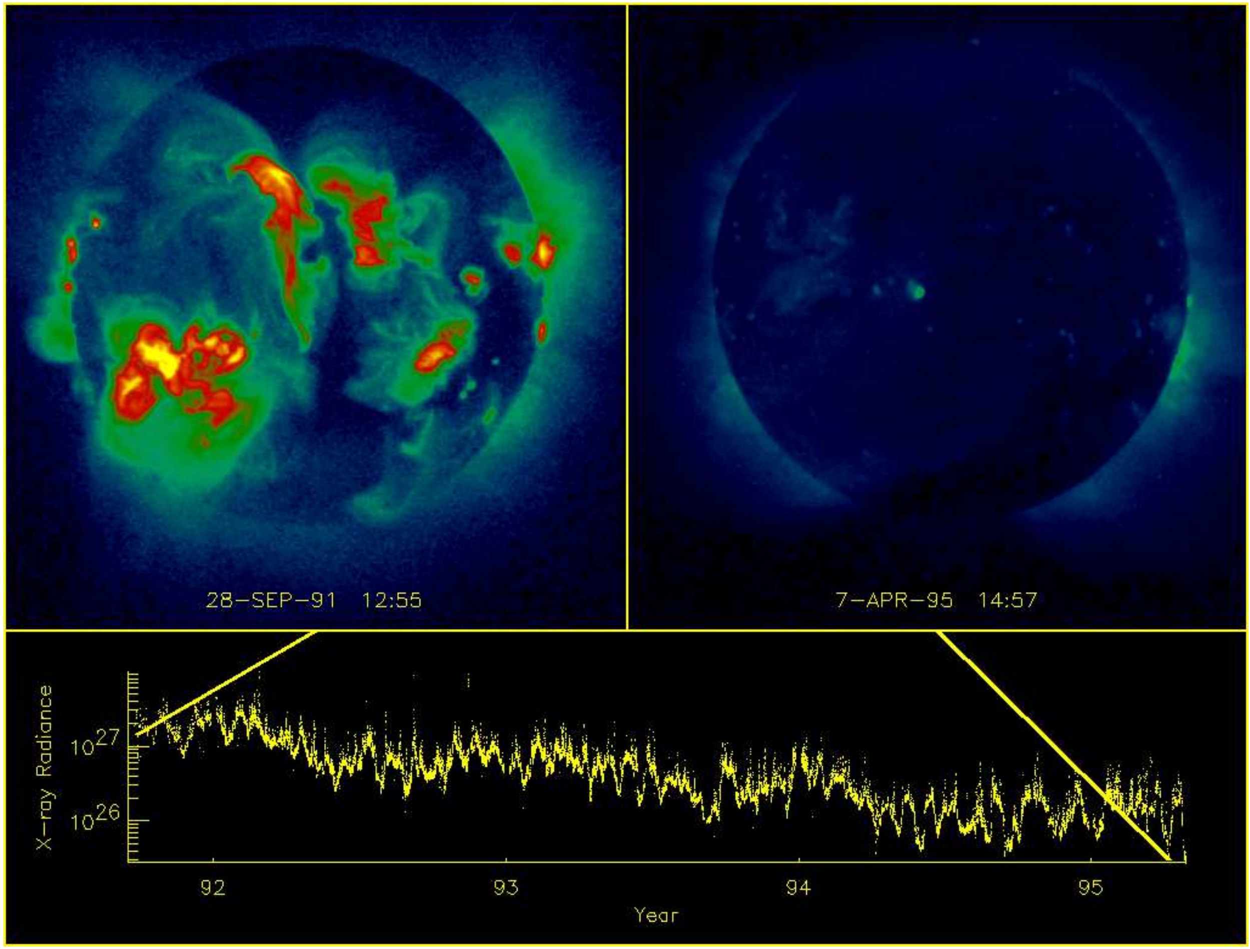
The Origin of Twisted Magnetic Fields in Solar Active Regions

George H. Fisher[1]
Dana W. Longcope[2]
Mark G. Linton[3]
Alexei A. Pevstov [4]
Yuhong Fan [5]

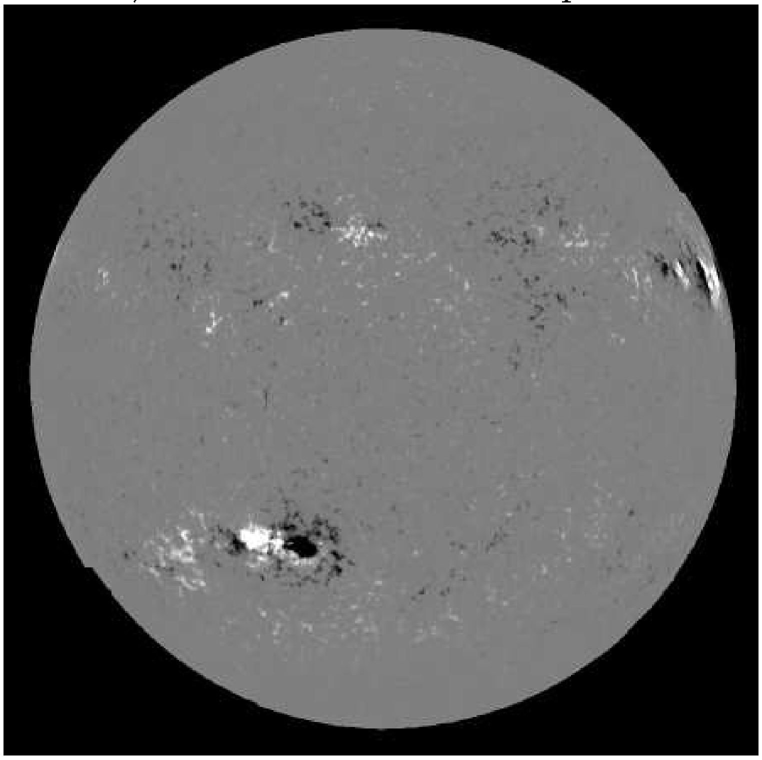
[1]SSL, UC Berkeley
[2]Physics Department, Montana State University
[3]SSL and Physics Department, UC Berkeley
[4]Physics Department, Montana State University
[5]HAO, NCAR, Boulder, CO

Why study twist in active regions?

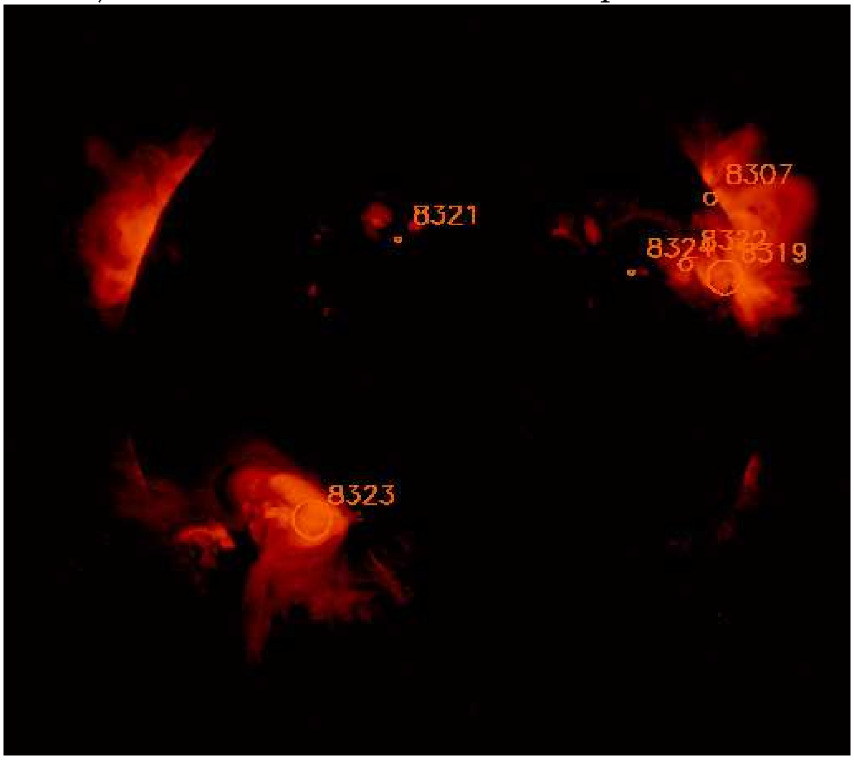


- Active regions are the most observable consequence of the Sun's dynamo
- Virtually all of the Sun's "activity" (such as X-ray emission) comes from active regions
- New measurements show a global pattern of twist in active regions
- Highly twisted active regions produce the largest solar flares

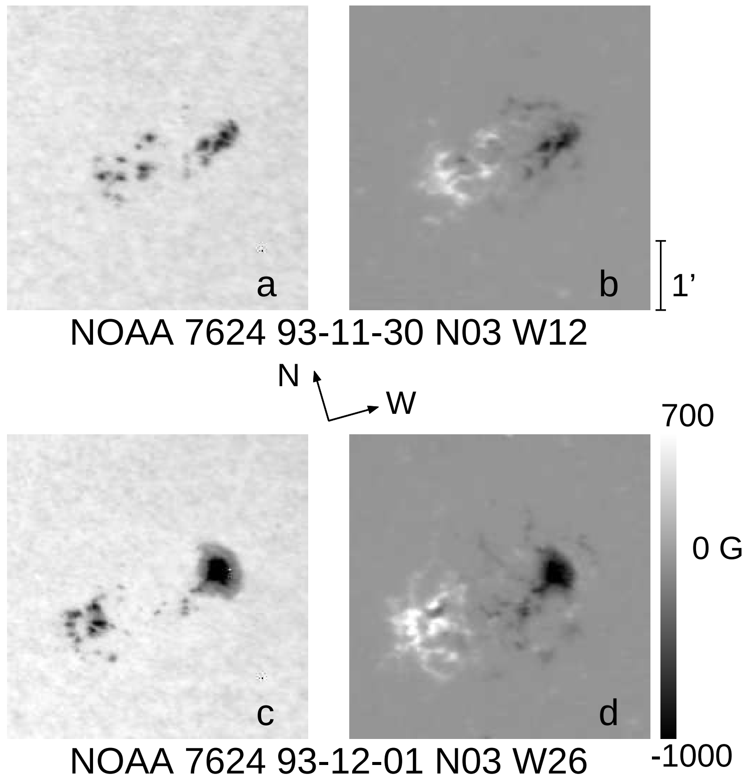
Sept. 2, 1998: KPNO Map of Sun's Magnetic Field:

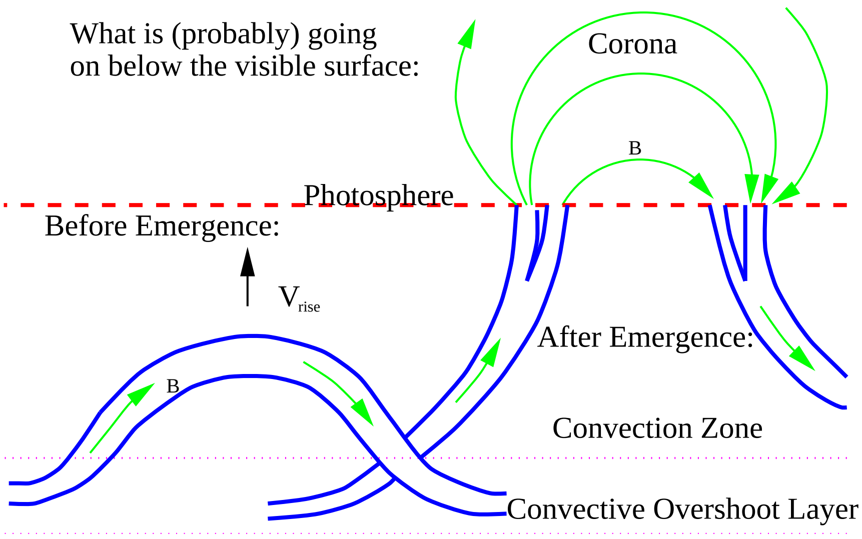


Sept. 2, 1998: Yohkoh SXT Map of Sun's X-ray Emission:

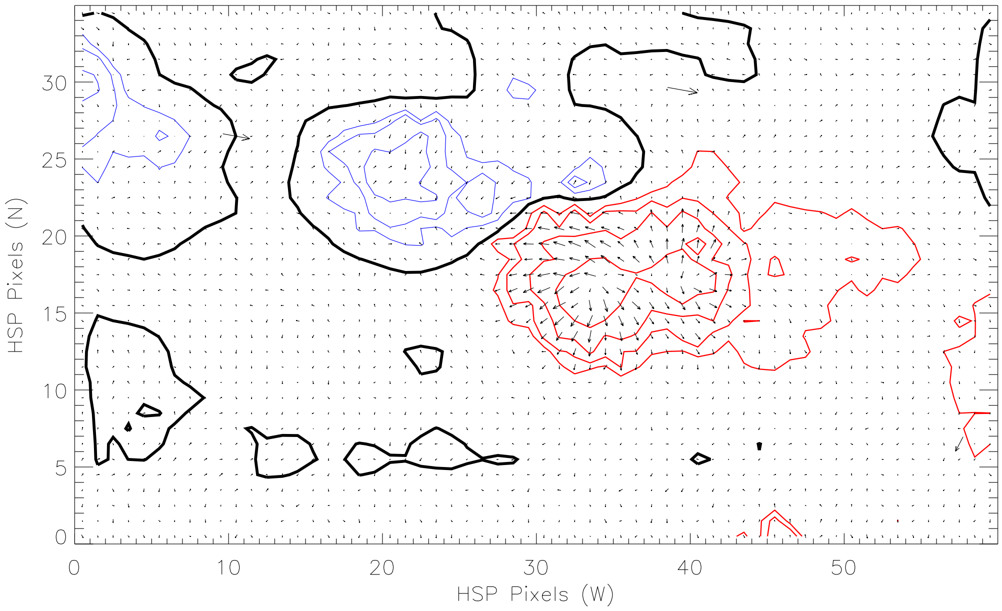


Emerging Active Regions – what we see at the photosphere: (from Cauzzi et al. 1996, Ap.J. 456, 850)





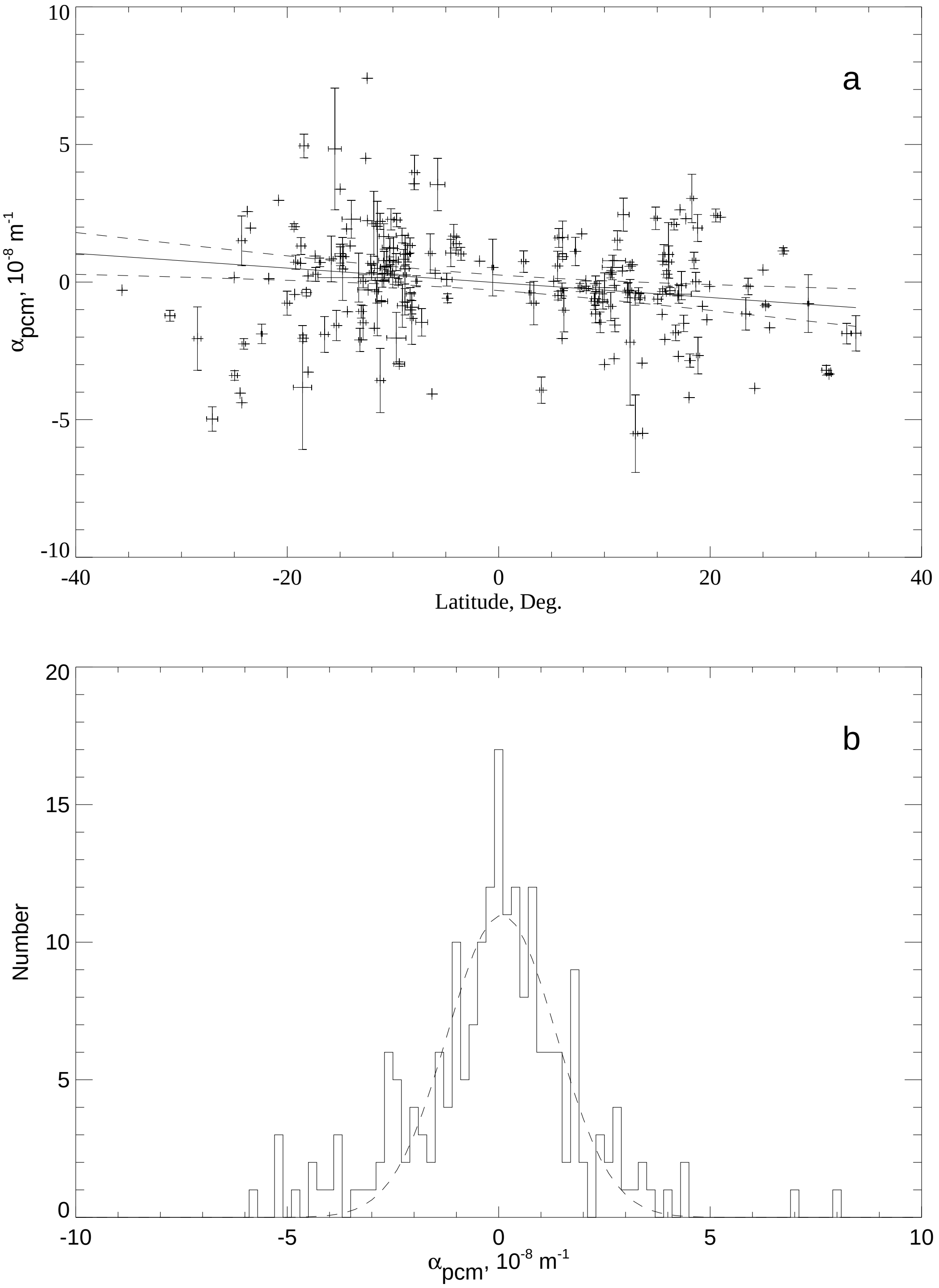
Vector magnetographs can measure all 3 components of $\mathbf{B}$ at the solar photosphere. Example shown is a vector magnetogram of NOAA 7452 on 1993 March 21 20:47 UT.



The curl of the horizontal components of the field can be taken to determine the vertical current density. From the vertical current density and the vertical field strength, a sign of magnetic twist can in principle be determined.

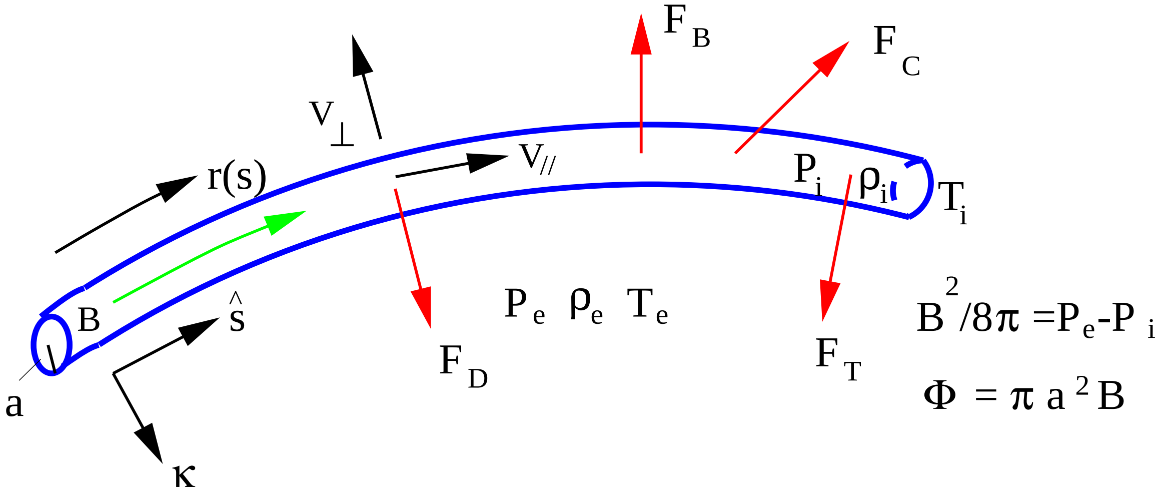
Pevtsov, Canfield & Metcalf (1995) and Longcope, Fisher & Pevstov (1998) did least squares fits to constant α fields ($i.e.$ $\mathbf{J} = \alpha\mathbf{B}$) in active regions to determine twists from vector magnetograms.

Measured twist in active regions:



Top panel shows twist α for 203 active regions versus latitude. Line shows fit to data. Bottom panel shows distribution of twists about the fit. Measured twist $\alpha = 2q$, where q is flux tube twist.

Untwisted Thin Flux Tube Models:



Use tube-like structure to transform MHD equations into an equation of motion for a 1-D tube moving in a 3D rotating model of solar interior:

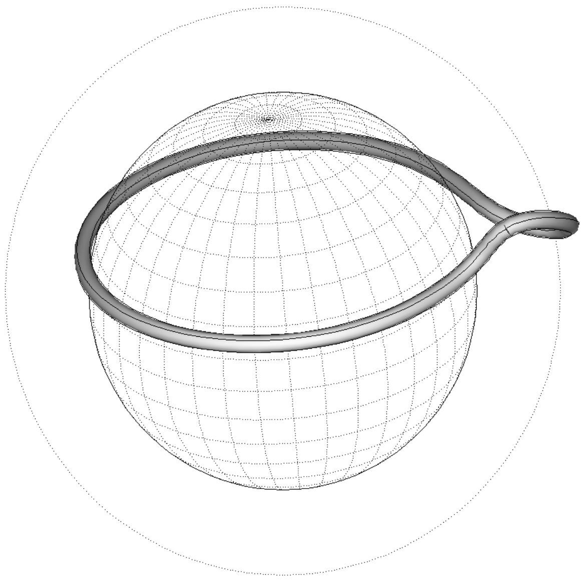
$$\rho_i D\mathbf{v}/Dt = \mathbf{F_B} + \mathbf{F_T} + \mathbf{F_C} + \mathbf{F_D} \ ,$$

where

$$\boldsymbol{F_B} = g\ (\rho_e - \rho_i)\ \hat{\boldsymbol{r}}\ ;\ \boldsymbol{F_T} = B^2/4\pi\ \boldsymbol{\kappa}\ ,$$

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

Thin Flux Tube Simulations:



Emerging

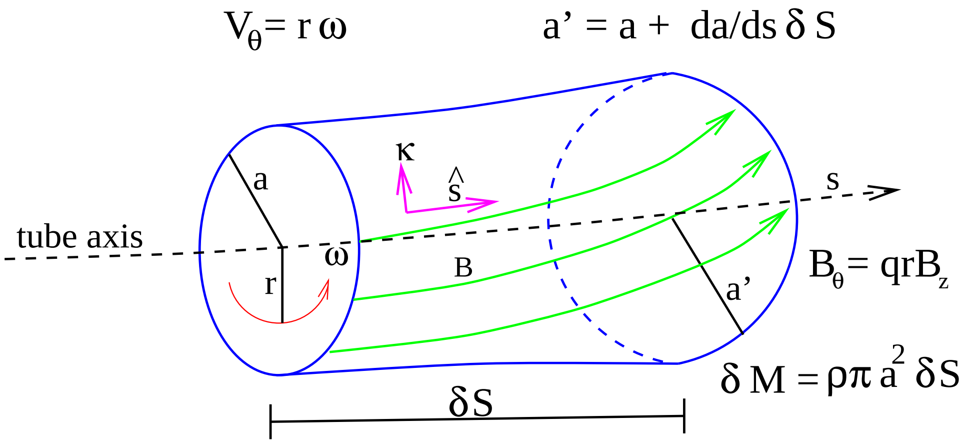
Active Region

Flux Loops

Tilted by

Coriolis Force

Slighly twisted flux tubes:



If twist is small ($qa << 1$) can still use untwisted flux tube equations, plus 2 independent "parasitic" equations for ω and q (Longcope & Klapper 1997, ApJ 488, 443):

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

where

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

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

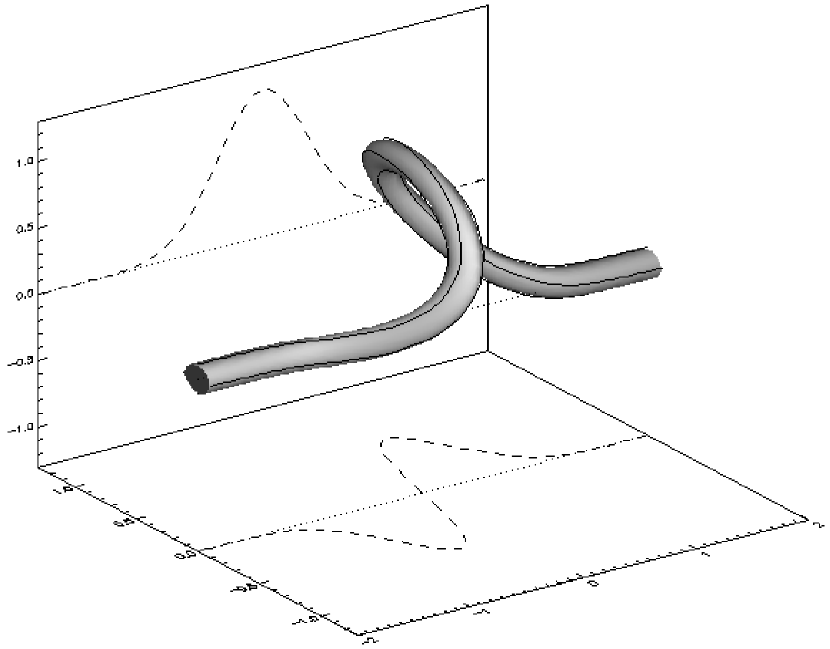
For a thin flux tube: $H = \Phi^2(Tw + Wr)$. (Conservation of Magnetic Helicity H, where Tw is "twist", Wr is "writhe".)

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

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

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

"Σ effect" – right handed twist from left handed writhe:



Possible sources of twist for solar active regions:

- Writhing from active region tilts (Joy's law) $q \sim 2\Psi/L \sim 10^{-3}$ Mm^{-1} – too small.

- Writhing from differential rotation (like Babcock 1961) $q \sim 1/R_{CZ} \sim 2 \times 10^{-3}$Mm^{-1} – too small.

- Writhing from kinetic helicity in convective turbulence – correct sign, but how important?

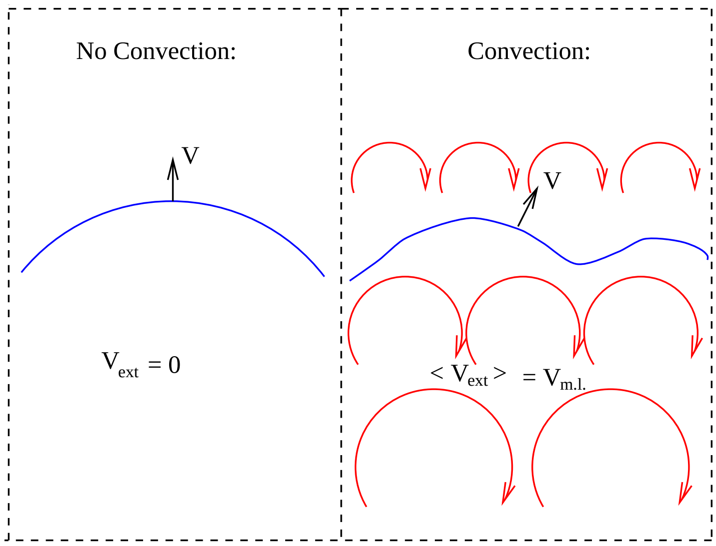
Writhing by Convective Turbulence:

- Develop tractible model of convective turbulence including kinetic helicity

- Solve equations of motion for flux tube rising through turbulent medium

Convective Turbulence Model

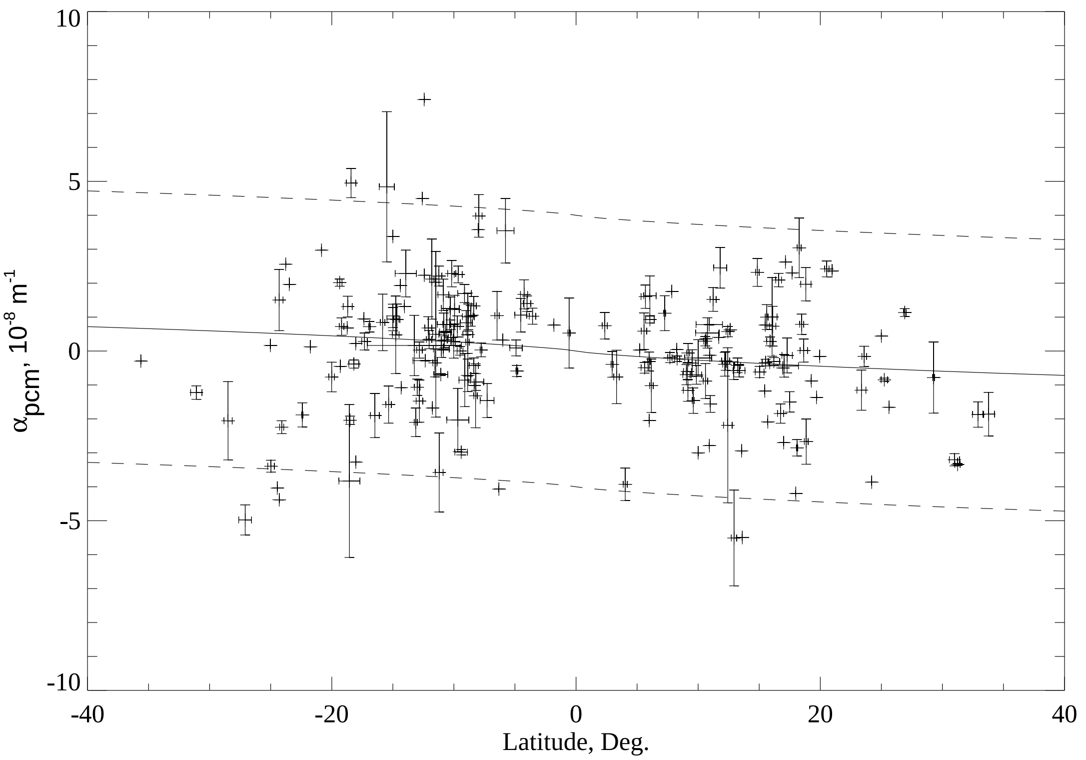
- Mean convective velocity given by a solar interior mixing-length model. Structure of the turbulence is a convolution of white noise with a spatial filter, with a correlation length equal to the "mixing length"(§3, Longcope & Fisher 1996, ApJ 458, 380.
- Mean kinetic helicity $< \mathbf{v_c} \cdot \nabla \times \mathbf{v_c} > \simeq -2 v_{m.l.} \Omega_\odot \sin(\theta)$, where $v_{m.l.}$ is the mixing length velocity, $\Omega_\odot$ is the solar rotation rate, and θ is latitude (see Longcope, Fisher & Pevtsov 1998 ApJ, in press, available as http://sprg.ssl.berkeley.edu/~fisher/alpha.ps.gz)



Writhing the Flux Tube

- Solve thin flux tube equations, and equations for ω and q, for an initially horizontal tube rising through the convective turbulence. Motions of tube coupled to convection through aerodynamic drag
- Σ effect most effective at high wave numbers (small size scales)
- Calculations repeated many times for different realizations of turbulence,different latitudes, and values of flux Φ.

Results for $\Phi = 10^{22}$ Mx :

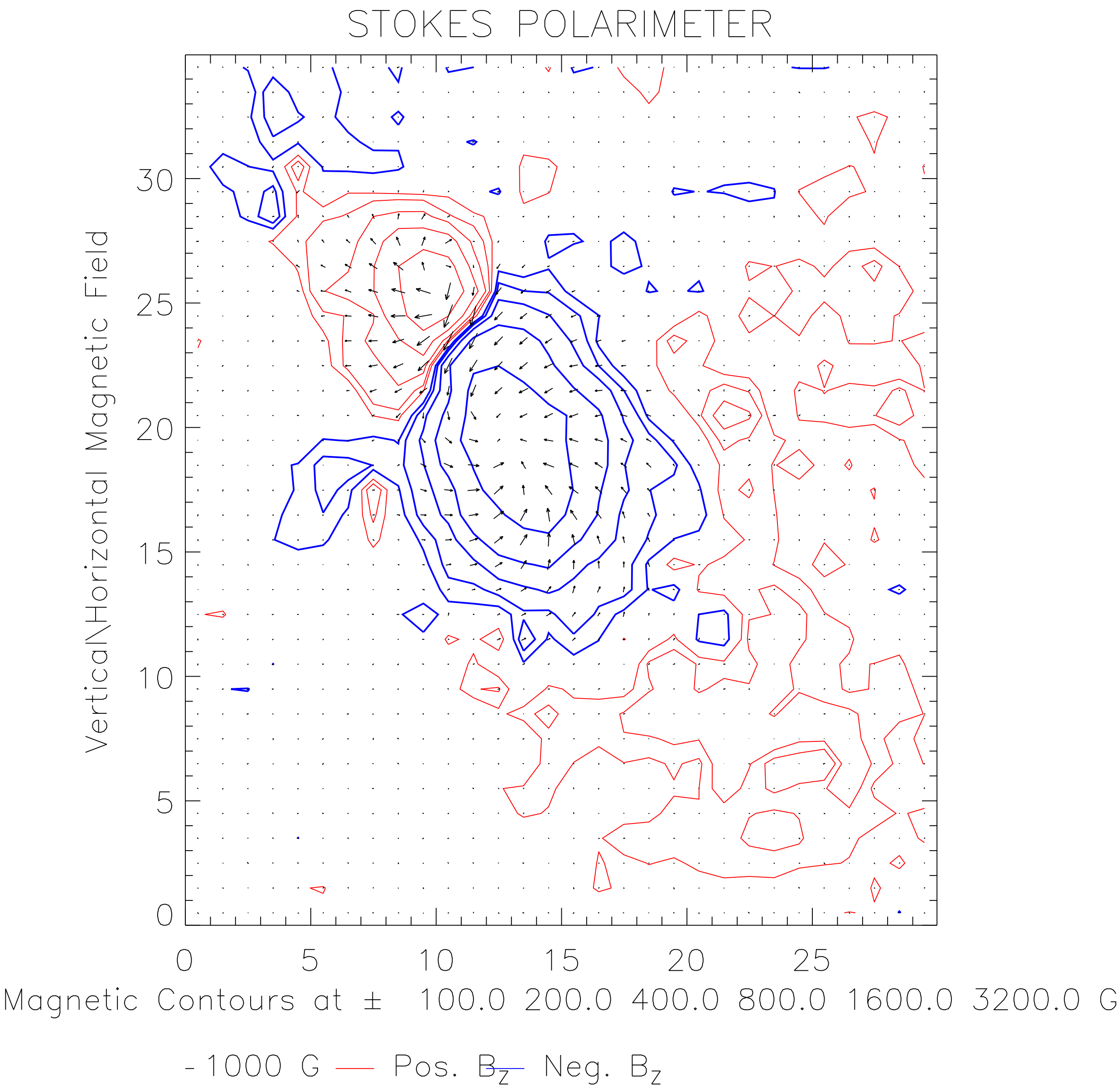


- Data points: measured values of α from vector magnetograms.
- Solid curve: mean value of $\alpha = 2q$ versus θ from Σ effect.
- Dashed curves: RMS scatter about mean values from Σ effect.

Can explain observed levels of twist for most active regions by the action of turbulent convective motions writhing active region flux tubes during emergence.

Highly Twisted Active Regions (δ Spot Regions):

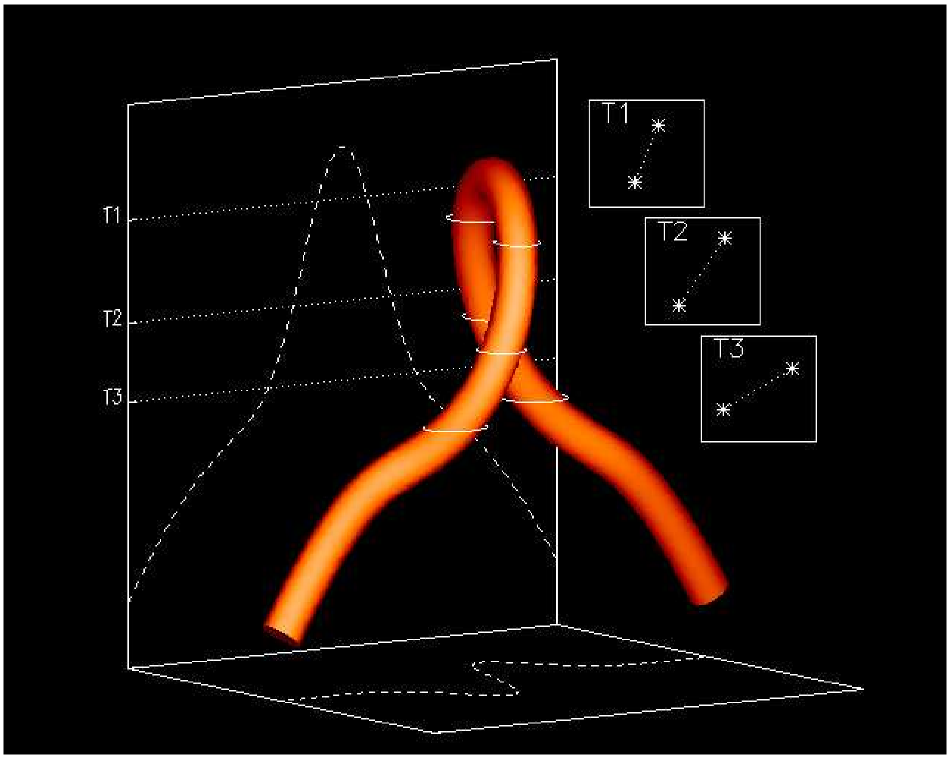
NOAA 6199 13-MAY-1991



- "Incorrect" (non E-W) orientation, rotation during emergence
- Opposite polarities jammed together
- Strong twist, and strong shear along neutral line
- Large solar flares

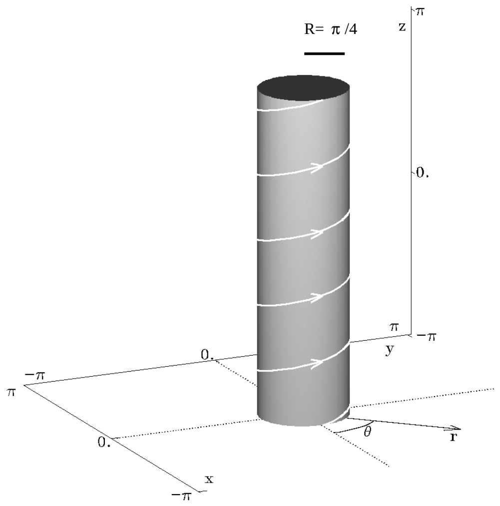
What is going on?

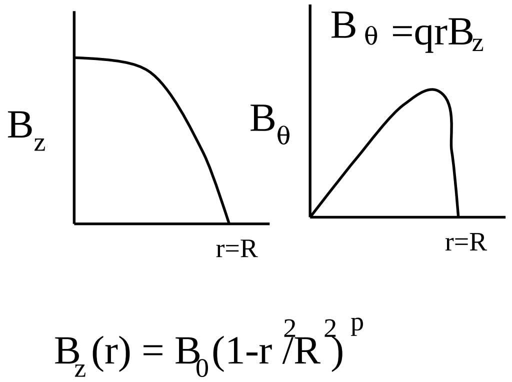
Perhaps highly twisted active regions are flux loops which are kink unstable:



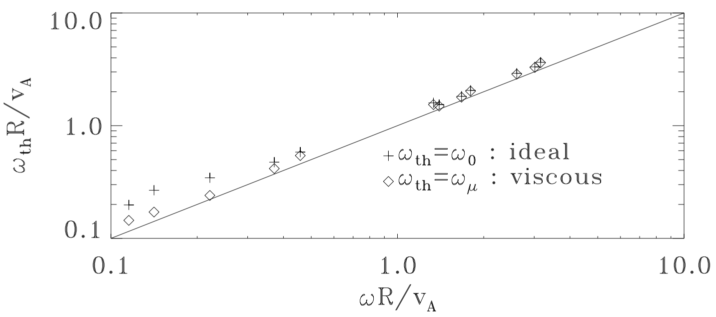
- Investigate the Kink Instability as a Mechanism for δ-spot formation

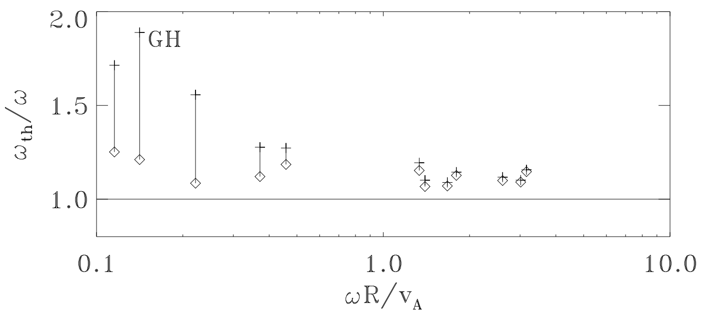
To understand how the kink mode might affect a highly twisted flux tube in the interior, first try to understand the simplest case possible: A twisted, cylindrical magnetic equilibrium $\mathbf{B_0}(r)$, illustrated schematically below:



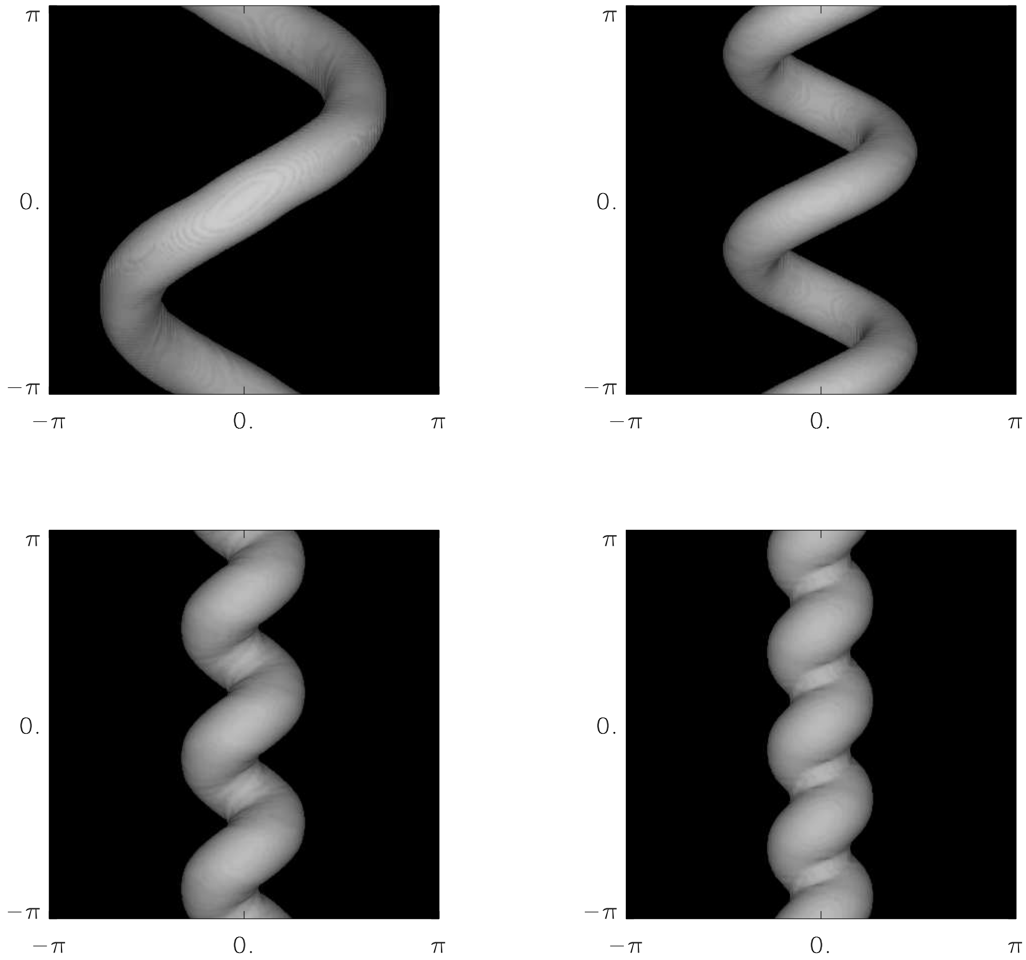


Linear Stability: Let $\boldsymbol{v}= d\boldsymbol{\xi}/dt$, and $\boldsymbol{B_1}=\boldsymbol{\nabla} \times (\boldsymbol{\xi} \times \boldsymbol{B_0})$. If one assumes that $\boldsymbol{\xi}$ has the form $\boldsymbol{\xi_0(r)}\ e^{\omega t}$, then the growth rate ω and the eigenfunction $\boldsymbol{\xi_0(r)}$ can be determined using the classical "energy" method (Linton, Longcope & Fisher 1996, ApJ 469, 954). A comparison of these growth rates with those from a full 3D 128^3 spectral MHD simulation shows extremely good agreement:





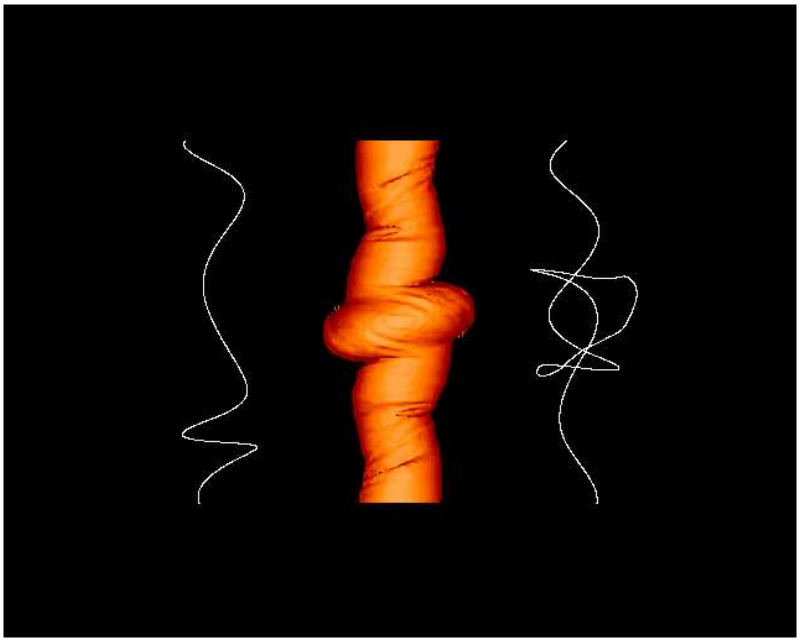
Single unstable kink modes (at saturation):

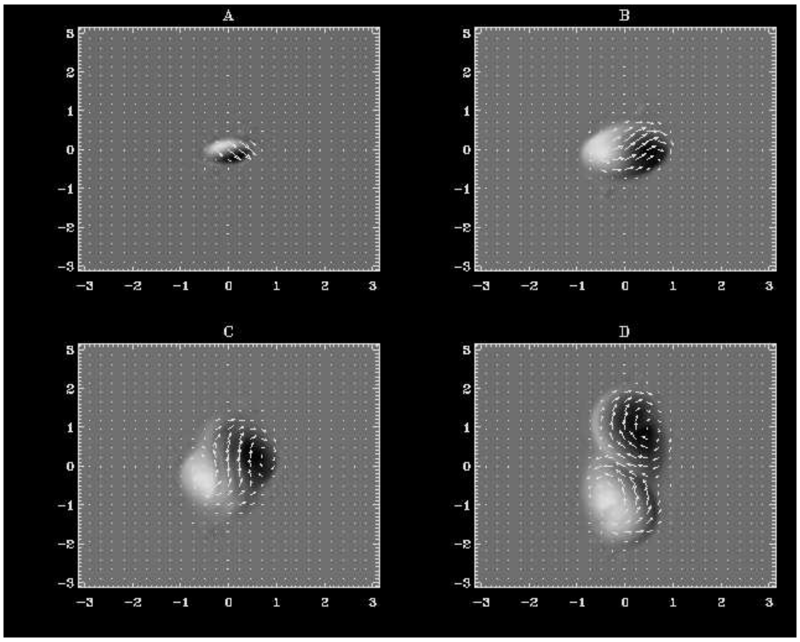


- Not quite a δ spot region.
- Simulations:
  Linton, Dahlburg, Fisher & Longcope (ApJ, 1998, in press – available as http://sprg.ssl.berkeley.edu/∼fisher/ldfl.ps.gz)

What about Multi-mode kinks?

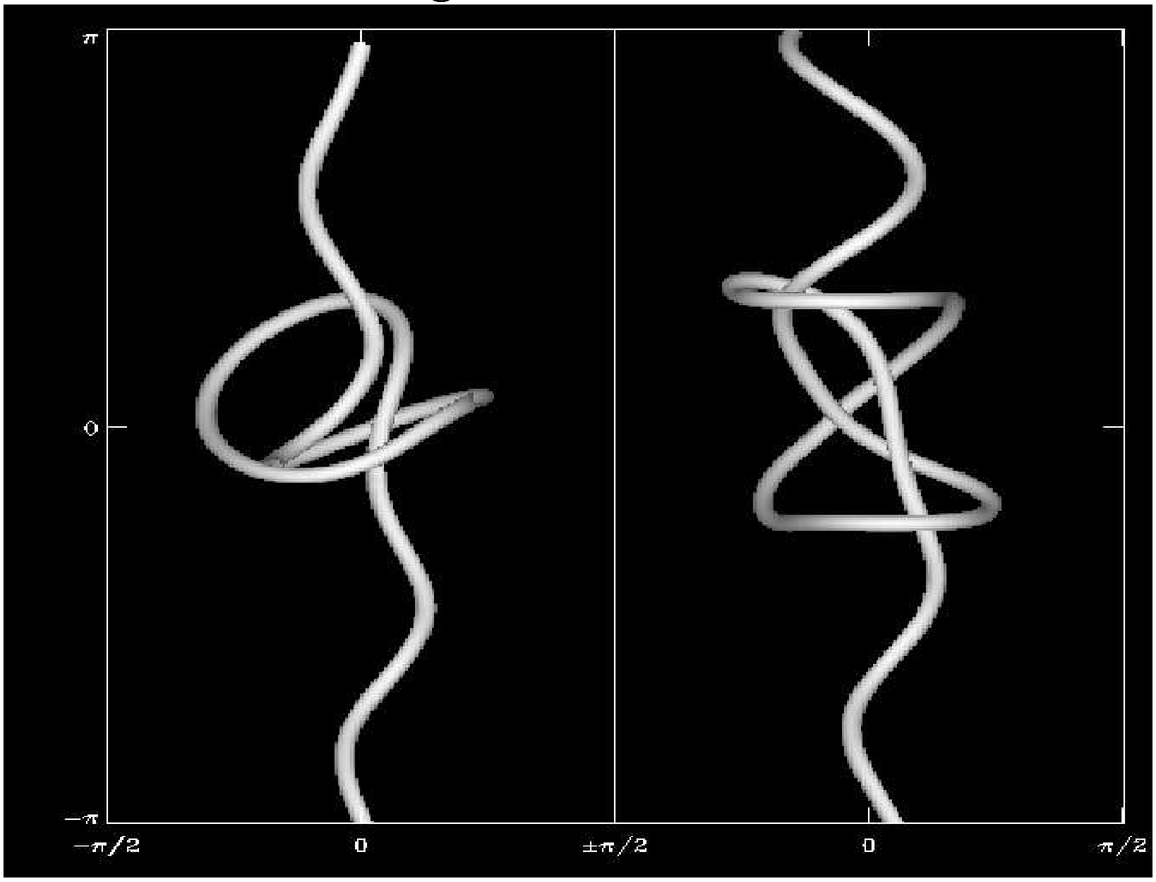
(see http://sprg.ssl.berkeley.edu/~linton/cospar.ps.gz)





- Magnetic morphology looks promising!

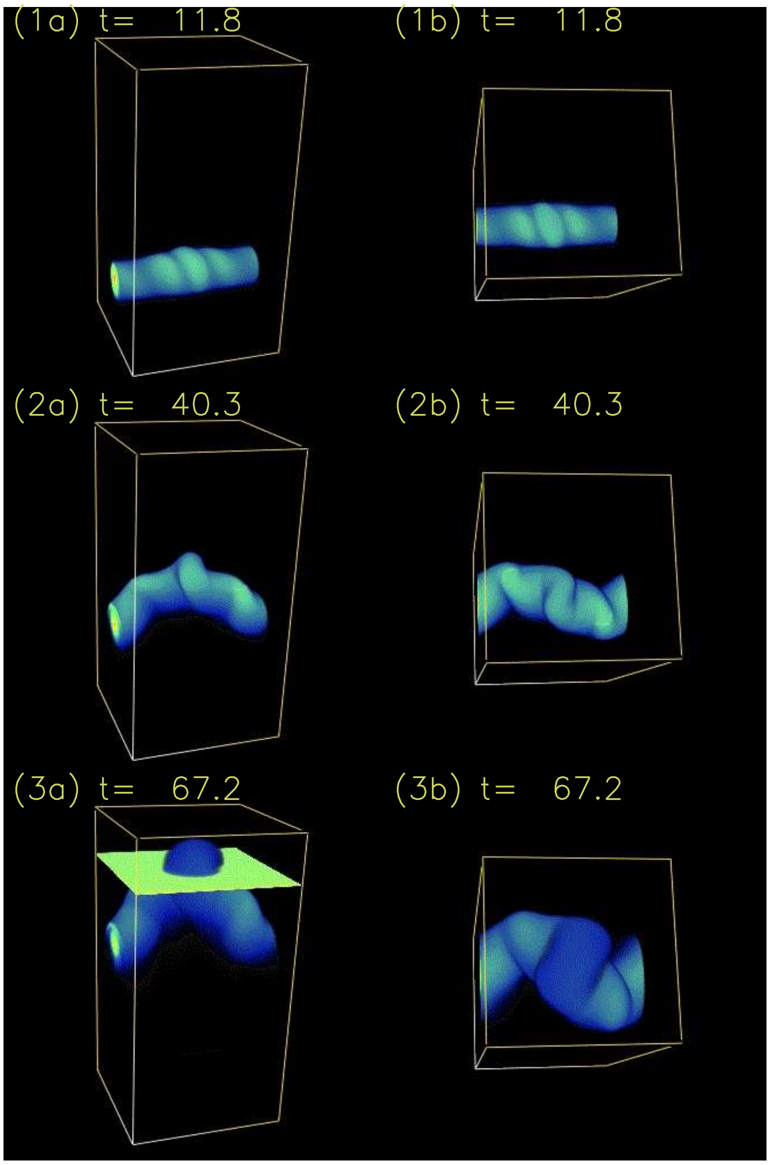
Structure of the magnetic "knot" after reconnection:



Many of the field lines actually become knotted.

Recent simulations of rising, kinking flux tube in a stratified atmosphere:

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 ApJ 505, L59):



Conclusions – What we (might) understand:

- How twist is introduced into ordinary active regions by kinetic helicity in convective motions
- How the features of δ spot active regions can be related to kinking of highly twisted, active region flux tubes

what we don't understand:

- Why ordinary active regions don't completely fragment during emergence with such small amounts of twist. Observed levels of twist too small to prevent fragmentation
- How δ-spot active regions acquire so much twist