The Solar Dynamo
and
Emerging Flux

George H. Fisher¹
Yuhong Fan²
Dana W. Longcope³
Mark G. Linton⁴
Alex A. Pevtsov⁵

¹SSL, UC Berkeley
²HAO, NCAR
³Physics Department, Montana State University
⁴Naval Research Laboratory
⁵Physics Department, Montana State University
What can we learn about magnetic fields generated by the Solar Dynamo by studying the properties of active regions emerging on the surface of the Sun?

Approach: Use theoretical models of active region flux ropes to compute dynamical behavior, and relate to observed properties of active regions. Then can deduce properties of the magnetic fields in the solar dynamo region near the base of the solar convection zone.

Other Major Contributors:

- Dean-Yi Chou (who got me started on this)
- Fernando Moreno-Insertis
- Arnab Choudhuri
- Antonio Ferriz Mas
- Sydney D'Silva
- Manfred Schüssler
- + many others · · ·
What properties of solar dynamo magnetic fields can we learn about?

- Magnetic Field Strength at base of convection zone
- Time for an active region to rise through the convection zone
- The role of convective motions upon active region orientation
- The origins and role of magnetic twist in some active regions

Features of active regions we can explain in terms of flux rope dynamics:

- The variation of “tilt angle” with latitude (Joy’s Law) and with active region size (total magnetic flux)
- The dispersion of tilt angles with active region size (magnetic flux)
- The “equatorial gap” in the distribution of active regions
- Asymmetries between the leading and following sides of active regions, e.g. proper motions
- The properties of δ-spot active regions as highly twisted, kink unstable flux ropes

What is (probably) going on below the visible surface:

Before Emergence:
- Photosphere
- Convection Zone
- Radiative Zone
- Convective Overshoot Layer

After Emergence:
- Corona

\[ B \]
\[ V_{\text{rise}} \]
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

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

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

$$\rho_i Dv/Dt = F_B + F_T + F_C + F_D$$

where

$$F_B = g (\rho_e - \rho_i) \hat{r}$$
$$F_T = B^2/8\pi \kappa$$
$$F_D = -\rho_e (2/\pi \Phi/B)^{1/2} v_\perp |v_\perp|$$
$$F_C = -2\rho_i \Omega \times v$$

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

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

"Following" Polarity: Fragmented

\[ \alpha \] is the active region "tilt" angle

\( d \) is the polarity separation distance
\( d \sim \Phi \) (Howard 1992 Sol. Ph. 142, 233)

"Leading" Polarity: Compact

Joy’s law: \( \alpha \sim \sin \) (latitude)
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?

Numbers represent $B/10^4$ G from simulations of Fan and Fisher (1996)
What do the thin flux tube models tell us about the forces resulting in Joy’s Law?

Side view:

Balancing $\mathbf{F}_D$ and $\mathbf{F}_B$ (see “side view”), results in $V_{\text{rise}} \sim (a/H_P)^{1/2}V_A$, 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 $\rho \Omega V_{\text{rise}} \sin \theta \approx \rho V_A^2 \tan \alpha$, from which it is simple to show $\alpha \propto \sin \theta \Phi^{1/4}$. where $\Phi$ is the magnetic flux in the tube. Now, we have also made a prediction about how $\alpha$ and $\Phi$ 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:

Curves: Theory
(Longcope & Fisher 1996)

Data points: Sunspot groups
(Fisher, Fan & Howard 1995)
Asymmetric Spot Motions

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 Schüssler (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.
Distribution of twist in active regions with latitude:

- Data points: measured twists from vector magnetograms.
- Dashed curves: RMS scatter about mean values from Σ effect.

The Σ effect results from the introduction of twist into a flux tube as a result of “writhing” the flux tube by convective motions. Because of magnetic helicity conservation, the twist and writhe changes in a flux tube are equal in magnitude but of opposite sign. This theory can explain observed levels of twist for most active regions by the action of turbulent convective motions writhing active region flux tubes during emergence. Further details can be found in the paper cited above, and in the contributed poster paper by Fisher et al. at this meeting.
Highly Twisted Active Regions (\(\delta\) Spot Regions):

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- "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 $B_0(r)$, illustrated schematically below:

$$B_z(r) = B_0(1 - r^2/R^2)^p$$

Linear Stability: Let $v = d\xi/dt$, and $B_1 = \nabla \times (\xi \times B_0)$. If one assumes that $\xi$ has the form $\xi_0(r) e^{\omega t}$, then the growth rate $\omega$ and the eigenfunction $\xi_0(r)$ 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 $\delta$ spot region.
- Simulations:
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:

Conclusions:

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

- Magnetic Field Strength at base of convection zone - $B \sim 3 - 10 \times 10^4$G
- Time for an active region to rise through the convection zone - $t \sim 1 - 3$ months
- The role of convective motions upon active region orientation - moderate deflections resulting statistically in dispersion of tilt orientations
- The origins and role of magnetic twist in active regions - from helicity in convective turbulence for many active regions; a few very highly twisted active regions kink and form δ-spot active regions

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