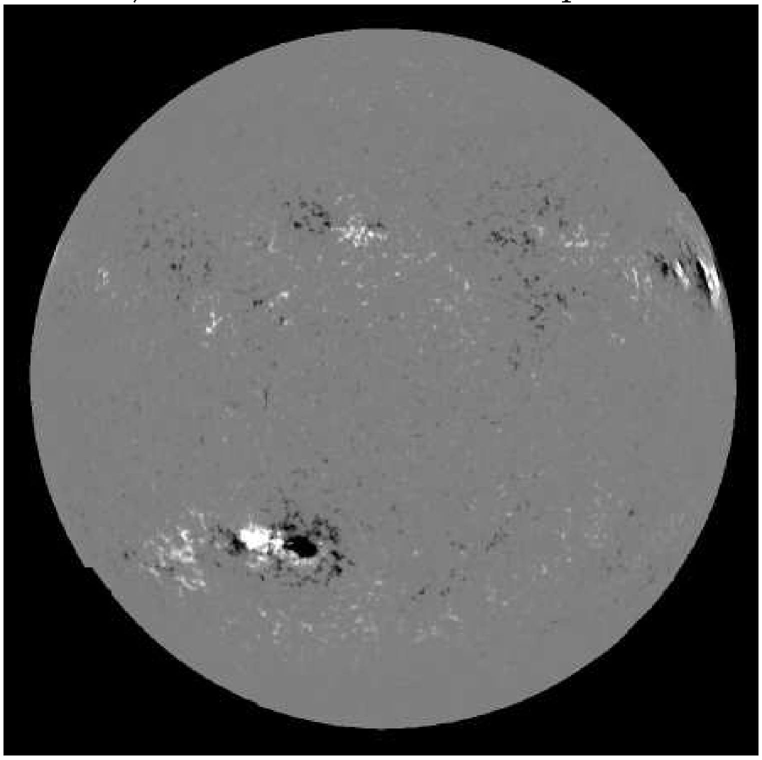
The Origin of Magnetic Fields On the Sun

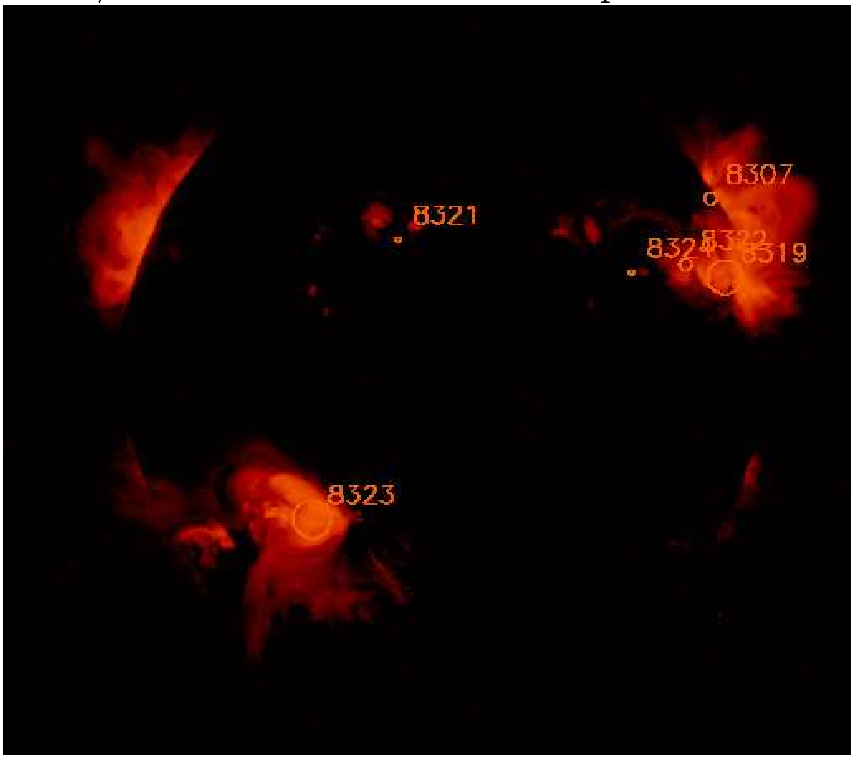
George H. Fisher[1]
Mark G. Linton[2]
Dana W. Longcope[3]
Yuhong Fan[4]

[1]SSL, UC Berkeley
[2]Physics Department, UC Berkeley
[3]Physics Department, Montana State University
[4]HAO, NCAR

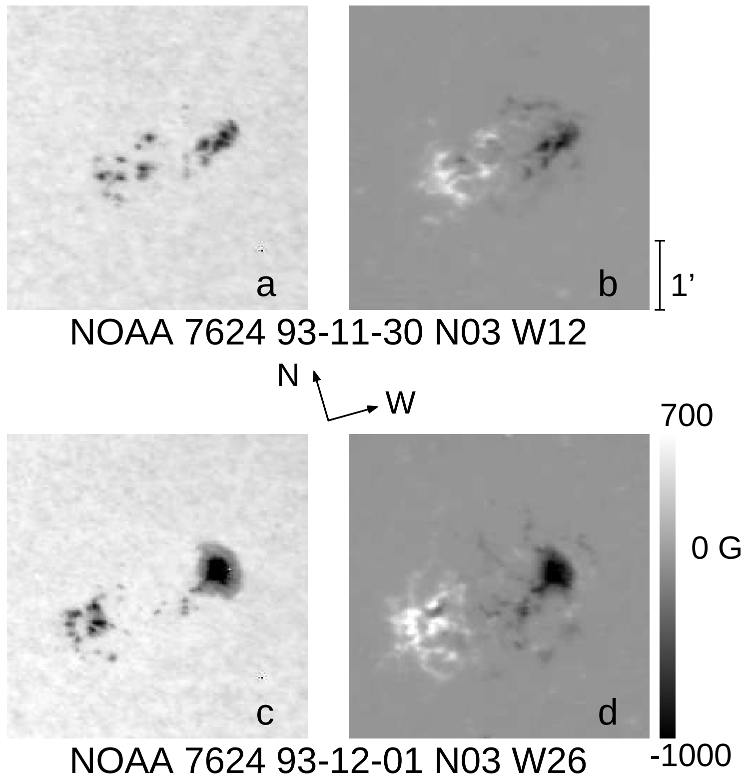
Sept. 2, 1998: KPNO Map of Sun's Magnetic Field:

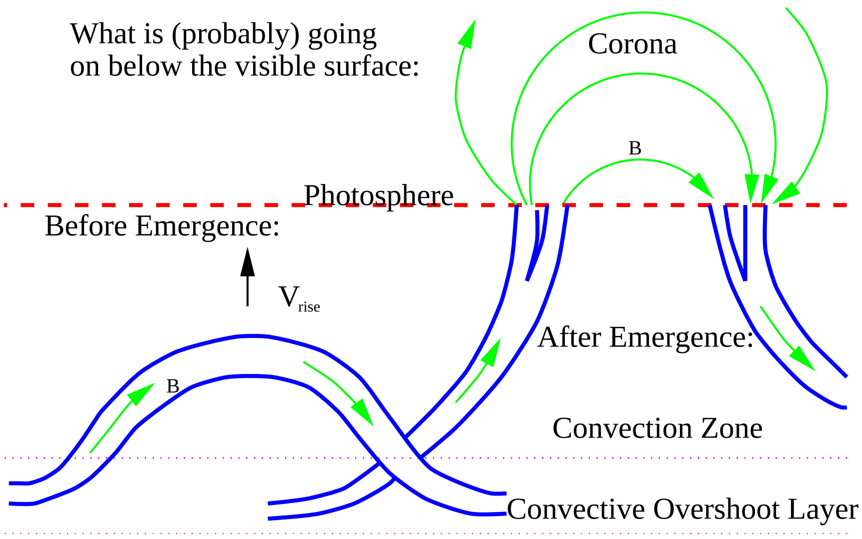


Sept. 2, 1998: Yohkoh SXT Map of Sun's X-ray Emission:

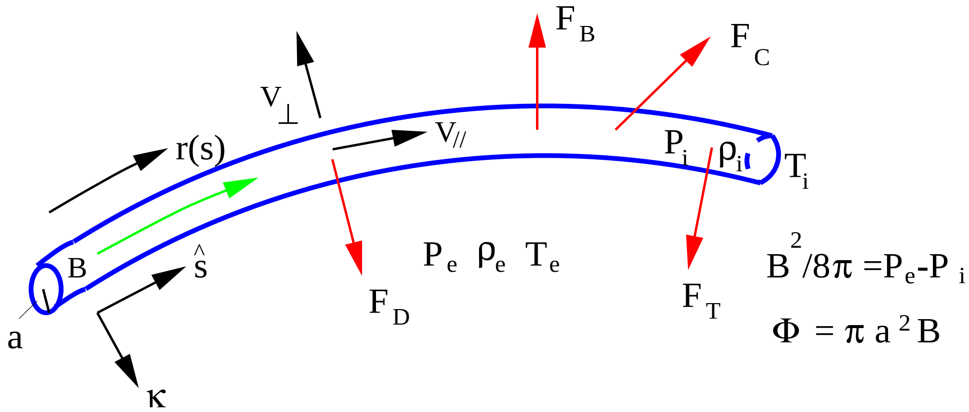


Emerging Active Regions – what we see at the photosphere: (from Cauzzi et al. 1996, Ap.J. 456, 850)





Untwisted Thin Flux Tube Models:



Since active region magnetic fields appear in a discrete tube-like form, use this fact to transform the momentum equation in ideal MHD

$$\rho D\mathbf{v}/Dt = -\nabla P + 1/c\ \mathbf{J} \times \mathbf{B} + \rho g \hat{\mathbf{r}} + \mathbf{F_C} \tag{1}$$

where $\mathbf{J} = c/4\pi \nabla \times \mathbf{B}$, into an equation of motion for a 1-D tube moving in a 3D rotating model of the solar interior:

$$\rho_i D\mathbf{v}/Dt = \mathbf{F_B} + \mathbf{F_T} + \mathbf{F_C} + \mathbf{F_D}\ , \tag{2}$$

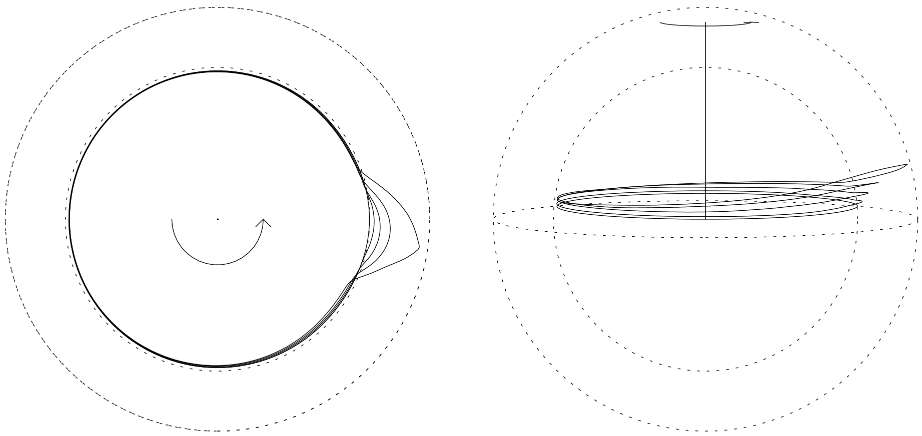
where

$$\boldsymbol{F_B} = g\ (\rho_e - \rho_i)\ \hat{\boldsymbol{r}}\ ;\ \boldsymbol{F_T} = B^2/8\pi\ \boldsymbol{\kappa}\ , \tag{3}$$

$$\boldsymbol{F_D} = -\rho_e \frac{C_D}{(\pi\Phi/B)^{1/2}} |v_\perp| \boldsymbol{v}_\perp\ ;\ \boldsymbol{F_C} = -2\rho_i \boldsymbol{\Omega} \times \boldsymbol{v}\ . \tag{4}$$

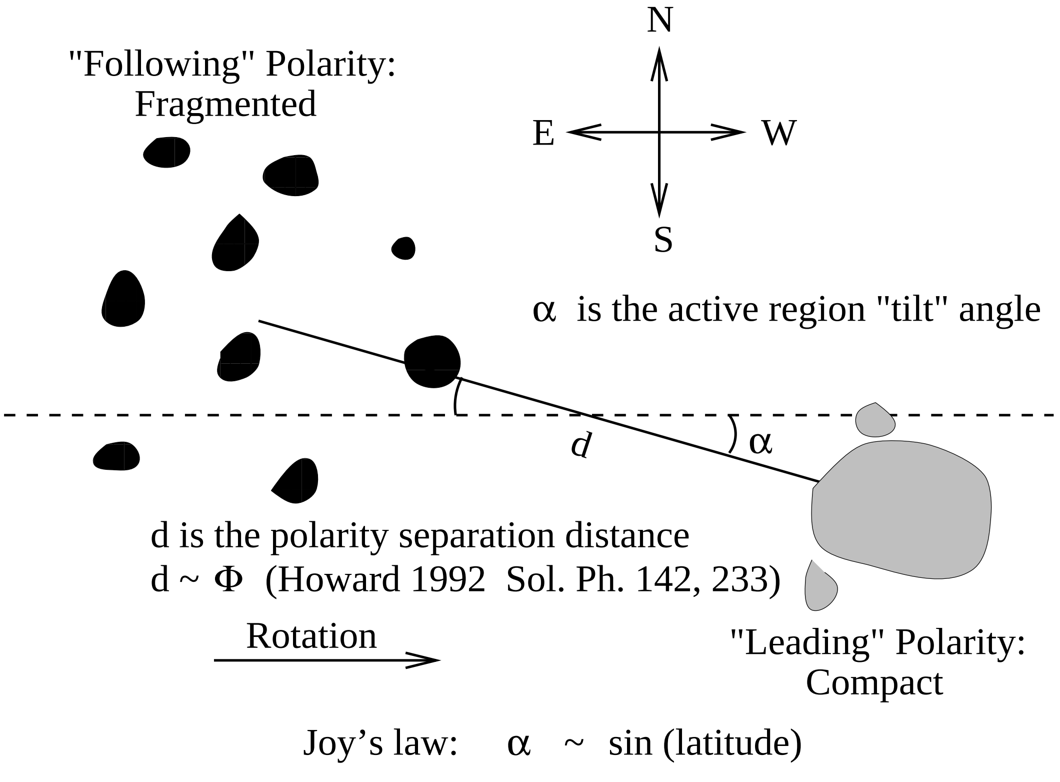
$\mathbf{F_B}$ is the magnetic buoyancy force, $\mathbf{F_T}$ is the force due to magnetic tension (field line bending), $\mathbf{F_C}$ represents the Coriolis Force (because D/Dt is the time derivative taken in the rotating reference frame), and $\mathbf{F_D}$ is an aerodynamic drag force resisting motion of the tube through the external, field-free plasma. The magnetic field $\mathbf{B}$ points in the direction of the tube's tangent vector $\hat{\mathbf{s}}$ ($\hat{\mathbf{s}} = \partial \mathbf{r}(s)/\partial s$), and the curvature vector $\boldsymbol{\kappa}$ which gives the direction of $\mathbf{F_T}$, is given by $\boldsymbol{\kappa} = \partial^2 \boldsymbol{r}(s)/\partial s^2$. The aerodynamic drag coefficient $C_D \sim 1$.

Assume magnetic flux is in a toroidal ring prior to emergence. How do the flux tube models evolve?

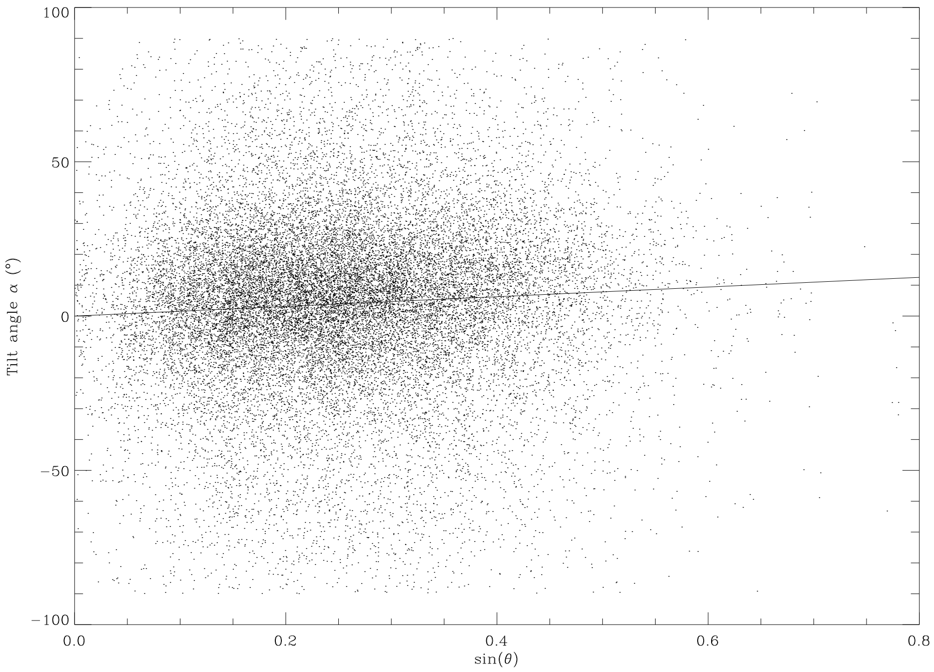


(a) (b)

What observational properties of active regions can be addressed with thin flux tube models? One example: active region tilt angles.

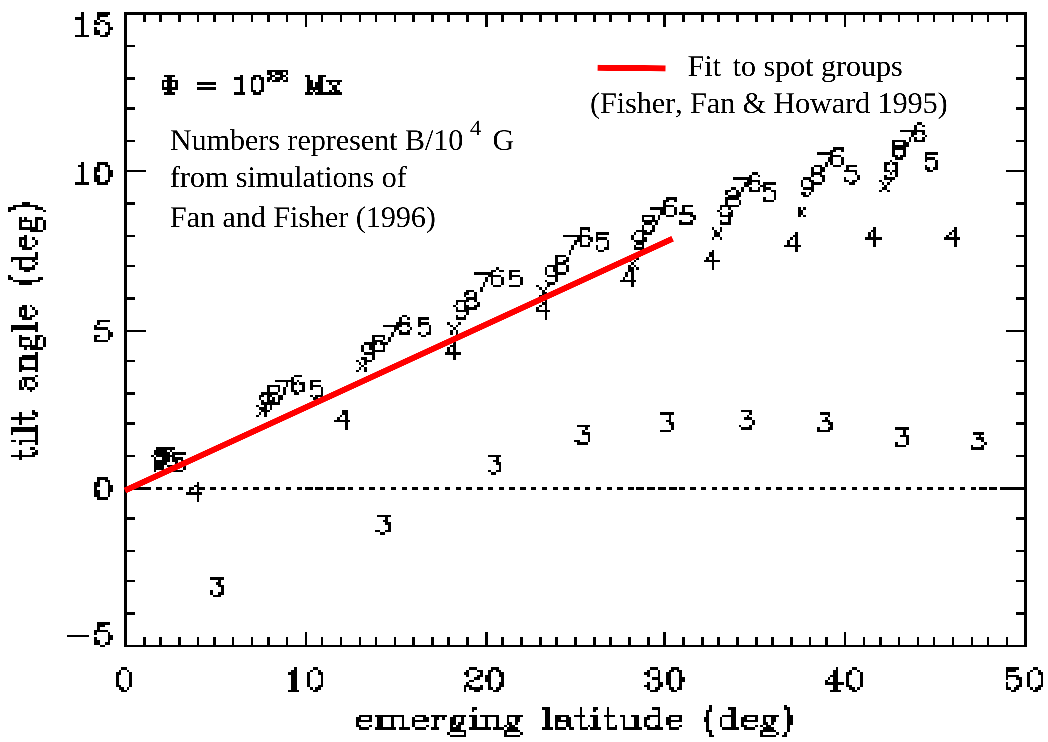


What do observations of tilt angles versus latitude look like? (24,701 Mt. Wilson sunspot groups since World War I)

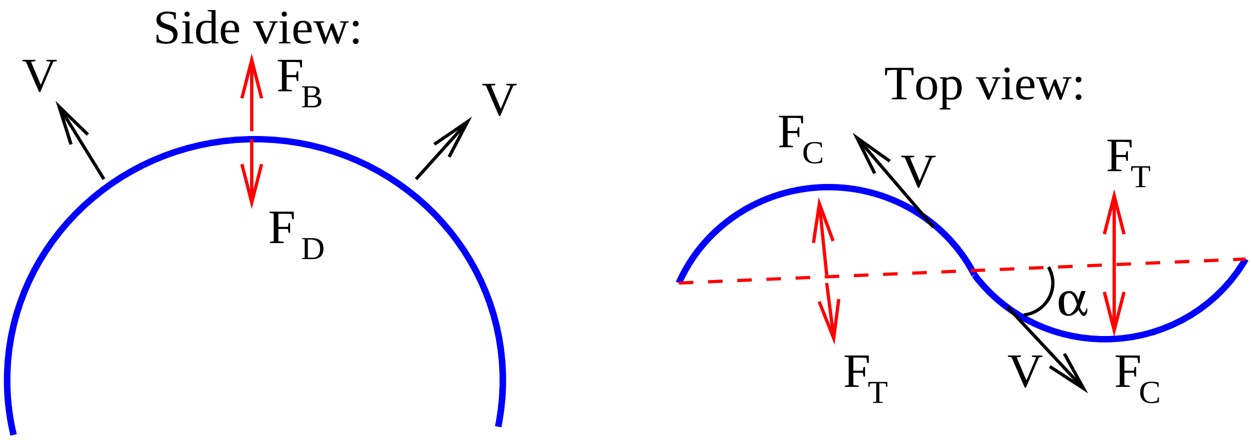


Least squares fit: $\alpha = (15.7 \pm 0.7)\ sin\ \theta$. This is known as "Joy's Law". Note the large scatter. In contrast to the mean tilt, the scatter does *not* depend on latitude.

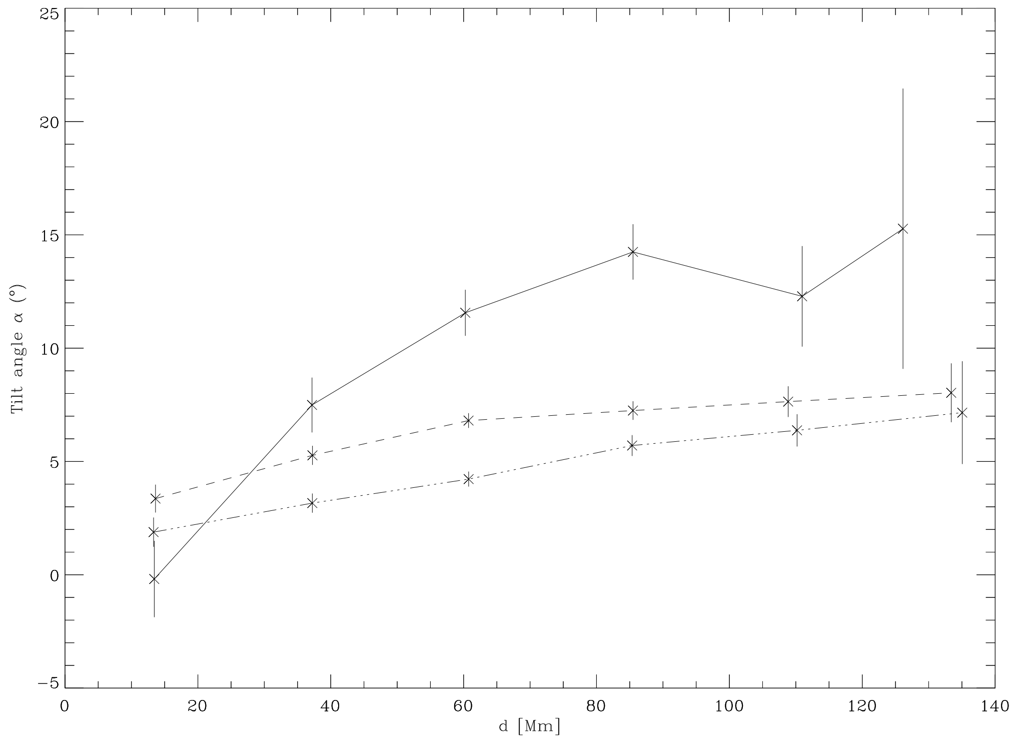
How do these measurements compare with the calculations?



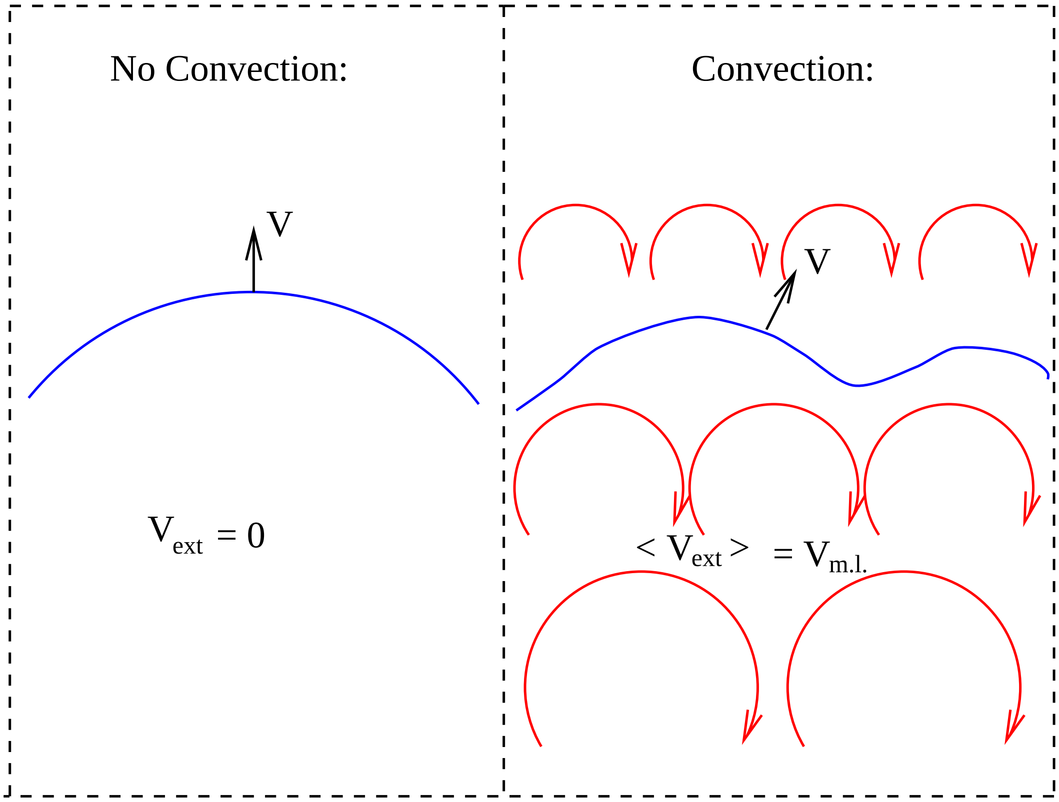
What do the thin flux tube models tell us about the forces resulting in Joy's Law?



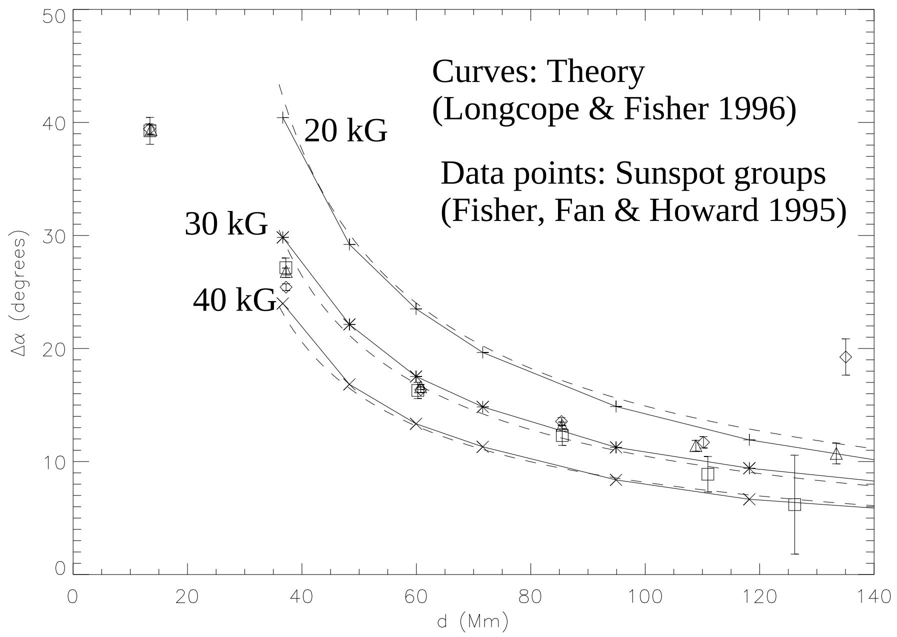
Balancing $\mathbf{F_D}$ and $\mathbf{F_B}$ (see "side view"), results in $V_{rise} \sim (a/H_P)^{1/2} V_A$, where a is the tube radius, H_P is the pressure scale height, and V_A is the Alfvén speed. Using this to evaluate the torque balance across the apex of the loop (see "top view", above), we find $\rho \Omega V_{rise}\ sin\ \theta\ \simeq \rho V_A^2\ tan\ \alpha$, from which it is simple to show $\alpha \propto sin\ \theta\ \Phi^{1/4}$. where Φ is the magnetic flux in the tube. Now, we have also made a **prediction** about how α and Φ should vary. What do the observations show?



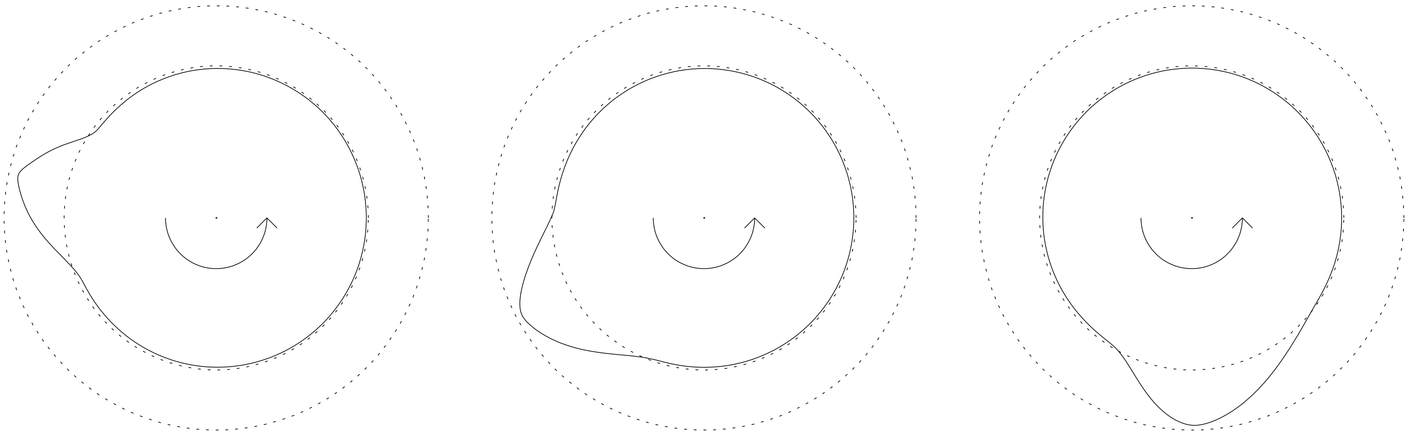
What about the large dispersion of tilt angles around the mean (Joy's Law) behavior seen in the spot group data? Is convective turbulence the culprit?



We performed Monte Carlo simulations of flux tube perturbations using a stochastic, mixing length model of convective turbulence. Comparison of simulations and observed dispersions:



Asymmetric Spot Motions



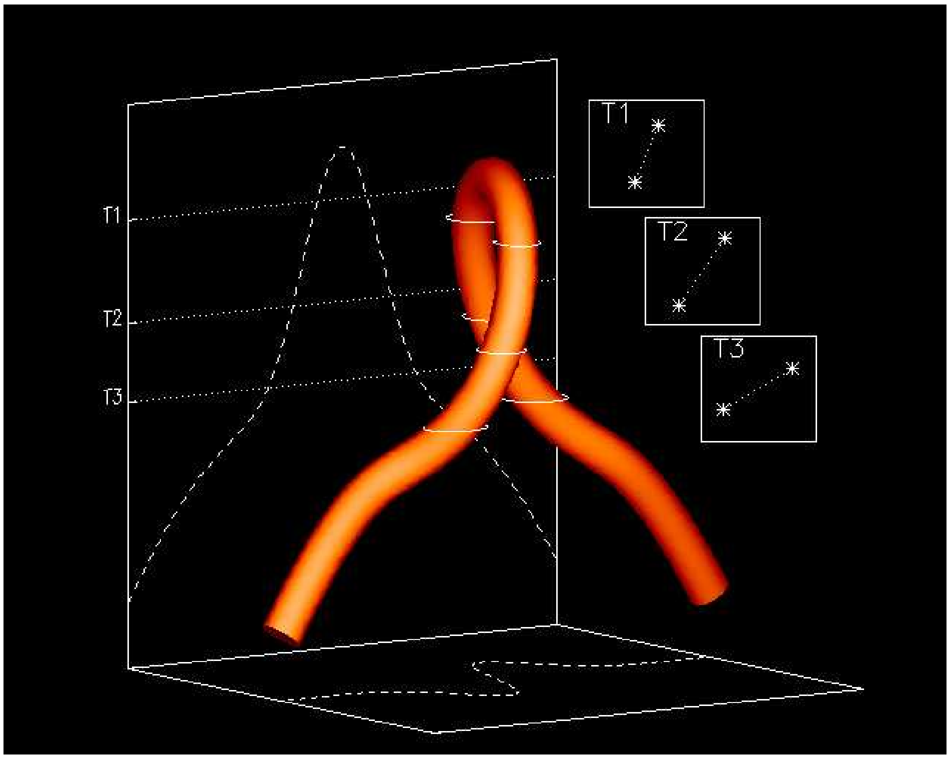
(a) (b) (c)

Panels (a), (b), and (c) correspond to field strengths at the base of the solar convection zone of 30, 60, and 100 kG, respectively. Results shown are from Fan & Fisher (1996, Sol. Phys. 166, 17).

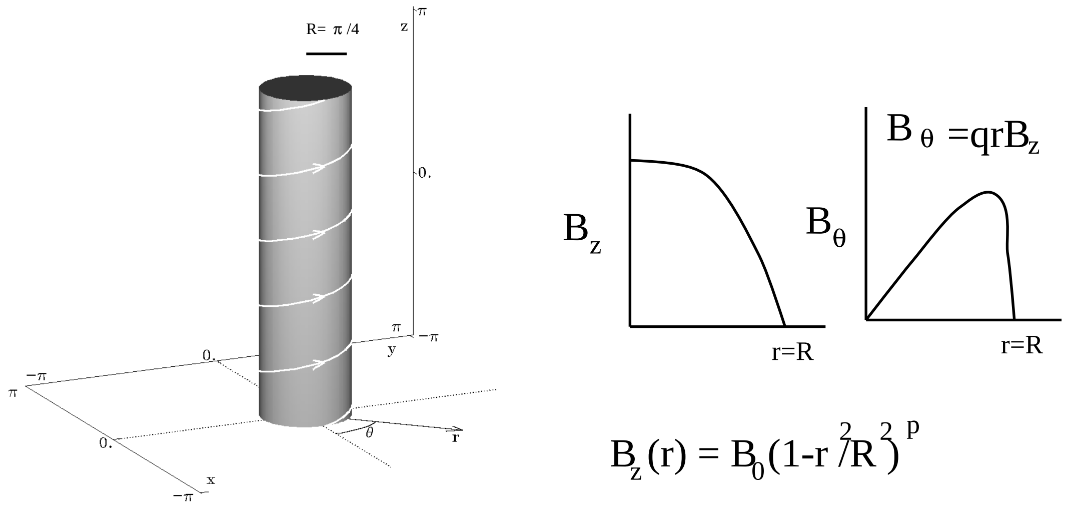
- Caligari, Moreno-Insertis, and Schússler (1995, Ap. J. 441, 886) have suggested that the emergence of these asymmetric loops will result in faster apparent motion of the "leading" spot group polarity c.f. the "following" spot polarity, a well known observational phenomenon.
- A possible explanation for the more rapid rotation of the Sun determined from spots than that from the photospheric gas?

Highly Twisted Flux Tubes: Kinks, δ-spots, and Flares

Most active regions behave as though they are untwisted, Ω-shaped flux loops that rise through the solar convection zone. But occasionally, active regions appear with reversed or highly tilted polarity orientations, they rotate rapidly after emergence, and appear to have magnetic fields that are very strongly sheared. These active regions also produce the largest solar flares. We speculate that these active regions come from flux tubes which have become very twisted, and have succumbed to the kink instability. Here we show what the configuration of such a tube might look like as it is emerging toward the photosphere:

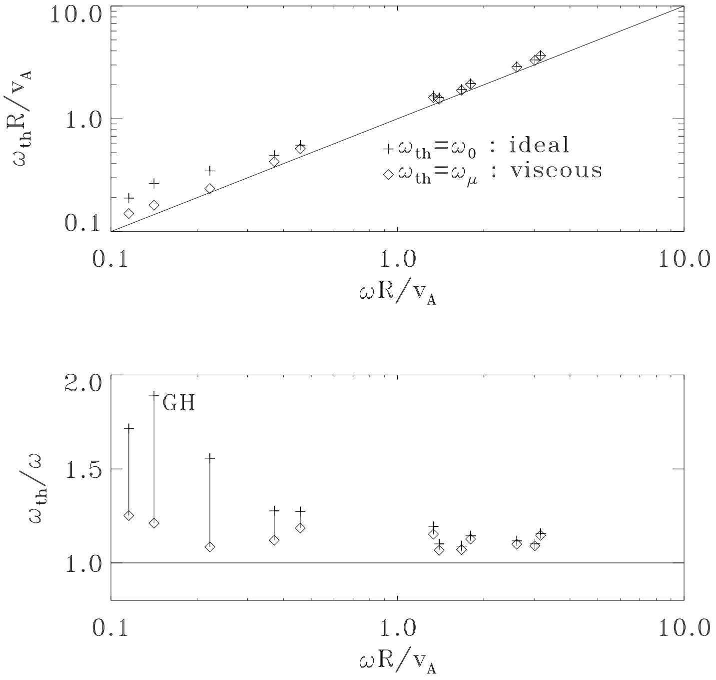


To understand how the kink mode might affect a highly twisted flux tube in the interior, first try to understand the simplest case possible: A twisted, cylindrical magnetic equilibrium $\mathbf{B_0}(r)$, illustrated schematically below:

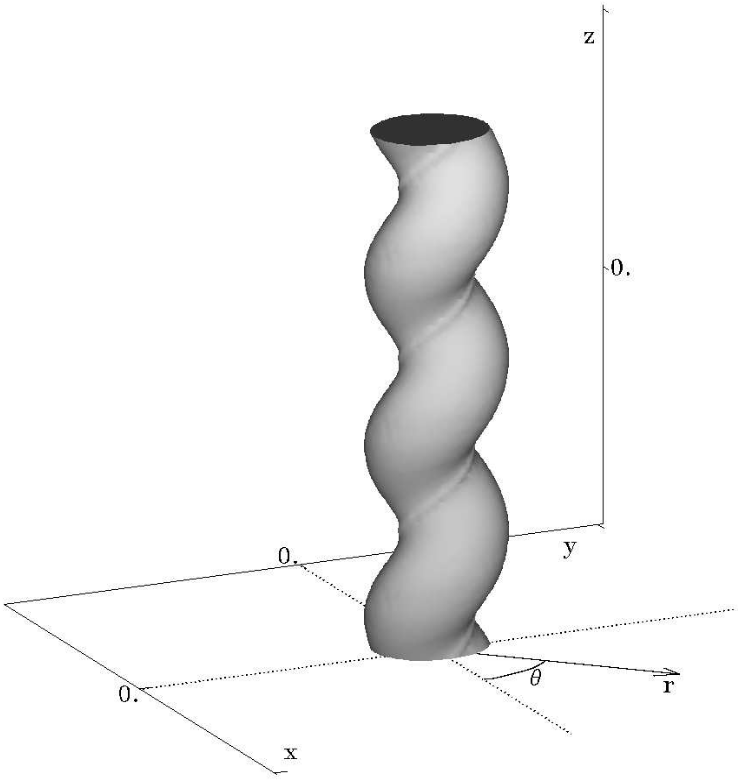


Linear Stability: Let $\boldsymbol{v}= d\boldsymbol{\xi}/dt$, and $\boldsymbol{B_1}=\boldsymbol{\nabla} \times (\boldsymbol{\xi} \times \boldsymbol{B_0})$. If one assumes that $\boldsymbol{\xi}$ has the form $\boldsymbol{\xi_0(r)}\ e^{\omega t}$, then the growth rate ω and the eigenfunction $\boldsymbol{\xi_0(r)}$ can be determined using the classical "energy" method (Linton, Longcope & Fisher 1996)

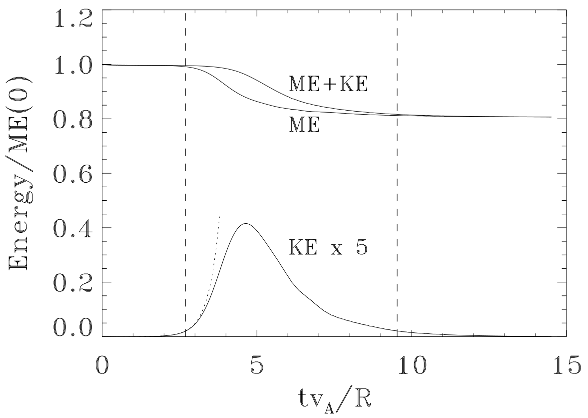
A comparison of these growth rates with those from a full 3D 128^3 MHD simulation shows extremely good agreement:

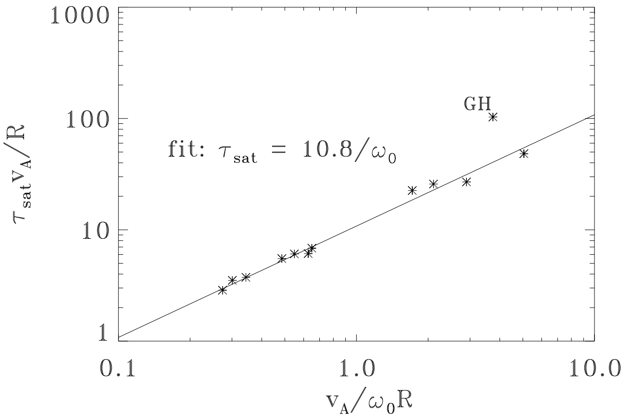


What happens in the nonlinear regime? The final equilibrium for one of the kink unstable tubes is shown below:



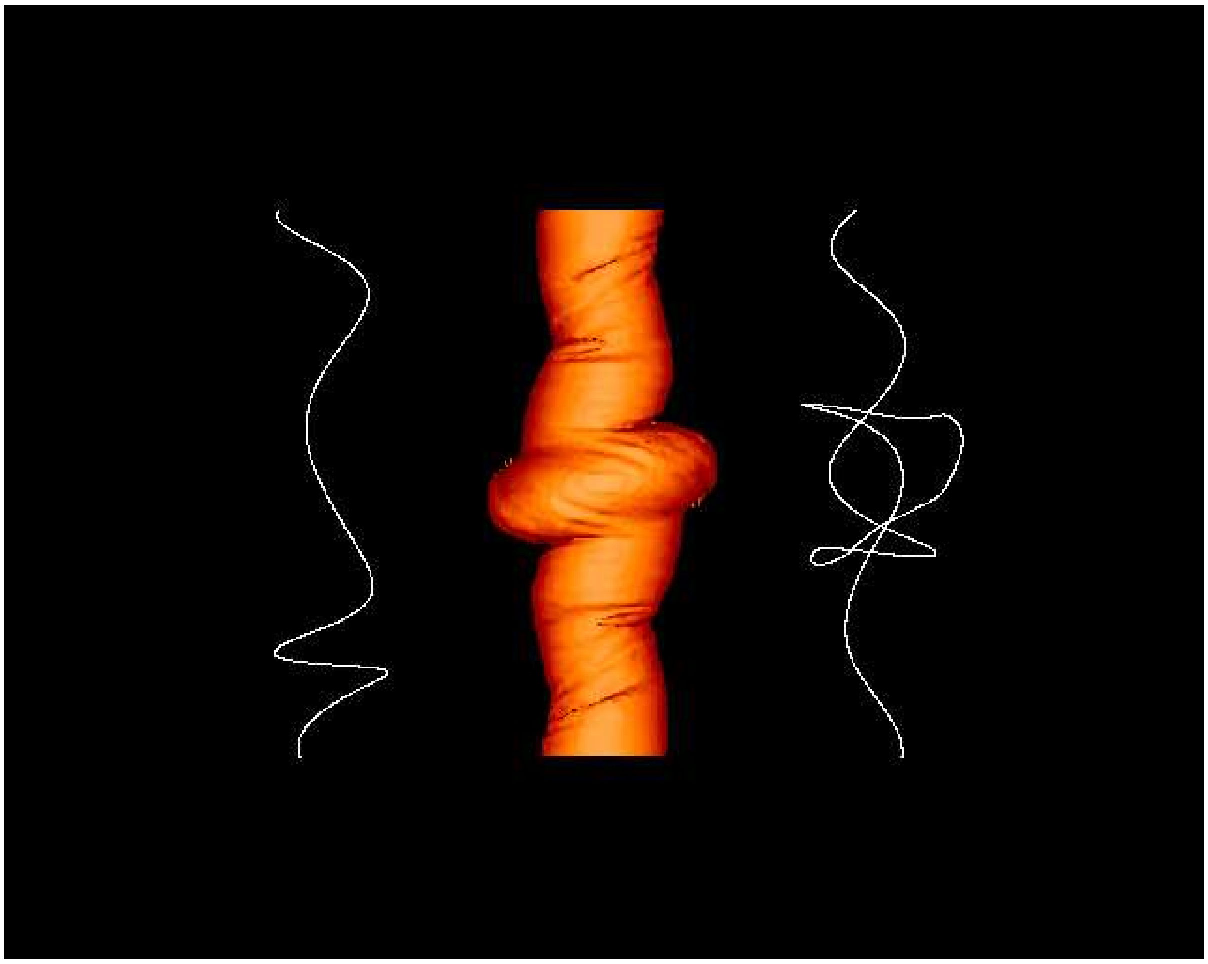
How long does it take to reach the new equilibrium?





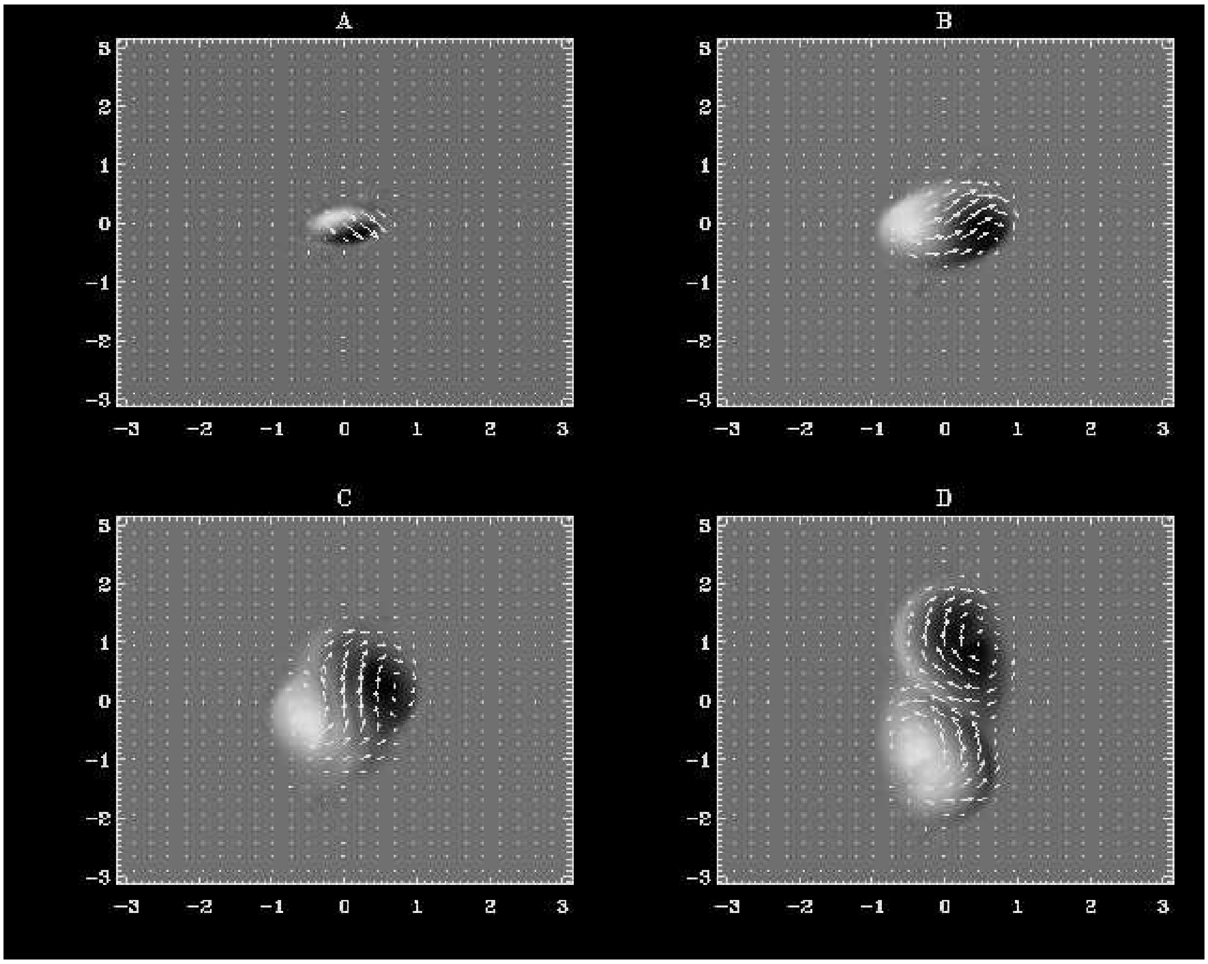
Bottom line: Kink is significant, but not enough to form a δ-spot region.

What if more than one unstable kink mode is present at the same time? Shown below is the final state of a tube with 4 unstable kink modes excited:



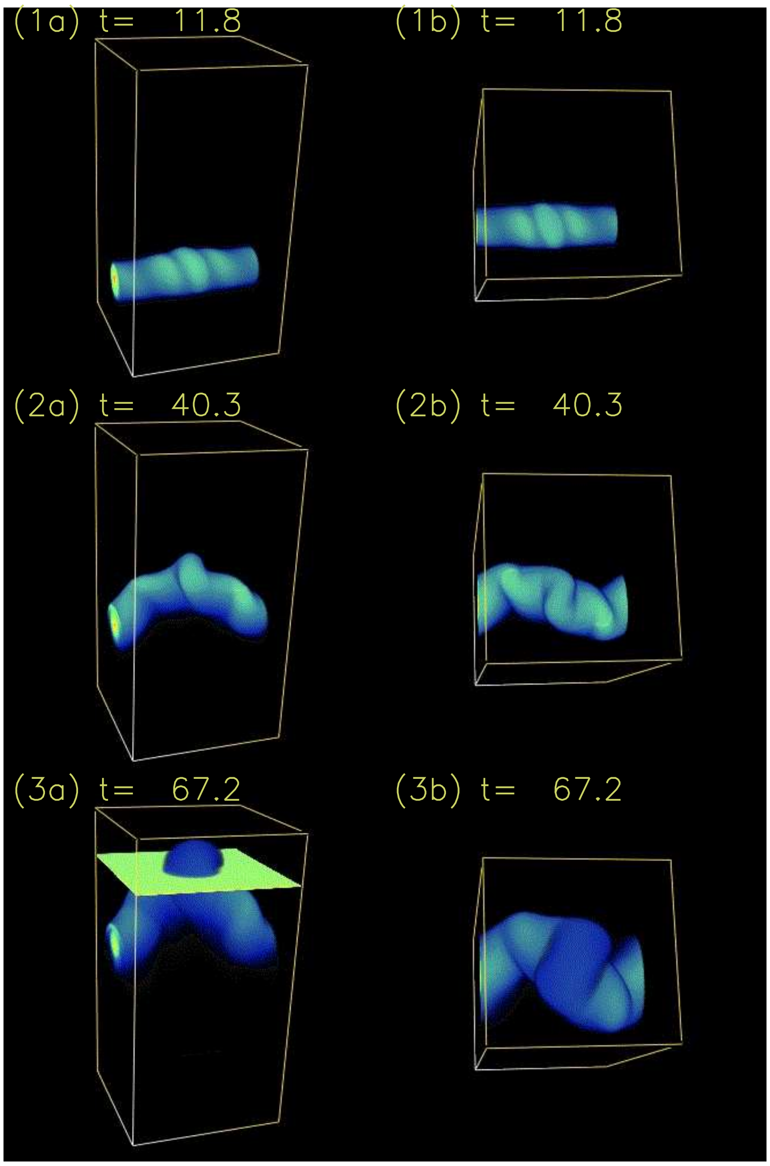
The trajectories of two representative field lines are also shown. Note that the modes seem to add together coherently in one place to form a "knot", much like the knots that form in highly twisted rubber bands.

Is it possible that the emergence of such a “knot” like structure could resemble the development of a δ-spot active region?



- non-“Hale” orientation of polarities
- rotation of opposite polarities as fields emerge
- opposite polarities stay close instead of separating
- development of strong magnetic shear along neutral line

Preliminary Results – 3D MHD simulations of a rising, kinking tube computed in the anelastic approximation – $128 \times 128 \times 256$ resolution – Fan, Zweibel, Linton & Fisher (1998):



These recent simulations appear confirm the existence of knot like structure at the apex of a rising, twisted loop. Conservation of axial and azimuthal magnetic fluxes argue that a twisted tube gets increasingly more kink unstable as it rises.

CONCLUSIONS:

- Magnetic flux emerges in a bipolar form, arguing that it emerges in the form of *magnetic flux tubes* surrounded by mainly field-free plasma
- Observed properties of most active regions (tilts, tilt dispersions) can be explained *quantitatively* in terms of the dynamics of riging, untwisted thin flux tubes. The value of free parameters, such as the field strength at the base of the convection zone, must be in the range of 40-60 kG to be consistent with the observed behavior of active region tilts.
- The qualitative behavior of the flare-productive δ-spot active regions can be explained by the rise of highly twisted, kink unstable flux tubes