The Origin and Role of Twist in Active Regions

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Abstract. The implications of twist in active region magnetic fields is considered in this paper. The latitudinal distribution of twist that has been derived from recent vector magnetogram observations may be explained by the effects of convective turbulence with a non-zero kinetic helicity acting on active region scale magnetic flux tubes as they rise through the convection zone. Highly twisted, kink unstable flux tubes are then discussed as a possible explanation for many of the observed properties of flare productive, "δ-spot" active regions.

1. Introduction

Active regions are the most visible consequence of the solar cycle. Active regions as observed in the photosphere consist of strong, concentrated bipolar magnetic fields which can be detected with polarized spectral line radiation, typically observed with a magnetograph. Global measures of solar activity, such as the X-ray radiance, are dominated by emission from active regions. Sunspots, which have historically been used as a proxy for the solar magnetic field, are formed entirely within active regions. Understanding the origin of active regions, their properties, and their dissolution is an essential part of understanding the solar cycle.

In this paper, we consider just one property of bipolar magnetic active regions: the amount of twist in the magnetic field. This topic is motivated by two recent developments. First, recent measurements with vector magnetographs – instruments capable of measuring all 3 components of the magnetic field at the photosphere – indicate a global pattern of active region twist. There is a slight tendency of active regions in the northern hemisphere to exhibit negative twist, while those in the southern hemisphere show a preference for positive twist. What does this pattern tell us about where active region magnetic fields come from and how they evolve? Second, recent work has shown that certain active region configurations, *i.e.* the δ-spot active regions, are suggestive of magnetic structures which are so twisted that they appear to have kinked.

In §2 of this paper, we consider the origin of the global pattern of twist in active regions by studying models of flux tubes rising through the solar convection zone. We suggest that the observed twist pattern can be understood by considering the effects that turbulent convective motions, including kinetic helicity, have on the dynamics of flux tubes as they rise. The helical kink instability of highly twisted flux tubes is then discussed in §3 as a possible interpretation for the morphology and evolution of δ-spot active regions. We find that many properties of δ-spot active regions can be explained by the nonlinear behavior of flux tubes which succomb to the multiple-mode helical kink instability.

2. Active Regions as Emerging Flux Tubes - Twist, and How it Gets There

Most active regions form and develop as if a simple loop of magnetic flux emerges through the photosphere and into the corona, with the top of the flux loop fragmenting into several pieces during the last stages of emergence through the upper convection zone. Figure 1, taken from Cauzzi et al. (1996), illustrates the photospheric signature of an active region and how this can be interpreted in terms of an active region flux tube emerging from the convection zone.

Twist in active regions can be determined by taking the curl of the horizonal components of the measured photospheric field to derive a vertical current density. By doing a least squares fit of the magnetogram data to a constant α force free field (*i.e.* $\mathbf{J} = \alpha\mathbf{B}$), it is possible to derive a twist parameter α for each active region observed. Pevtsov, Canfield & Metcalf (1995) have performed such an analysis for a large number of active regions, and find a slight variation of twist with latitude underlying a large degree of scatter (Figure 2). Active regions in the northern hemisphere show a preference for negative twist, while those in the southern hemisphere tend to exhibit positive twist.

Why should active region twist depend on latitude? We have examined several different mechanisms, including differential rotation, active region tilt driven by Coriolis forces, and kinetic helicity in convection zone flows, and have concluded that only the latter mechanism can produce values of the twist parameter α at the level that is observed (Longcope, Fisher & Pevtsov 1998, henceforth LFP).

To evaluate how convection zone motions influence twist in active region scale flux tubes, we first assume that the thin flux tube approximation (*e.g.* Spruit 1981) holds, and then incorporate twist into the flux tube equations

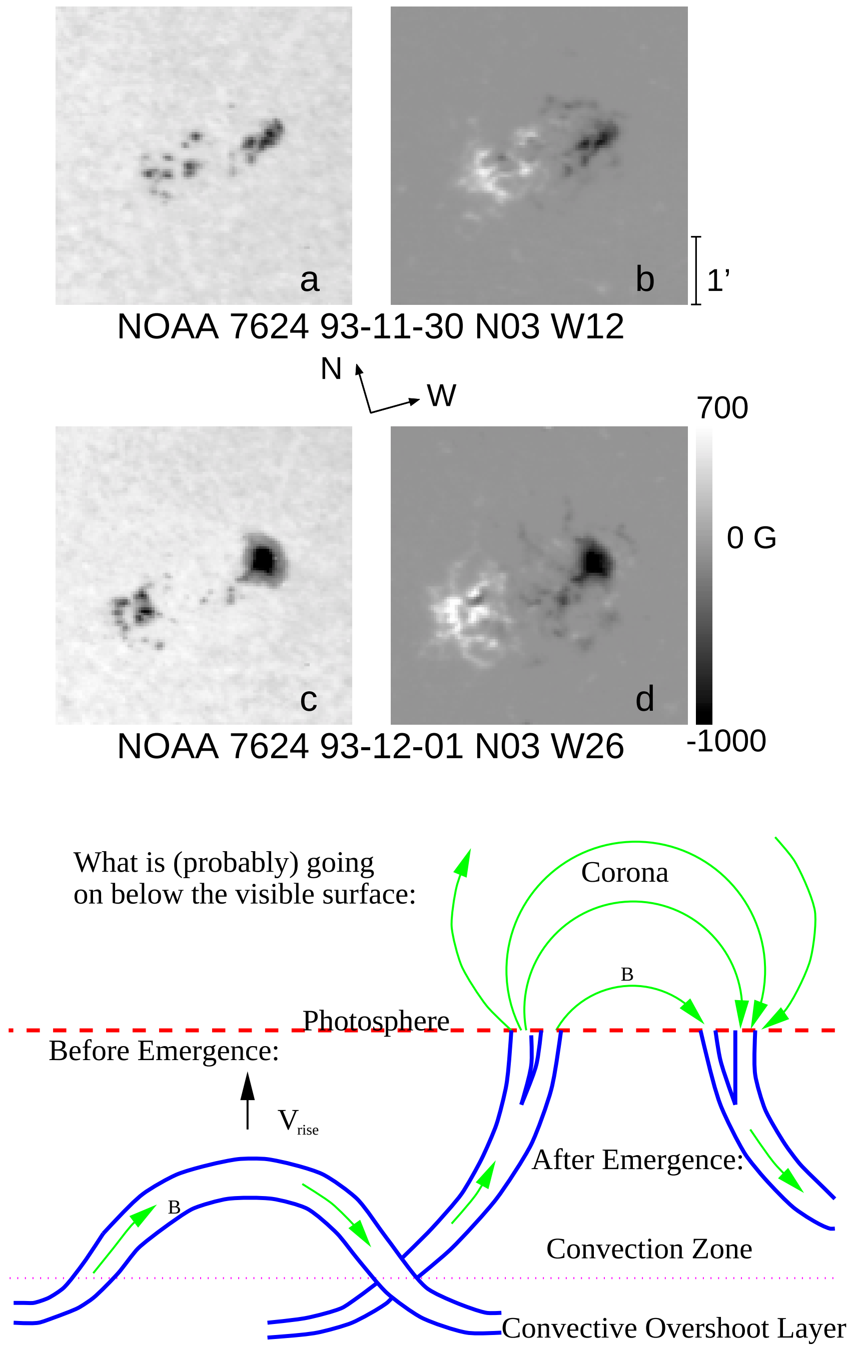

Figure 1. Top 4 panels show an emerging active region as observed at the photosphere, seen both as a white light image and as a magnetogram. Diagram at bottom shows likely magnetic structure below photosphere.

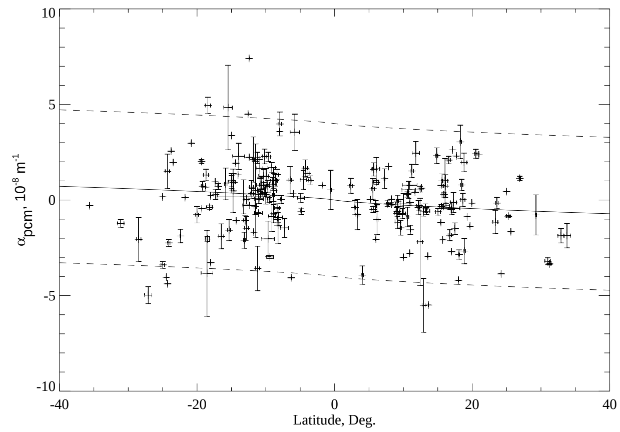

Figure 2. Measured values of $\alpha = 2q$ as a function of latitude for many different active regions. Solid line is from theoretical model described in LFP, and dashed lines are expected levels of scatter in the model, for an assumed active region flux of $\Phi = 10^{22}$Mx.

of motion (Ferriz-Mas, Schüssler & Anton 1989, Ferriz-Mas & Schüssler 1990, Longcope & Klapper 1997), assuming that the twist is small ($qa << 1$, where q is the twist per unit length, and a is the flux tube radius). In this case, one can derive two dynamic equations for q and ω (ω is the angular frequency of rotation about the flux tube axis) that supplement the normal thin flux tube dynamics equations:

$$\frac{d\omega}{dt} = -\frac{2}{a}\frac{da}{dt}\,\omega + v_A^2\frac{\partial q}{\partial s} \quad ; \quad \frac{dq}{dt} = -\zeta q + \frac{\partial \omega}{\partial s} + \Sigma(s,t) \ ,$$

where

$$\zeta \equiv \frac{d\ \ell n\ \delta S}{dt} = \hat{\boldsymbol{s}} \cdot \frac{\boldsymbol{\partial v}}{\boldsymbol{\partial s}} \ , \text{ and } \ \Sigma = (\hat{\boldsymbol{s}} \times \boldsymbol{\kappa}) \cdot \frac{\partial \boldsymbol{v}}{\partial s} \quad .$$

Here, δS represents the length of a small Lagrangian tube element, $\hat{\mathbf{s}}$ and $\boldsymbol{\kappa}$ are the tangent and curvature vectors of the flux tube axis respectively, and $\mathbf{v}$ is the velocity.

In the equation for q, there is a source term (Σ) which depends only the motion of the tube axis. What is the origin of this?

For a thin flux tube: $H = \Phi^2(Tw + Wr)$ (Moffatt & Ricca 1992). (Conservation of magnetic helicity H, where Tw is "twist", and Wr is "writhe".)

$$Tw = \frac{1}{2\pi}\oint q(s)ds \ ; \ Wr = \frac{1}{4\pi}\oint ds' \oint ds'' \frac{\hat{\mathbf{s}'} \times \hat{\mathbf{s}''} \cdot (\mathbf{r}'' - \mathbf{r}')}{|\mathbf{r}'' - \mathbf{r}'|^3} \ ,$$

$$\text{and} \quad \frac{dTw}{dt} = -\frac{dWr}{dt} = \oint \Sigma(s)ds \ .$$

Thus the Σ term exchanges writhe (Wr) with twist (Tw). The writhe represents the contribution of the shape of the flux tube axis to magnetic helicity, while twist represents the helicity due to the wrapping of field lines about the tube axis.

The conservation of twist plus writhe implies that if a large scale, left handed writhe is imposed on a thin flux tube, a right handed twist of the opposite sense will be added to the initial twist within the tube.

To estimate the contribution of turbulent convective motions to the writhing and twisting of magnetic flux tubes, one must (1) develop a tractible model of convective turbulence that includes a non-zero kinetic helicity due to the effects of Coriolis forces, and (2) develop an algorithm for solving the equations of motion for a rising flux tube, including the equations for twist evolution described above.

Our model of the convection zone is based on a mixing length formalism. The structure of the turbulence is a convolution of white noise with a spatial filter, where the correlation length of the filter is equal to the mixing length (Longcope & Fisher 1996). The turbulent convection is assumed to have a mean kinetic helicity $< \mathbf{v_c} \cdot \nabla \times \mathbf{v_c} > \simeq -2 v_{m.l.} \Omega_{\odot} \sin(\theta)$, where $v_{m.l.}$ is the mixing length velocity, $\Omega_{\odot}$ is the solar rotation rate, and θ is latitude. A complete description of the convective turbulence model is given in §4 of LFP.

The flux tube is assumed to be coupled to the turbulent motions of the plasma by an aerodynamic drag term during its rise through the convection zone. The thin flux tube and twist evolution equations are solved using the techniques described in §3, §5, and Appendix B of LFP. Calculations were repeated many times for different realizations of turbulence, different latitudes, and different values of the active region magnetic flux Φ. The flux tubes were assumed to be initially untwisted. Figure 2 shows a comparison of computed twists, for an active region flux of $\Phi = 10^{22}$ Mx, as a function of latitude versus the levels of twist that were measured.

The mean behavior, as well as the variance about the mean, agrees surprisingly well with the observationally derived values. Taken at face value, the observed variation of active region twist with latitude can be explained entirely by the writhing of initially untwisted flux tubes by convection zone motions. A caveat to this conclusion is that other studies indicate that an initially untwisted flux tube is likely to fragment before it can rise any significant distance through the convection zone, implying that any flux tube that reaches the surface must initially have some twist. (Fan, Zweibel, & Lantz 1998, Emonet & Moreno-Insertis 1998, Longcope, Fisher & Arendt 1996).

3. δ-Spot Active Regions as Highly Twisted, Kink-Unstable Flux Tubes

The active regions responsible for the largest and most disruptive solar flares are typically of a configuration known as "δ-spot" active regions (see *e.g.* Zirin 1988). In addition to their high level of flare activity, δ-spot active regions commonly exhibit these characteristics: "Incorrect" (non E-W) orientation, showing rotation during emergence; opposite polarity spots are jammed together within a common penumbra; and the magnetic fields exhibit strong twist, with large shear along the magnetic neutral line.

These morphological properties suggest that the active region flux tube(s), rather than consisting of a simple "Ω"-loop shape, as depicted in Figure 1 have an apex which is kinked, much like what occurs when twist is applied to a loop of a rubber band (see Figure 3).

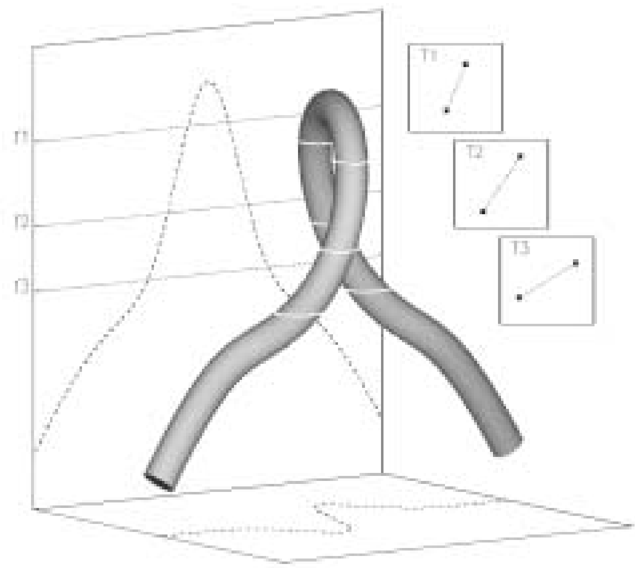

Figure 3. Illustration of a kinked omega loop. Insets show how the apparent location of footpoints observed at the photosphere would appear to rotate as the active region emerged.

This idea prompted us to investigate the helical kink instability in detail, with the objectives of understanding the conditions under which kinks can occur, predicting their growth rates, understanding how the kink mode saturates, and exploring the dynamics of flux tubes which are simultaneously unstable to several different kink modes.

Our investigation of the linear stability of the kink mode is described in detail in Linton, Longcope & Fisher (1996, henceforth LLF). In this paper we considered flux tubes with an axial field B_z which depends only on the distance r from the tube center, and an azimuthal field, B_θ which is related to B_z by the twist q: $B_\theta(r) = qrB_z(r)$. The most important result of that work is that there is a critical twist q_{cr} for the kink instability which depends solely on the axial field variation with distance from the center of the tube. If the axial field is written $B_z(r) = B_0(1 - \alpha r^2 + \cdots)$, then $q_{cr} = \sqrt{\alpha}$, and any tube with $q > q_{cr}$ will be kink unstable. The growth rates and the range of unstable wavenumbers are described in detail in LLF.

Nonlinear evolution of the kink instability has been explored by carrying out 3D MHD simulations of kink unstable flux tubes. Linton et al. (1998) studied the evolution of kink unstable flux tubes using a fully compressible, 3D 128^3 MHD code based on spectral techniques. That work confirmed the growth rate predictions of LLF, and showed that saturation to a new helical equilibrium occurs in roughly 10 linear growth times, for wavenumbers corresponding to the most unstable modes. The amplitude of the helically deformed tube that results after saturation is modest, typically 30% of the initial tube radius.

Surprisingly, the amplitude of kinking during the nonlinear phase can be much more severe for modes with lower growth rates and lower wavenumbers than those corresponding to the most linearly unstable modes. Linton et al. (1999) have used 3D numerical simulations to study how the kink amplitude varies with wavenumber, and find that saturated kink amplitudes can be as large as $1-2$ times the initial tube radius for certain long wavelength modes.

Of greater interest is what occurs when several unstable kink modes are excited simultaneously, as seems likely in the highly turbulent convection zone. In that case, several kink modes can interfere constructively at a localized region along the tube to form a knot, similar to the knots that can form along highly twisted rubber bands. These knots seem to occur only if the initial twist is higher than a second critical twist threshold, substantially greater than the value q_{cr} necessary for simple kinks. In the simulations, reconnection occurs where the two different parts of the flux tube fold against one another in the knot. We speculate that the reconnection in such knots may be related to the high flare activity of δ-spot active regions. In some of our simulations, reconnected field lines form true knots – simple or double overhand knots.

Finally, we have performed 3D numerical simulations of the kink instability using a new 3D anelastic MHD code described by Fan et al. (1999), in which gravity and gravitational stratification can be included. Gravitational effects appear to amplify the kink instability, resulting in a greater rotation of the rising, kinked apex of the tube than is found in simulations without gravitational stratification. The kinked tube arches upward, forming a kinked emerging loop that is very similar to the structure illustrated in Figure 3. A further effect of gravitational stratification is that a twisted flux tube becomes increasingly kink unstable as it rises through the convective envelope, to the extent that even a weakly twisted flux tube, which is initially kink stable, can become kink unstable if it rises through sufficiently many pressure scale heights (Fan et al. 1998, Linton et al. 1999, Fan et al. 1999).

All of these studies, both with and without gravity, predict that the observed sign of twist in a δ-spot active region should be the same as the observed sign of writhe. A number of efforts are now under way to test whether this prediction is seen in the observational data. Pevtsov & Canfield (1997), for example, find some evidence that "unjoyful" active regions (those which disobey Joy's Law) have a positive corelation between twist and writhe, which can be interpreted in terms of kinking flux ropes.

4. Summary

We have described recent measurements of the global twist distribution of active regions over the solar disk, showing that there is a weak hemispheric preference for negative twist in the northern hemisphere, and positive twist in the southern hemisphere. We find a promising explanation for this pattern in the idea that kinetic helicity of convection zone motions can impart a twist of the right amplitude and handedness to initially untwisted active region scale flux tubes as they rise through the convection zone. A potential oversimplification of this explanation is that other work shows that untwisted flux tubes are likely to be disrupted before they can rise any significant distance.

We have also discussed the evidence that the properties of δ-spot active regions can be explained by highly twisted flux tubes which have become kink unstable. The non-E-W orientation, the apparent rotation of the active region during emergence, the close proximity of opposite polarity spots within a common penumbra, and the association with high flare activity, all suggest that δ-spot active regions result from highly twisted flux tubes which have succombed to multi-mode kink instabilities during the last stages of their emergence through the convection zone. A further result of our work is a prediction that the sign of twist and writhe in δ-spot active regions should be the same if the kink mode is indeed responsible for their properties. Finally, if the kink conjecture is true, there is a real puzzle of how δ-spot active regions can acquire such large amounts of twist, given that most active regions (see Figure 2) have a modest amount of twist many times smaller than the threshold for the kink instability.

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