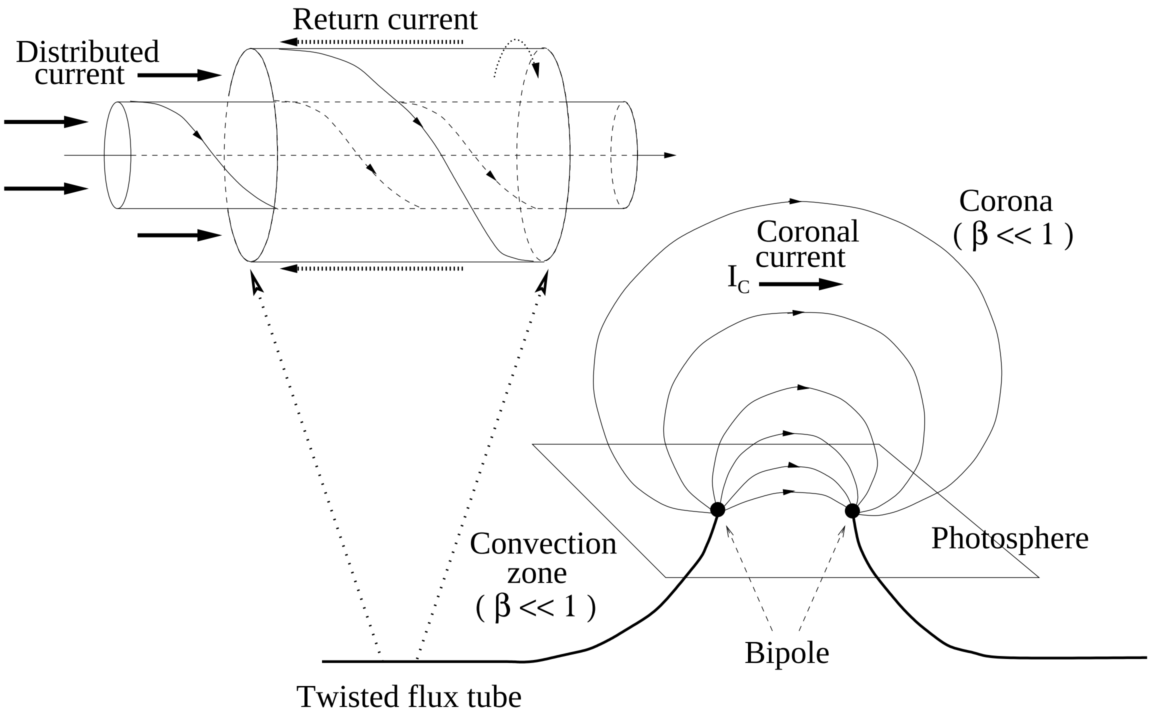

Fig. 2. Schematic of the twisted flux tube joined to the force-free coronal equilibrium

free ends will change the relative helicity of the equilibrium, $H_c(I_c)$, thereby driving its evolution. Choosing $\hat{\mathbf{s}}$ parallel to the magnetic field the photospheric surface-normal is $+\hat{\mathbf{s}}$ in the positive pole and $-\hat{\mathbf{s}}$ on the negative pole. The change in coronal helicity due to horizontal motion takes the form (Berger and Field, 1984)

$$\frac{dH_c}{dt} \;=\; -\frac{\Phi^2}{2\pi}\left[\omega(s_+,t) \;-\; \omega(s_-,t)\right] \tag{7}$$

This may be recast as an equation for the coronal current using the interface condition (6) and its analog for w_R^-

$$\frac{dI_c}{dt} \;=\; -\frac{\Phi v_{\rm A}}{2\pi H_c'(I_c)}\left[\; I_c - 2\Phi(w_R^+ + w_L^-)\;\right] \;-\; \frac{1}{H_c'}\left.\frac{\partial H_c}{\partial t}\right)_{I_c} \quad , \tag{8}$$

where $H_c'(I_c) \equiv \partial H_c/\partial I_c$, and the partial time derivative captures the possible effects of changing photospheric anchoring.

According to equation (8), the coronal current will approach a value, $\bar{I}_c = 2\Phi(w_R^+ + w_L^-)$, which combines the distributed current from both torsional waves incident on the surface. It will relax to this value on a time scale $\tau_{\rm fp} = 2\pi H_c'/\Phi v_{\rm A}$. As an illustrative example consider the quasi-static sequence defined by constant-α equilibria anchored to footpoints separated by a distance d. The relative helicity of such equilibria will be

$$H_c(I_c) \;\sim\; \frac{\alpha d}{2\pi}\Phi^2 \;=\; \frac{I_c\Phi d}{2\pi} \quad . \tag{9}$$

This leads to a twist-relaxation time $\tau_{\rm fp} \sim d/v_{\rm A}$ which is the time for a sub-photospheric Alfvén wave to travel the distance separating the active region's poles; for $v_{\rm A} = 1$ km/sec and $d = 100$ Mm, this is roughly one day (Longcope and Welsch, 2000).

The last term in (8) leads to a suppression of the current as an active region first emerges. (In the constant-α approximation the term is $-I_c\dot{d}/d$.) This reflects a dearth of helicity in the expanding coronal field, which will ultimately be overcome as the footpoint spin injects helicity. A byproduct of this process will be the propagation of downward waves, w_L^+ and w_R^- containing opposite helicity (Longcope and Welsch, 2000). This effect is required by the conservation of helicity: as helicity is injected into coronal fields the flux tube must lose helicity. Recent observational data from an emerging active region (AR9139) obtained by Pevtsov et al. (2003) provides evidence for the relaxation of $\alpha_{\rm best}$ on time scales of roughly one day (see Fig. 3).

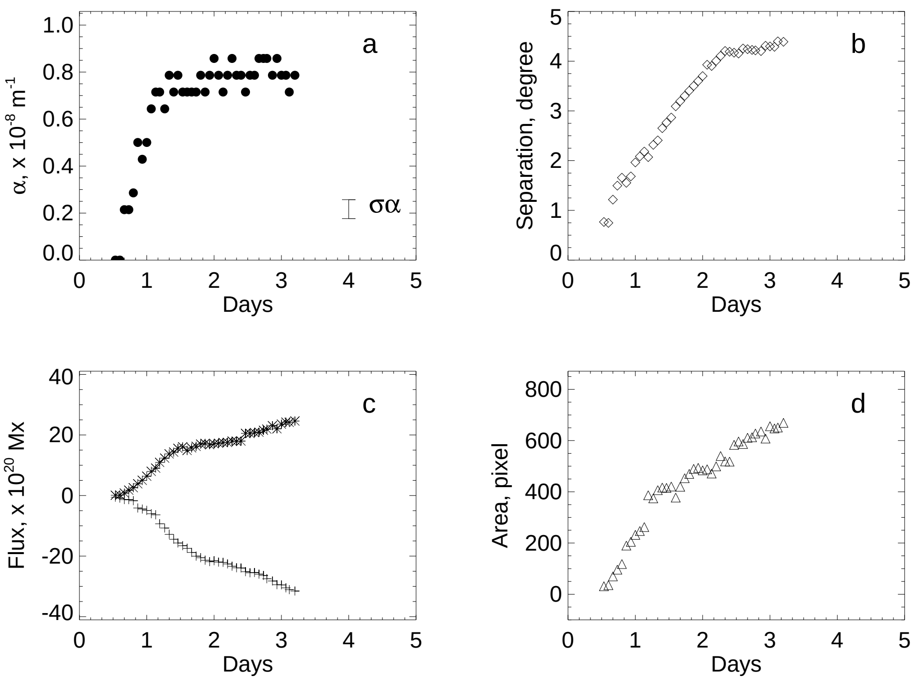

Fig. 3. Data from the emergence of AR 9139, from Pevtsov et al. 2003.

THE SOURCE OF FLUX TUBE TWIST

The foregoing section showed that the observed active region twists reflect the twist in emerging flux tubes. This raises the question of how the active region flux tubes become twisted prior to emergence. Equation (3) indicates that the twist could be added or subtracted from a flux tube through the source term $\Sigma(s,t)$ if the axis undergoes a writhing motion. Alternatively, the flux tube might leave the dynamo layer with an initial twist $q(s,0) = q_0(s)$. The observations provide important constraints on each of these alternatives.

Several important facts are well established by the wide variety of photospheric observations discussed above. The sign of q is preferentially negative in the North and positive in the South. Making the association $q = \alpha_{\rm best}/2$ (Longcope et al., 1998) provides the average twist at latitudes of 20 degrees, $\langle q\rangle \sim 3\times10^{-9}\,{\rm m}^{-1}$. The hypothetical source produces either sign of twist in each hemisphere, with rms level larger than the mean $\Delta q \sim 10^{-8}\,{\rm m}^{-1}$. This fact alone rules out steady mechanism, such as the Coriolis effect or differential rotation, which lack inherent fluctuations.

Dominant fluctuations strongly implicate the convection zone turbulence in the introduction of twist. This mechanism, called the Σ-effect (Longcope et al., 1998), can be quantified by expressing the twist-source $\Sigma(s,t)$ explicitly in terms of turbulence velocity $\mathbf{v}^{\rm e}$. Using expression (1) for velocity yields $\Sigma = (\hat{\mathbf{s}}\times\mathbf{k})\cdot(\partial\mathbf{v}^{\rm e}/\partial s)$, after dropping several terms under the assumption that the vorticity of the turbulence $|\nabla\times\mathbf{v}^{\rm e}| \gg (v_{\rm A}/R)\tau\sqrt{a/R}$ where τ and R are the tube's torsion and radius of curvature (recall that the thin flux tube equations assume $a/R \ll 1$). This expression for Σ will obviously fluctuate, since it is proportional to the turbulent velocity field $\mathbf{v}^{\rm e}$. The average contribution of the twist-source, averaging over turbulent fluctuations, is

$$\langle\Sigma\rangle \;=\; \left\langle \delta\mathbf{k}\times\frac{\partial\mathbf{v}^{\rm e}}{\partial s}\right\rangle\cdot\langle\hat{\mathbf{s}}\rangle \;-\; \left\langle \delta\hat{\mathbf{s}}\times\frac{\partial\mathbf{v}^{\rm e}}{\partial s}\right\rangle\cdot\langle\mathbf{k}\rangle \;=\; -\tfrac{1}{5}\tau_{\rm c}\int k^2F(k)\,dk \quad , \tag{10}$$

neglecting the third order correlations between the fluctuating quantities $\mathbf{v}^{\rm e}$, $\delta\mathbf{k}=\mathbf{k}-\langle\mathbf{k}\rangle$, and $\delta\hat{\mathbf{s}}=\hat{\mathbf{s}}-\langle\hat{\mathbf{s}}\rangle$. The final expression follows from straightforward analysis under the assumption of homogeneous, isotropic turbulence $\mathbf{v}^{\rm e}$, with correlation time $\tau_{\rm c}$. The spectral density of kinetic helicity, $F(k)$, is defined so that the α-coefficient in mean-field electrodynamics is (Moffatt, 1978; Longcope et al., 1998)

$$\alpha \;=\; -\tfrac{1}{3}\tau_{\rm c}\langle\mathbf{v}^{\rm e}\cdot\nabla\times\mathbf{v}^{\rm e}\rangle = \tfrac{1}{3}\tau_{\rm c}\int F(k)\,dk \quad . \tag{11}$$

Comparison of expression (10) and (11) shows that the Σ-effect and α-effect have opposite signs. It is generally agreed that the effect of rotation on the the CZ turbulence will create negative kinetic helicity, $\langle\mathbf{v}^{\rm e}\cdot\nabla\times\mathbf{v}^{\rm e}\rangle$, in the Northern hemisphere (Moffatt, 1978). If the entire helicity spectrum is of the same sign then $F(k)\geq 0$ in the North yielding a negative value of $\langle\Sigma\rangle$ there. This will generate twist of a sign consistent with observation, $\langle q\rangle<0$, as a natural consequence of the left-handed helical turbulence distorting the axes of tubes in a generally right-handed sense. It should be stressed that this mechanism does not change the net helicity of the flux tube, rather it introduces opposing twist and writhe contributions.

Of equal importance is the level of fluctuations in the source term $\Sigma(s,t)$. Averaging Σ^2 and retaining only the lowest order in fluctuating quantities yields

$$\langle\Sigma^2\rangle \;=\; |\mathbf{k}|^2\int k^2\,E(k)\,dk \quad , \tag{12}$$

where $E(k)$ is the energy spectrum of the turbulent velocity. While the average of Σ depends on the helicity spectrum, $F(k)$, its variance depends on the energy spectrum. The former will generally be smaller especially for turbulence turning over rapidly compared to the solar rotation rate (anywhere above a depth of 100 Mm). Thus the level of fluctuations in the twist generation is naturally larger than the mean, and appear to be independent of latitude. Detailed numerical simulations show the values of $\langle q\rangle$ and Δq produced by turbulence are in good quantitative agreement with observation (Longcope et al., 1998).

It is not yet possible to apply these same observational constraints to models of a source of initial twist $q_0(s)$. There are presently no mean-field dynamo models which predict flux tube formation, nor any dynamo models in which the helicity or even the α-effect are fluctuating quantities. This deficiency may, however, reflect the current status of the theory than of its ultimate plausibility.

DISCUSSION

The foregoing reviewed some of the observational evidence for a hemispheric segregation in the chirality of magnetic fields, and presented theoretical interpretations of this data. A wide variety of observational data has motivated the model of isolated magnetic flux tubes. These models have recently been generalized to include the dynamics of twist within flux tubes. The net helicity in a flux tube is a sum of twist and writhe contributions, but net torque balance requires that the observed photospheric twist match only the *twist*.[4] Thus we cannot conclude that an observed trend in the photospheric twist reflects a trend in the net magnetic helicity of the sub-photospheric field.

To illustrate this conclusion we showed how the Σ-effect will naturally introduce twist into rising flux tubes, without changing their helicity. The handedness of the twist reflects that of the turbulence. Intrinsic variations in turbulent flows lead naturally to a large scatter in the twist it introduces. The mean trend in the twist, observable within the scatter, is a left-handed twist in the North and a right-handed twist in the South. Both the trend and the dominance of scatter are consistent with the observations.

[4] The relative helicity of a given active region depends on α, which depends in turn on the twist of the flux tube. The writhe affects only the heliographic coordinates of the AR poles and thus not its relative helicty. The flux tube's writhe could possibly contribute to the overall coronal helicty through a mutual helicty term characterizing inter-connections between active regions at different heliographic coordinates. Since this contribution to coronal helicity has never been measured it is does not (yet) require a theoretical explanation.

When a twisted flux tube emerges, it must transport helicity into the corona. Considering only that contribution due to horizontal photospheric motions $\mathbf{v}_\perp$,

$$\frac{dH_c}{dt} = -2\int\limits_{z=0} (\mathbf{A}_0\cdot\mathbf{v}_\perp)\,B_z\,dx\,dy \quad , \tag{13}$$

led us to an expression, (7), for the generation of downward-propagating torsional Alfvén waves as a result of helicity flux into the corona. In this way, a net helicity flux into the corona (and beyond), would be balanced by an opposing downward flux into the convection zone.

Some authors have argued (Berger and Ruzmaikin, 2000) that emerging flux tubes carry their net helicity into the corona. Modeling this process would require the full helicity flux expression

$$\frac{dH_c}{dt} = -2\int\limits_{z=0} (\mathbf{A}_0\cdot\mathbf{v}_\perp)\,B_z\,dx\,dy \;+\; 2\int\limits_{z=0} (\mathbf{A}_0\cdot\mathbf{B}_\perp)\,v_z\,dx\,dy \quad , \tag{14}$$

where $v_z(x,y)$ is flow across the photospheric level. Observations have indicated that the second term is sometimes important (Kusano et al., 2002). Even if this process is included,however, torque balance still requires that the final twist in the coronal field match the twist in the legs of the flux tube. If the submerged section of the tube is twisted, as observations say it is, then there will ultimately be a net helicity transport into the corona and compensating transport into the CZ.

The Σ-effect is a mechanism by which a flux tube's twist is changed without affecting its helicity. If the tube is created in a twisted state by the dynamo, then the Σ-effect will simply add to this. Moreover, if the twist from the creation process depended on latitude, this would form part of the trend in observed photospheric twist. Unfortunately, we cannot presently distinguish between twist present from the beginning and introduced during rise. Recent observations of a correlation between the twist and the inferred writhe of a tube might soon provide this evidence (Lopez Fuentes et al., 2003). Until such a distinction can be made, however, we cannot say definitively that the observed twist trend *is not* a manifestation of a helicity trend.

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