# The Importance of Sub-surface Magnetic Field Structure and Evolution

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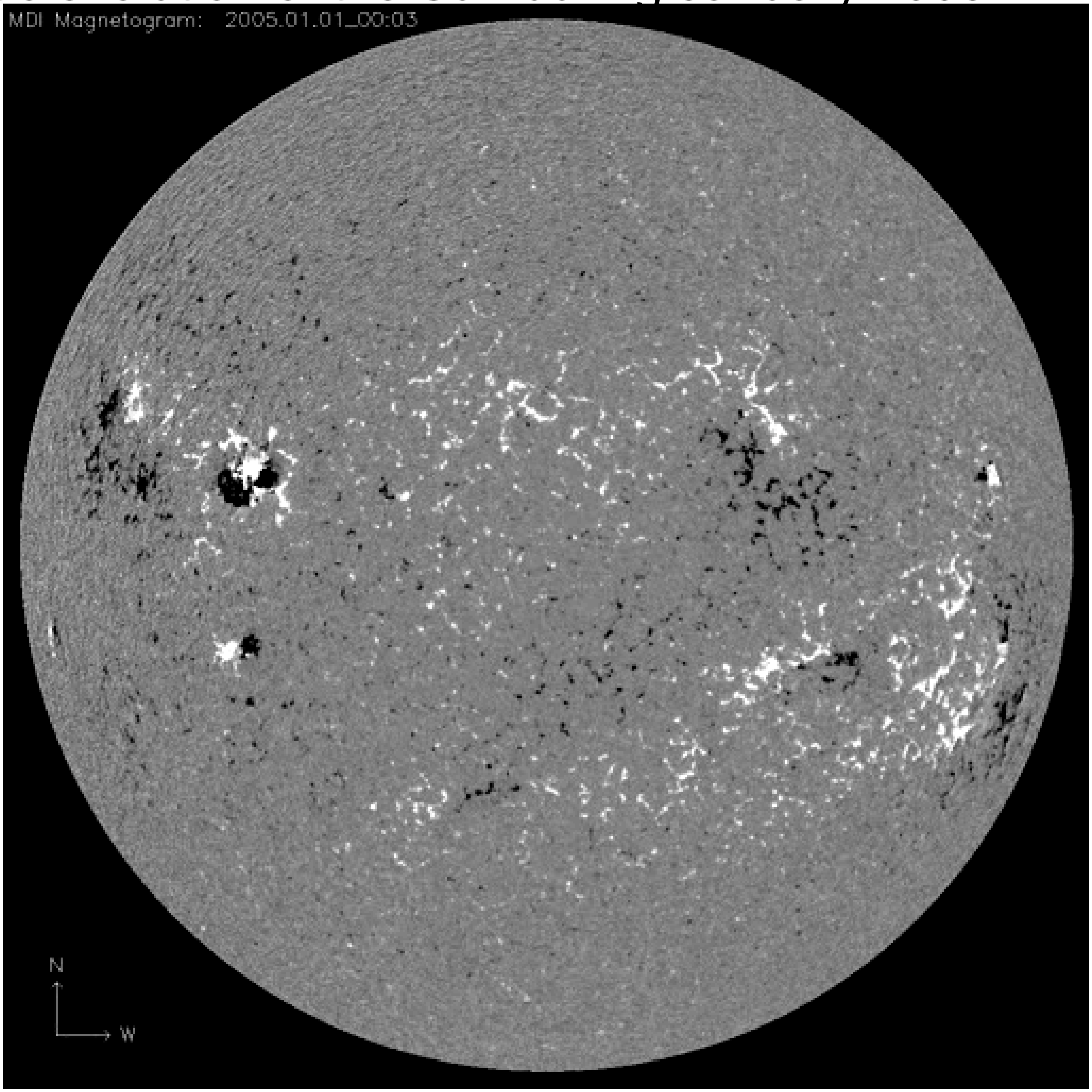
# Abstract

Where does the energy for solar flares and coronal mass ejections come from? Most of the time, we as solar and heliospheric physicists take the magnetic field evolution at the surface of the Sun for granted: Active regions emerge and disperse, complex magnetic topologies in the corona develop and evolve, and violent space weather events occur, all apparently driven by dynamics we observe at the Sun's surface.

Yet the evolution of the solar magnetic field at the surface is ultimately governed by forces acting on magnetic flux elements at and below the photosphere, in the solar interior. To fully understand the mechanisms that control magnetic fields in the solar atmosphere, we must understand how magnetic fields evolve in the solar interior.

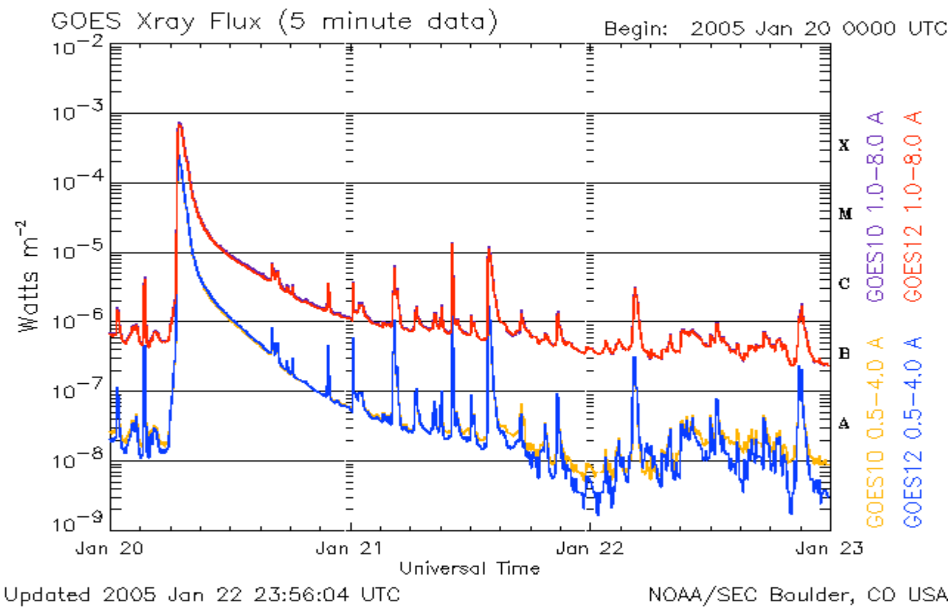
In this talk, I will discuss what we have learned about magnetic field evolution in the solar interior, what aspects of the observations can be explained in terms of interior MHD models, what remains mysterious, and directions for future research.

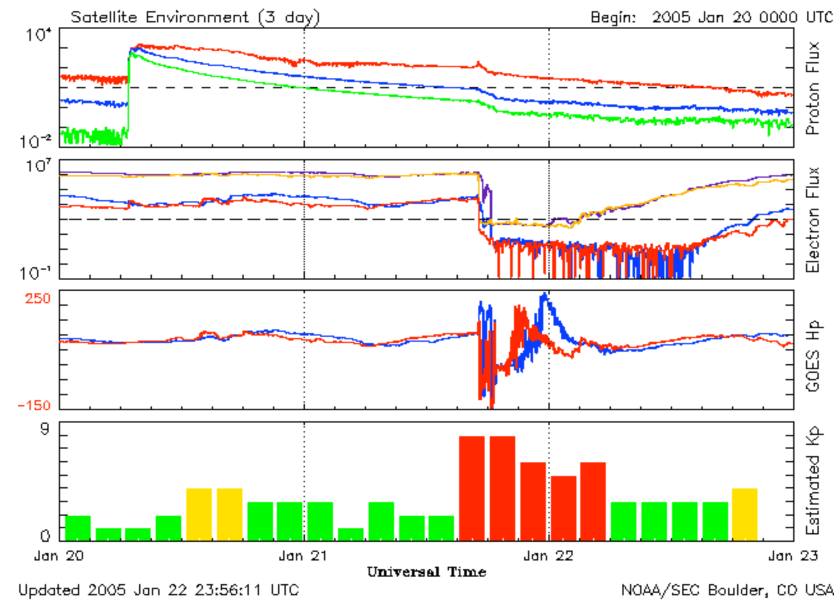
# Surface magnetic evolution of the Sun during January 2005:

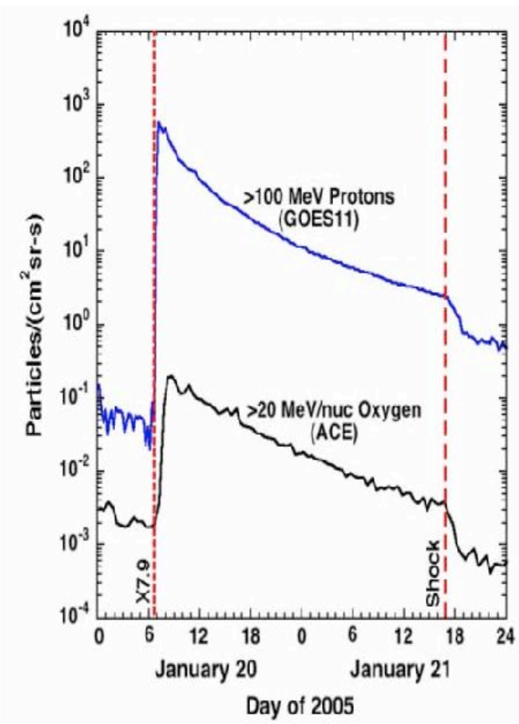


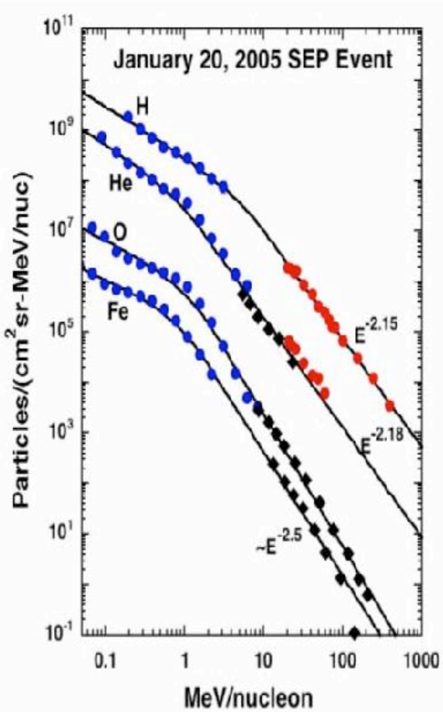

- Movie of full disk MDI data for January 2005
- This shows the evolution of AR 10720 (and other ARs) as they rotate across the solar disk. Note the rapid rotation of the magnetic polarities.
- Other smaller active regions appear as simple bipoles which appear and then dissipate.

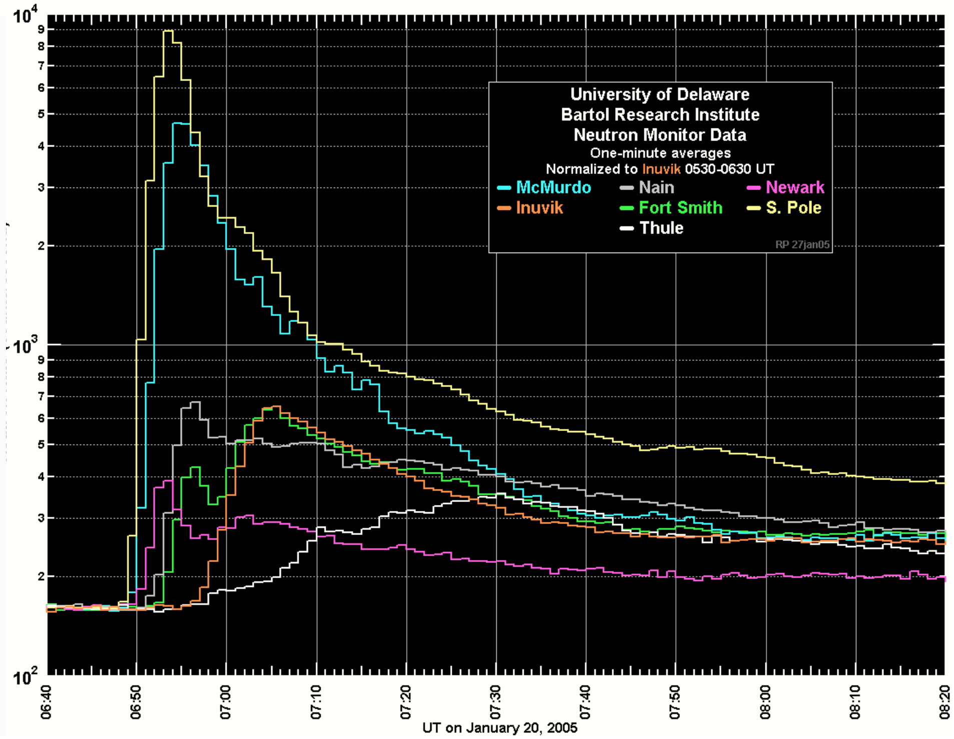
# The January 20, 2005 event:



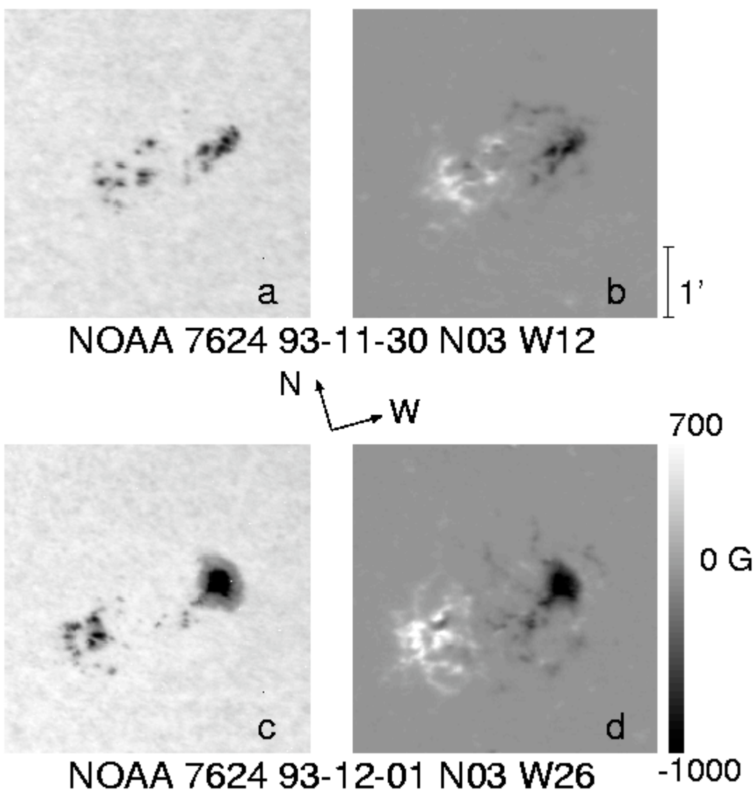
# Where does the energy for these giant flares come from?

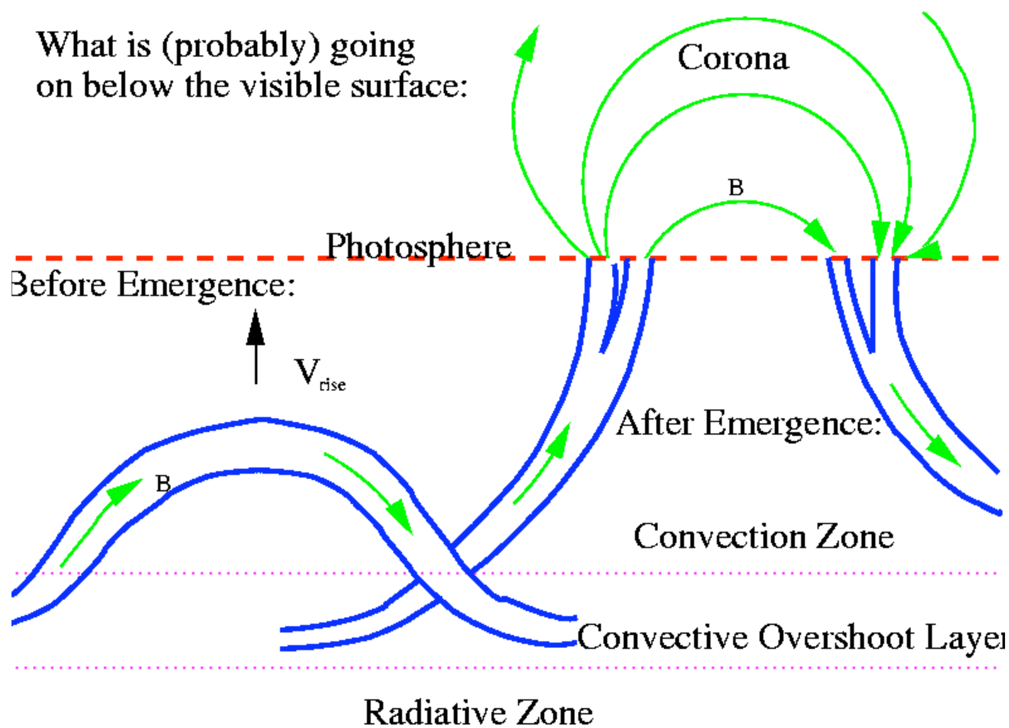
- Ultimately, it must come from the sub-photospheric magnetic roots of active regions.
- Surface flows, such as super-granular motions and differential rotation do not contain sufficient power to energize flare productive active regions at the rate observed (McClymont & Fisher 1989).
- While active regions can exhibit large velocities and shearing motions, these almost certainly result from large forces acting over a much greater volume of the magnetic structures in the solar interior, and then show up as apparent motions of magnetic features at the photosphere.
- What do we understand about the sub-surface structure and evolution of active regions? What remains mysterious? These questions will be the focus of this talk.

# What sub-surface magnetic field models have been able to explain

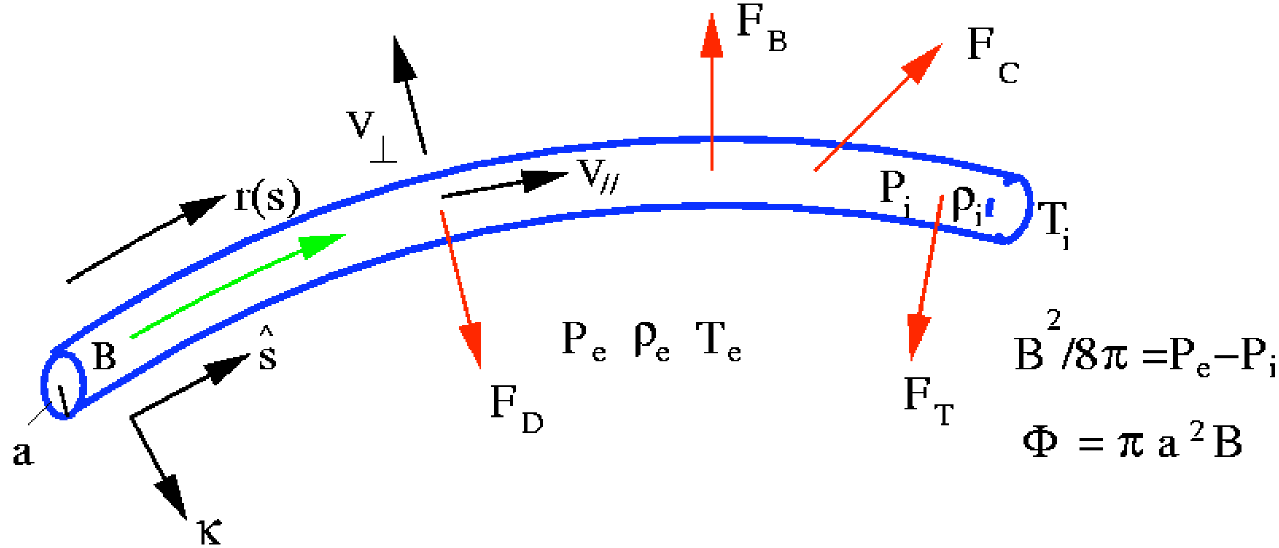
- Equatorial zone of avoidance of active regions
- Hale’s law and Joy’s law (active region orientation)
- The dependence of active region tilt on  AR size
- The *dispersion* of tilt versus active region size
- Asymmetric spot motions (leading vs following)
- Morphological asymmetry
- Helicity distribution of active regions with latitude
- Stability of active region flux tubes (_-loops) in 3D
- Quiet Sun magnetic flux:  A near-surface convective dynamo can account for it
- The transition between active region flux tube dynamics and flux transport models (new result)
- _-spot active regions as highly twisted kinking flux tubes (maybe)

# Why do we think of active regions as flux tubes? (this shape of flux tube is known as an _-loop)



# Untwisted thin flux tube models




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

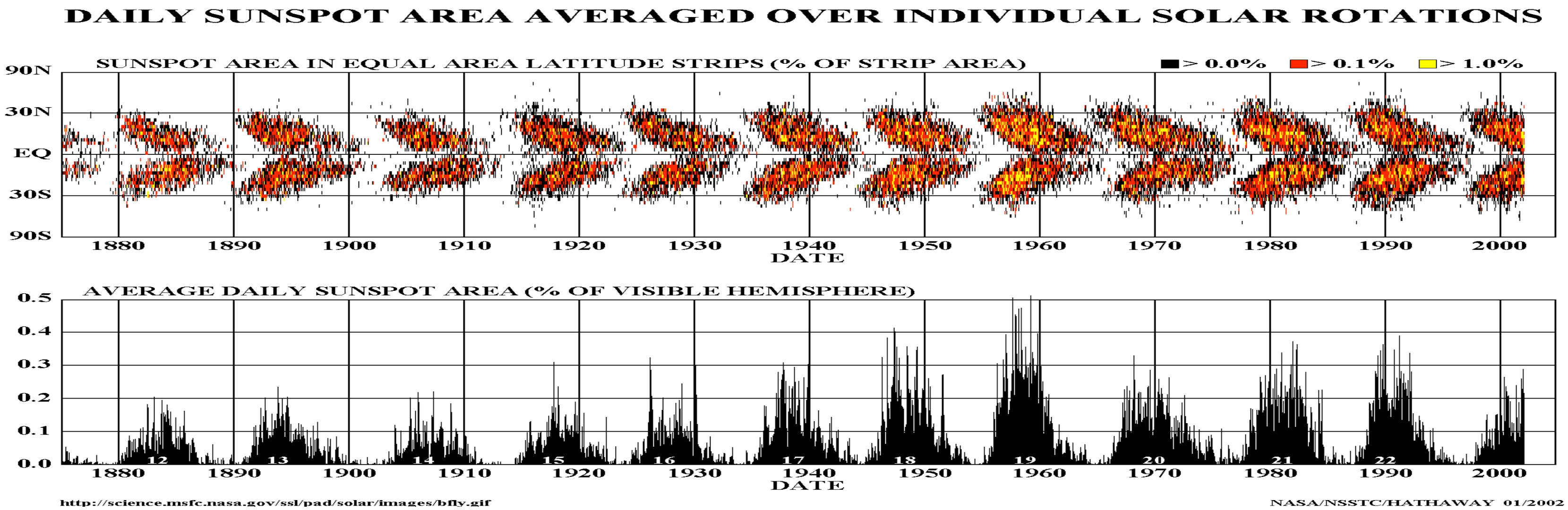
$$\mathbf{F_b} = g(\rho_e - \rho_i)\hat{\mathbf{r}}$$

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

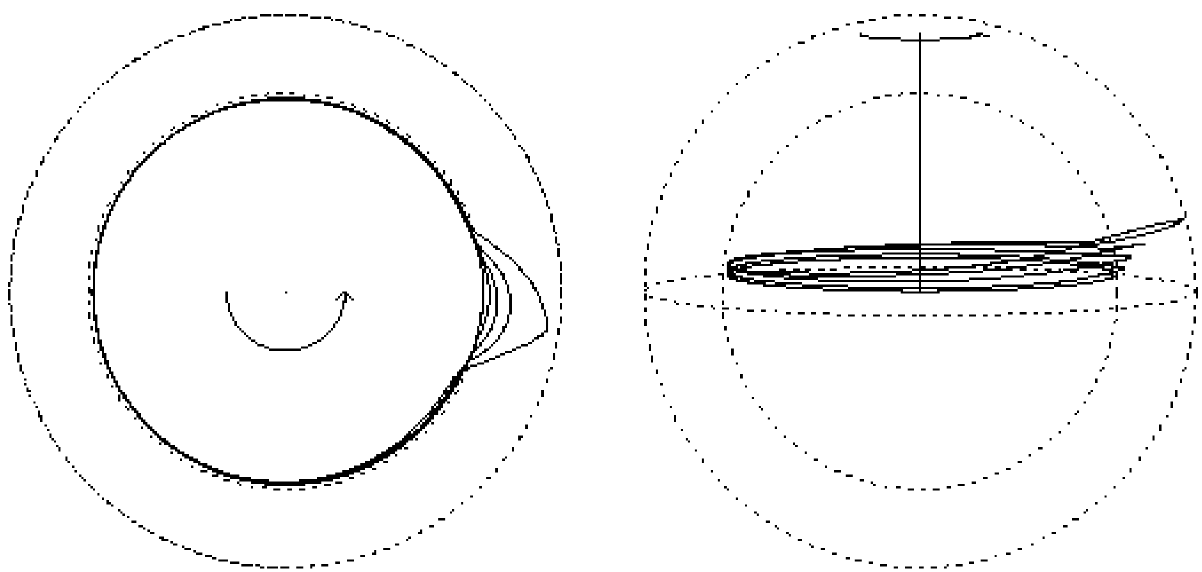
$$\mathbf{F_t} = \frac{B^2}{4\pi}\boldsymbol{\kappa}$$

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

# Success: Equatorial avoidance:

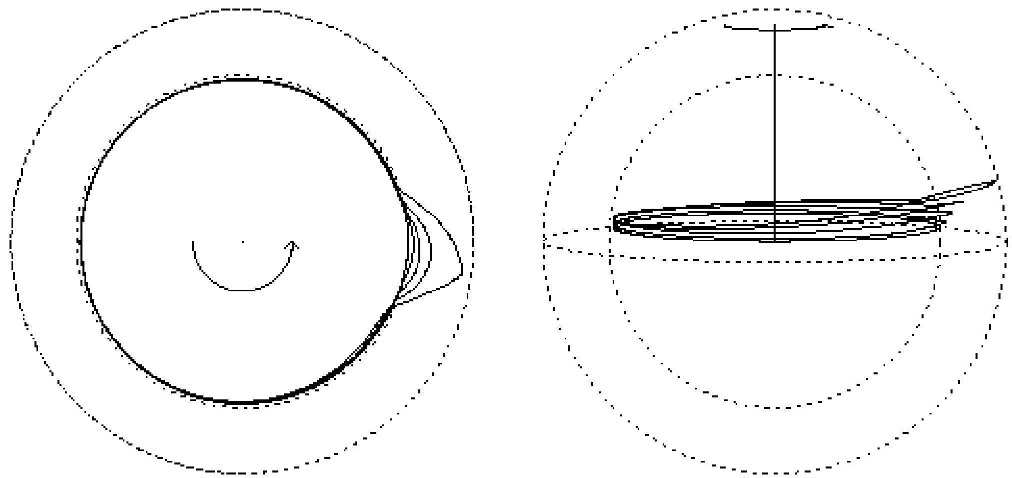



- Coriolis force deflects tube toward the poles as it tries to rise radially



(a) (b)

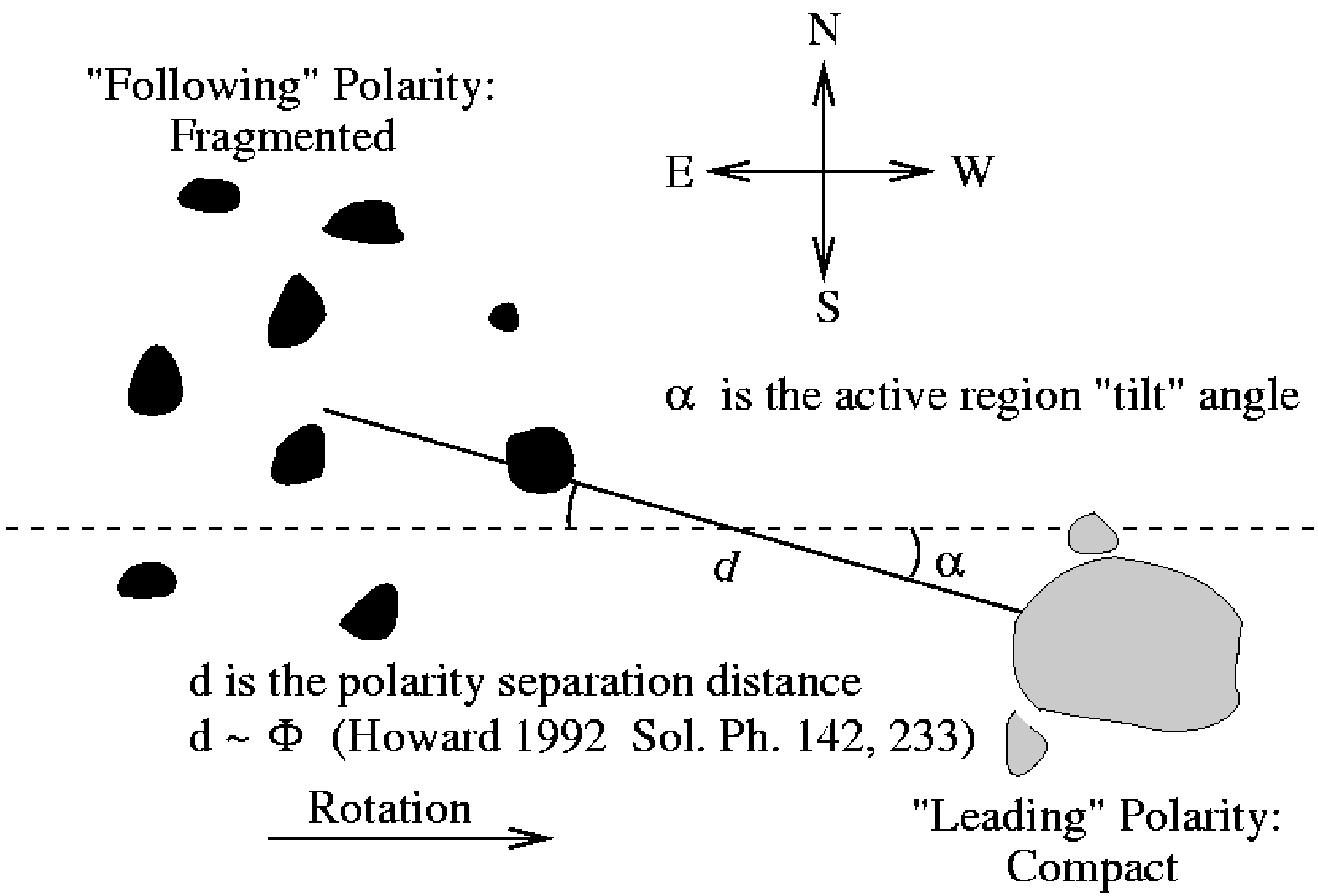
# Latitude constraints based on initial equilibria, dynamic motions



(a) (b)

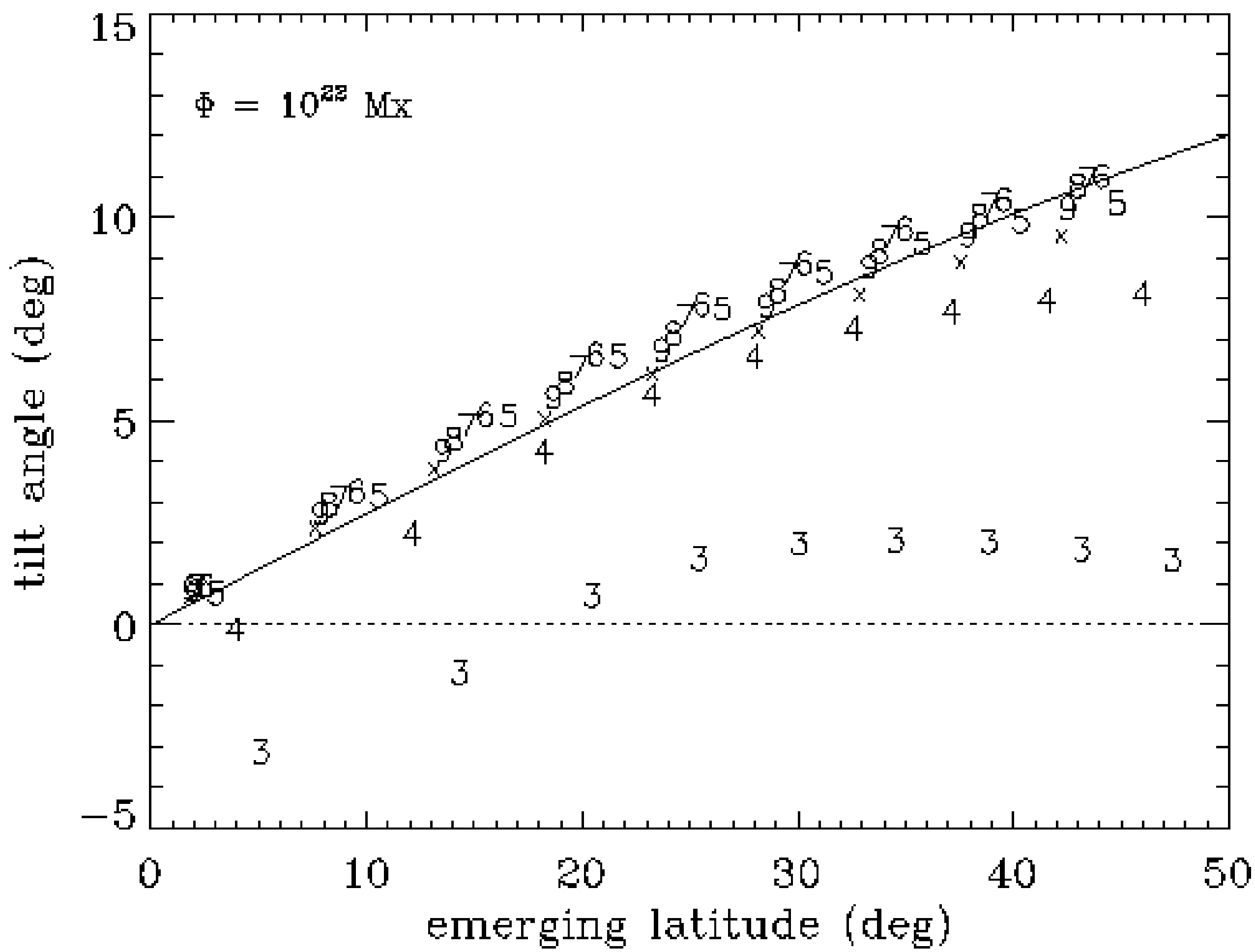
- If B > $10^5$G, no low-latitude equilibria possible
- If B < $3 \times 10^4$G, poleward motion too great for observed latitude distributions
- If active region flux tubes are initially toroidal, field strength is constrained.

# Active Region Tilts and Joy's Law

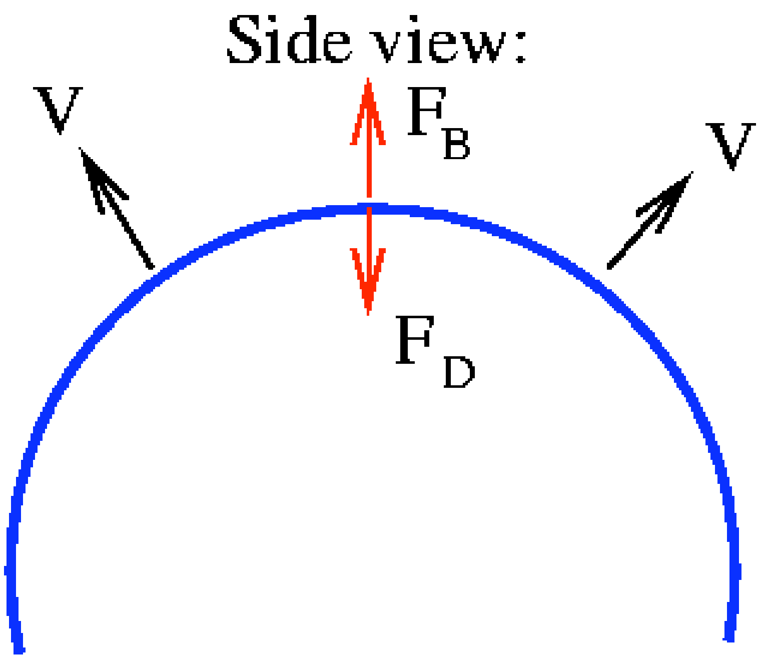


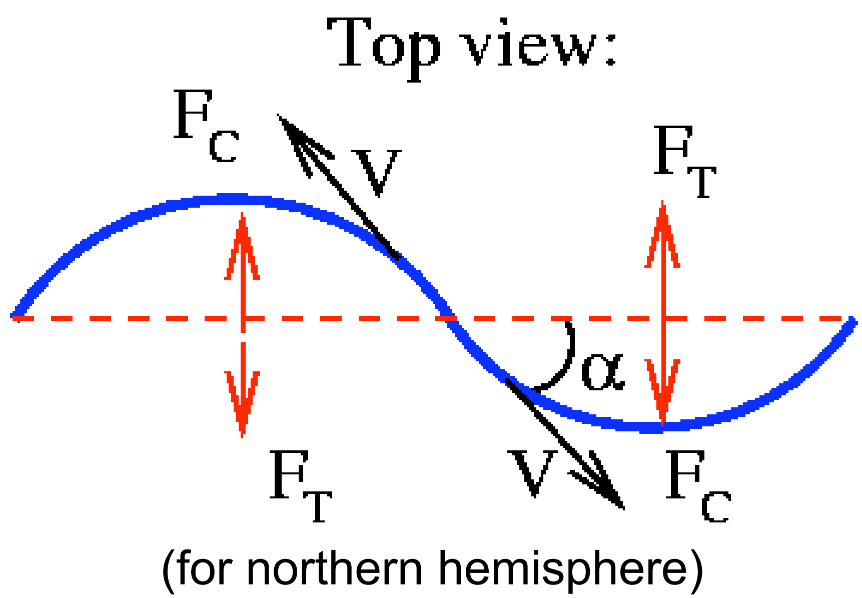

Joy's law: $\alpha \sim \sin(\text{latitude})$

# Success: Comparison of model tilts versus average observed values:



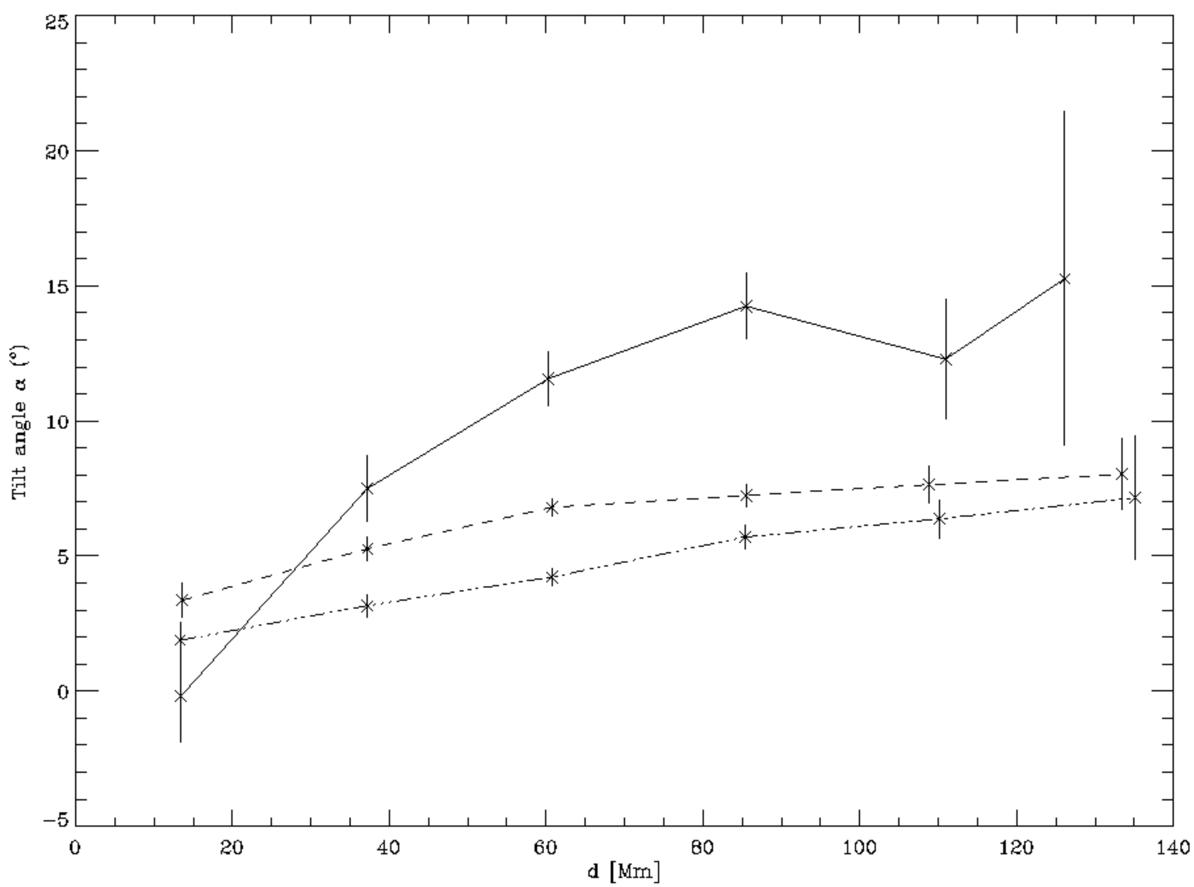
# Simple idea for torque balance to determine amount of tilt



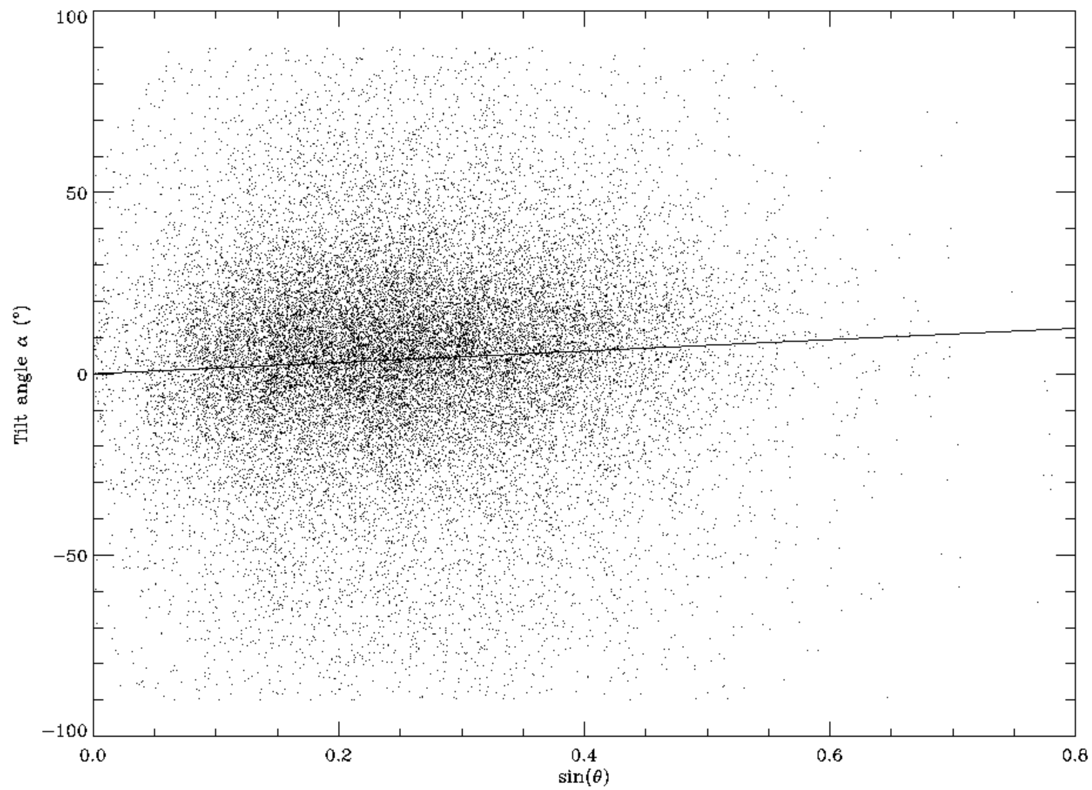

The result is that $\alpha \propto \sin\theta \, \Phi^{1/4}$.

# Success: The variation of tilt with magnetic flux (polarity separation distance)



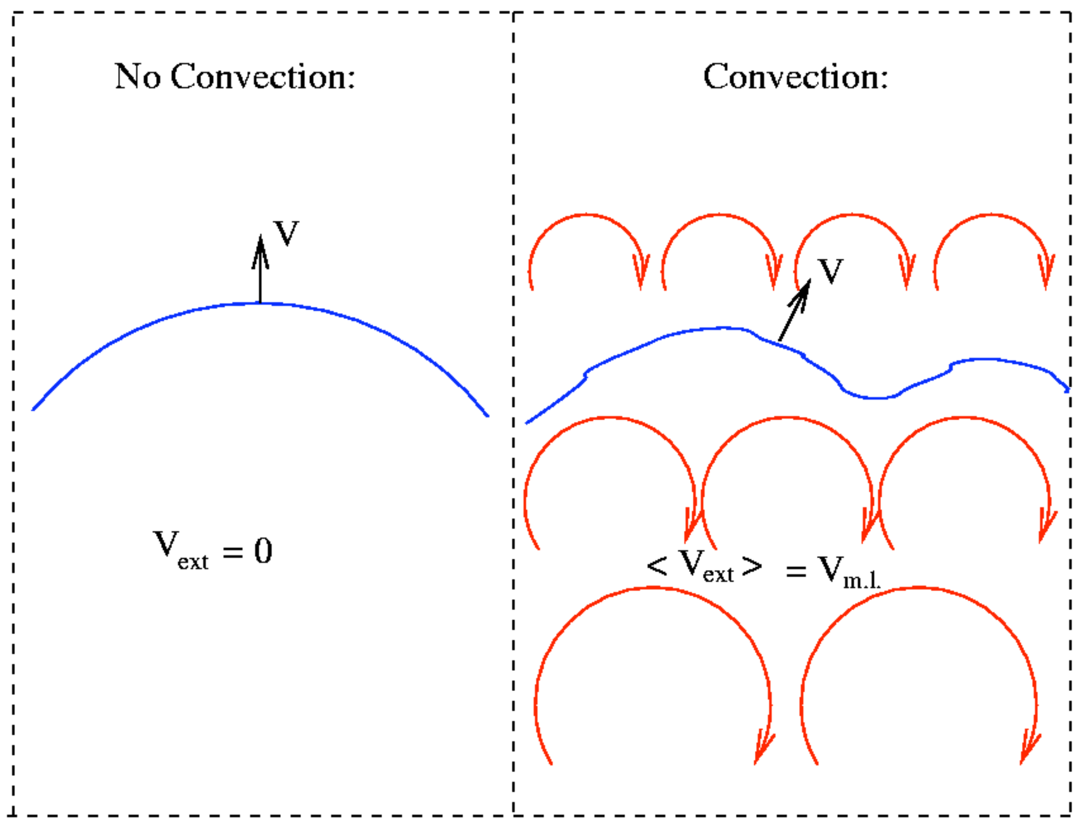

Since this work was done, Tian & Liu (2003) have updated these results with magnetic fluxes instead of polarity separations.

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

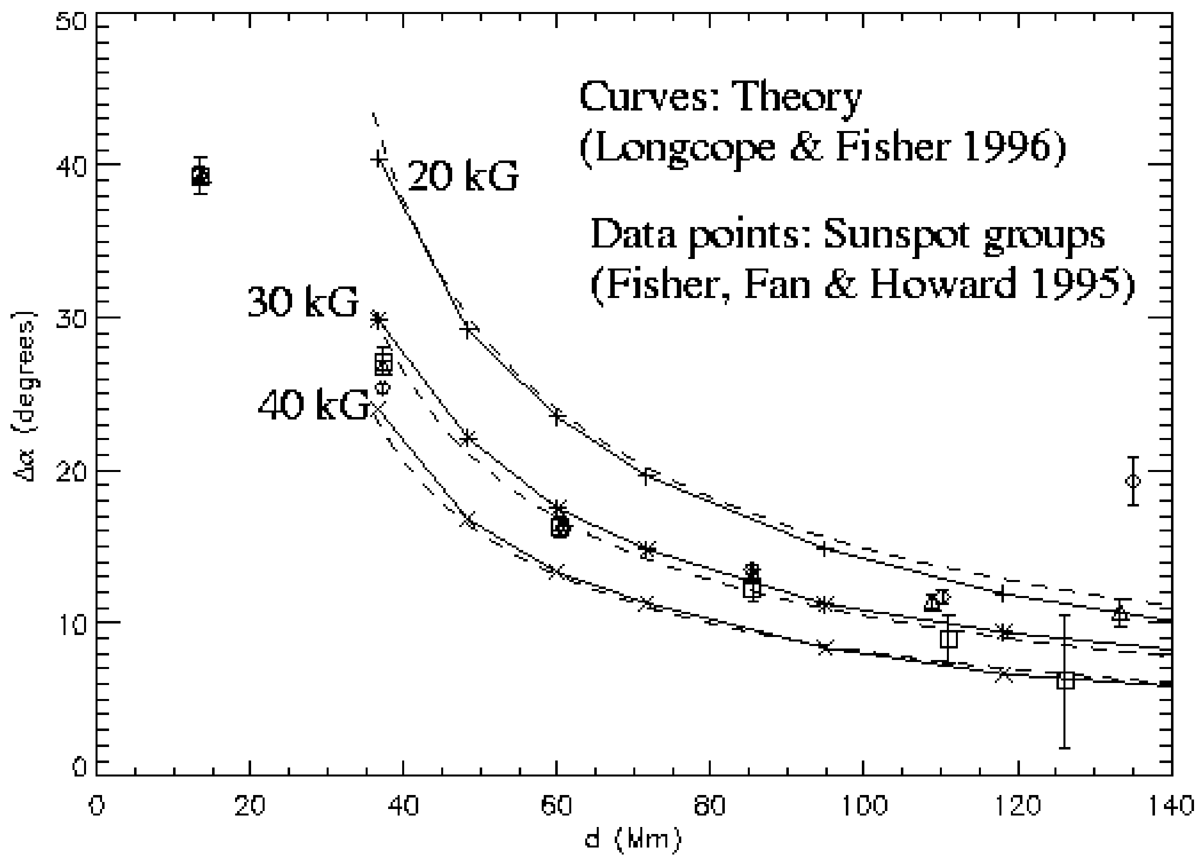



Analysis of ~24,000 spot groups shows tilt dispersion is *not* a function of latitude, but *is* a function of d, with $\Delta\alpha \sim d^{-3/4}$.

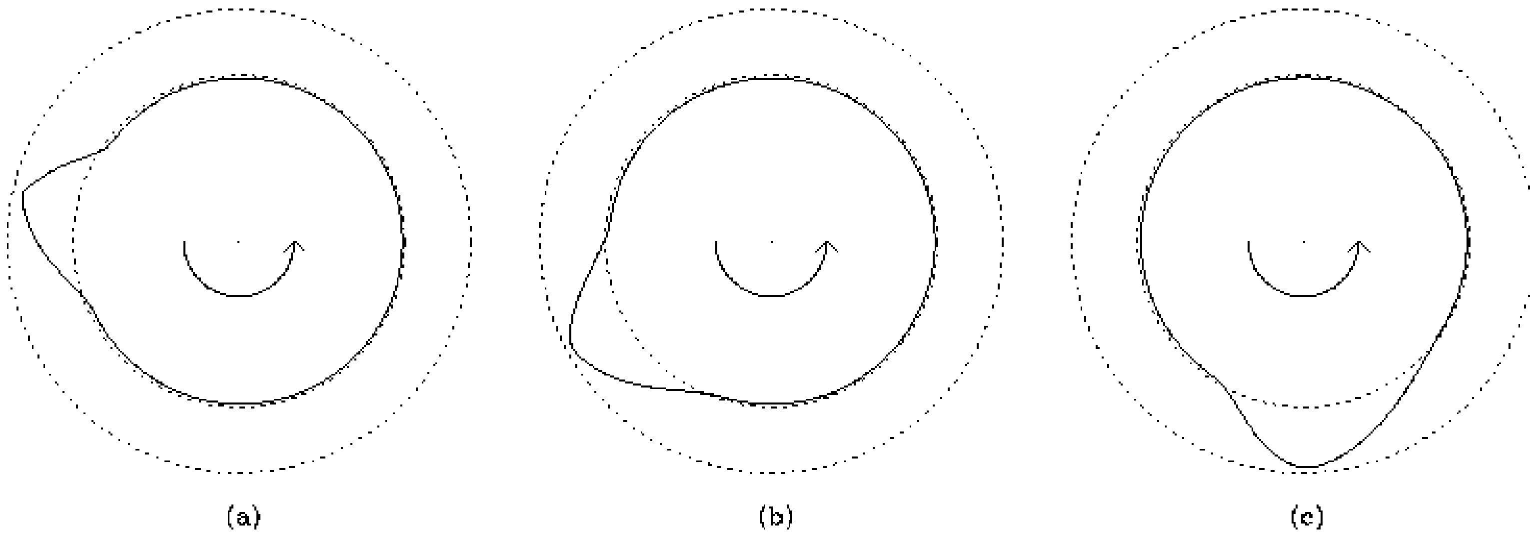
# Observed variation of $\alpha$ with *d* suggests convective turbulence as a possible mechanism for tilt fluctuations…



# Success: Tilt fluctuations using tube dynamics driven by convective turbulence



# Asymmetric spot motions

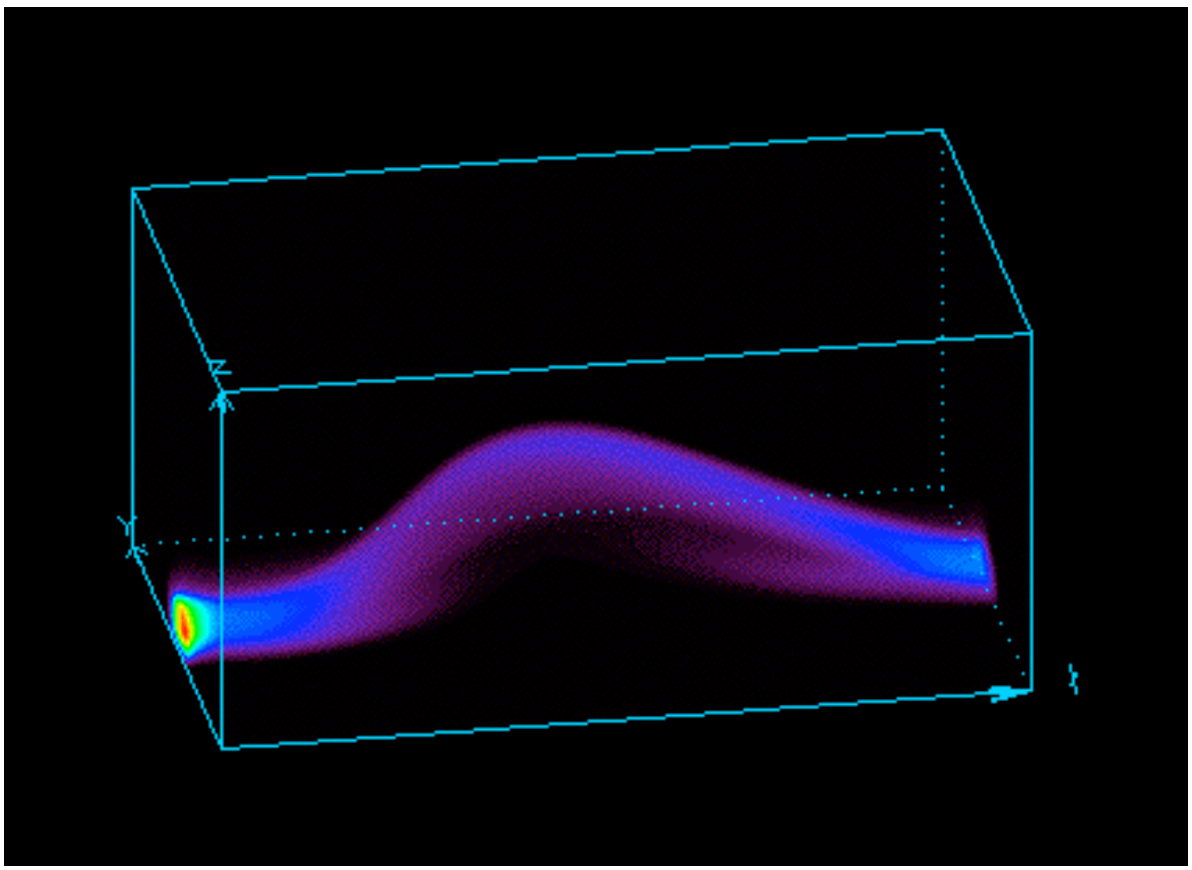



- Panels (a), (b), (c) correspond to field strengths at the base of the convection zone of 30, 60, and 100 kG respectively (Fan & Fisher Sol. Phys. 166, 17)

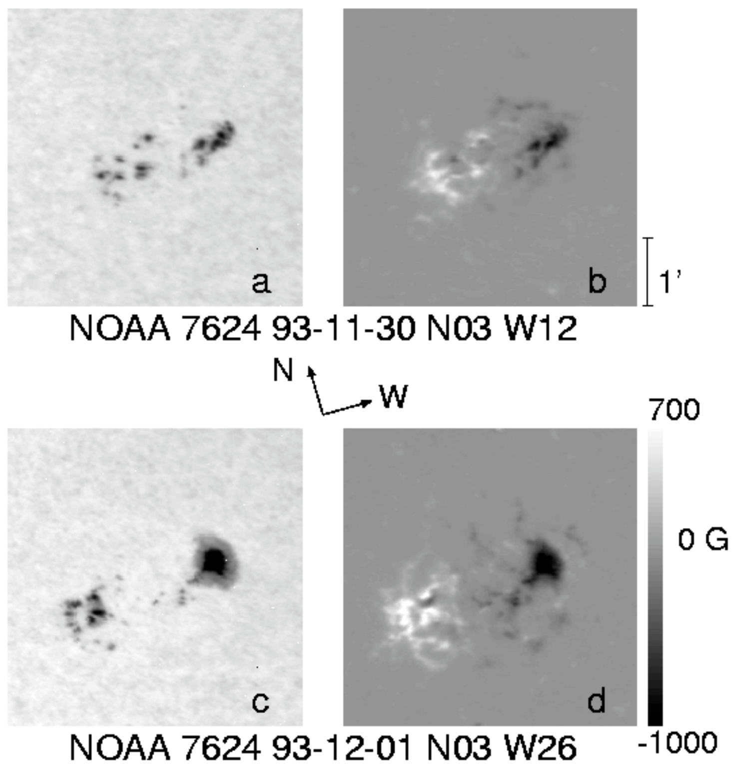
# Success:  Asymmetric spot motions

- Caligari Moreno-Insertis & Schüssler (1995) 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…

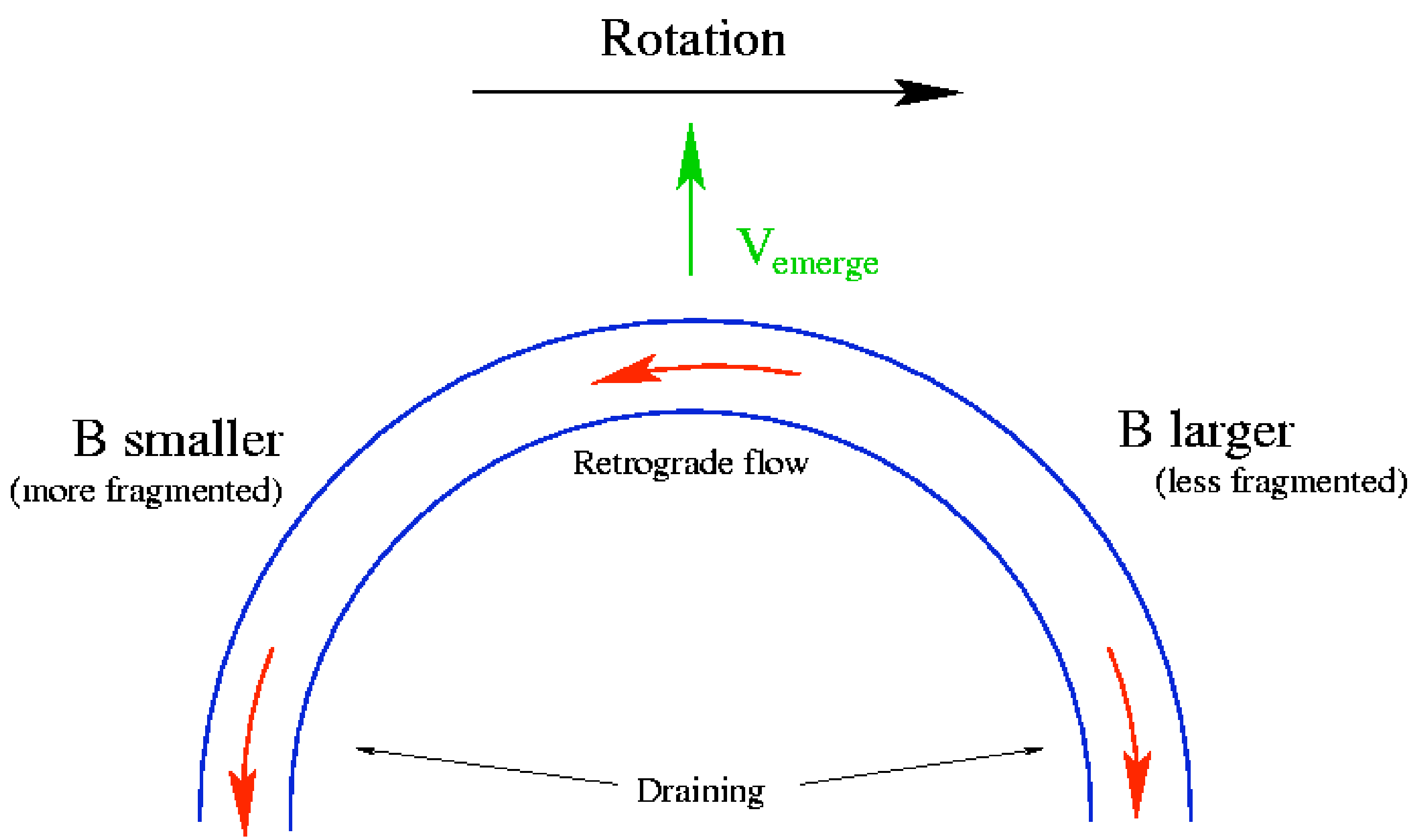
Success: 3D-MHD models of flux emergence confirm the asymmetric shape of the $\Omega$ loop (Fig. 2 from Abbett Fisher & Fan 2001)



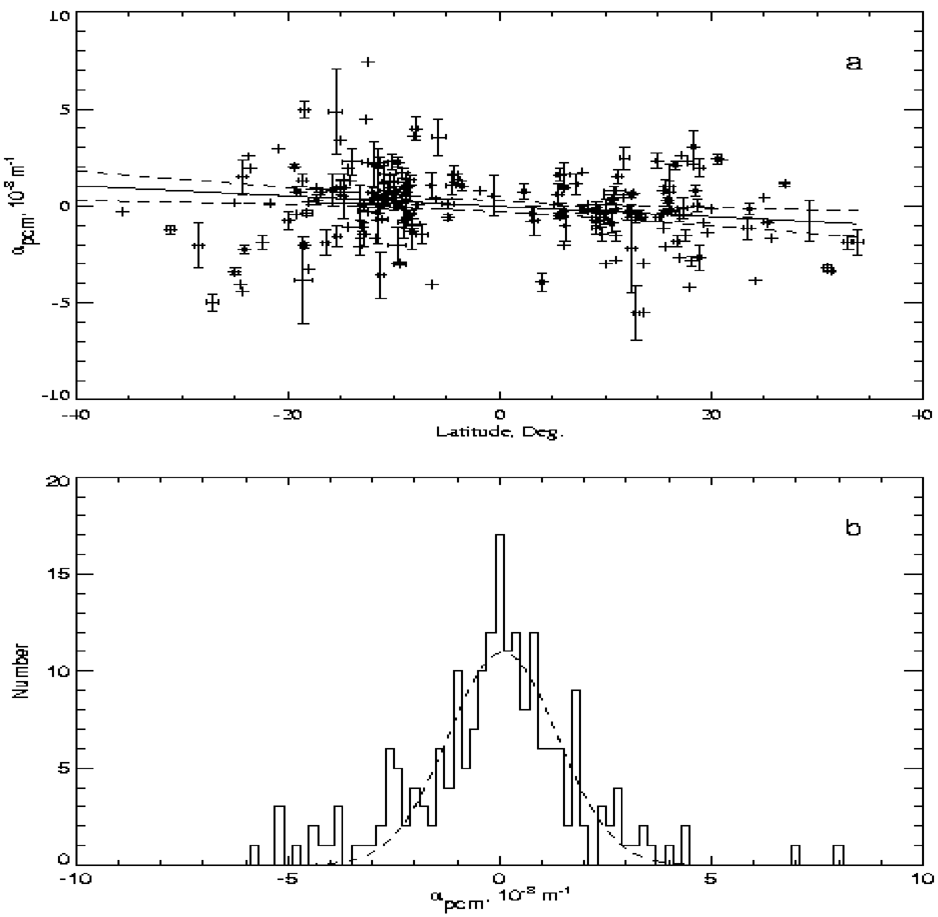
# The Coriolis force is a possible explanation for asymmetries in the morphology of active regions…



# Possible success: Field strength asymmetries could lead to morphological differences between leading and following polarity…

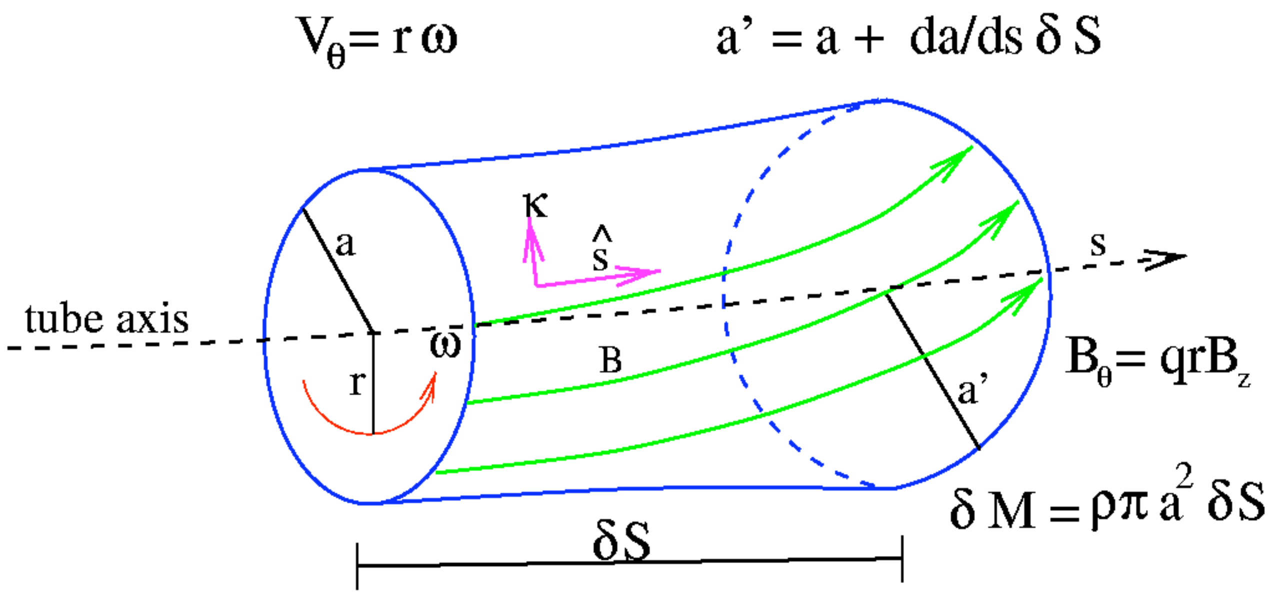


# How twisted are typical active regions?




Where does active region twist come from?

# Slighly twisted flux tubes:




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

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

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".)

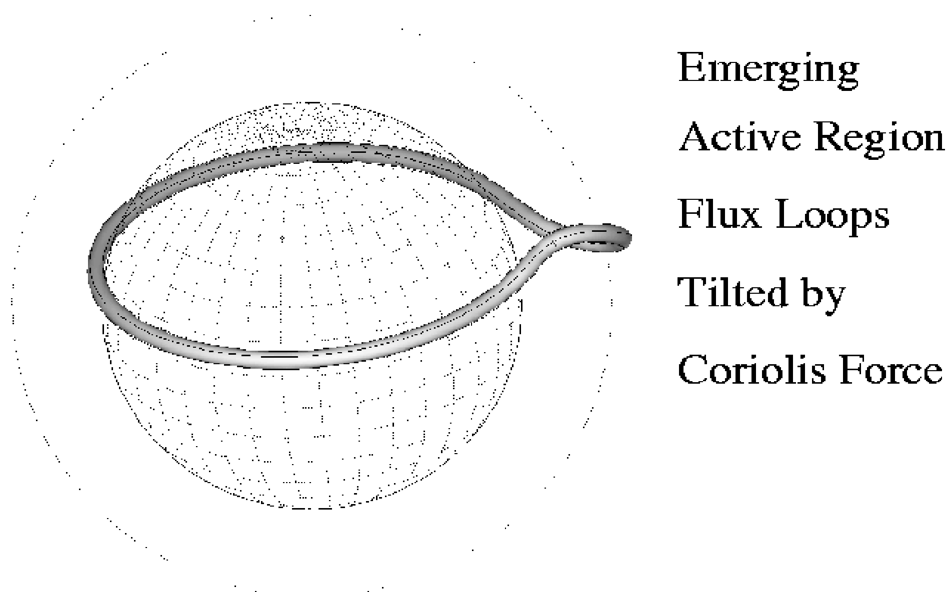
$$Tw = \frac{1}{2\pi} \oint q(s)\,ds; \;\; Wr = \frac{1}{4\pi} \oint ds' \oint ds'' \frac{\hat{\mathbf{s}}' \times \hat{\mathbf{s}}'' \cdot (\mathbf{r}'' - \mathbf{r}')}{|\mathbf{r}'' - \mathbf{r}'|^3},$$

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

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

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

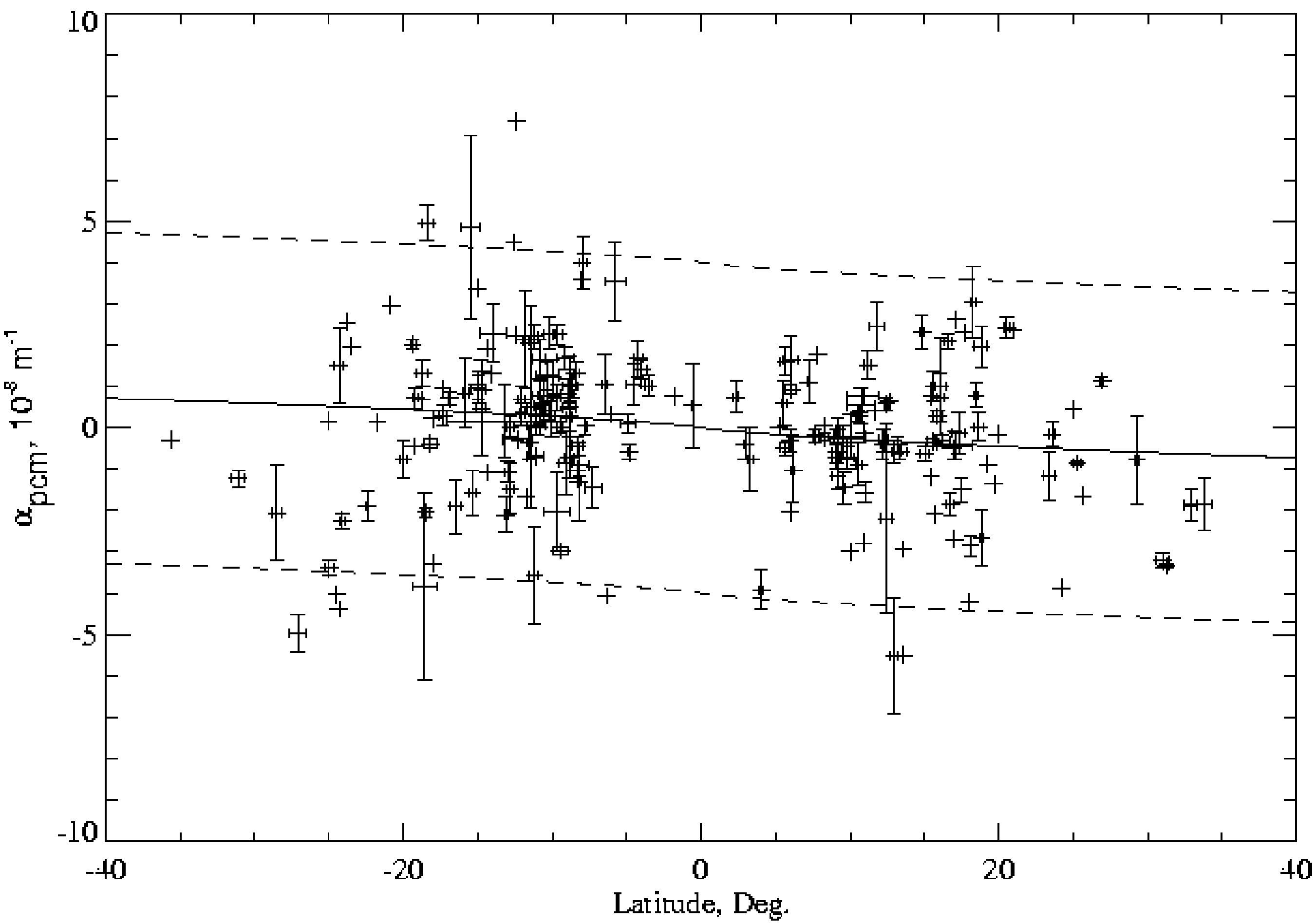
- “Joy’s Law” tilts of active regions during emergence is one possibility, but is too small…



# Writhing by convective turbulence is another possibility…

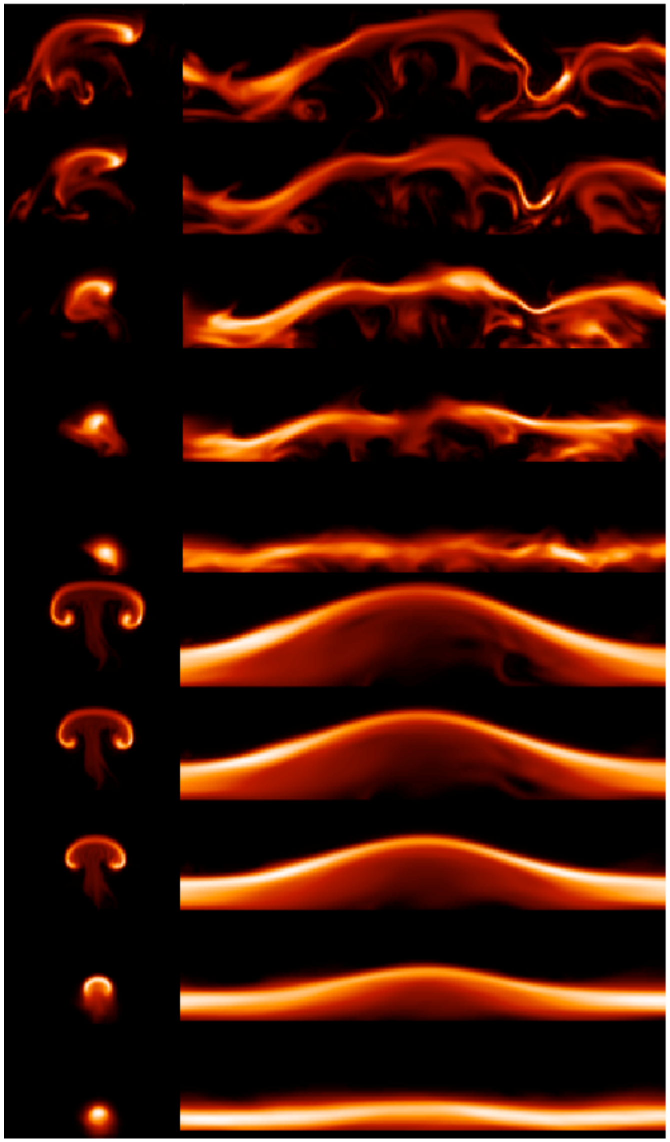
- Develop a tractable model of convective turbulence including kinetic helicity
- Solve equations of motion and twist evolution for a flux tube rising through such a turbulent medium
- Such a model was explored by Longcope et al. (1998)

# Success: Writhing by convective turbulence is consistent with observations…



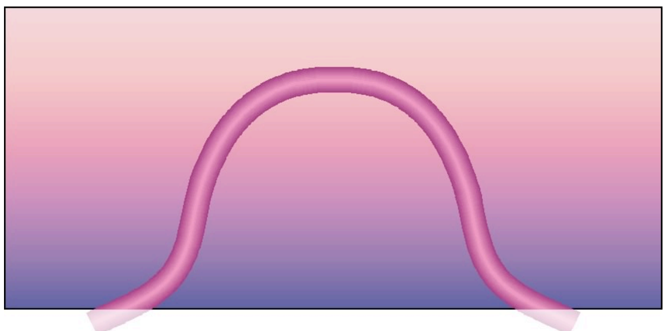
# Success: Active region flux tubes, even untwisted, are able to maintain their integrity as they rise through the turbulent convection zone

- Early work in 2D (eg Longcope, Fisher & Arendt 1996, Emonet & Moreno-Insertis 1998, Fan et al 1998) indicated that untwisted flux tubes were unstable to emergence in the solar interior, due to the effects of long vortices that rip the tubes apart. Magnetic twist can stabilize these tubes against fragmentation, but the amount of twist required was much greater than that observed for most active regions.
- MHD simulations done in 3D result in a completely different conclusion. First, if only the apex of a flux tube is rising, the destructive force of the vortices is greatly reduced because they are shorter. Second, if solar rotation is included in the MHD simulations, the Coriolis force acts to disrupt the formation of the vortices, also increasing the flux tube's cohesion. (Abbett, Fisher & Fan 2000, 2001)
- Finally, if the convection zone is actually convecting, the critical parameter is the ratio of the turbulent pressure to the magnetic pressure. The panels at the right show the evolution of 2 different cases. The top case shows a small field-strength case, while the bottom shows a larger field strength case. Convective motions strongly affect the top case but not the bottom one.
- The condition separating the 2 regimes is determined by a rough equality between the gradient in the dynamic pressure with magnetic tension forces due to both the axial and azimuthal components of the magnetic field in the tube (Abbett et al, 2004).

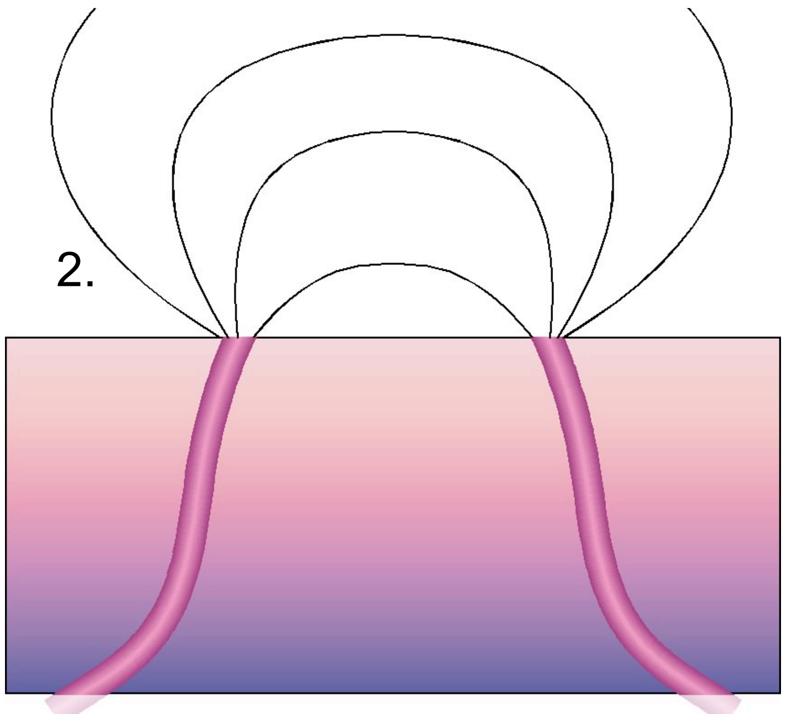


# Success: The transition between active region evolution in terms of emerging flux tubes versus active region decay as described by passive flux transport models (Schüssler & Rempel 2005)

1.

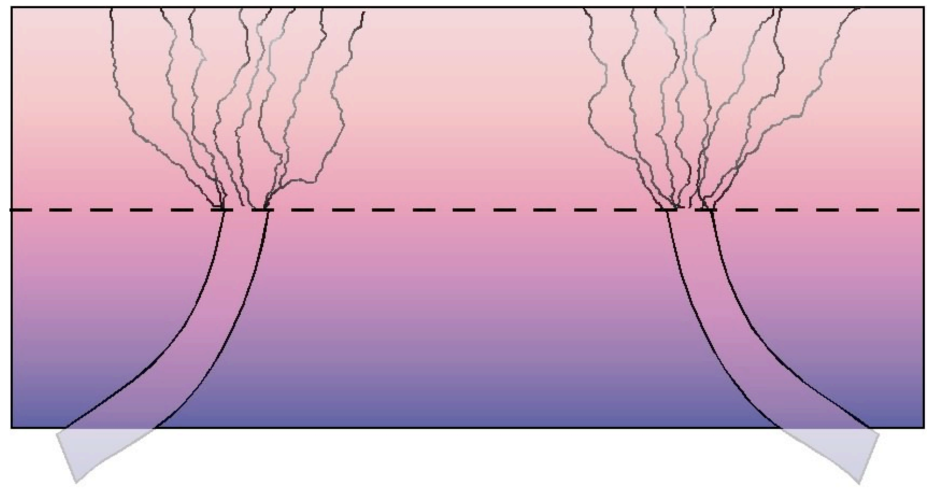


2.



Images courtesy of Loraine Lundquist

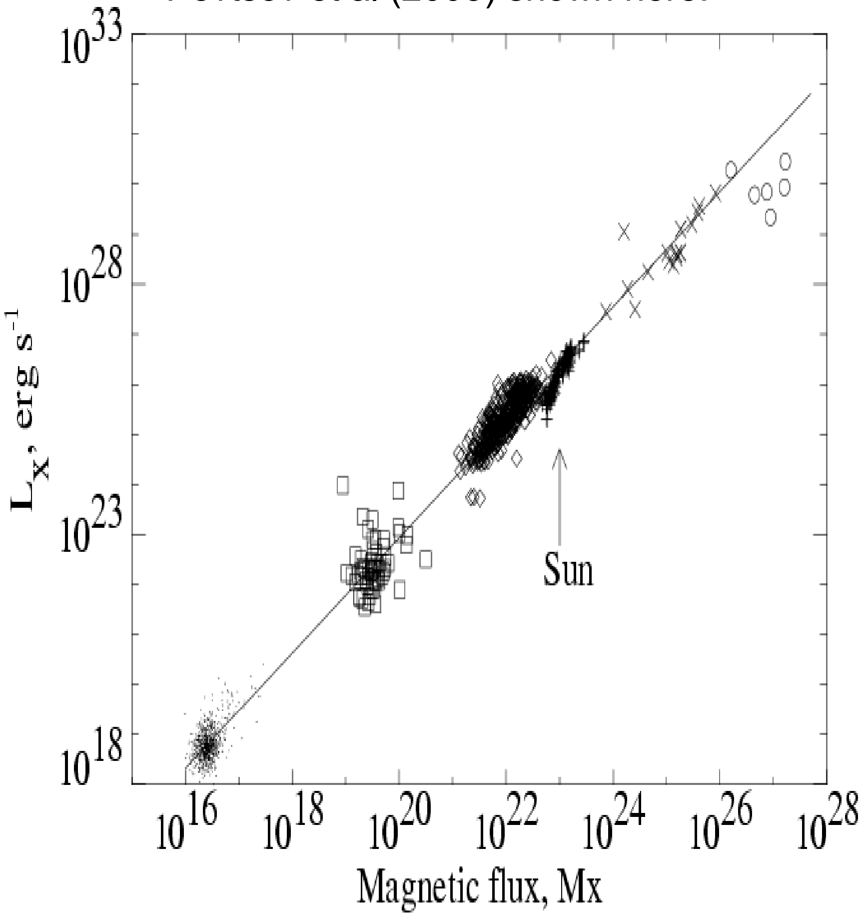
3.

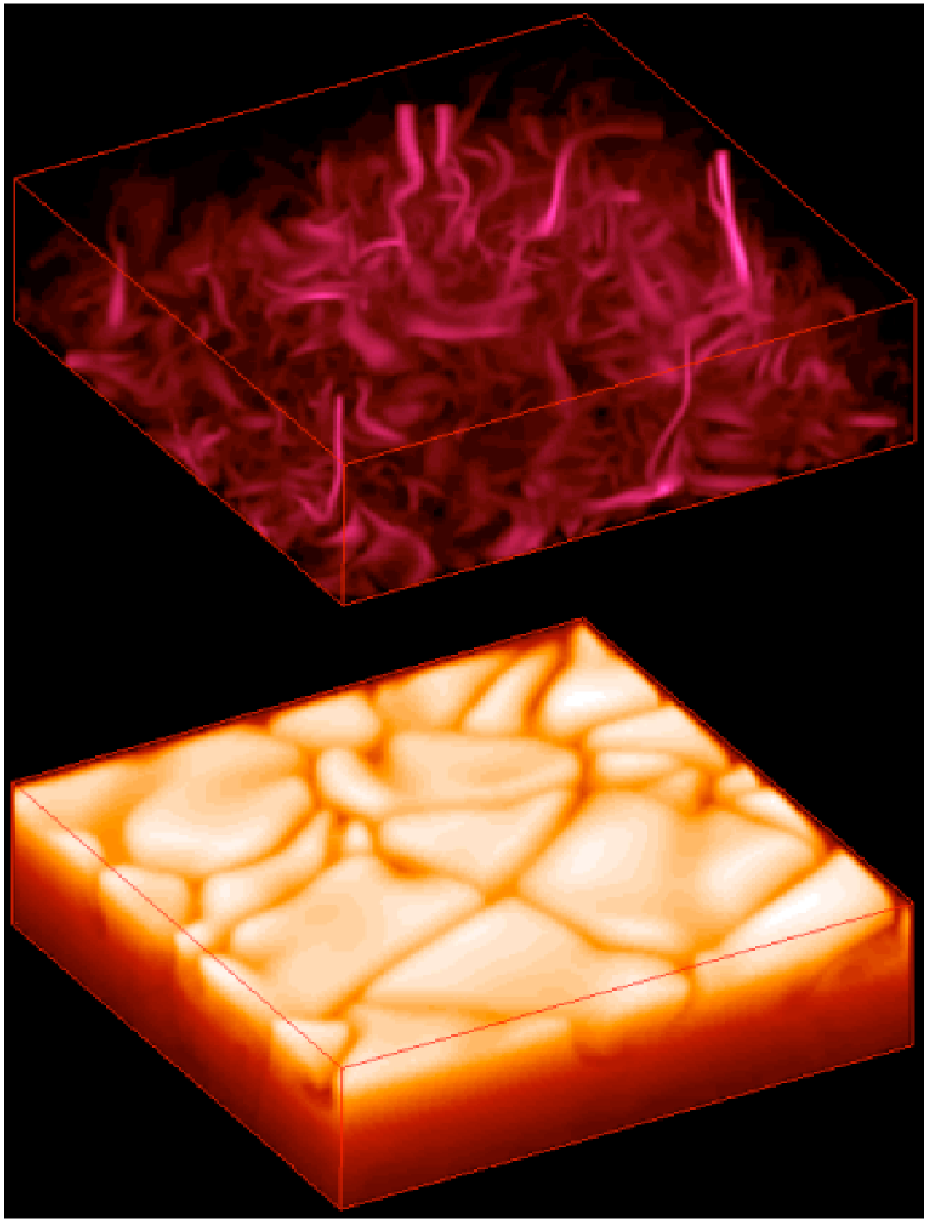


1. Active region below the surface is an emerging _-loop
2. As the magnetic flux breaks through the photosphere, sunspots form and the initial coronal magnetic field is established
3. As the plasma in the spots cools and sinks, and the buoyant plasma from below emerges, the upper parts of these flux tubes are blown apart and are then controlled by convective motions. Passive flux transport models then describe the surface evolution of the active region field

Success:  Convective dynamo acting near the surface predicts roughly the correct unsigned magnetic flux density in the Quiet Sun

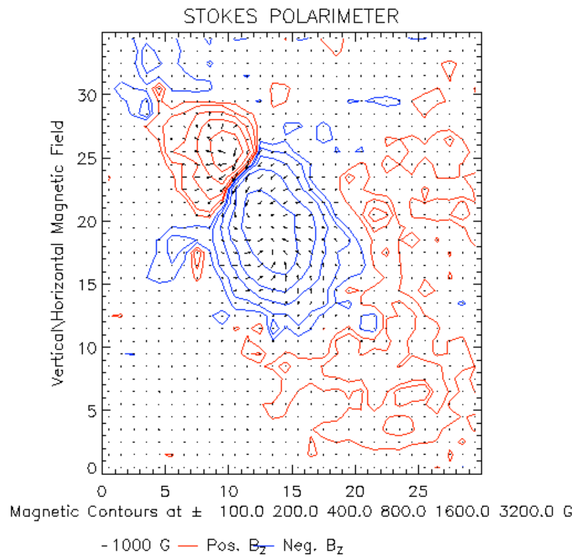
- Right panel: magnetic field strength (top) and entropy (bot) for a surface convective dynamo from Bercik et al (2005)
- Bottom panel:  X-ray radiance versus unsigned magnetic flux.  The simulations on the right yield the quiet Sun fluxes from Pevtsov et al (2003) shown here.

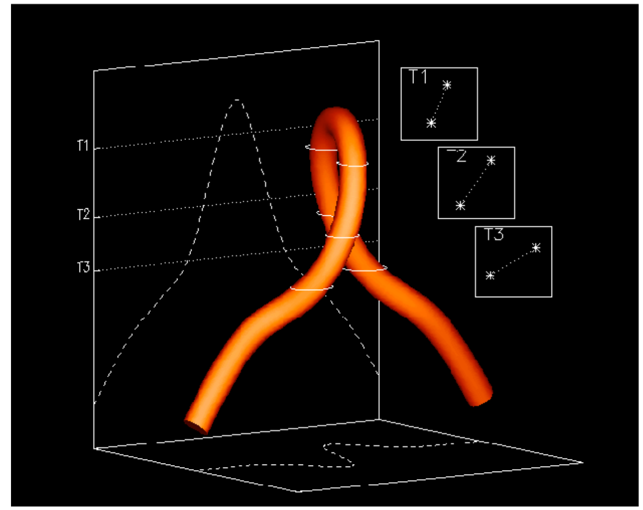


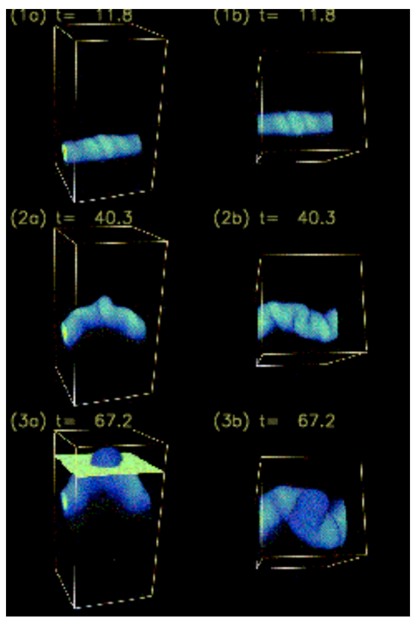



# _-spot active regions as twisted, kinking flux tubes (Linton, Fan)

- Properties of _-spot regions:
- Sunspot umbrae of opposite polarity in a common penumbra
- Strong shear along neutral line
- Active region rotates as it emerges
- Large and frequent flares and CMEs
- Kinked geometry explains rotation, shear along neutral line
- Flares/CMEs might be explained by reconnection between the 2 legs of the intertwined loop structure




# Questions

- What triggers the eruption of active regions from the base of the convection zone? Instability, secular heating, convective overshoot, or something else?
- Most active regions exhibit only small amounts of twist, and are consistent with a tube lying initially at the base of the convection zone with no twist. How then do the island _-spot regions acquire so much twist?
- How is the free energy from sub-surface fields transported into the corona?
- What is the magnetic connection between different active regions? Are active regions magnetically connected to each other in the dynamo region, or are they all separate?
- How do we relate “active longitudes” and “active nests” to a magnetic picture of the large-scale dynamo region at the base of the convection zone?
- Is the magnetic flux that gives birth to active regions in a smooth, slab-like geometry, or is the flux already pre-existing in the form of tubes?
- What happens when active region flux tubes collide in the solar interior? What happens when a new active region emerges into an old one?
- How do active region flux tubes interact with the small scale field in the Quiet Sun?
- What is the 3D analogue of the surface flux transport models? How does the following polarity from decaying, emerged active regions return to the dynamo regions? What happens to the magnetic roots of an emerged active region once the active region begins decaying?
- Can we infer the sub-surface structure of an active region by studying its surface evolution? (Try this for AR 8210!)
- Can we predict the emergence of new active regions before it happens, either from helioseismic observation, or from a better knowledge of the physics of magnetic evolution below the photosphere?

# Conclusions

- While the physics of magnetic fields in the interior has not reached the level of sophistication and detail that modeling of the corona and heliosphere have achieved, the successes are significant, and indicate more progress can be made.
- A research program on space weather that ignores the sub-photospheric evolution of magnetic fields is doomed to treat the emergence of active regions as random, statistical events.
- While a vigorous research effort on interior magnetic fields does not guarantee we will attain a better long-term predictive capability for dangerous active regions, the lack of such an effort does guarantee we won't ever do better than we do now.