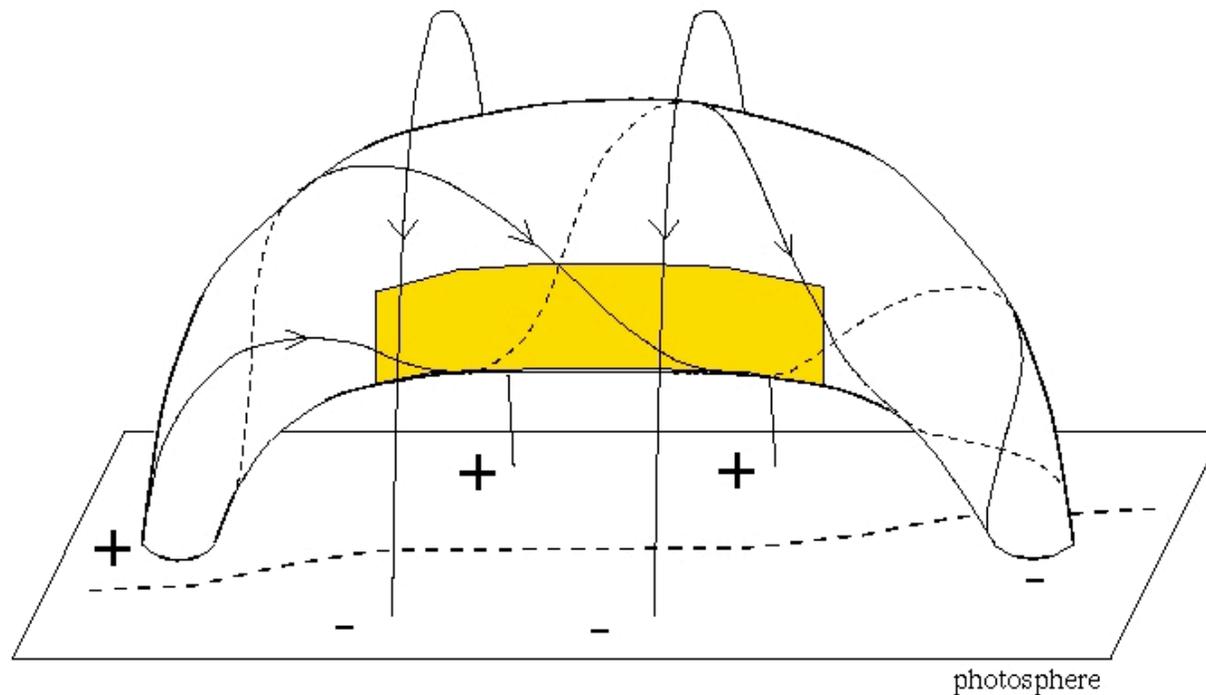# The Role of Sub-Surface Processes in the Formation of Coronal Magnetic Flux Ropes

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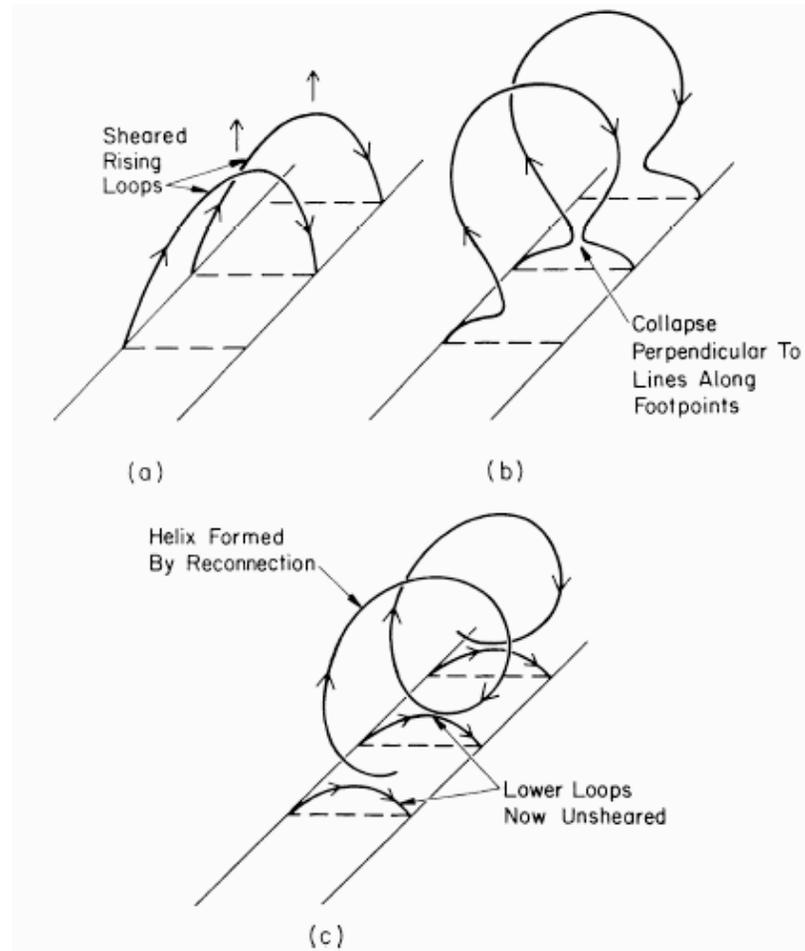Cambridge, MA

Pre-CME Magnetic Structure

Sheared photospheric magnetic fields (Pevtsov, Canfield & Metcalf 1995) and S-shaped coronal X-ray structures (Rust & Kumar 1996) suggest presence of a *magnetic flux rope* in corona:

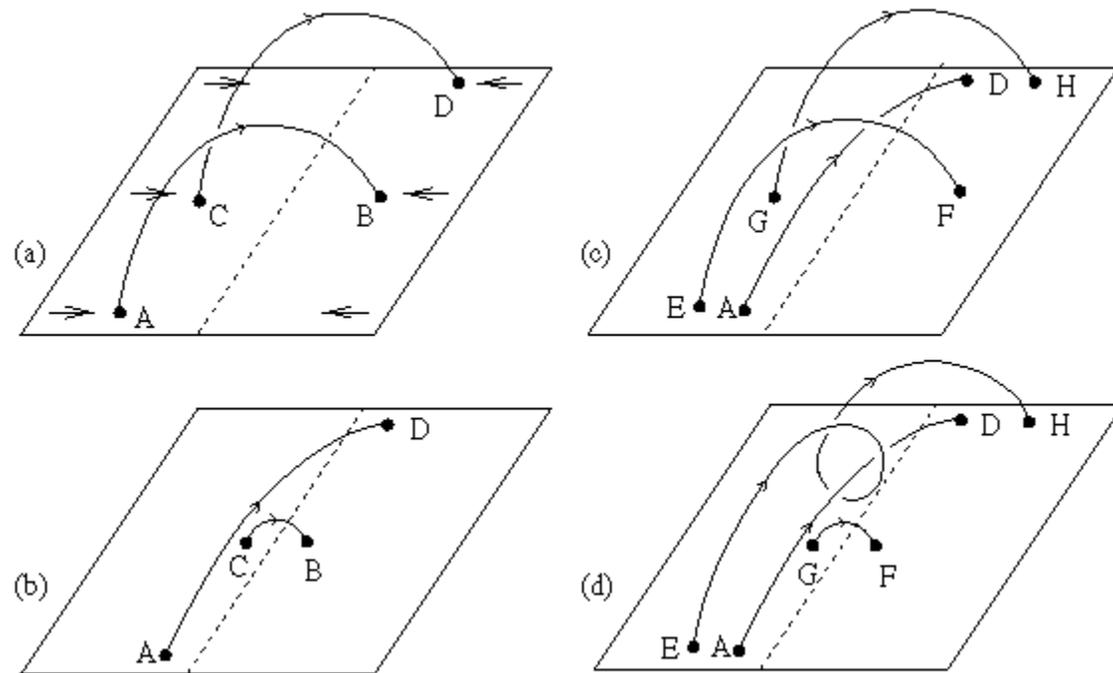Flux rope must be held down by overlying coronal arcade.

Formation of Coronal Flux Ropes
by Reconnection

Pneuman (1983):

Formation of Coronal Flux Ropes
by Reconnection

Photospheric flux cancellation in a *sheared arcade* involves reconnection, creating a helical field:

From: van Ballegooijen & Martens (ApJ 343, 971, 1989)

Formation of Coronal Flux Ropes
by Reconnection

<u>Mean-field approach</u> to modeling the evolution of the coronal field over many days (e.g., van Ballegooijen et al, ApJ 539, 983, 2000):
- The coronal field is sum of *mean* and *fluctuating* components.
- The fluctuating field is due to small-scale random footpoint motions, which produce *diffusion* of the mean field.
- Only the mean field **B**(r,_,_,t) is actually simulated.
- Mean field is assumed to be *force free* (magneto-friction: **v** ~ **j** _ **B**).
- At the photosphere, field is subject to diffusion and differential rotation
- Surface diffusion of B_r results in flux cancellation, but there is no radial diffusion of horizontal field:

$$\frac{\partial A_\theta}{\partial t} = v_\phi B_r - \frac{D}{r \sin\theta} \frac{\partial B_r}{\partial \phi}, \qquad \frac{\partial A_\phi}{\partial t} = -v_\phi B_r + \frac{D}{r} \frac{\partial B_r}{\partial \theta},$$

# Formation of Coronal Flux Ropes
by Reconnection

Example:
- Evolution of a single bipole.
- Coronal field evolves in *ideal* MHD.
- Various degrees of active-region tilt and helicity were considered.
- Initial field is *weakly sheared* (no helix).
- Photospheric flux is subject to *diffusion* and *differential rotation*.
- Flux cancellation at the neutral line involves magnetic *reconnection*, produces a flux rope after ~ 3 days.
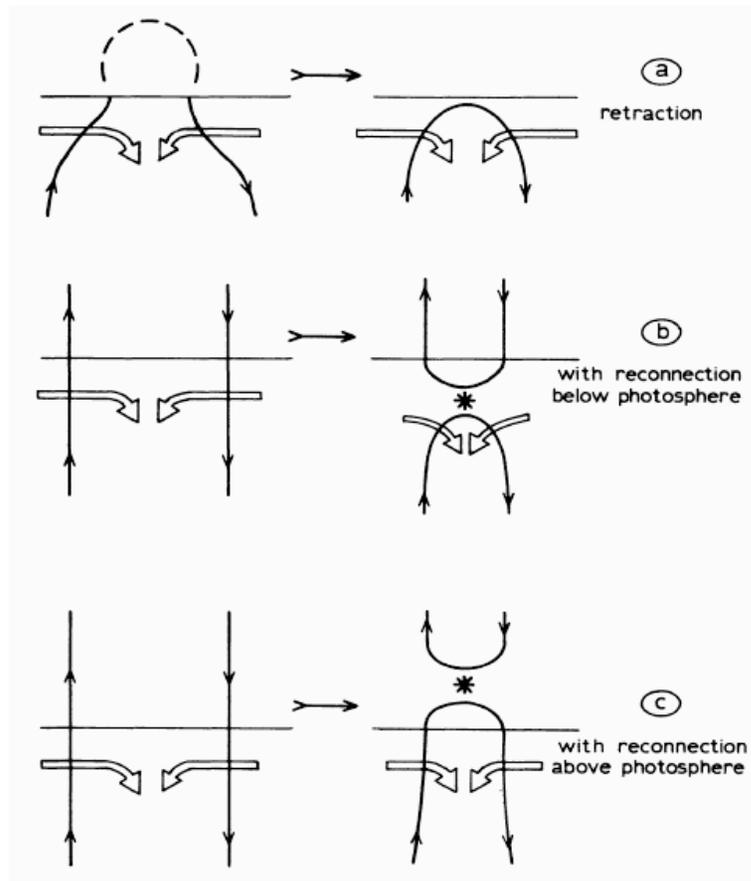
See: Mackay & van Ballegooijen
ApJ 560, 445, 2001
ApJ 621, L77, 2005
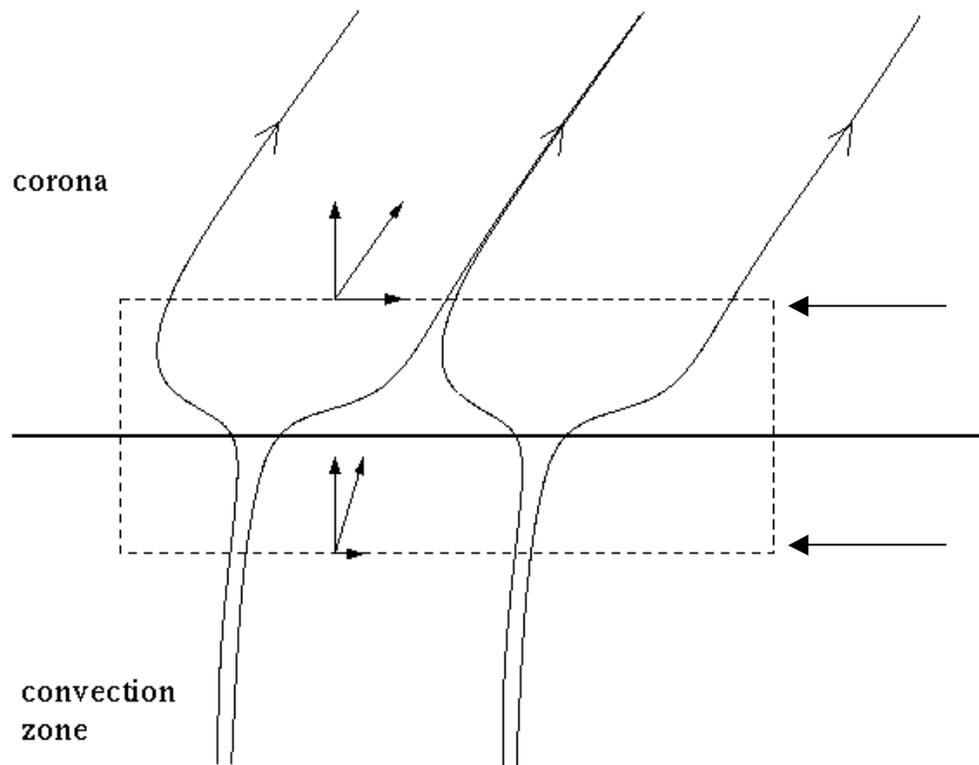
t=0

t=3
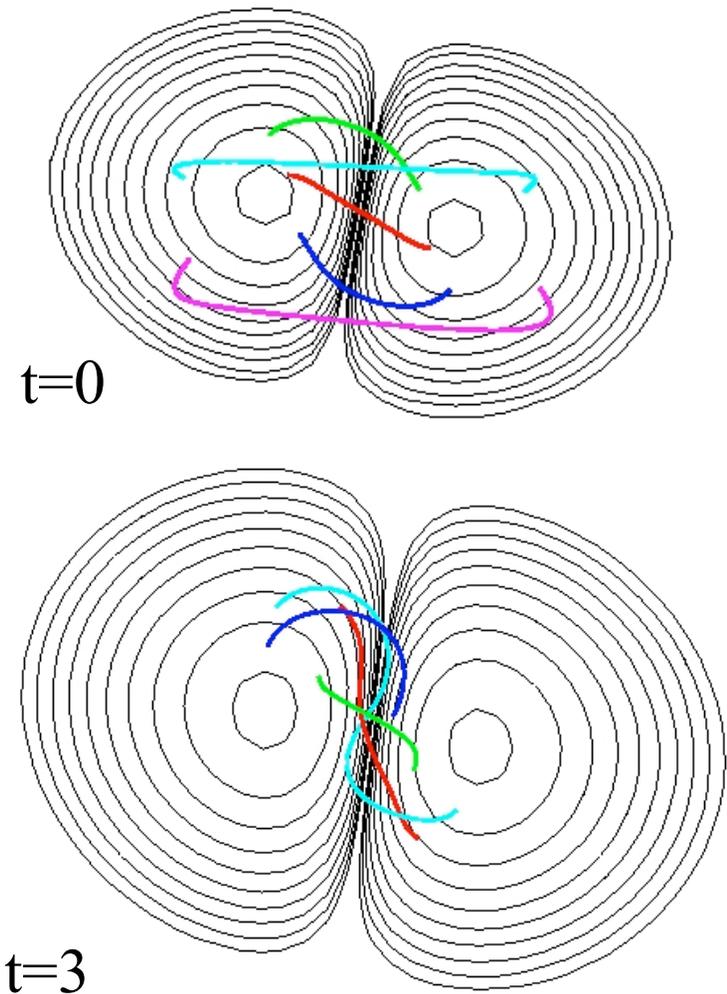
Flux Cancellation

Modes for removal of magnetic flux from the photosphere:

From: Zwaan (1987)
Ann. Rev. A&A 25, 83

Fibril Structure of Sub-Surface Field

At photosphere-corona interface, continuity of mean magnetic stress ($M_{xz,phot}=M_{xz,cor}$) and mean vertical field ($B_{z,phot}=B_{z,cor}$) implies there is a *discontinuity* in mean horizontal field (f=filling factor):

$$B_{x,phot} = fB_{x,f} = fB_{x,cor}$$

$$M_{xz,cor} = B_{x,cor}B_{z,cor}$$

$$M_{xz,phot} = \langle B'_x B'_z \rangle = fB_{x,f}B_{z,f}$$

$$B_{z,phot} = \langle B'_z \rangle = fB_{z,f}$$

corona

convection zone

Sub-Surface Structure of Active Regions
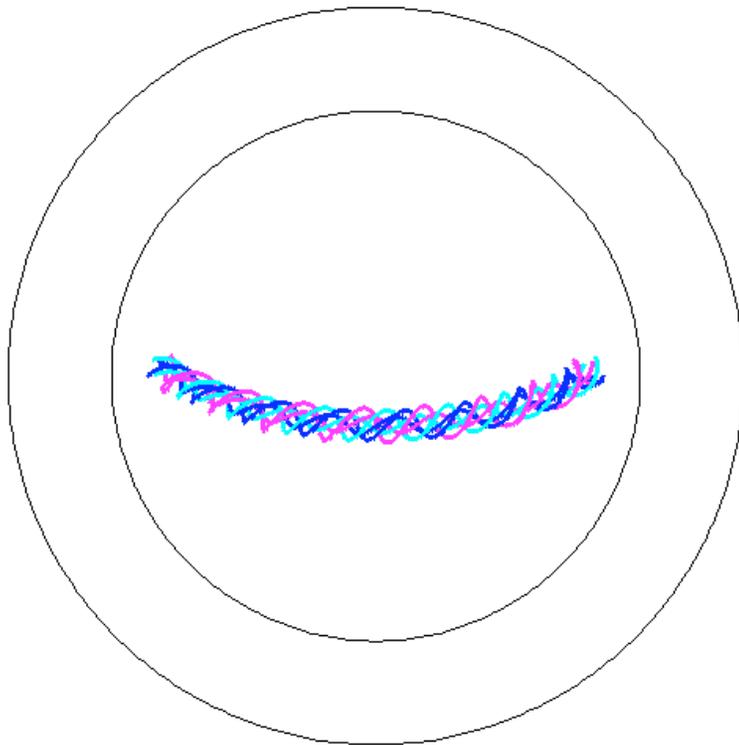
Simple 2D model of active-region decay and repair of toroidal field:
- Diffusion (600 km^{2}s^{-1}) and magnetic pumping (-20 m/s) in convection zone.
- Potential field in corona.
- Constant filling factor (f=0.1).

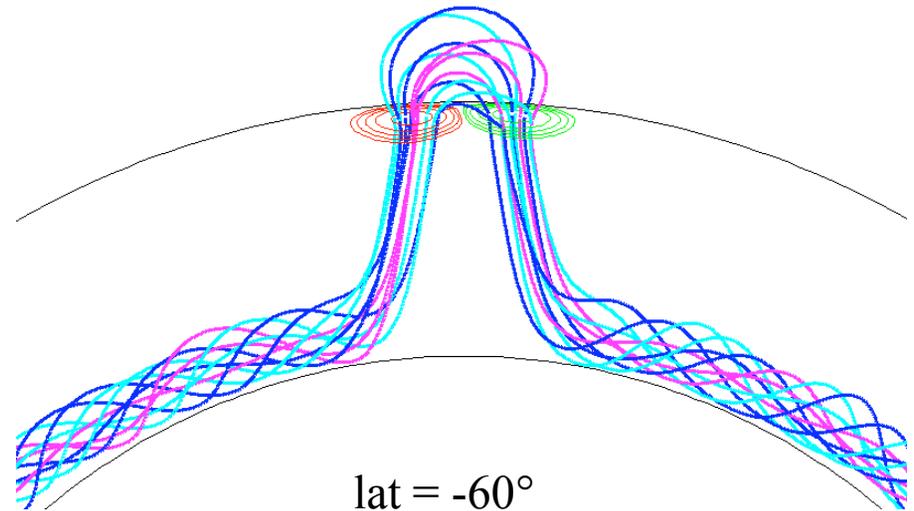See: van Ballegooijen (1997) in Synoptic Solar Physics, ASP Conf. Ser. v140, p17.
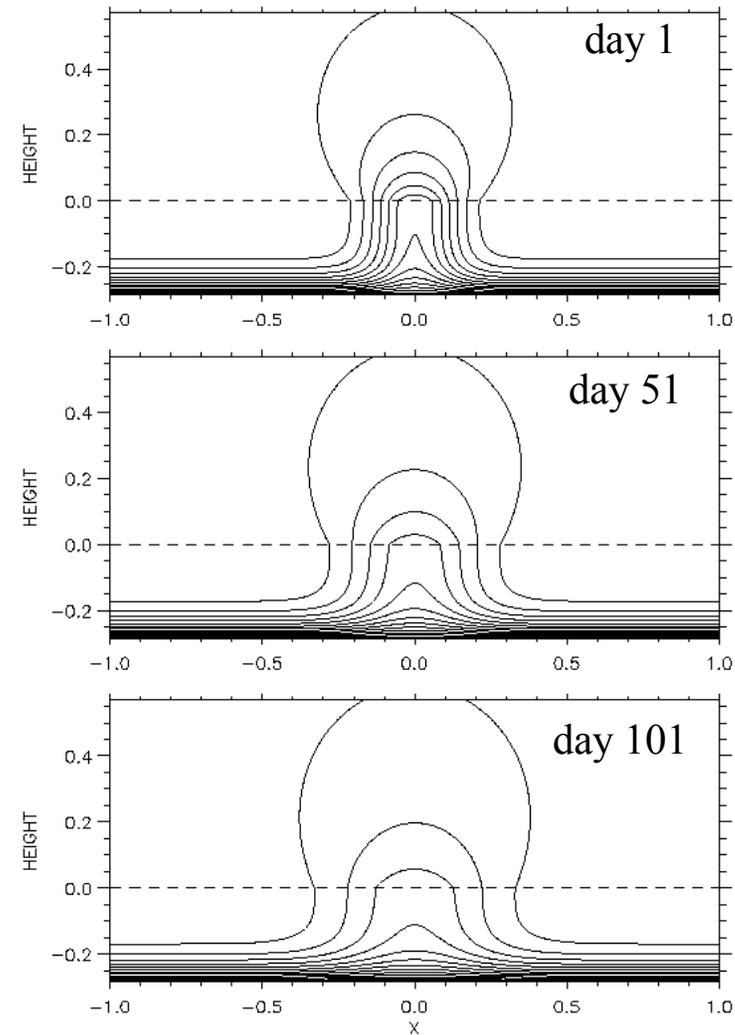
Model of Active-Region Evolution

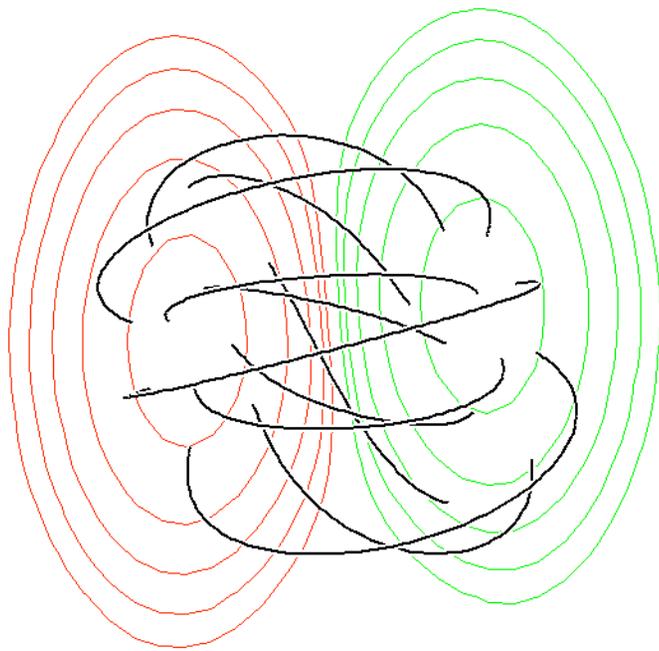Initial state is a toroidal flux rope
with left-helical twist:
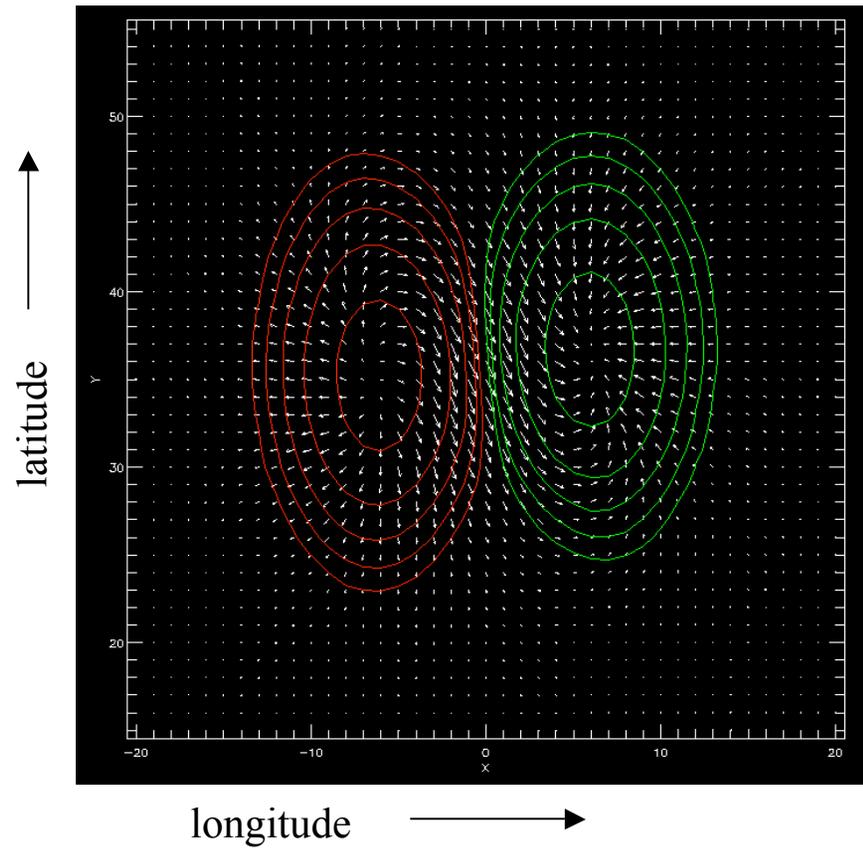
Simulated flux emergence:

lat = -60°

lat = +30°

Model of Active-Region Evolution

Coronal field lines (*left*) and photospheric vector field (*right*)
just after emergence:

lat = +20°
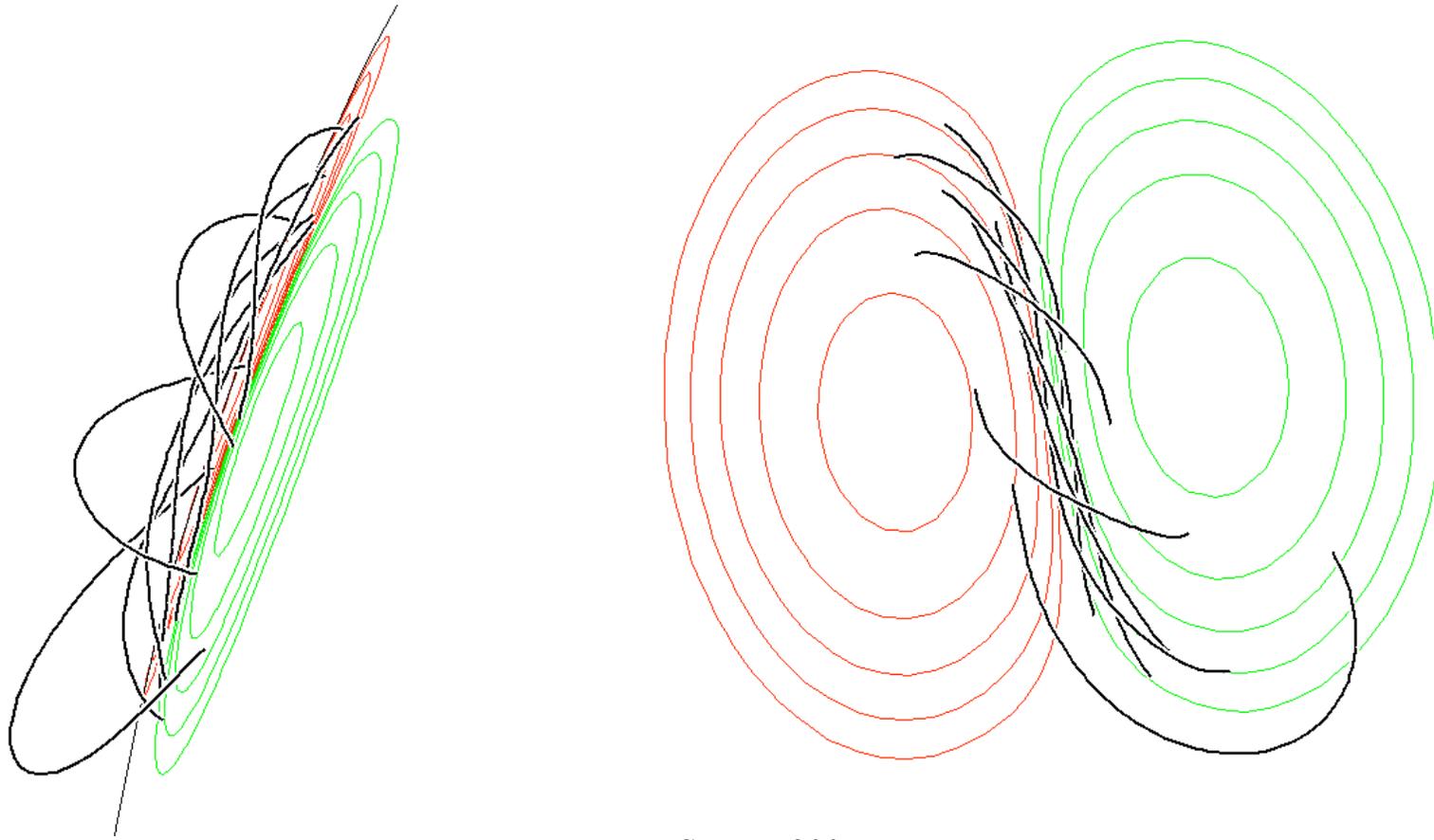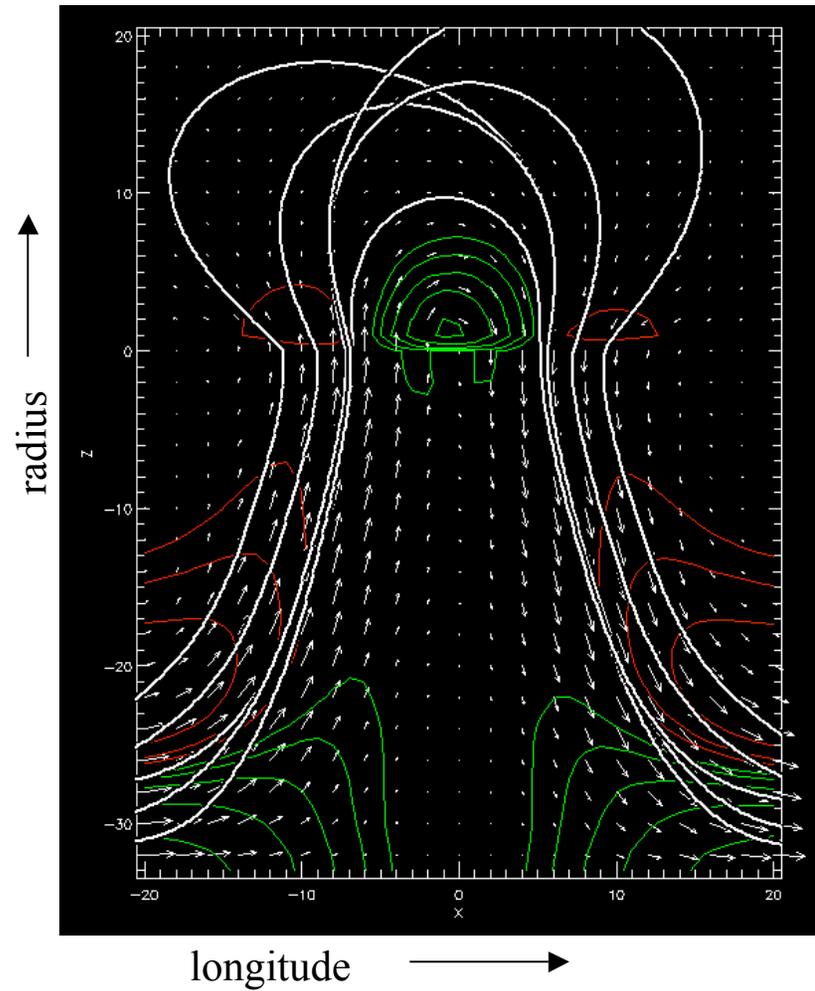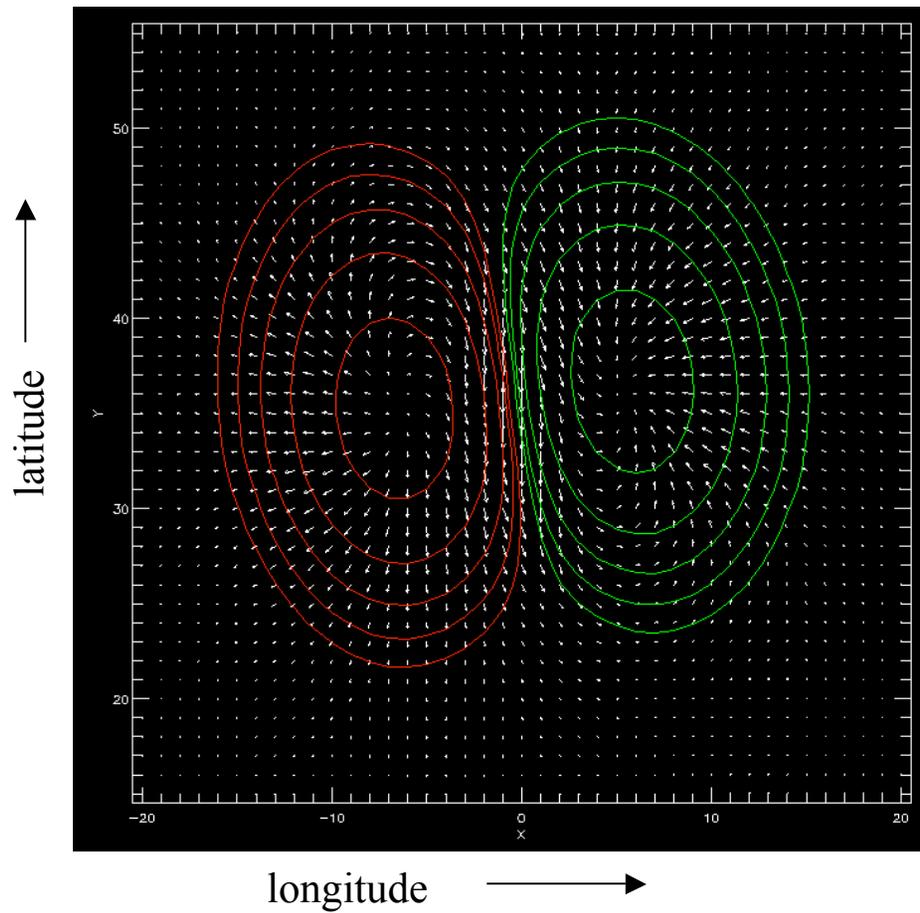
longitude ⟶

Model of Active-Region Evolution

Sub-surface evolution with diffusion (600 km^{2}s^{-1}), differential rotation, and downward pumping (-15 m/s). Ideal-MHD, non-linear force free field in corona. Coronal flux rope forms after only 2 days:
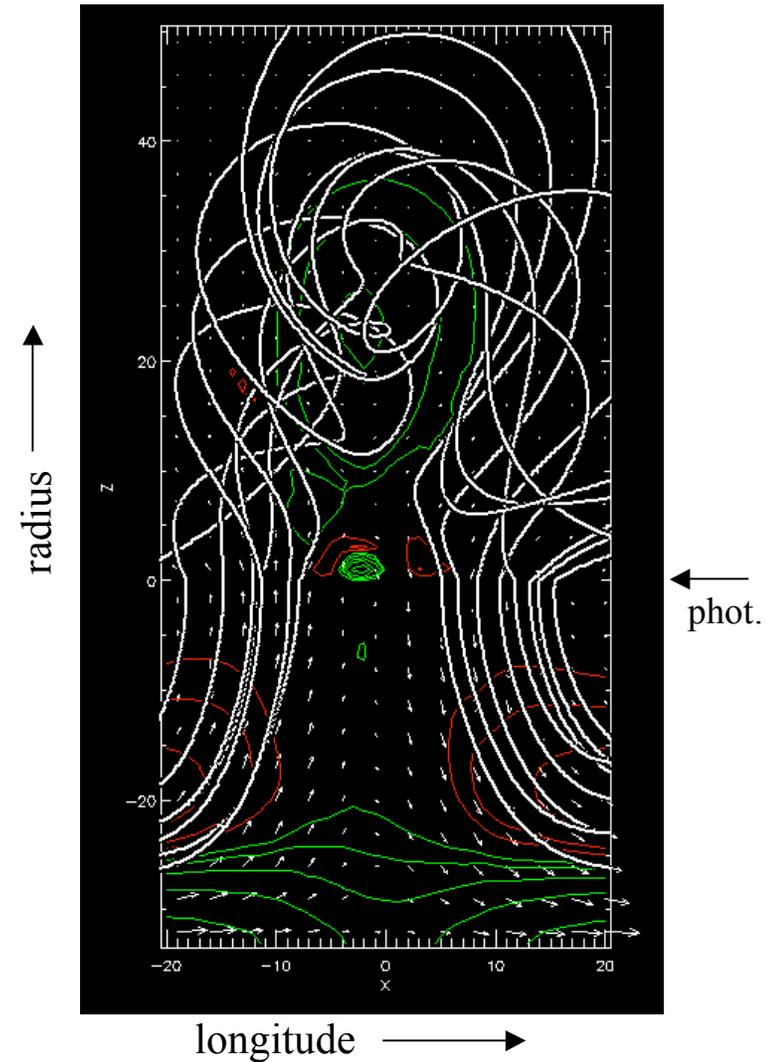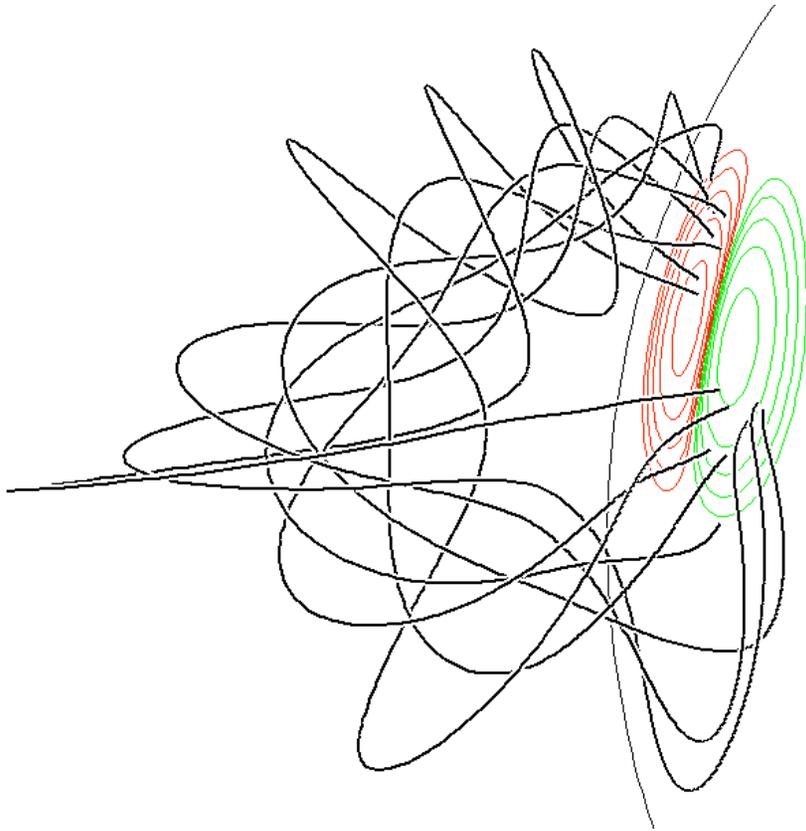
Model of Active-Region Evolution

Surface and sub-surface fields (day 2):

latitude

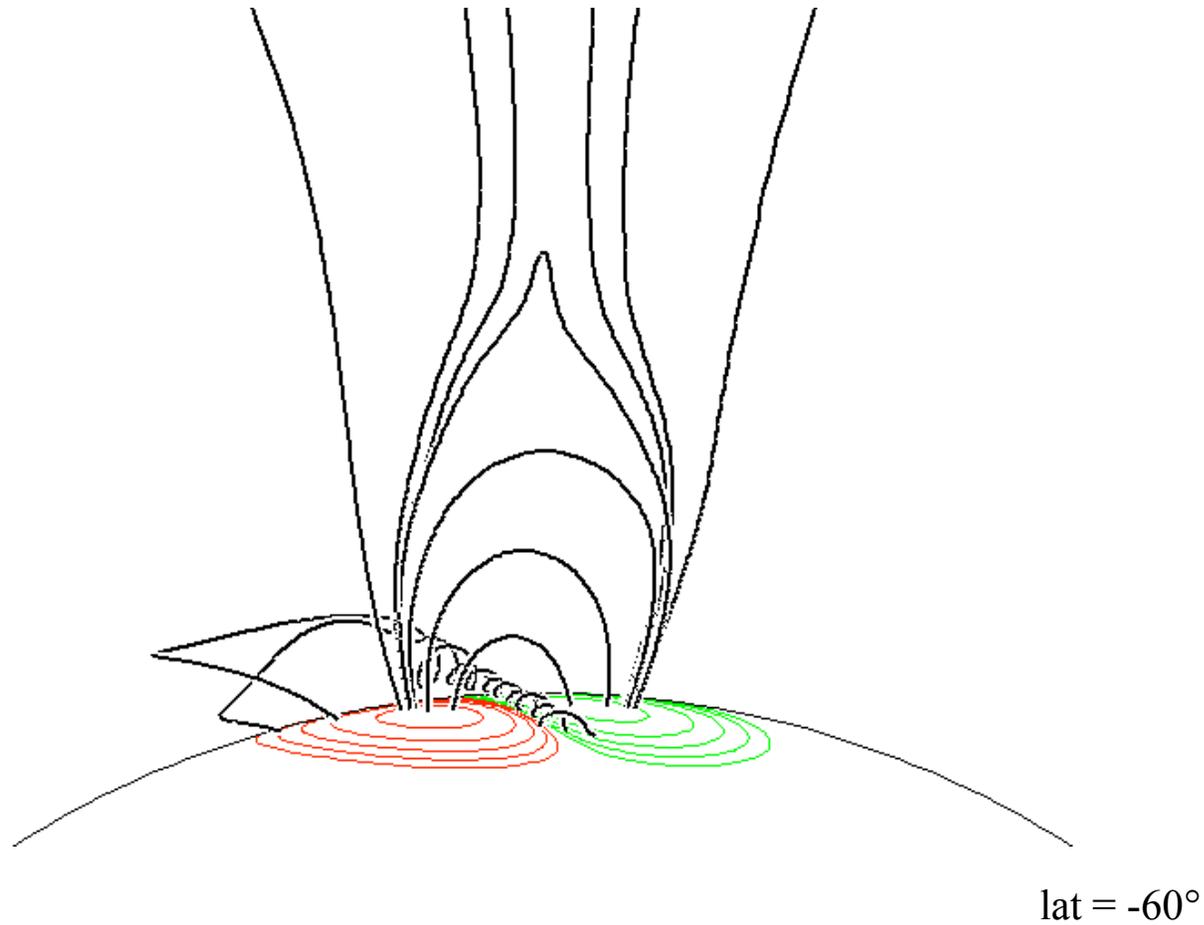longitude

radius

longitude

Model of Active-Region Evolution

Flux rope lifts off (day 13):

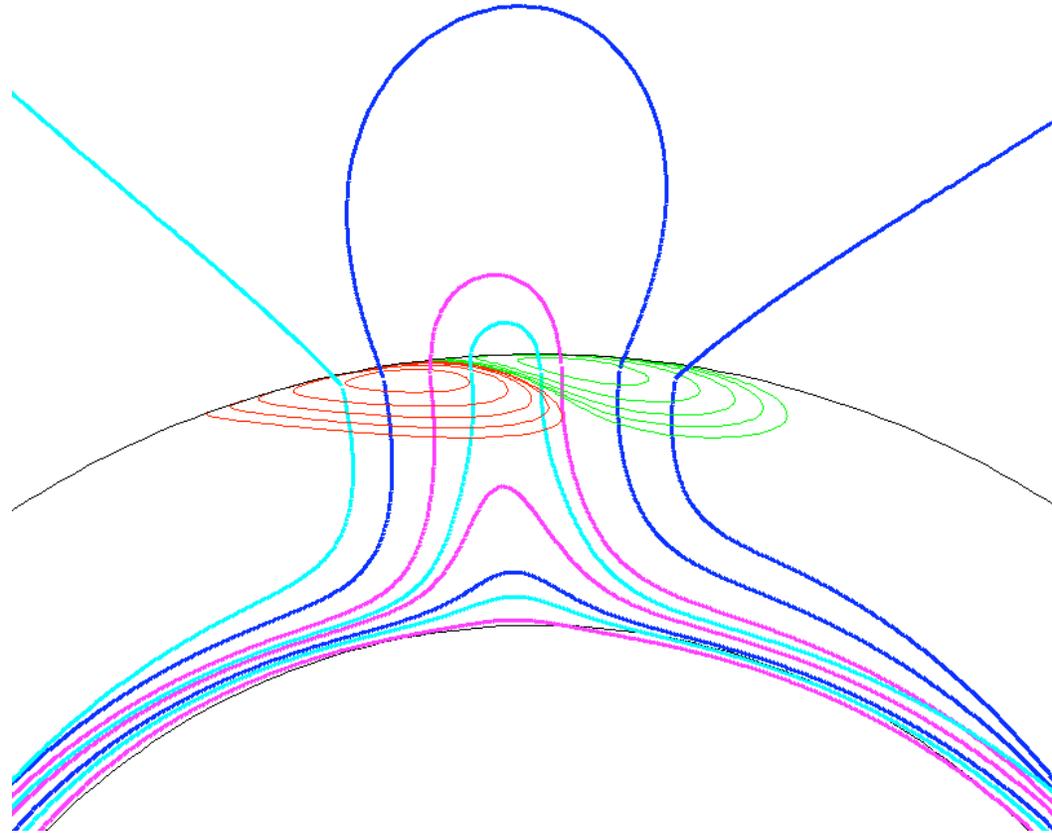radius ⟶

longitude ⟶

← phot.

Model of Active-Region Evolution

The field opens up after lift-off, and a new flux rope forms (day 20):

lat = -60°

Model of Active-Region Evolution

Cancelled flux submerges and "repairs" the toroidal field:

day 20
lat = -60°

Problem with this simulation: toroidal field has lost its twist.

Conclusions

1. Magnetic helicity of active regions *originates* in the convection zone. Initially, the coronal field is only weakly sheared (no helix).
2. Continuity of magnetic stress at photosphere-corona interface requires that the fibril field at top of convection zone is near vertical. This prevents the submergence of sheared (horizontal) fields.
3. During the decay of an active region, magnetic flux submerges, but magnetic helicity stays in the corona. Helical flux ropes are formed by reconnection associated with flux cancellation. The helicity is eventually removed by coronal mass ejections.
4. The submergence of magnetic flux into the convection zone leads to the repair of the toroidal field.