# Global Magnetic Field Evolution

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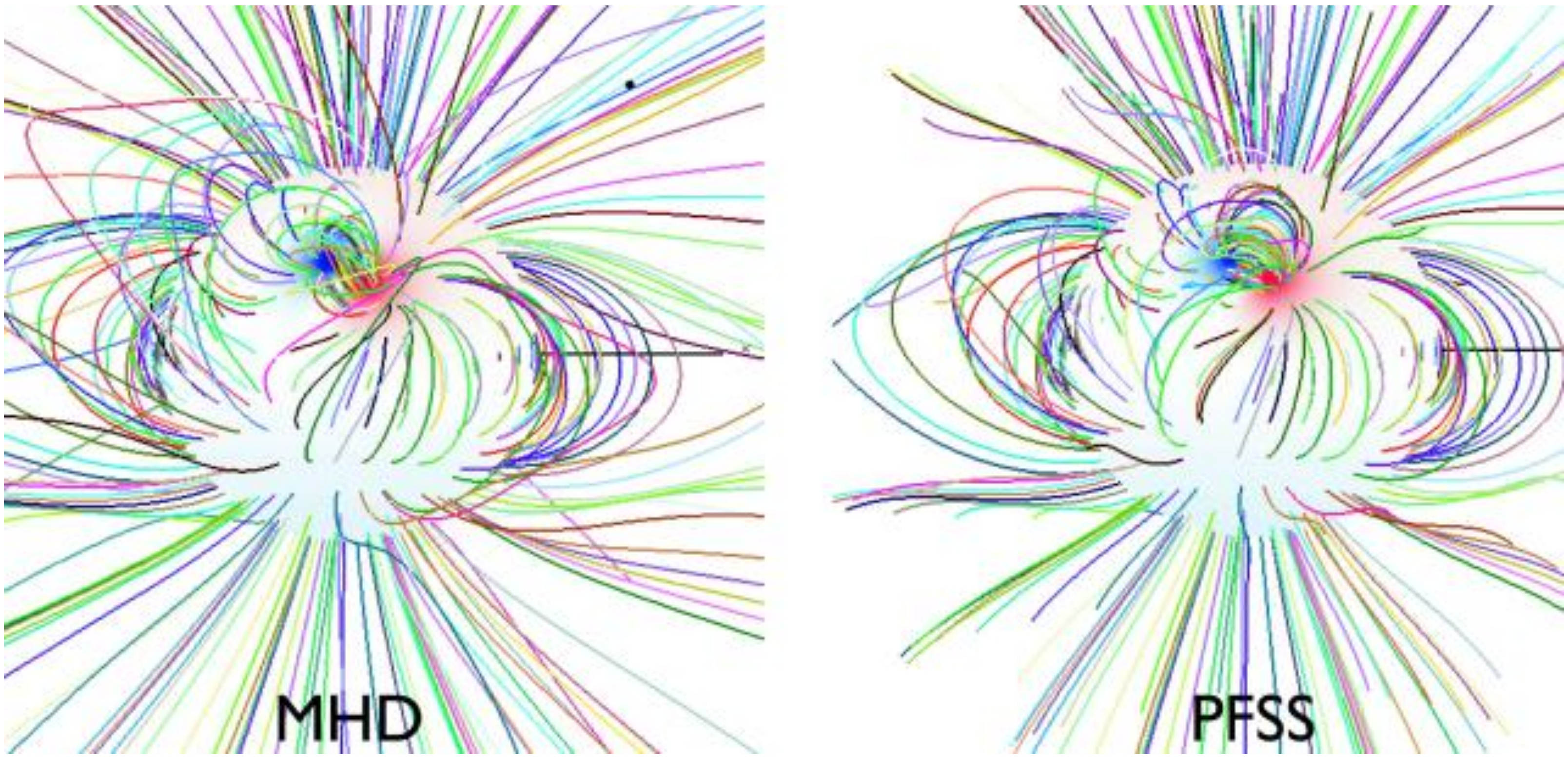
Outline:

- Introduction
- Modeling active regions
- Modeling the global corona
- Modeling the solar dynamo

In collaboration with S. Cranmer, A. Yeates (SAO), D. Mackay (St. Andrews)

# Introduction

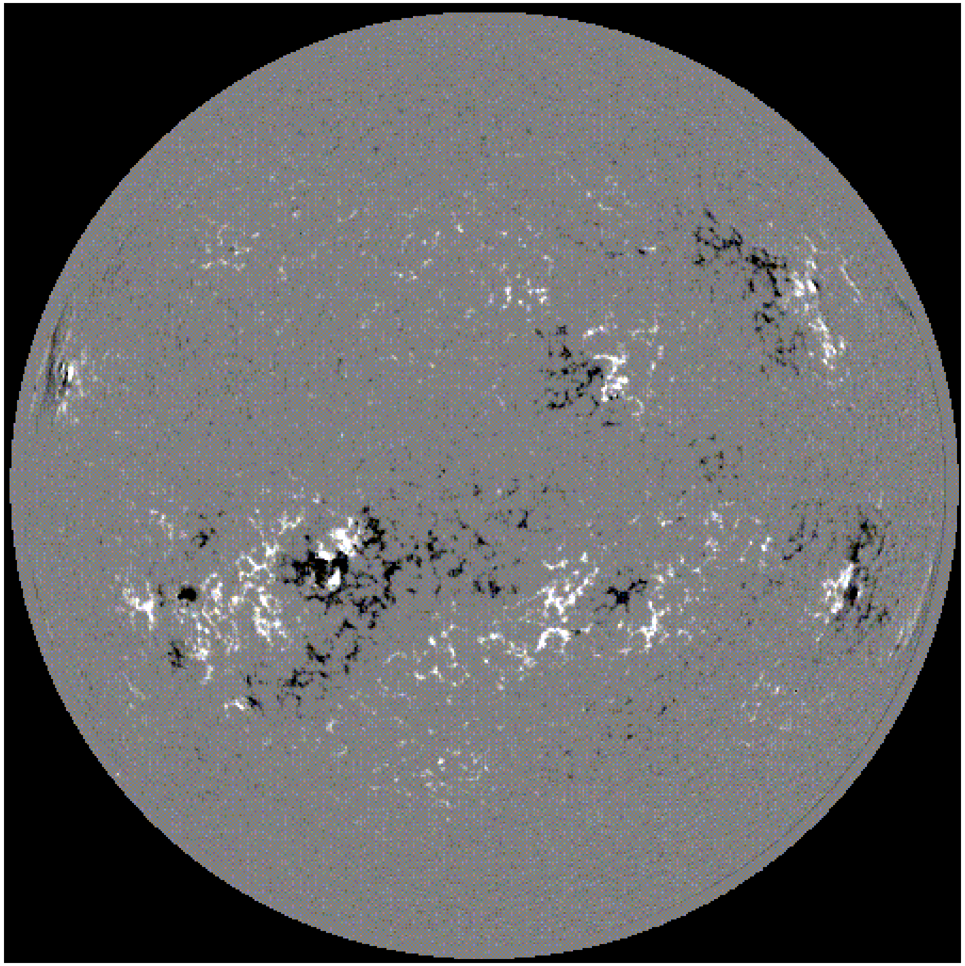
The *global structure* of the Sun's magnetic field can be determined by extrapolation of measured photospheric fields:




Field lines in MHD and potential-field source-surface (PFSS) models (Riley 2006)

# Introduction

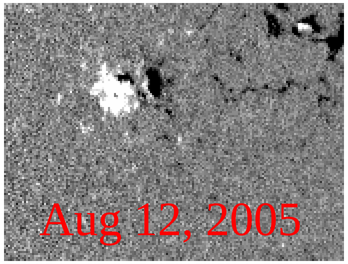
The magnetic field *evolves* due to the birth and decay of ***active regions***:

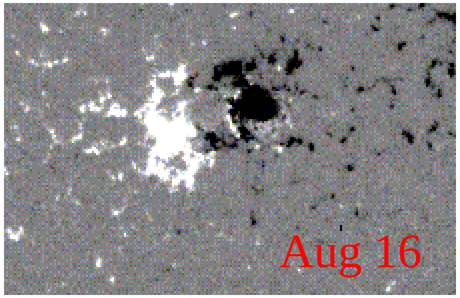


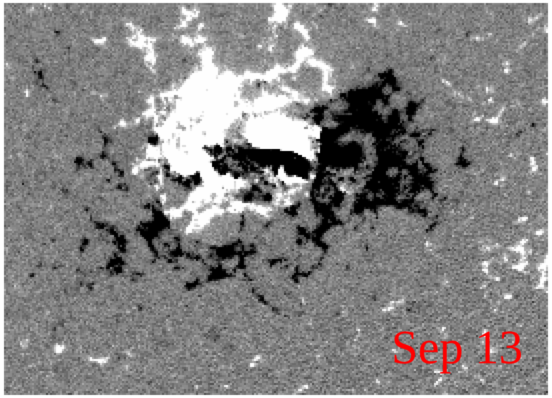
Magnetogram
SOHO/MDI
Apr 8, 2000

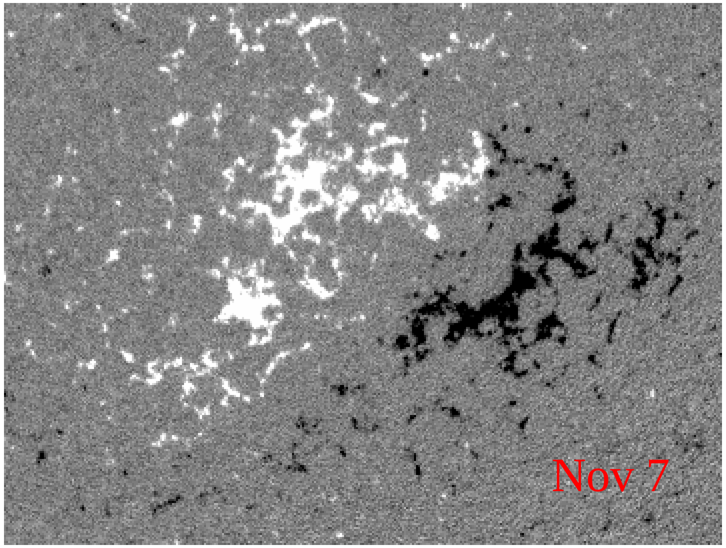
# Introduction

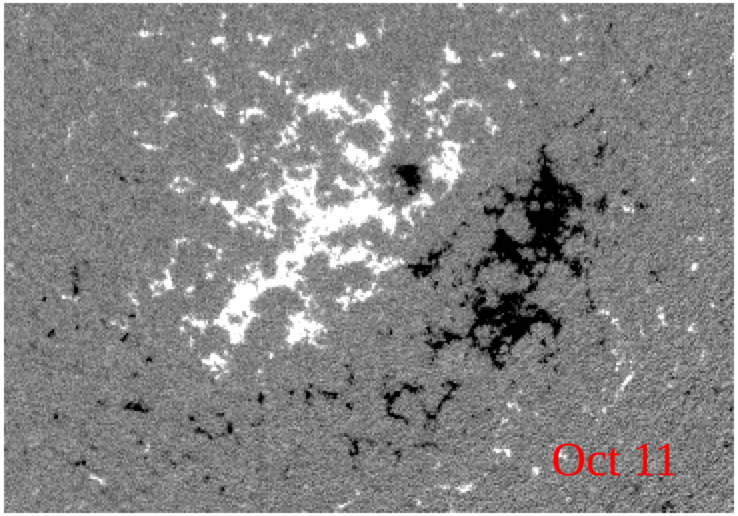
Evolution of an active region (AR 10797) over a 3-month period:



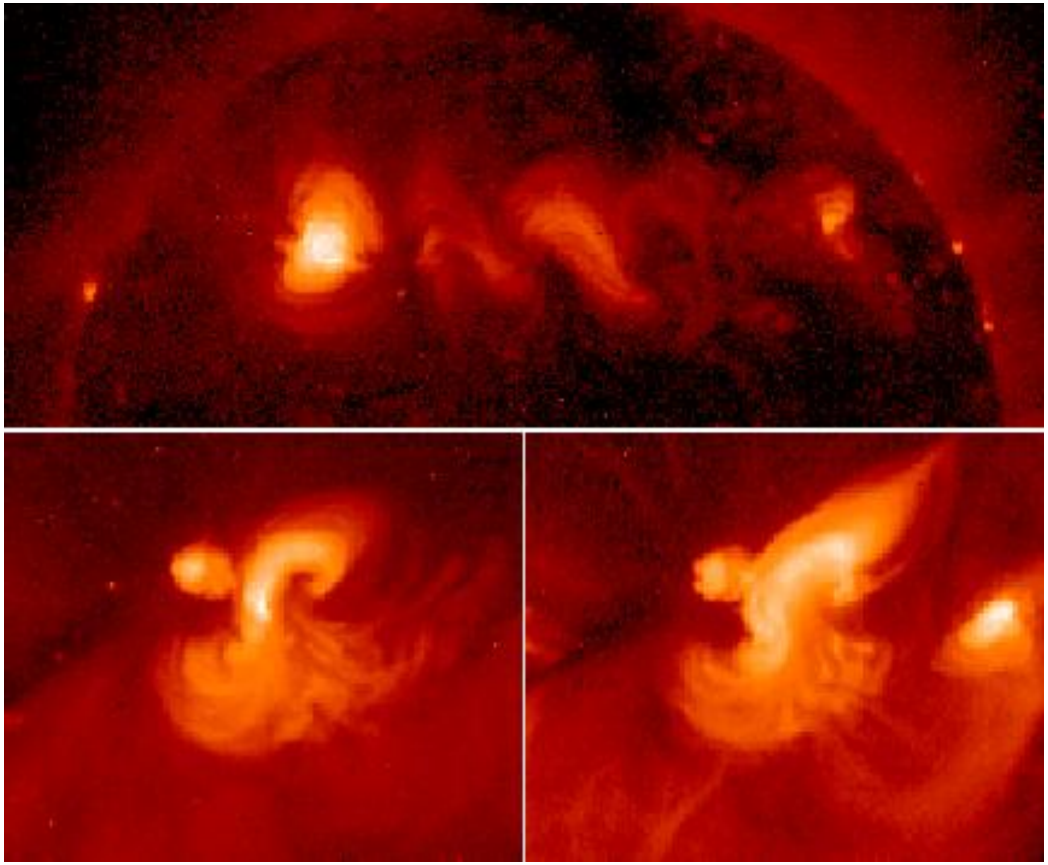




SOHO MDI

# Introduction

Yohkoh/SXT and Hinode/XRT observations show the corona contains S-shaped structures (sigmoids), indicating coronal magnetic fields are sheared and/or twisted:

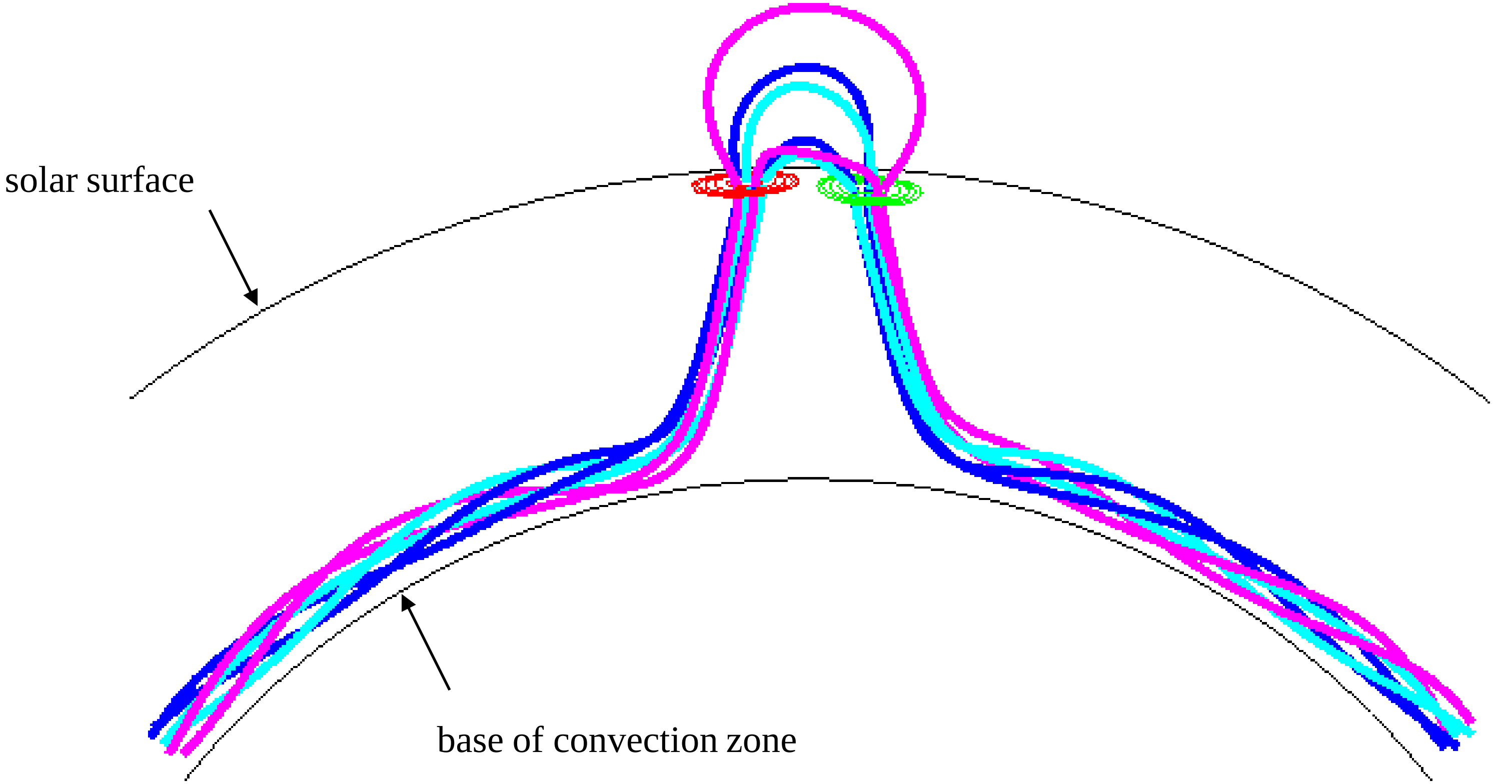


Two sigmoids,
May 15, 1998

Sigmoid before and
after eruption,
June 8-9, 1998.

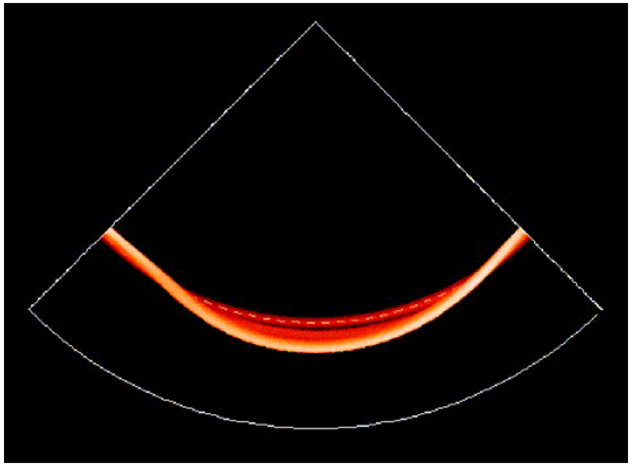
# Part 1 - Modeling Active Regions

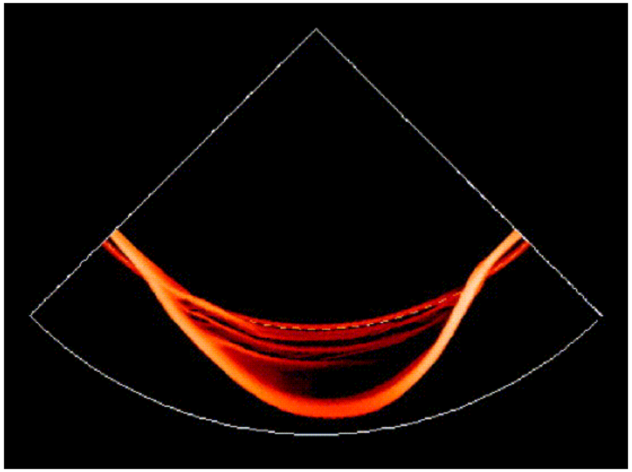
Active regions are thought to be *$\Omega$-shaped loops* emerging from a *toroidal field* located near the base of the convection zone:



# Modeling Active Regions

Fan (2008) simulated the buoyant rise of Ω-loops in the convection zone (view along rotation axis):

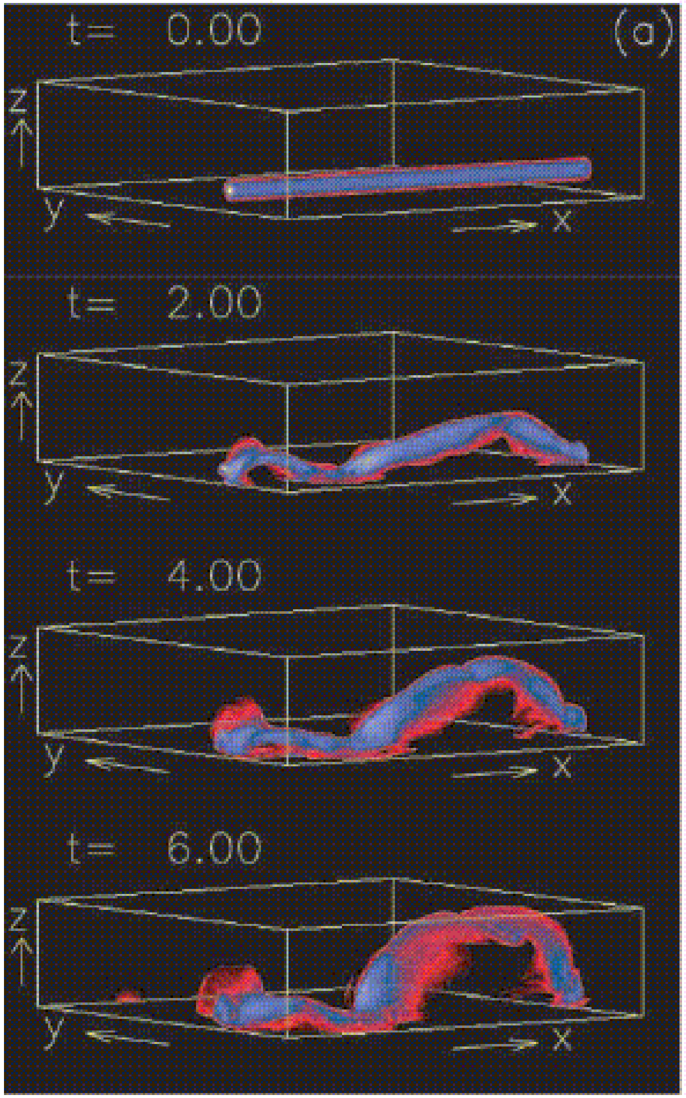




*Note*: the modeled Ω-loops have large azimuthal extent (~ 90 degrees), much larger than observed active regions.
This suggests that *cyclonic convective motions* play an important role in the birth of active regions.

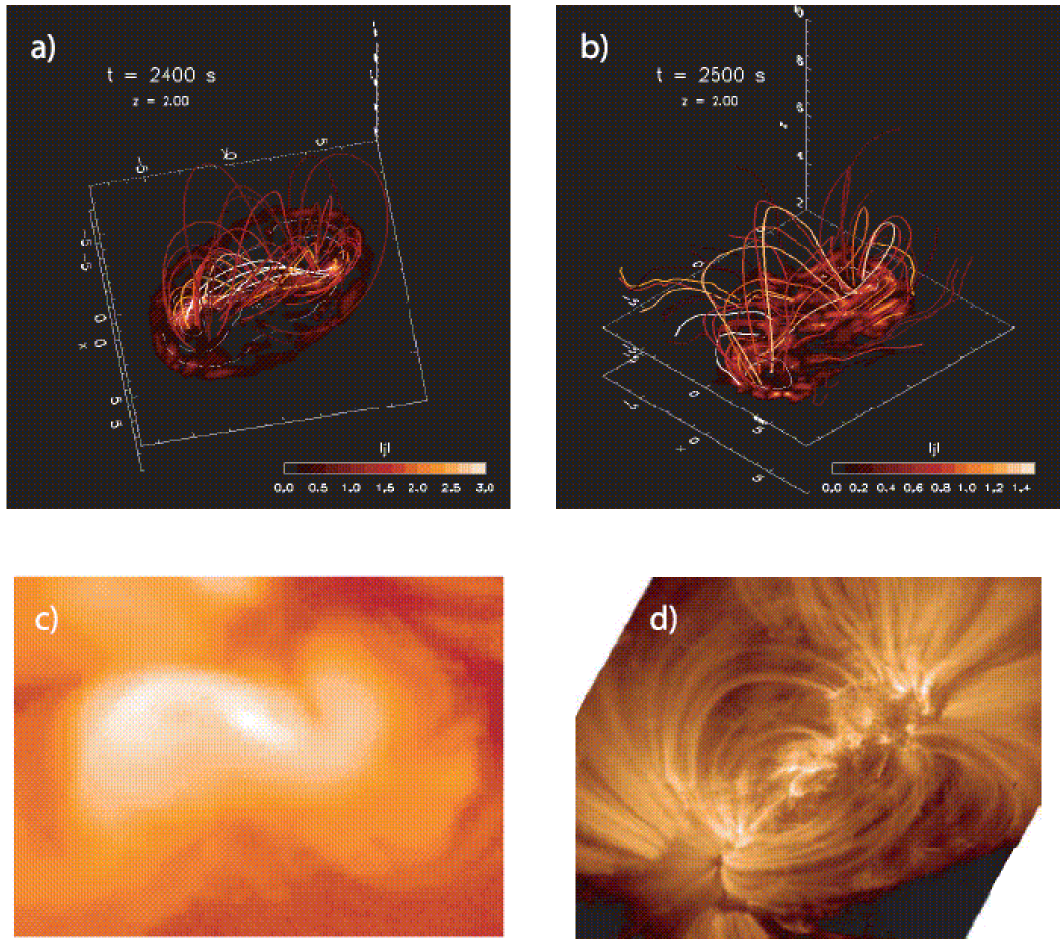
# Modeling Active Regions

Fan, Abbett & Fisher (2003) considered the interaction of a flux rope with convection, leading to the formation of an Ω-loop:



# Modeling Active Regions

Magara (2006) simulated the emergence of a twisted Ω-loop into the corona:



# Modeling Active Regions

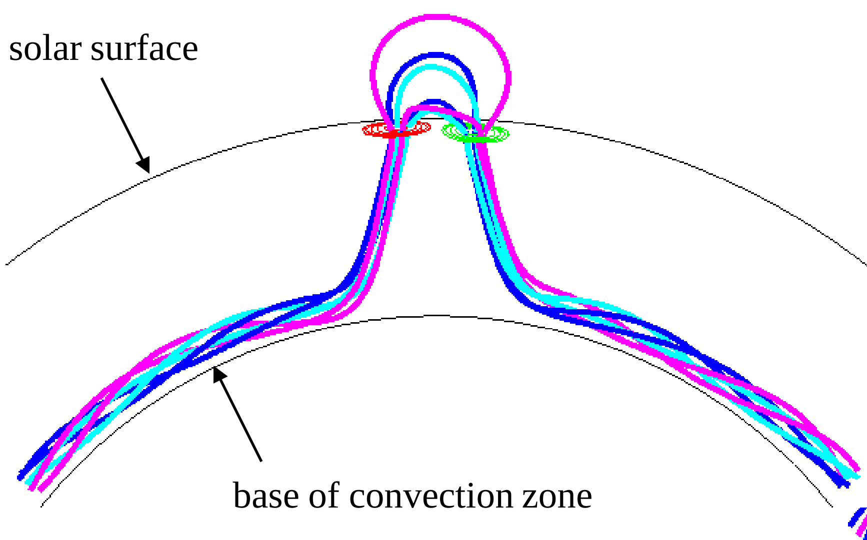
*Coupled evolution* of an Ω-loop in the corona and convection zone (CZ) (van Ballegooijen & Mackay 2007):

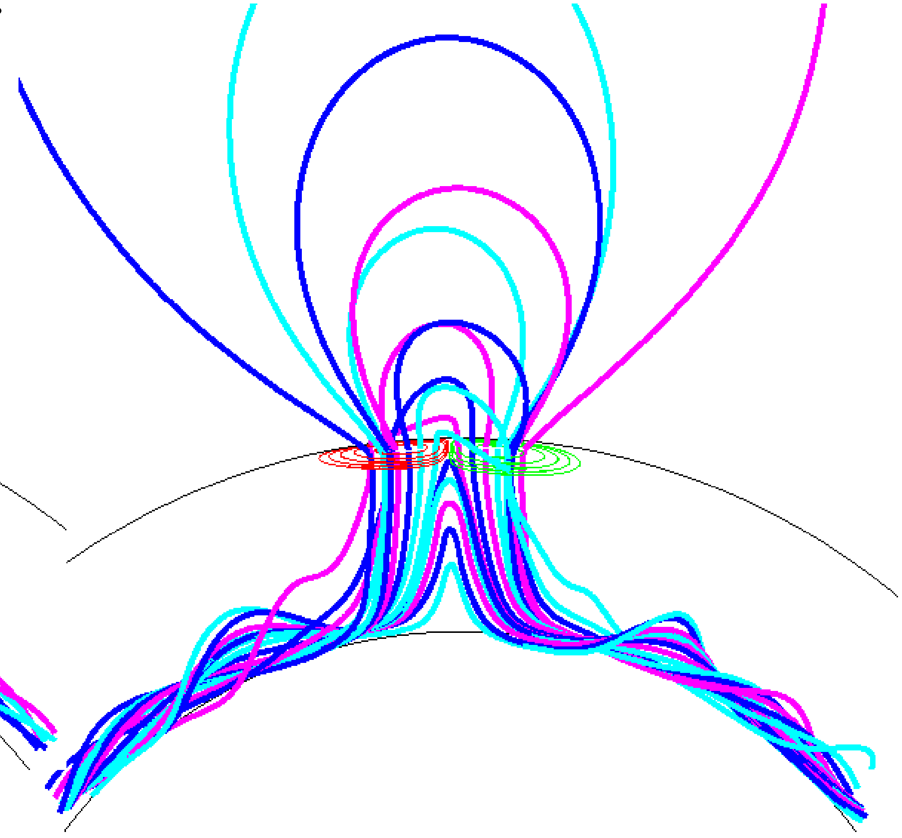
- Ω-loop assumed to emerge from a left-helical flux rope in N hemisphere.
- Simulate *after* Ω-loop has fully emerged into corona.
- At the photosphere the field changes from *small filling factor* in CZ to *space-filling* in the corona, and horizontal magnetic stress is balanced.
- In the CZ the field is subject to
  - solar differential rotation
  - turbulent diffusion ($\eta_2$ = 500 $km^2$ $s^{-1}$)
  - downward *convective pumping* ($v_r \approx$ -20 m/s).
- Magnetic diffusion in CZ is modified to conserve magnetic helicity:

$$\frac{\partial \vec{A}}{\partial t} = \vec{v} \times \vec{B} - \eta_2 \left( \vec{\nabla} \times \vec{B} \right)_\perp , \qquad \vec{B} \equiv \vec{\nabla} \times \vec{A}.$$

# Modeling Active Regions

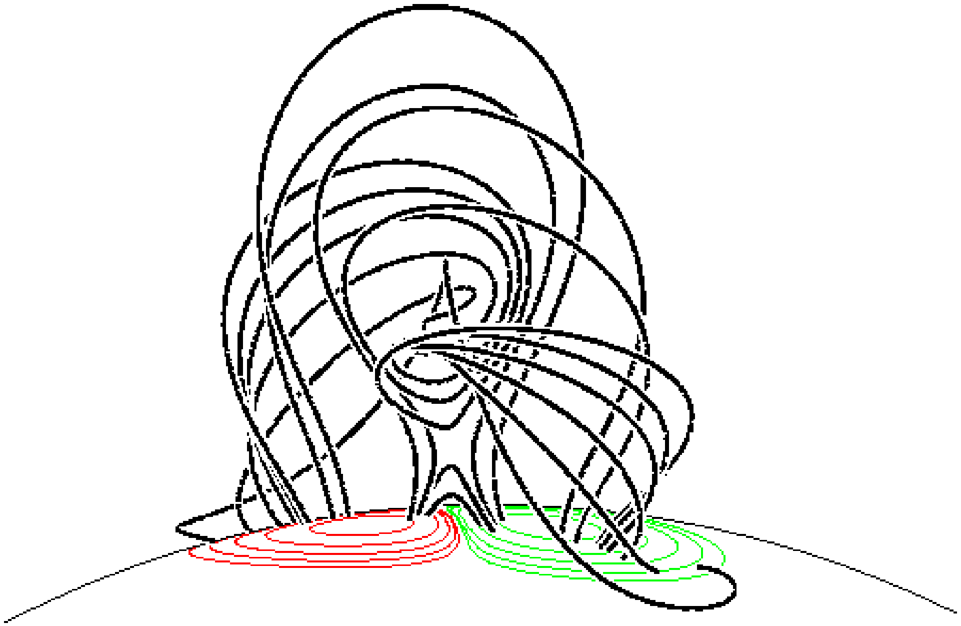
Magnetic field spreads out as a result of diffusion in CZ, and is *nearly radial* in the upper CZ. Active region decays by *submergence* of magnetic flux. However, sheared fields cannot submerge through upper CZ, so *magnetic helicity remains trapped in the corona:*

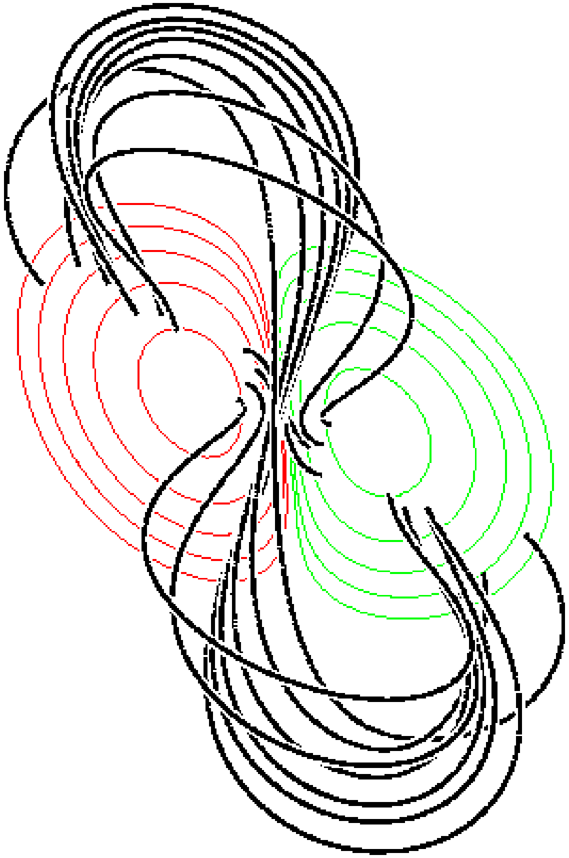


# Modeling Active Regions

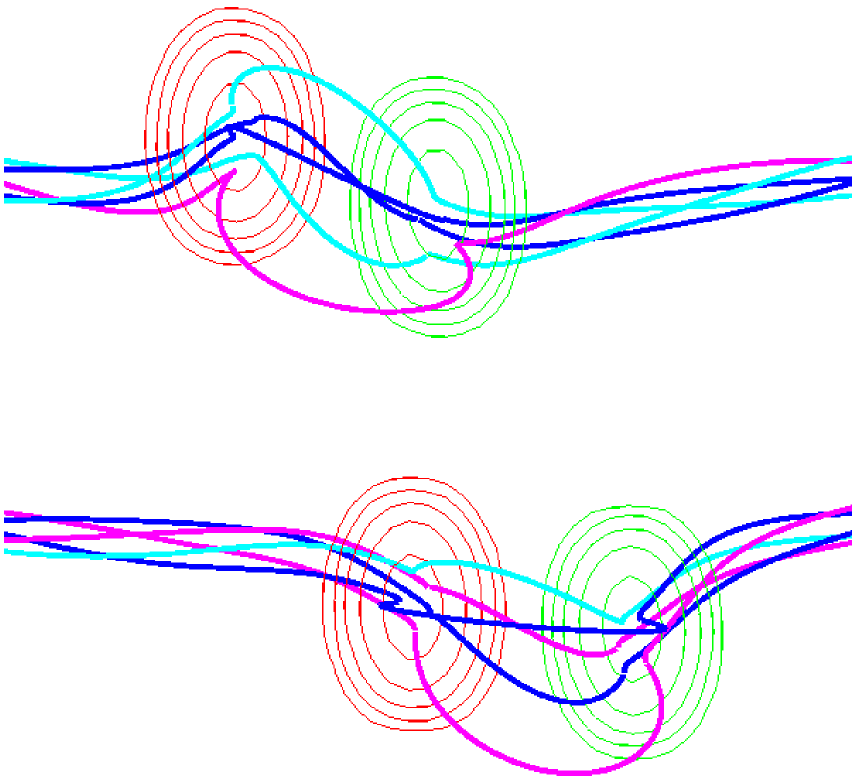
The build-up of magnetic helicity in the corona eventually leads to *loss of equilibrium* and eruption of sheared helical field:

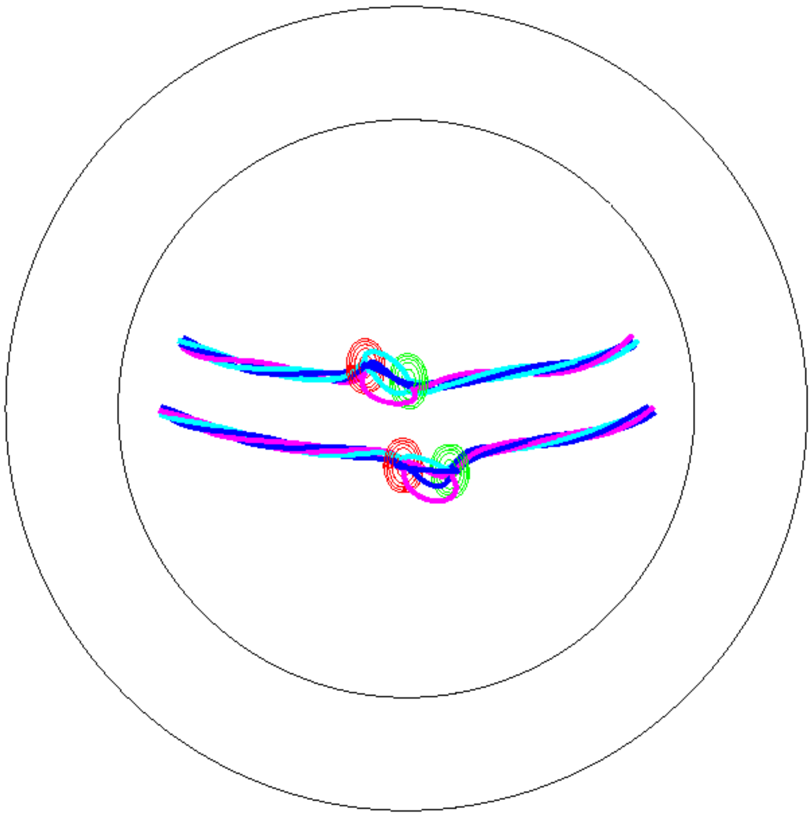




# Modeling Active Regions

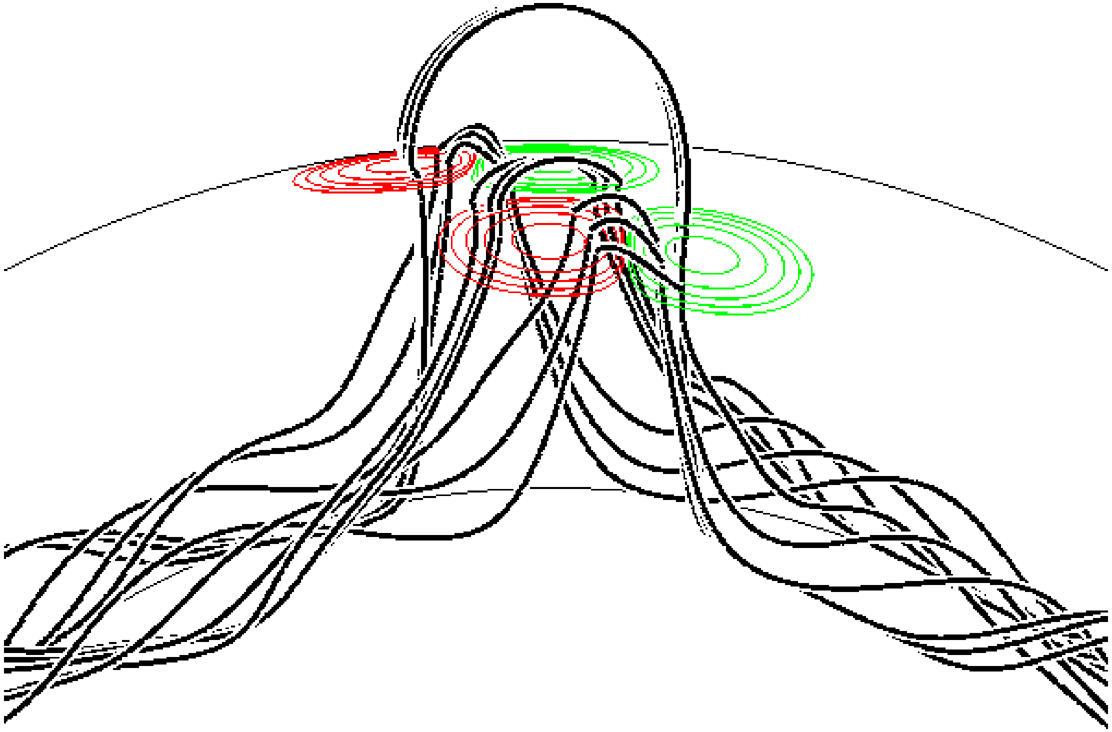
We also simulated the interactions between two Ω-loops on two *different* toroidal flux ropes in the same hemisphere:



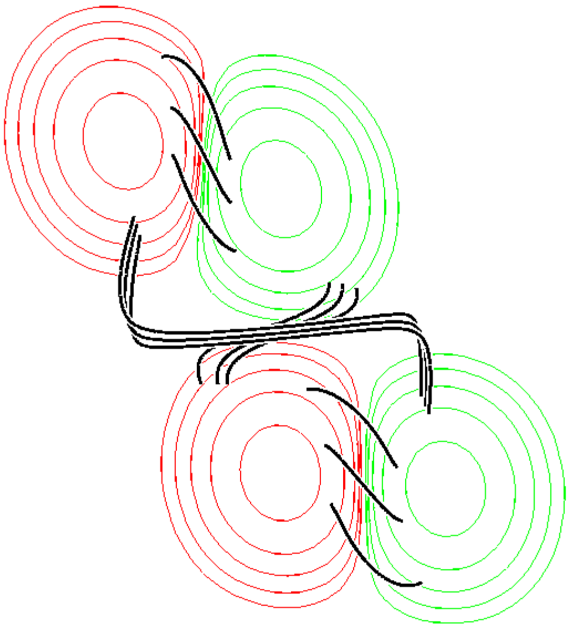


# Modeling Active Regions

Spreading of active regions leads to reconnection of Ω-loops in corona:

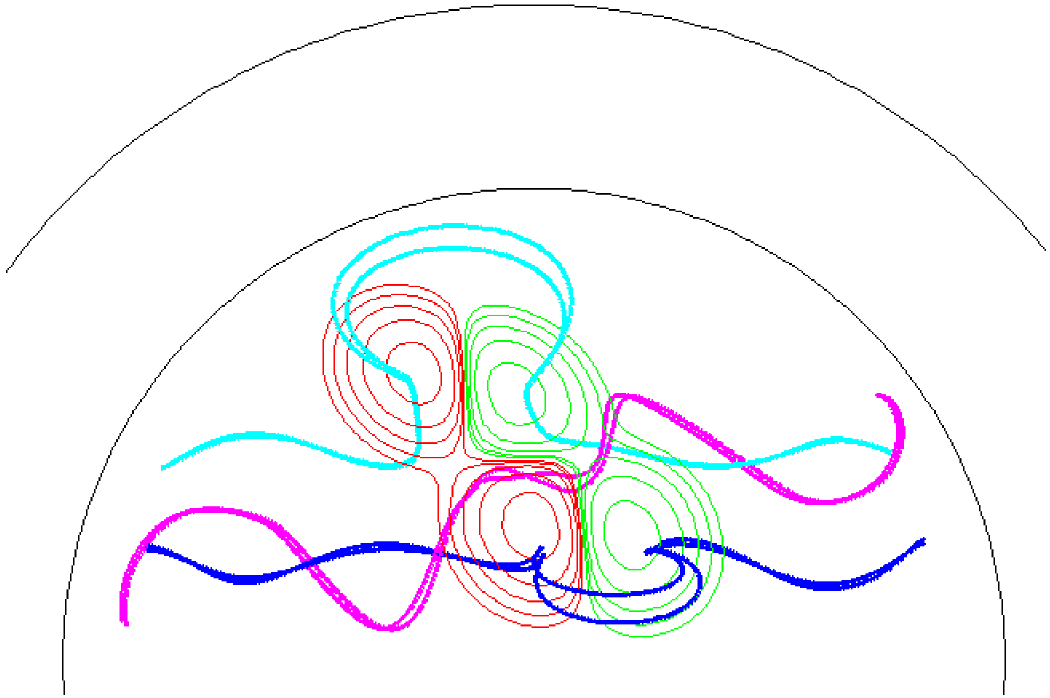


view from the top



# Modeling Active Regions

New connections (pink) are formed between the toroidal flux ropes.
As the active regions decay, this flux is transported down to the base of the CZ:



*Note*: The change in the N-S component of subsurface field is consistent with that required for reversal of the poloidal field of the dynamo.

# Part 2 - Modeling the Global Corona

Yeates, Mackay & van Ballegooijen (2007, 2008) studied the evolution of surface- and coronal magnetic field over a 6-month period in 1999:

- Properties of active regions (lon-lat position, tilt, flux, emergence time) determined from NSO/KP synoptic maps.
- Twisted bipoles inserted into 3D time-dependent magnetic model:
  - surface field evolves by differential rotation, meridional flow, diffusion
  - corona evolves by magneto-friction
- Formation of "flux ropes" in corona above polarity inversion lines.
- Simulation results are compared with observations of filaments.

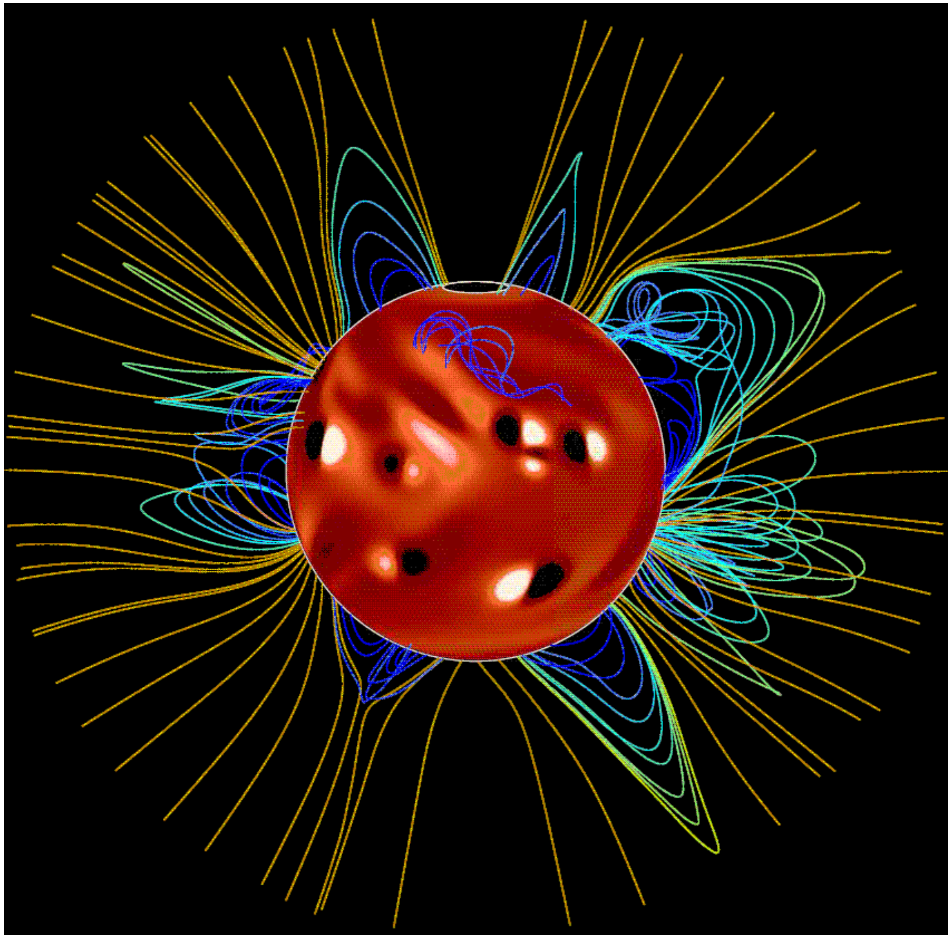
# Modeling the Global Corona

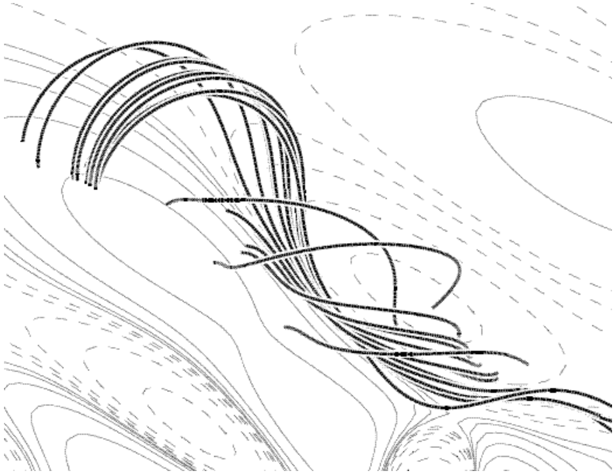
Evolution:

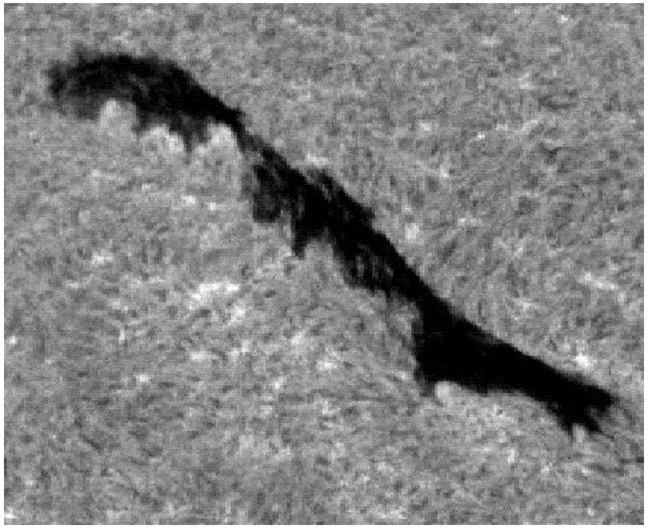
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

# Modeling the Global Corona

Comparison with filament observations:

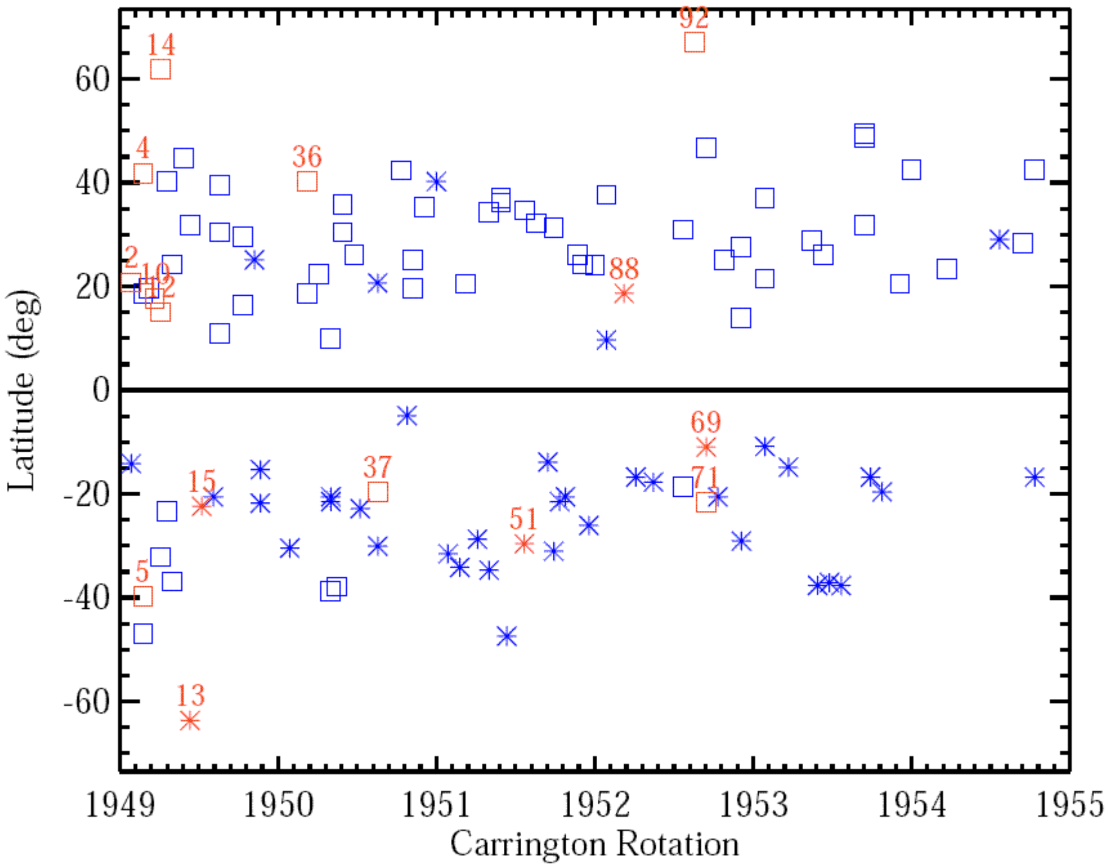






# Modeling the Global Corona

Predicted chirality of the modeled flux ropes agrees with the chirality of the observed filaments in most cases:




Symbol shapes denote chirality of observed filaments (squares for dextral, stars for sinistral).

Red symbols indicate where predicted chirality does not match observations.

From Yeates et al. (2008, Sol. Phys. 247, 103).

# Modeling the Global Corona

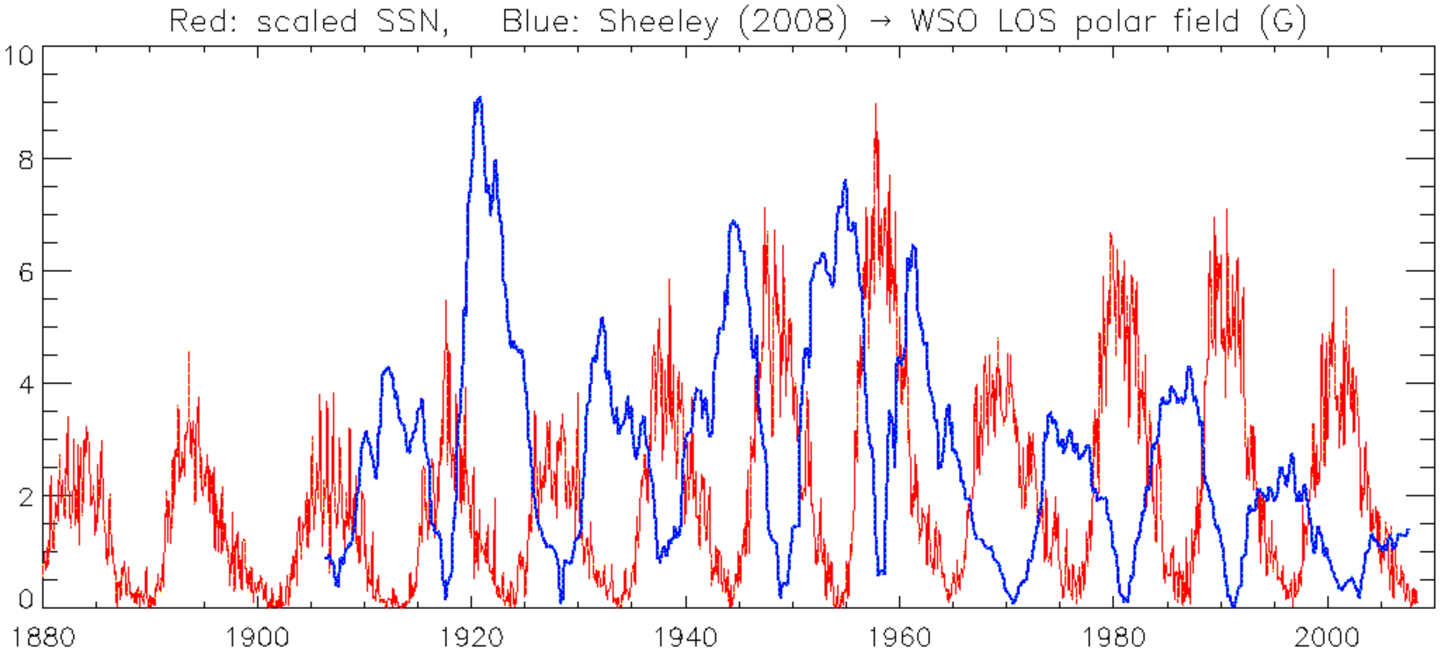
Transport of magnetic helicity from active regions to the surrounding corona.
Longitude-latitude maps of current helicity in low corona over 2-year period:

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

# Part 3 - Modeling the Solar Cycle

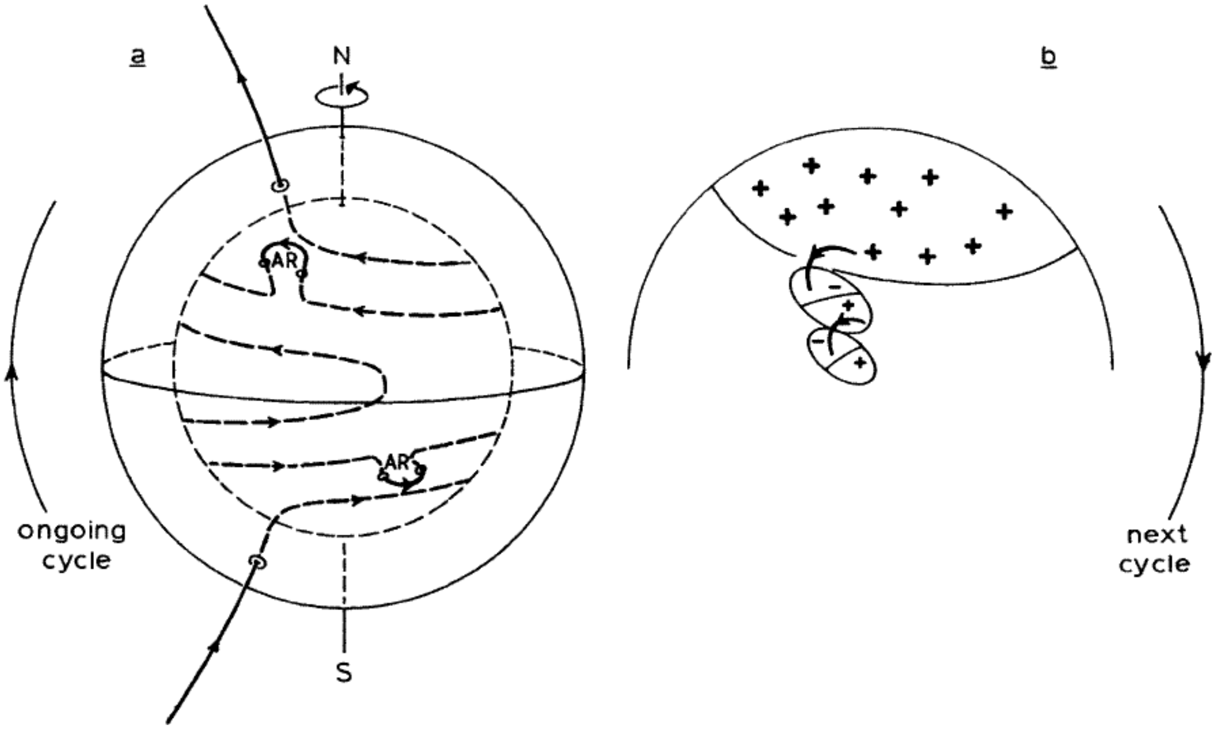
The solar magnetic field is generated by a cyclic dynamo.

Plot of scaled sunspot number vs. time, and reconstruction (by S. Cranmer) of Sun's polar field from measurements of polar faculae (Sheeley 2008):



# Modeling the Solar Cycle

The toroidal field is generated by the solar differential rotation.
As the active regions decay, they cancel and eventually reverse the Sun's polar magnetic field (Babcock 1961, Leighton 1969, Zwaan 1996):

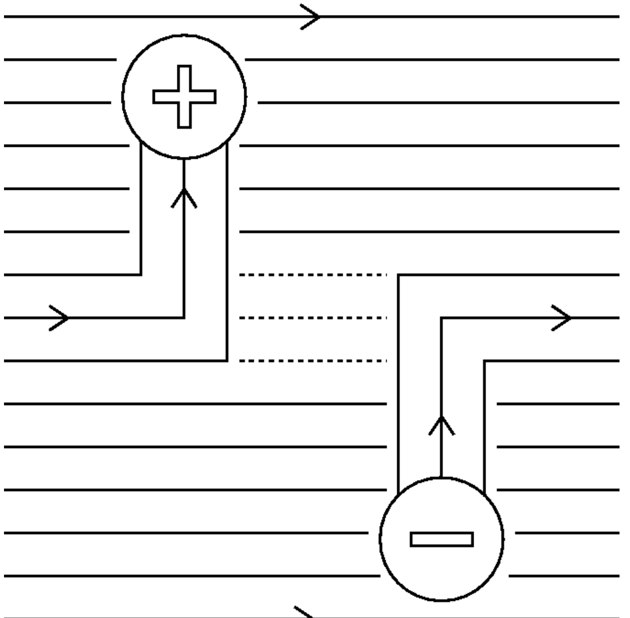



The effects of active regions on the subsurface field are not well understood.

# Modeling the Solar Cycle

Babcock-Leighton type dynamo model (van Ballegooijen & Cranmer, in prep.):

- Magnetic fields in the CZ are subject to *downward convective pumping*, which pushes the field to the base of the CZ.
- In addition there is differential rotation, meridional flow, and turbulent diffusion.
- Ω-loops emerge randomly wherever horizontal fields are located.
- The Ω-loops emerge tilted w.r.t. underlying horizontal field (see figure), consistent with observed *tilts of active regions* (Joy's law). This is the only α-effect in the model.
- The cyclic reversal of the poloidal field is the cumulative effect of these tilts.



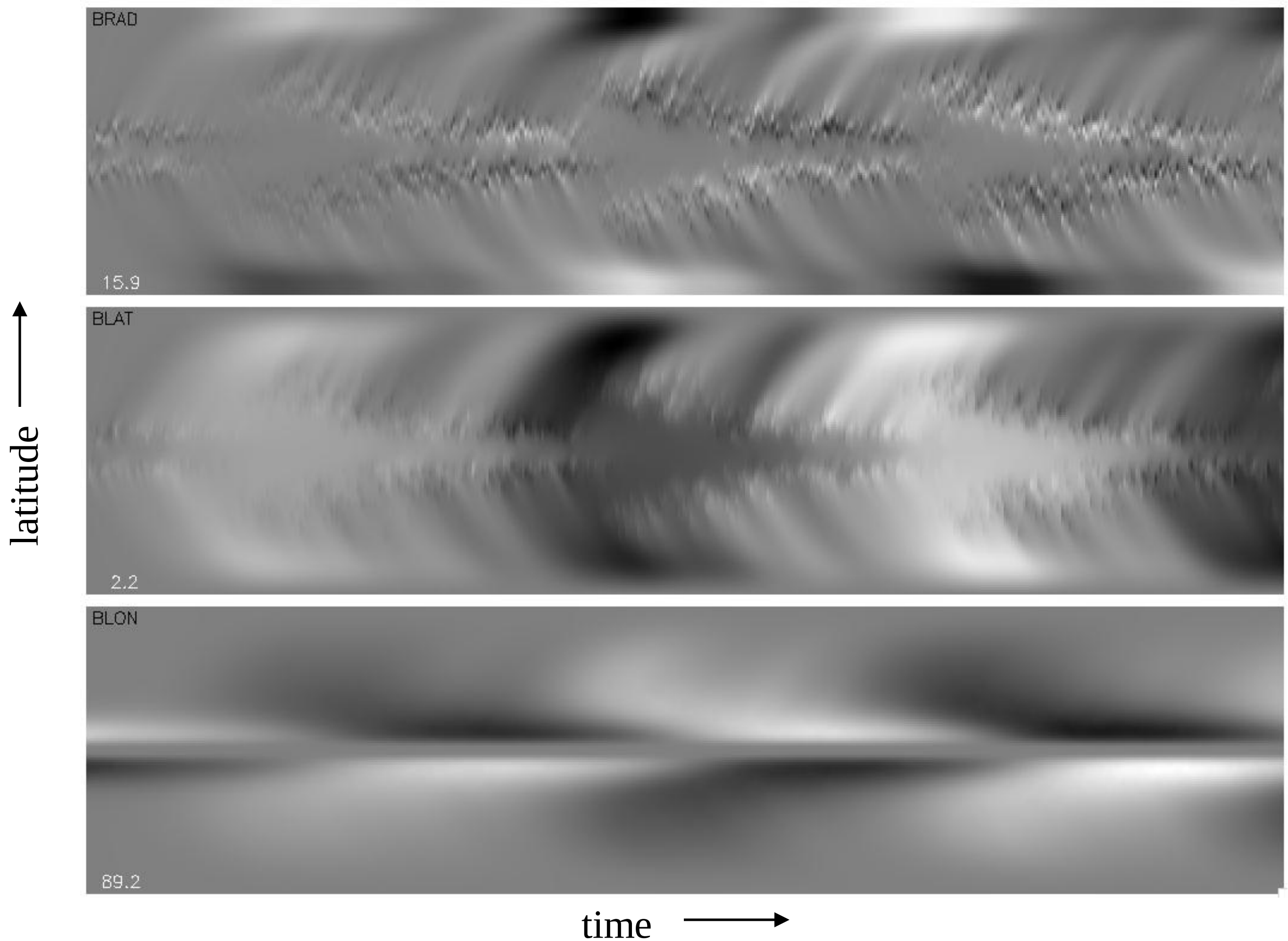
# Modeling the Solar Cycle

Latitude-time diagrams over period of 27.4 years:

Radial field at solar surface

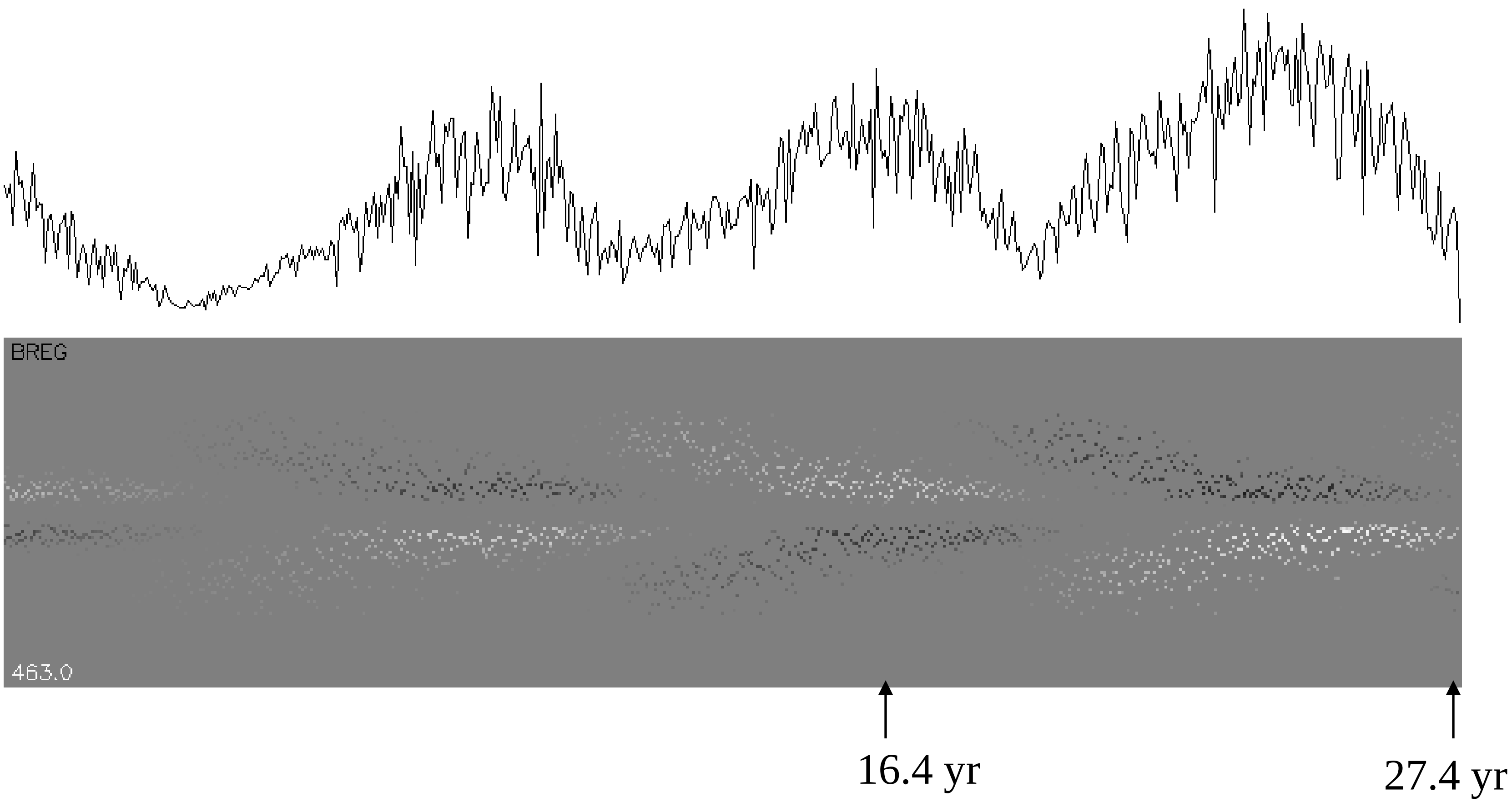
Latitudinal field at CZ base

Longitudinal field at CZ base



# Solar Dynamo Model

Rate of flux emergence (top) and butterfly diagram:



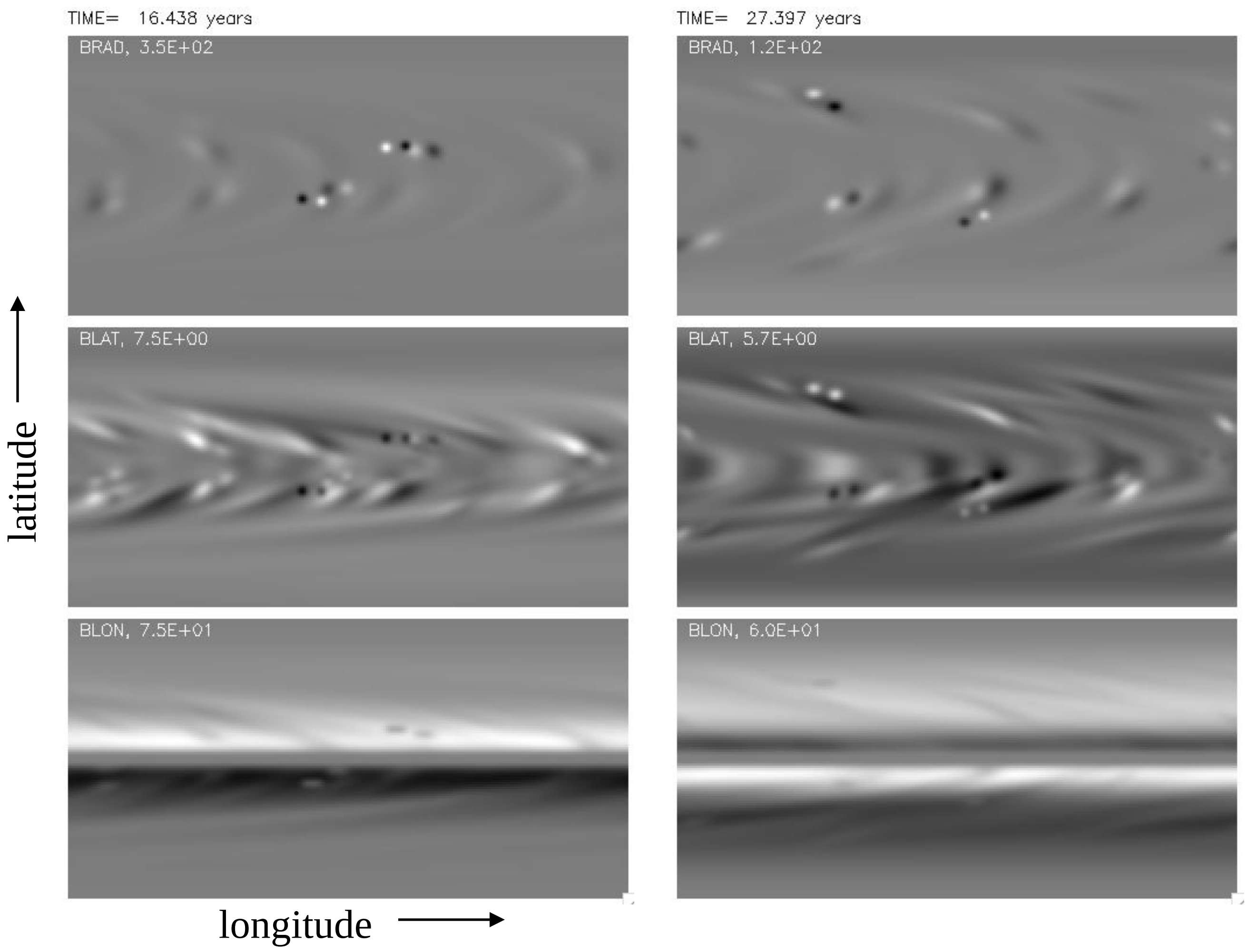
# Modeling the Solar Cycle

Magnetic field maps at cycle max (16.4 yr) and cycle min (27.4 yr):

Radial field at solar surface

Latitudinal field at CZ base

Longitudinal field at CZ base



# Modeling the Solar Cycle

Evolution:

Radial field at
solar surface

Latitudinal field
at CZ base

latitude

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Longitudinal field
at CZ base

longitude

# Modeling the Solar Cycle

There are four mechanisms for *dissipation of the Sun's toroidal field*:

1. Radial outward diffusion in convection zone. This can be suppressed by downward convective pumping.
2. Mutual cancellation (at the equator) of oppositely directed toroidal fields from N and S hemispheres. Can be suppressed by storage in a low-diffusion layer below the base of the CZ.
3. Loss due to emergence of Ω-loops. Not included in most dynamo models.
4. Cancellation of old-cycle flux by new-cycle flux in each hemisphere.

# Conclusions

- The fibril field in the upper convection zone presents a barrier for the submergence of sheared magnetic field. As an active region decays, the helicity can only be removed by ejection into the heliosphere.

- The emergence and subsequent evolution of active region changes the topology of the underlying toroidal fields, enabling cyclic dynamo action.