Flux emergence: An overview of thin flux tube models

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How can we learn about magnetic fields in the solar dynamo by studying magnetic active regions at the surface?

- Approach: Use thin flux tube models of active region scale flux tubes to compute dynamical behavior, and compare to observed properties of active regions.
- Use comparisons with observations to deduce properties of magnetic fields in the solar dynamo layer near the base of the convection zone.

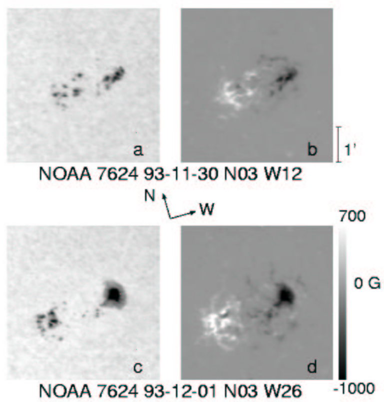
What properties of solar dynamo magnetic fields can we learn about?

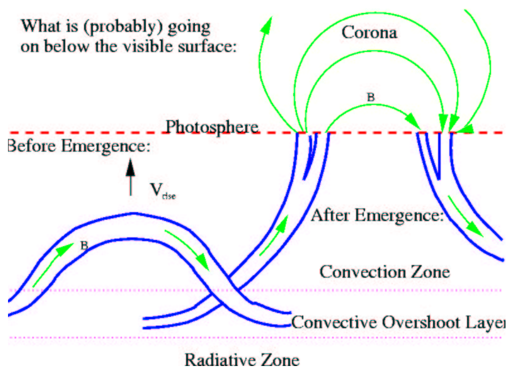
- Magnetic field strength at the base of convection zone
- The role of convective motions on active region orientation
- Why active regions diffuse away after emergence
- The origin and role of magnetic twist in some active regions

Features of active regions we can explain with flux tube dynamics:

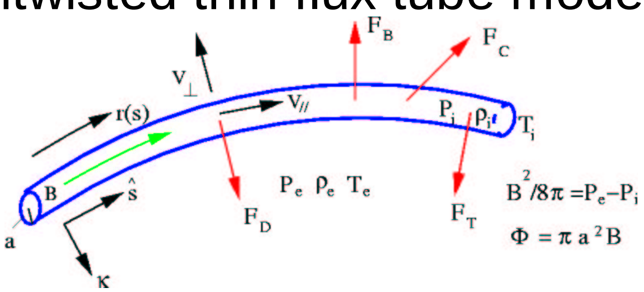
- The “equatorial gap” in the distribution of active regions
- Asymmetries between the leading and following sides of active regions
- The variation of “tilt angle” with latitude and with active region size
- The dispersion of tilt angles with active region size
- The distribution of active region twist with latitude
- The properties of δ-spot active regions as highly twisted, kink unstable flux ropes (see talk by Fan)

Why is a flux tube paradigm appealing for emergence?





Untwisted thin flux tube models:



$$\rho_i \frac{D\mathbf{v}}{Dt} = \mathbf{F_b} + \mathbf{F_t} + \mathbf{F_c} + \mathbf{F_d}$$

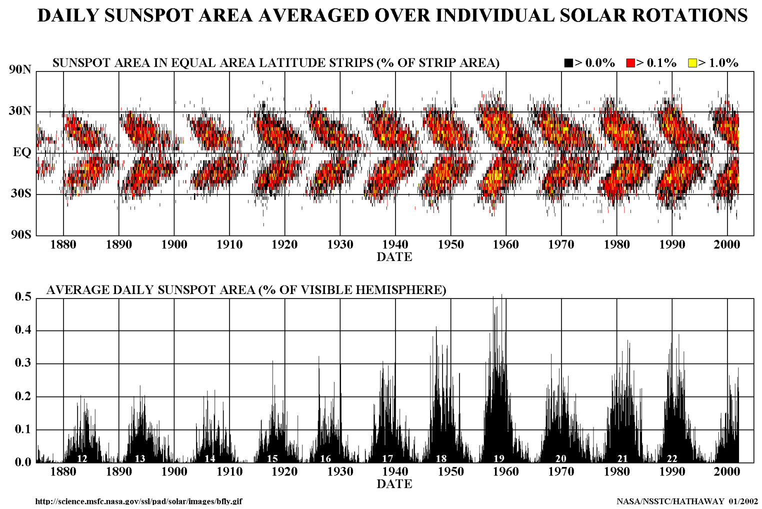
$$\mathbf{F_b} = g(\rho_e - \rho_i)\hat{\mathbf{r}}$$

$$\mathbf{F_c} = -2\rho_i \mathbf{\Omega} \times \mathbf{v}$$

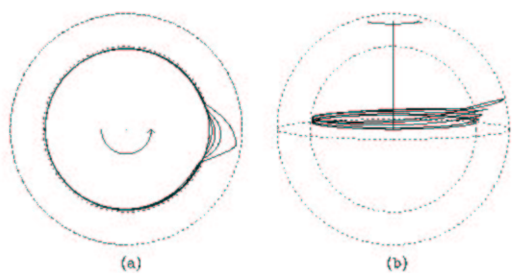
$$\mathbf{F_t} = \frac{B^2}{4\pi}\boldsymbol{\kappa}$$

$$\mathbf{F_d} = -\rho_e \frac{C_D}{(\pi\Phi/B)^{1/2}} |\mathbf{v}_\perp| \mathbf{v}_\perp$$

Can thin flux tube models say anything about the latitude distribution of active regions?

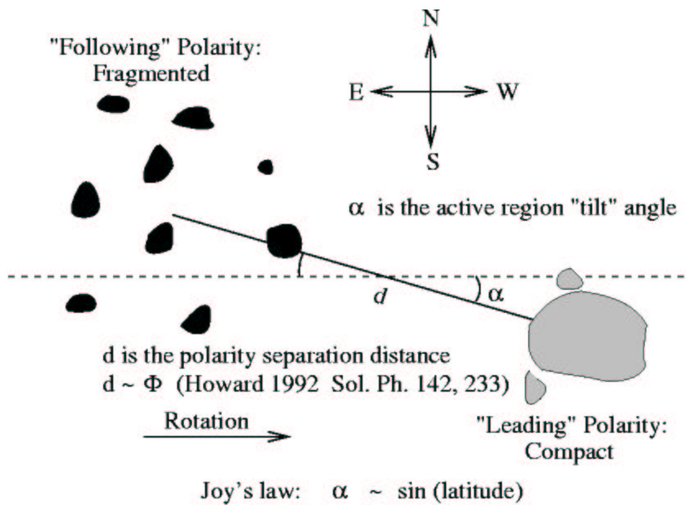


Latitude constraints based on initial equilibria, dynamic motions:

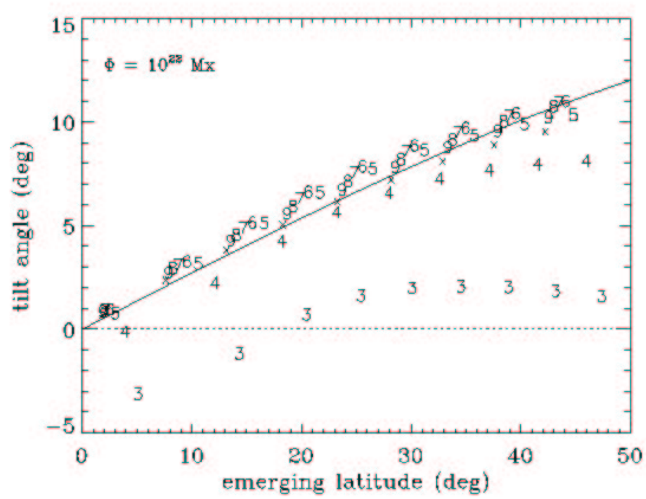


- If B > 10^5G, no low-latitude equilibria possible
- If B < 3×10^4G, poleward motion too great for observed latitude distributions
- If active region flux tubes are initially toroidal, field strength is constrained.

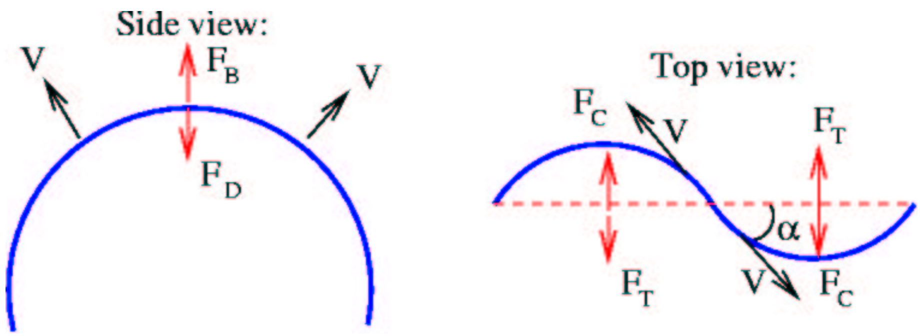
Active Region Tilts and Joy's Law



Comparison of model tilts versus average observed values:

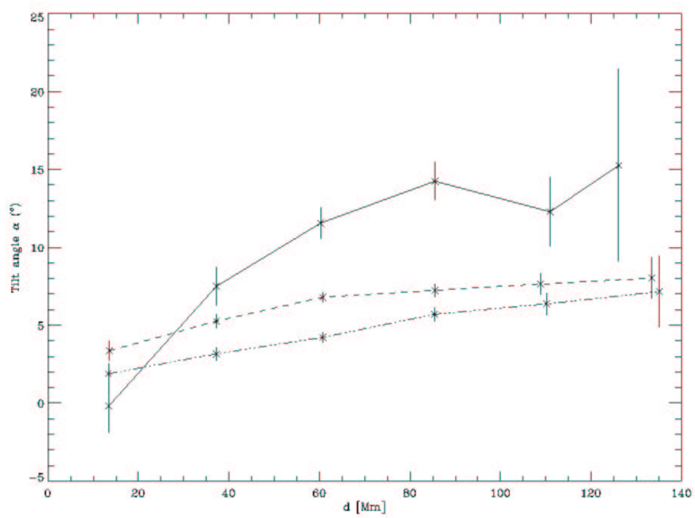


Simple idea for torque balance to determine amount of tilt

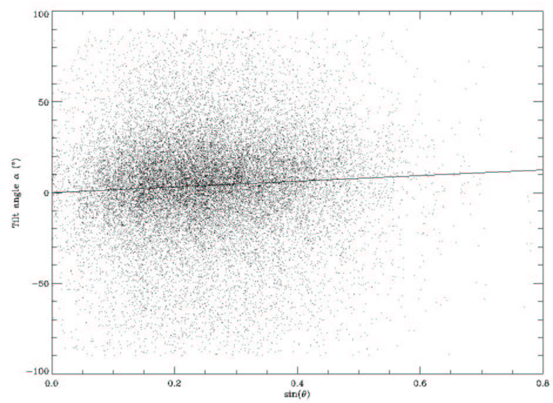


The result is that $\alpha \propto \sin\theta \, \Phi^{1/4}$.

How does tilt vary with magnetic flux?

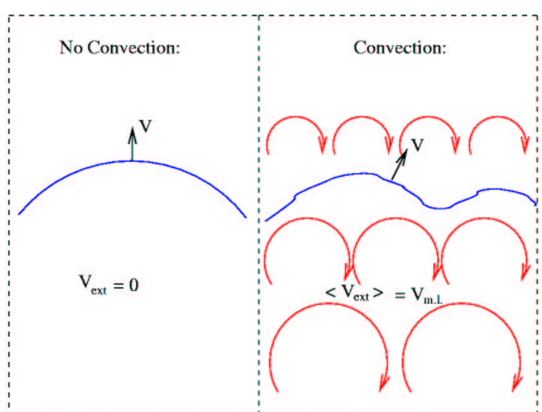


Not only are there tilts, but quite significant fluctuations of tilt…

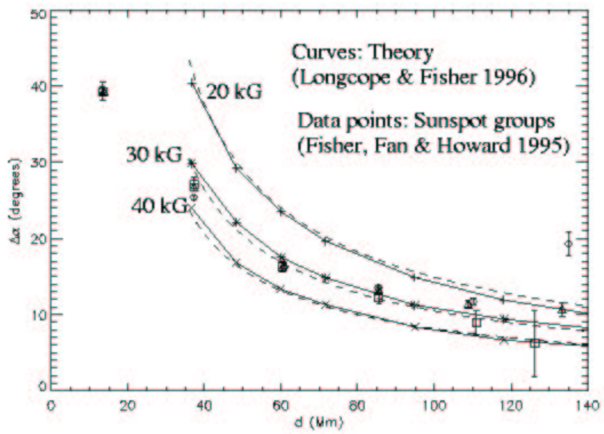


Analysis of ~24,000 spot groups shows tilt dispersion is *not* a function of latitude, but *is* a function of d, with $\alpha \sim d^{-3/4}$.

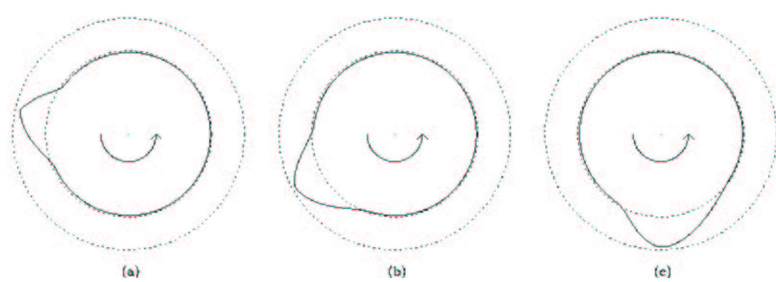
Observed variation of α with *d* suggests convective turbulence as a possible mechanism for tilt fluctuations…



Compute tilt fluctuations using tube dynamics driven by turbulence consistent with standard mixing length theory:



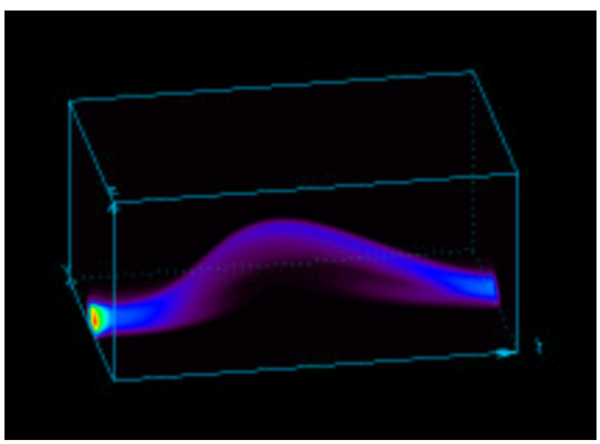
Asymmetric spot motions



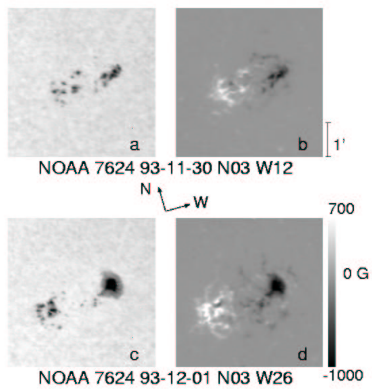
- Panels (a), (b), (c) correspond to field strengths at the base of the convection zone of 30, 60, and 100 kG respectively (Fan & Fisher Sol. Phys. 166, 17)

- Caligari Moreno-Insertis & Schüssler suggest that the emergence of these asymmetric loops will result in faster apparent motion of the “leading” spot group polarity c.f. the “following” polarity, a well known observational phenomenon…

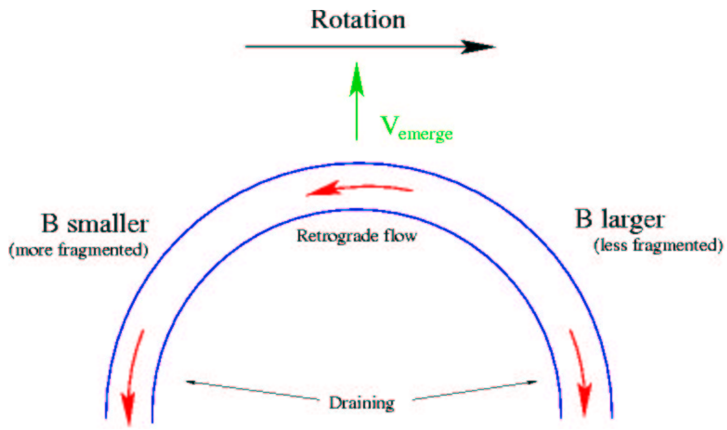
3D-MHD models of flux emergence confirm the asymmetric shape of the Ω loop



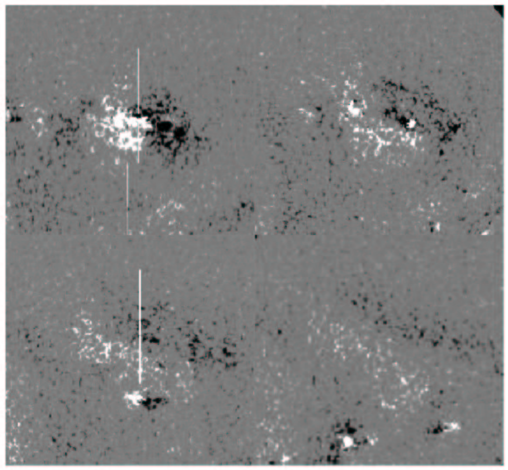
The Coriolis force might be a possible explanation for asymmetries in the morphology of active regions…



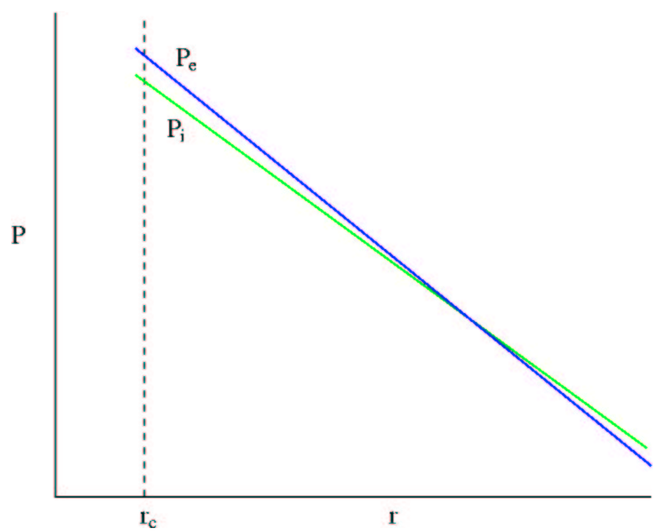
Field strength asymmetries could lead to morphological differences between leading and following polarity…



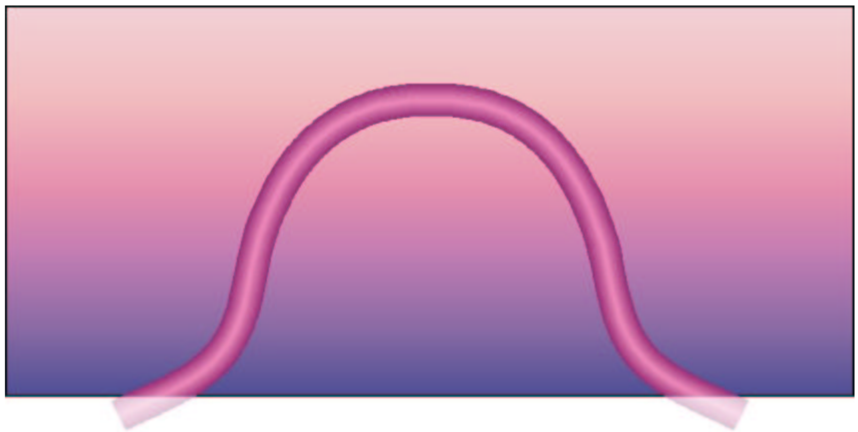
Why does magnetic flux diffuse away once it has emerged?



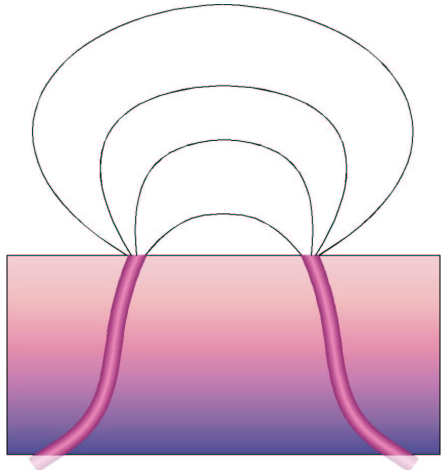
"Dynamic Disconnection" of active region flux tubes after emergence…



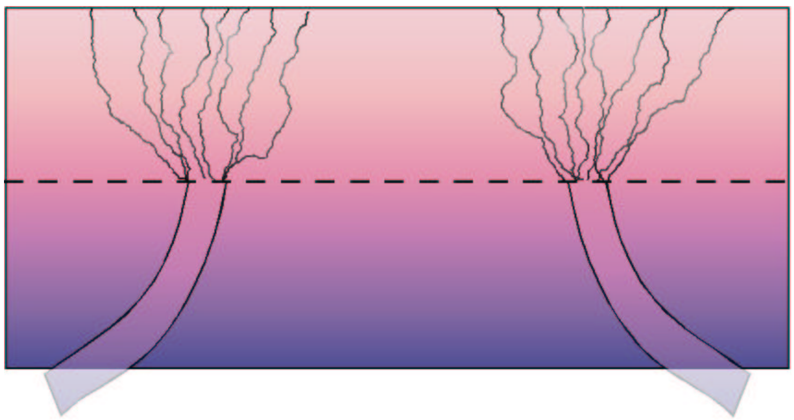
First – flux emerges through convection zone as Ω-loop



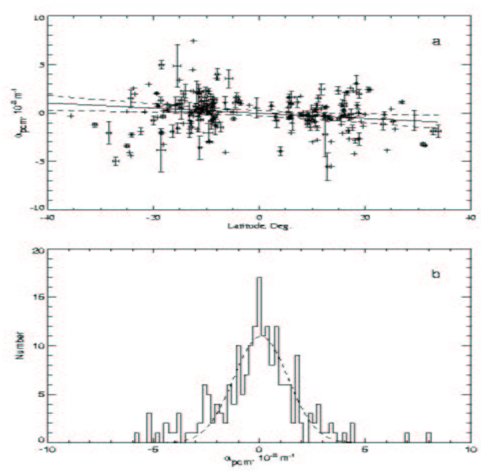
Apex of flux loop emerges through photosphere and corona



Once emergence has ceased, flux tube tries to establish hydrostatic equilibrium (but can't)…

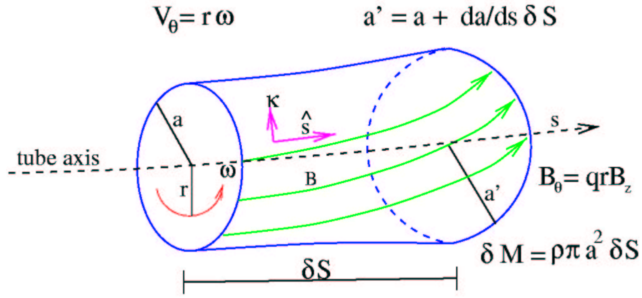


How twisted are typical active regions?



Where does active region twist come from?

Slighly twisted flux tubes:



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

where $\zeta \equiv \frac{d \ln \delta S}{dt} = \hat{\mathbf{s}} \cdot \frac{\partial \mathbf{v}}{\partial s}$, and $\Sigma = (\hat{\mathbf{s}} \times \kappa) \cdot \frac{\partial \mathbf{v}}{\partial s}$.

What is the physical meaning of the source term Σ?
Σ depends only on the motion of tube axis.

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

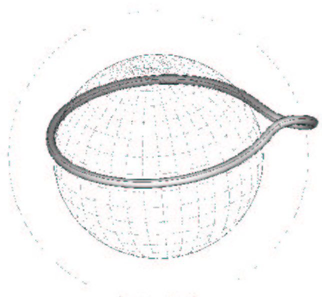
$$Tw = \frac{1}{2\pi}\oint q(s)ds; \;\; Wr = \frac{1}{4\pi}\oint ds' \oint ds'' \frac{\hat{\mathbf{s}}' \times \hat{\mathbf{s}}'' \cdot (\mathbf{r}'' - \mathbf{r}')}{|\mathbf{r}'' - \mathbf{r}'|^3},$$

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

Therefore, Σ exchanges writhe (*Wr*) with twist (*Tw*).

Could flux tube writhing account for observed levels of active region twist? Possible sources of writhing:

- "Joy's Law" tilts of active regions during emergence is one possibility, but is too small…

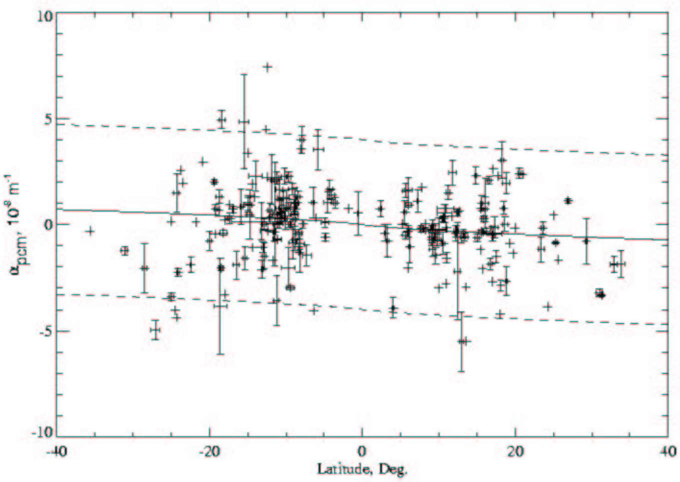


Emerging Active Region Flux Loops Tilted by Coriolis Force

Writhing by convective turbulence is another possibility…

- Develop tractable model of convective turbulence including kinetic helicity
- Solve equations of motion and twist evolution for a flux tube rising through such a turbulent medium
- Such a model was explored by Longcope, Fisher and Pevtsov…

Writhing by convective turbulence consistent with observations…



Conclusions

- Thin flux tube models provide a useful tool for gaining qualitative understanding of active region dynamics and constraints on the magnetic field at the base of the solar convection zone
- Better models will require detailed 3D MHD simulations