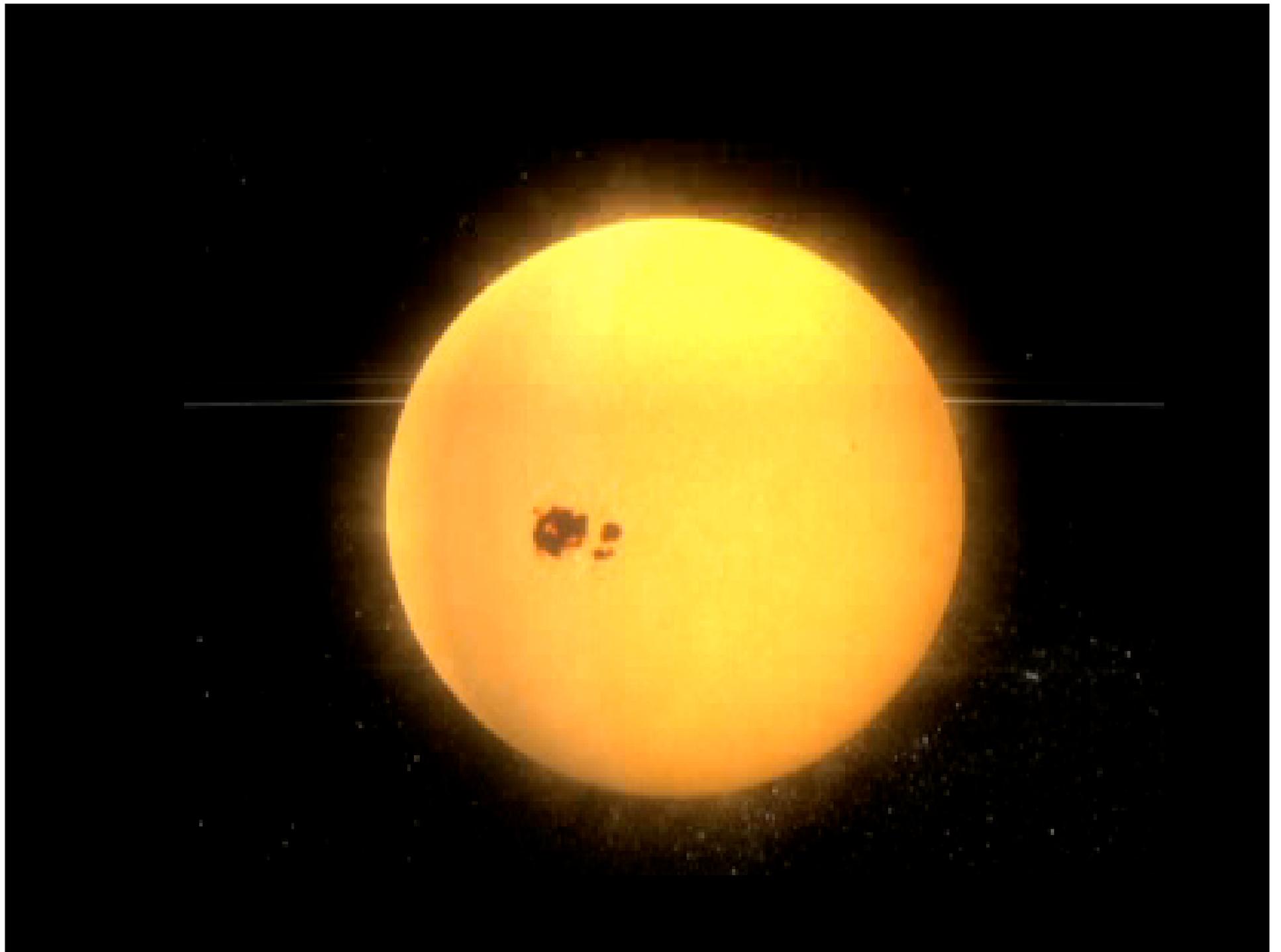


# Connecting Sun and Heliosphere





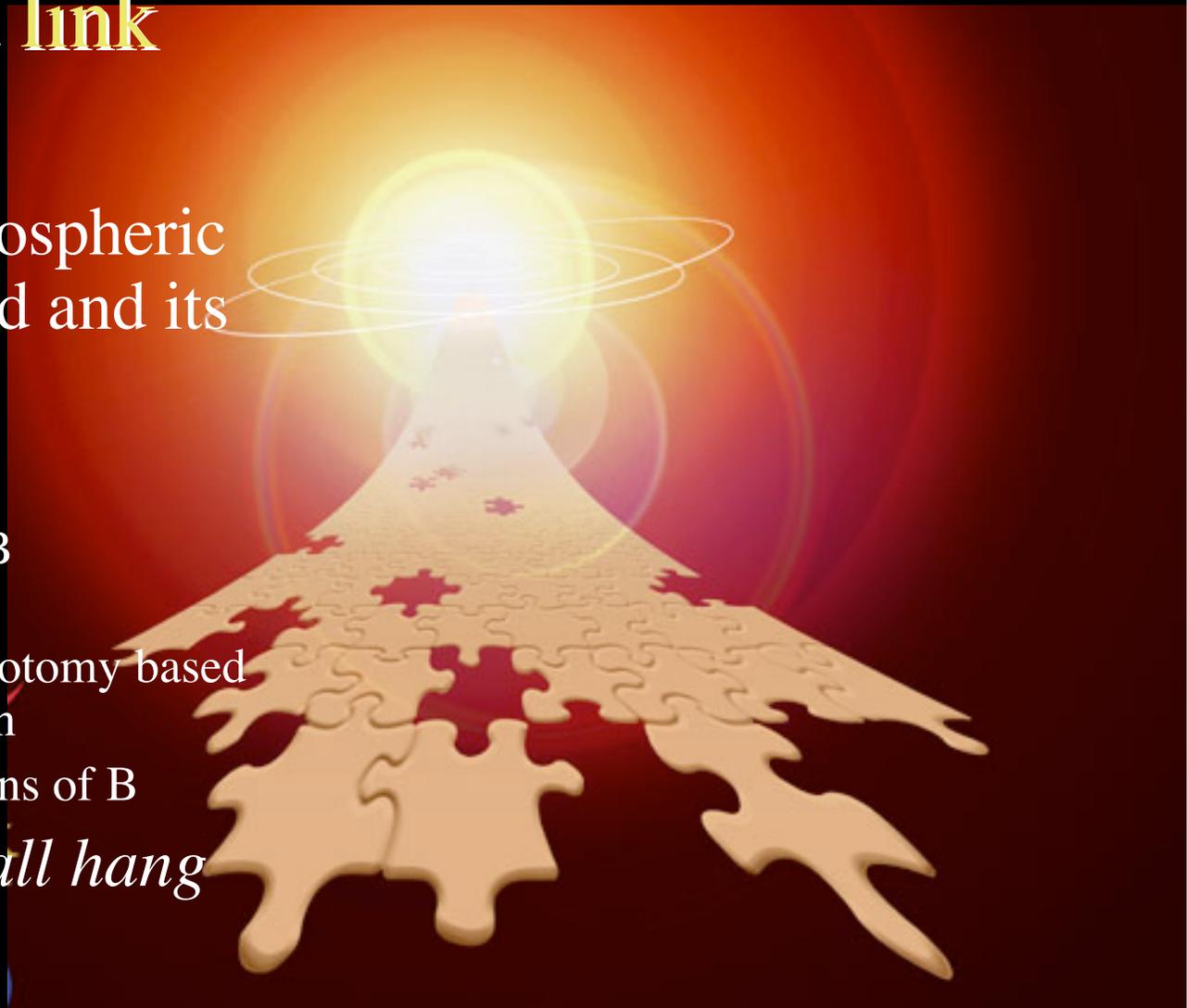
# Heliospheric magnetic field: the weakest link..

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University of Michigan

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# The weakest link

- Coronal/Heliospheric magnetic field and its structure
- Motivation
  - Photospheric B reorganization
  - Fast/slow dichotomy based on composition
  - Large deviations of B
- *How does it all hang together?*



# Outline

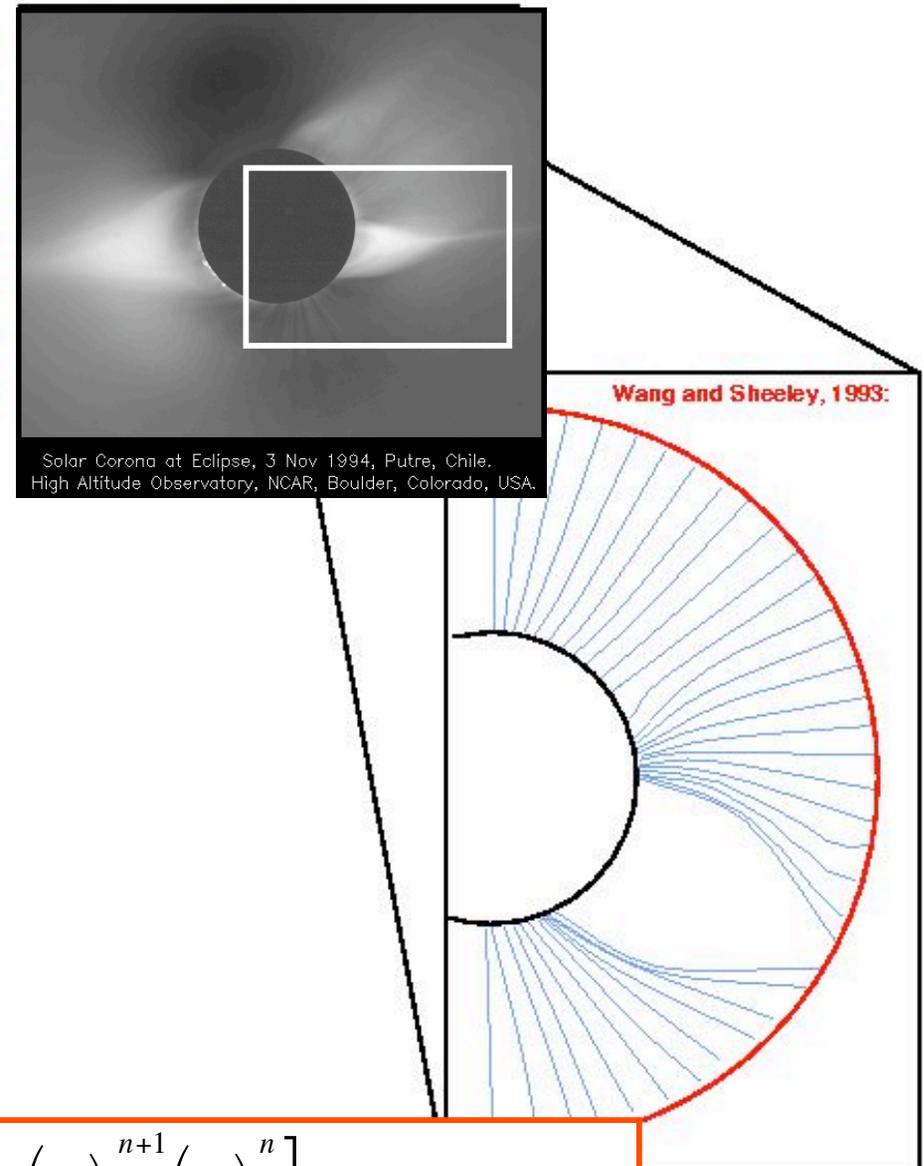


- Magnetically dominated models
  - Potential field models, Source surface models
  - Force free models
- Solar wind dominated models
  - MHD models – status quo
- Ongoing work
  - Interactions and topology
  - Diffusion models

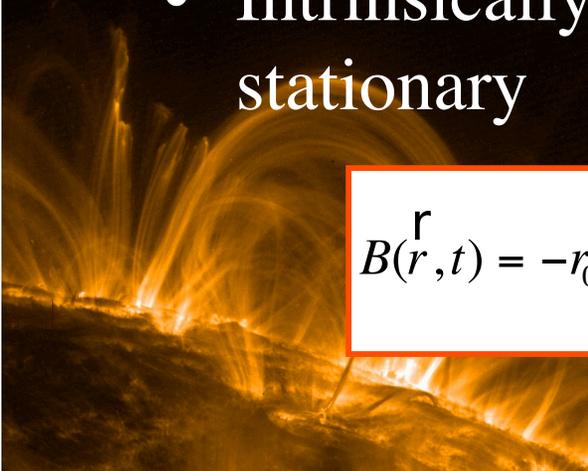


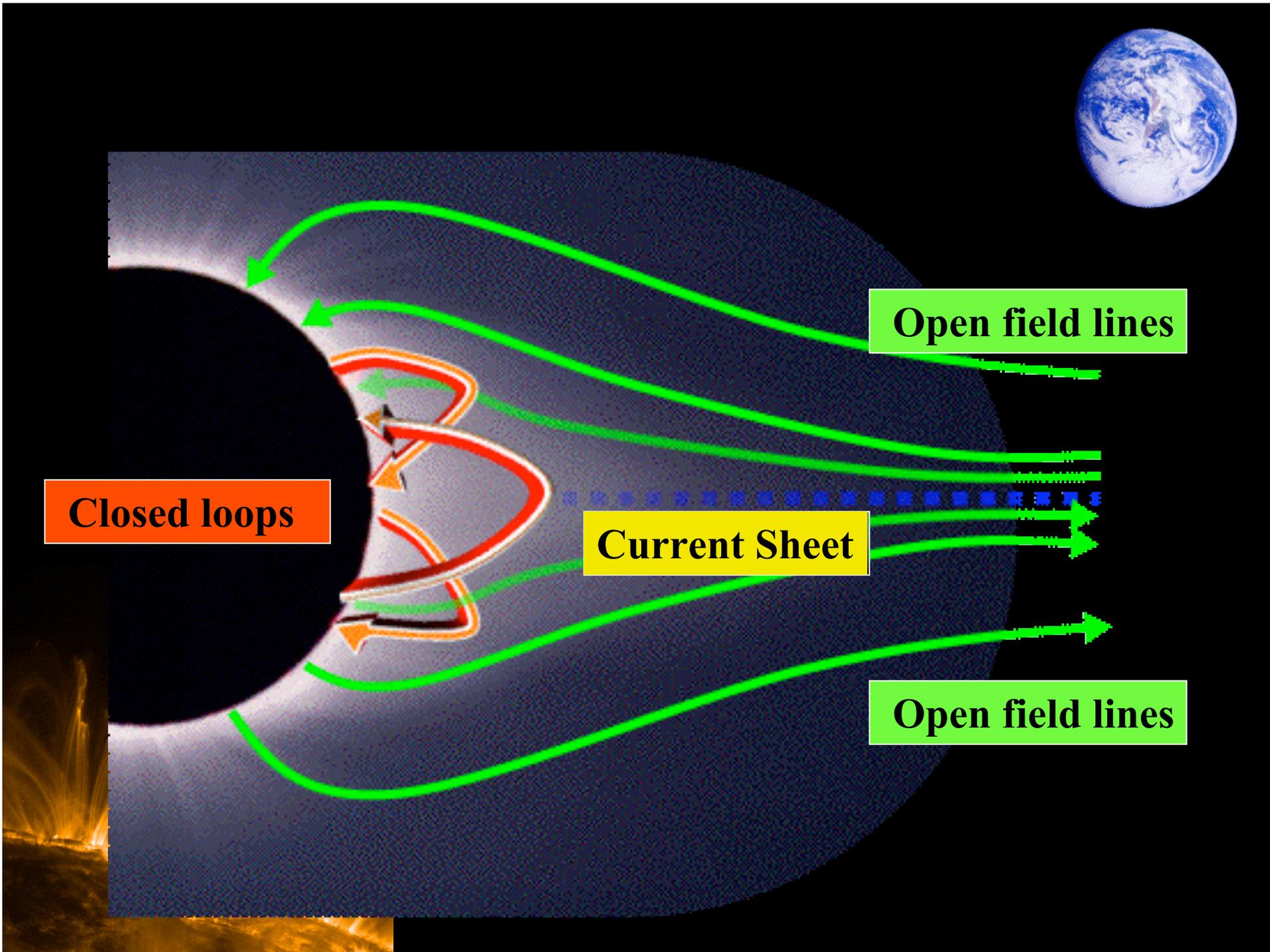
# Potential Fields

- Solve Laplace equation for
  - given inner boundary
  - Assuming outer boundary is conductor
  - No currents!
- Intrinsically time-stationary



$$B(r, t) = -r_0 \nabla \sum_{n=1}^{\infty} \sum_{m=0}^{\infty} \left[ \left( \frac{r_0}{r} \right)^{n+1} - \left( \frac{r_0}{r_s} \right)^{n+1} \left( \frac{r}{r_s} \right)^n \right] c_n^m P_n^m(\theta) e^{i(m\phi - \omega t)}$$





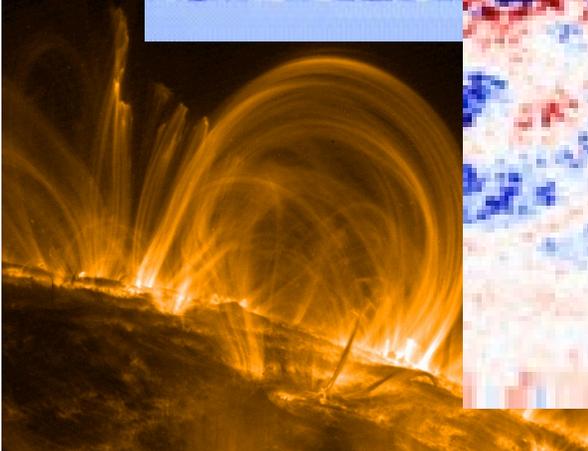
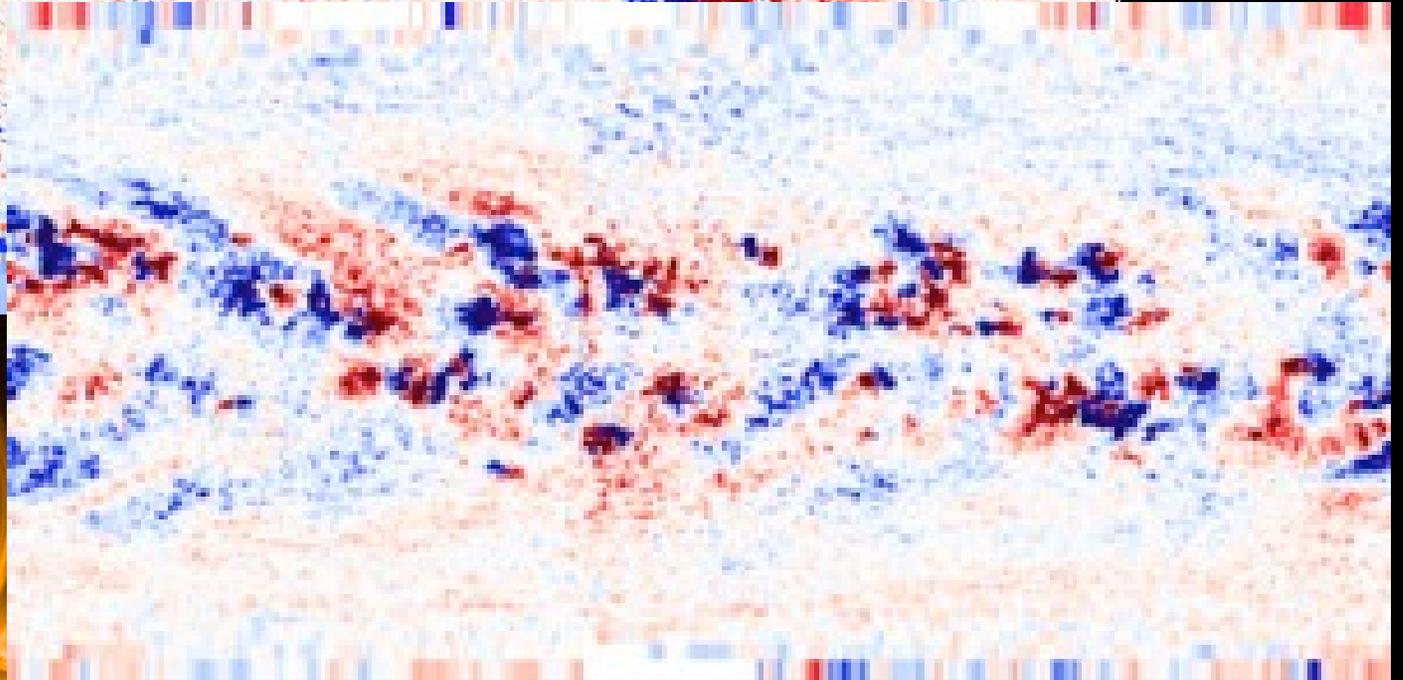
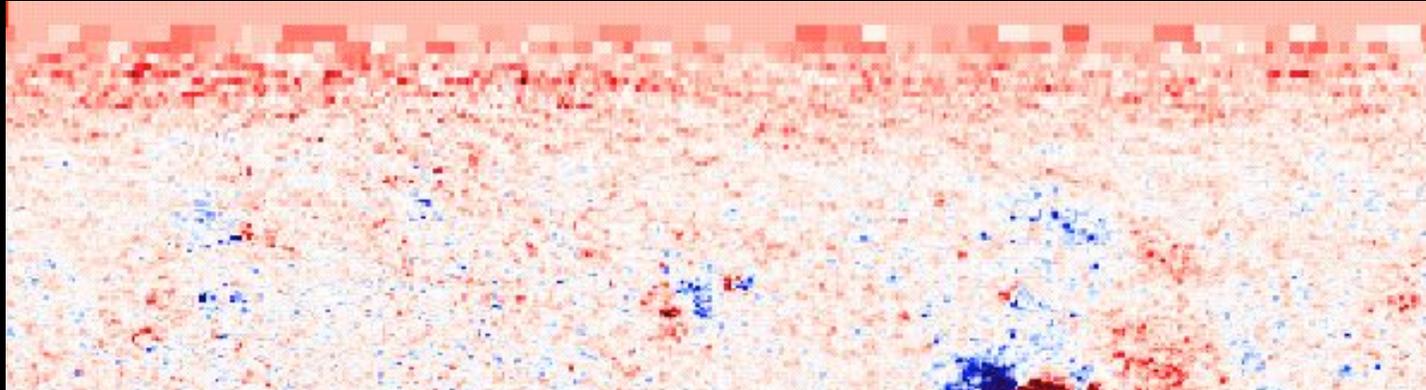
**Closed loops**

**Current Sheet**

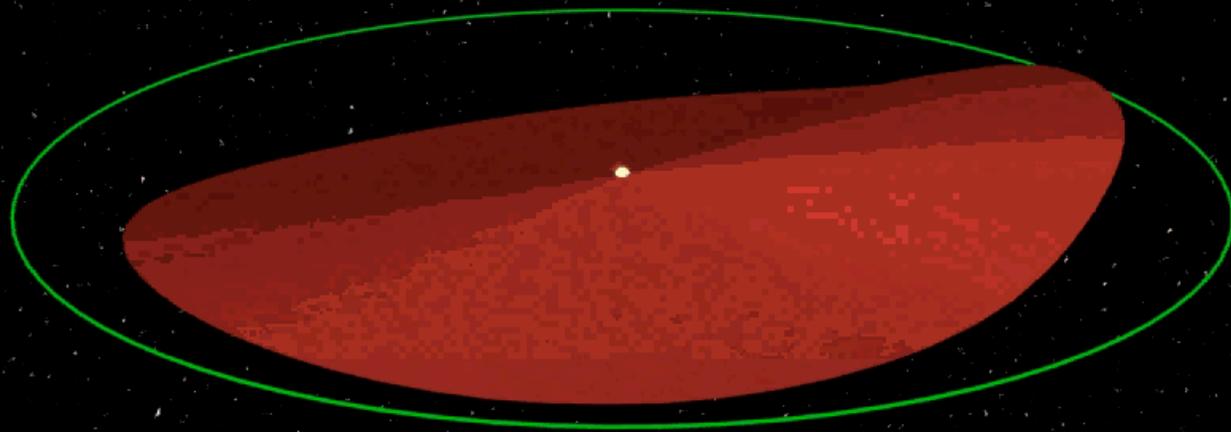
**Open field lines**

**Open field lines**

# Photospheric Field

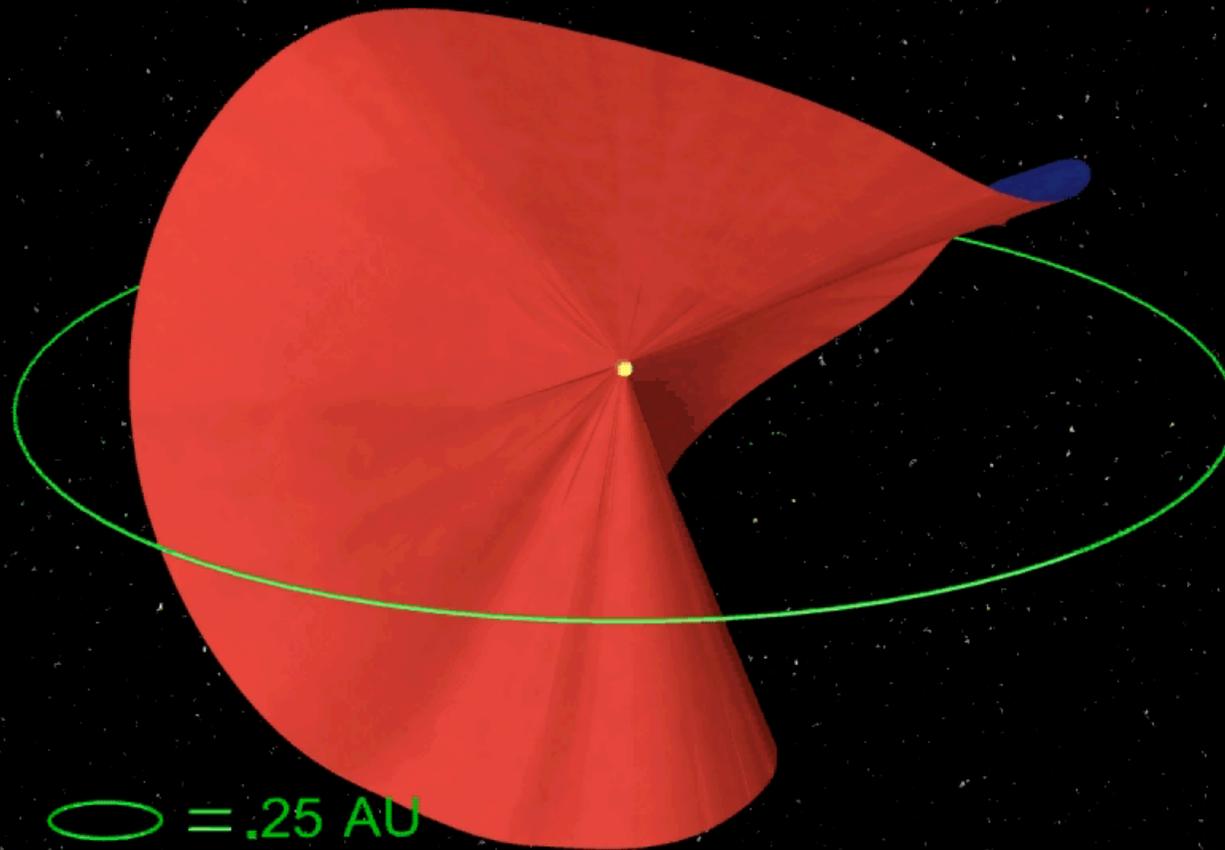


# Solar Minimum



○ = .25 AU

# Elevated Solar Activity





## Summary: Magnetically dominated models

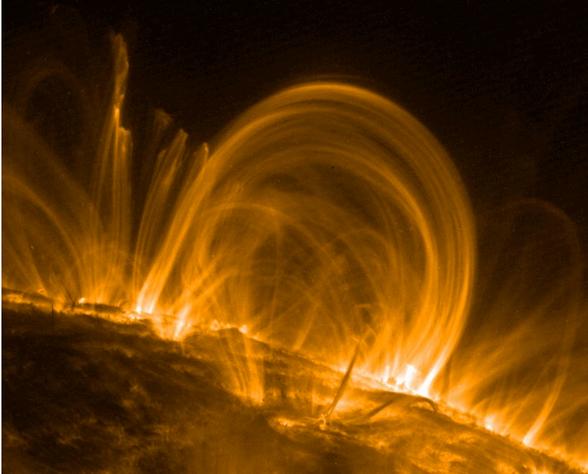
- Properties
  - Ignore effects of non-magnetic forces
  - Ignores bulk pressure of solar wind
- Successes, Drawbacks
  - Accurately describes global structure
  - Highly successful in estimating global structure of corona, heliosphere
  - Outer surface does not allow for foot-point motion
  - Not suitable to model time-dependence

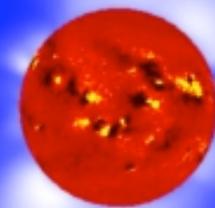
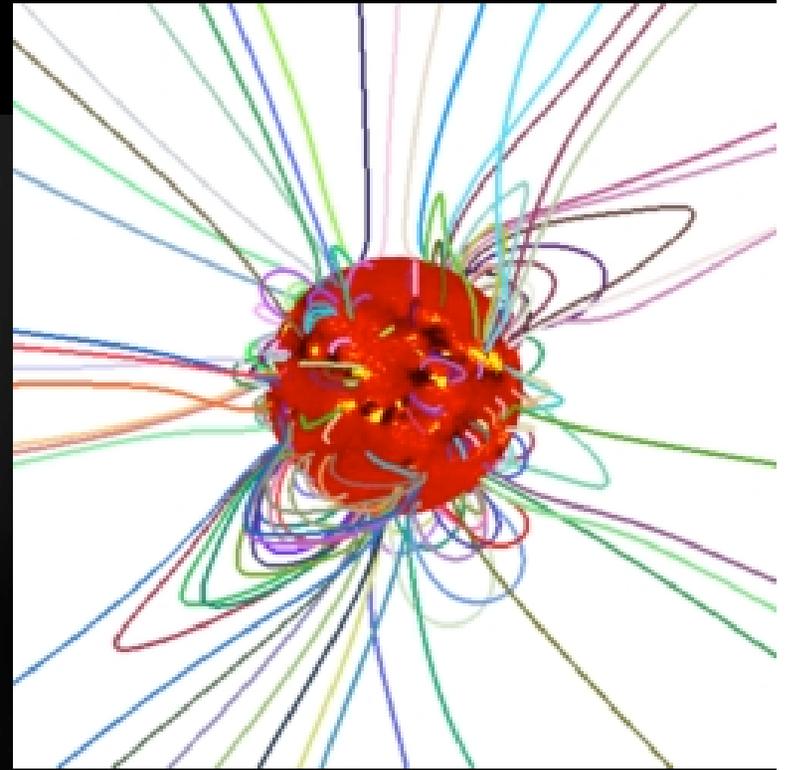
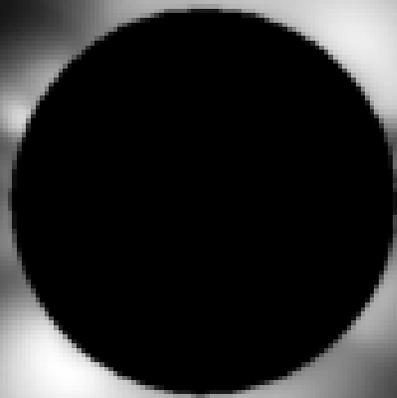


## Address other forces, solar wind



- Use analytic models (Munro and Jackson)
- Use MHD models
  - Use same B condition
  - But – heating problem???





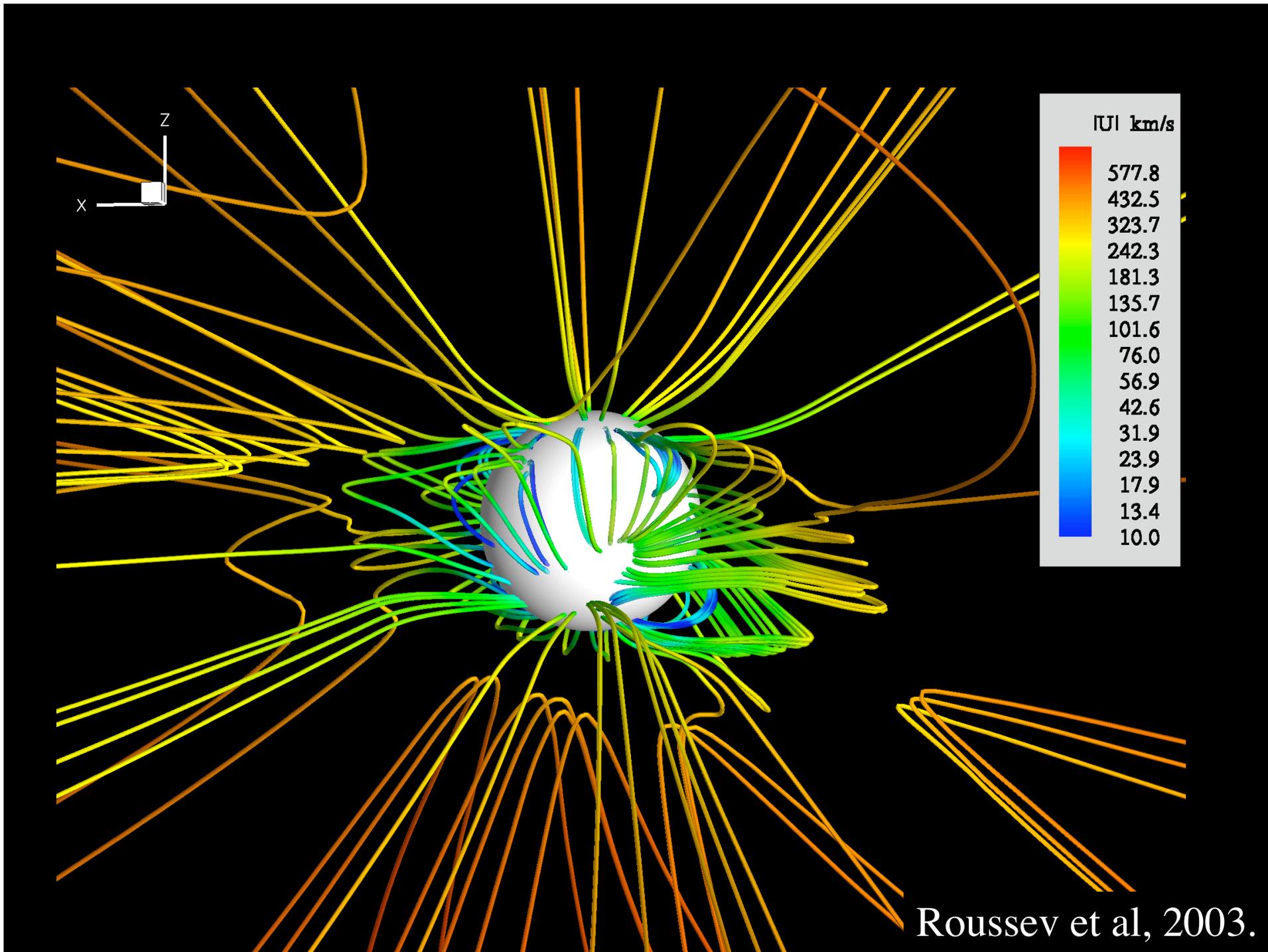
**Linker et al., 2001.**

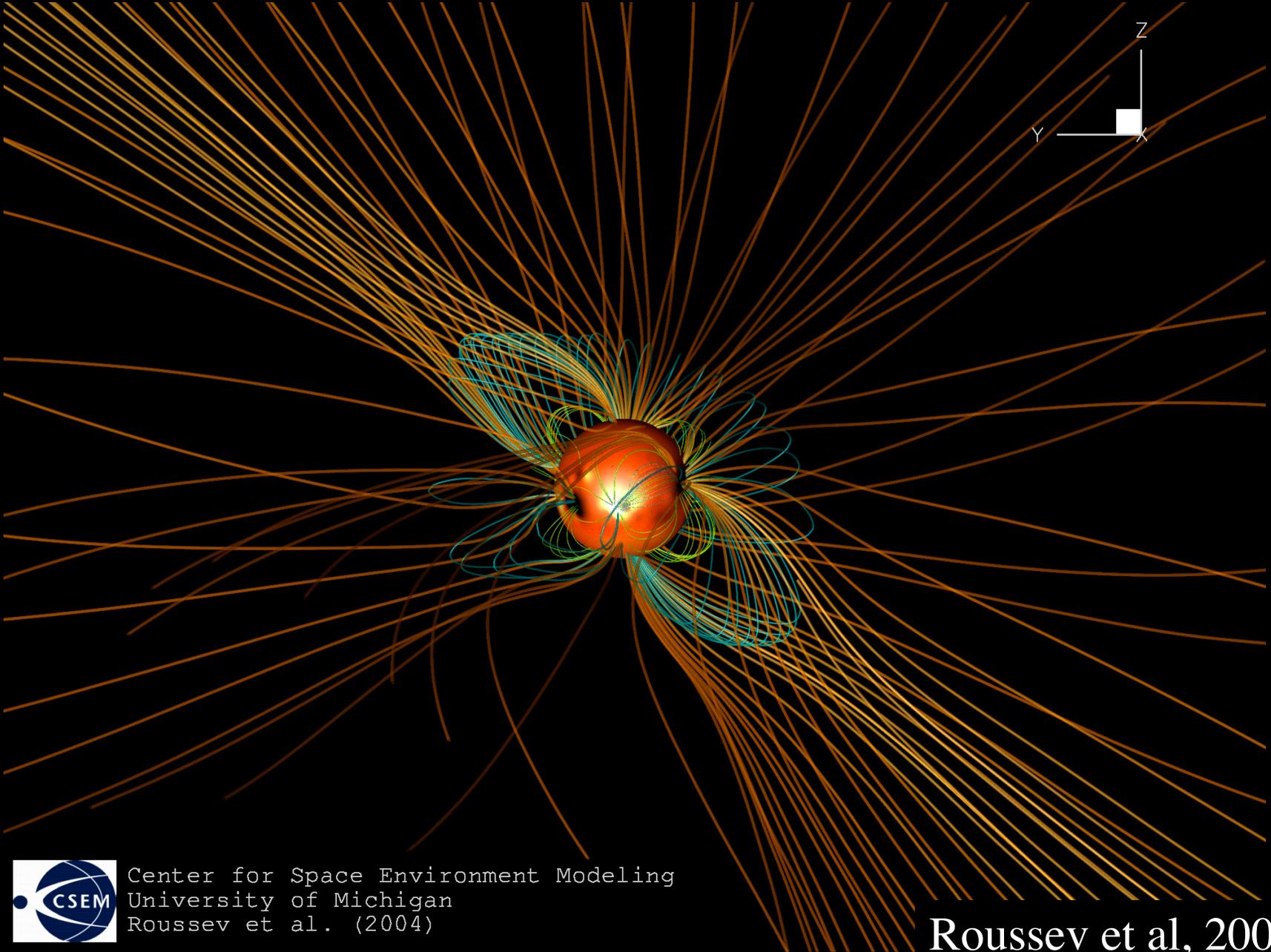
# Assumptions



- Generally
  - Put boundary condition into corona
  - Use spatially dependent T
  - Tailor open and closed field regions using different thermodynamics
- Limited by our understanding of physics!







Center for Space Environment Modeling  
University of Michigan  
Roussev et al. (2004)

Roussev et al, 2004.



## Why different?

- Still solves, assuming potential  $B$
- Depends on location of source surface
- Heating profile needs to be adjusted based on topology
  - Open fields  $\sim$  isothermal
  - Closed fields  $\sim$  adiabatic
- Requires a priori information about topology

$$B = B_{pot} + \delta B$$



## Summary: MHD models



- Include coupling of non-magnetic forces.
- But, there is no rigorous way to determine a priori heating
  - Closed field vs open field.
- Cannot a priori predict heliospheric flux
  - Use data to constrain



## Three issues



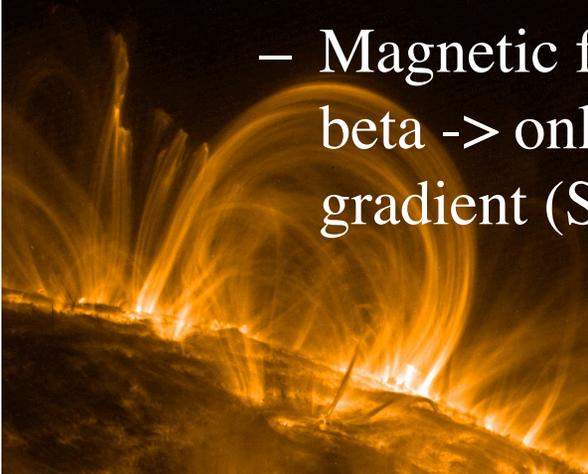
1. Open flux expansion?
2. Time-dependences of the source?
3. Interactions between open and closed flux?



# 1. Open flux expansion



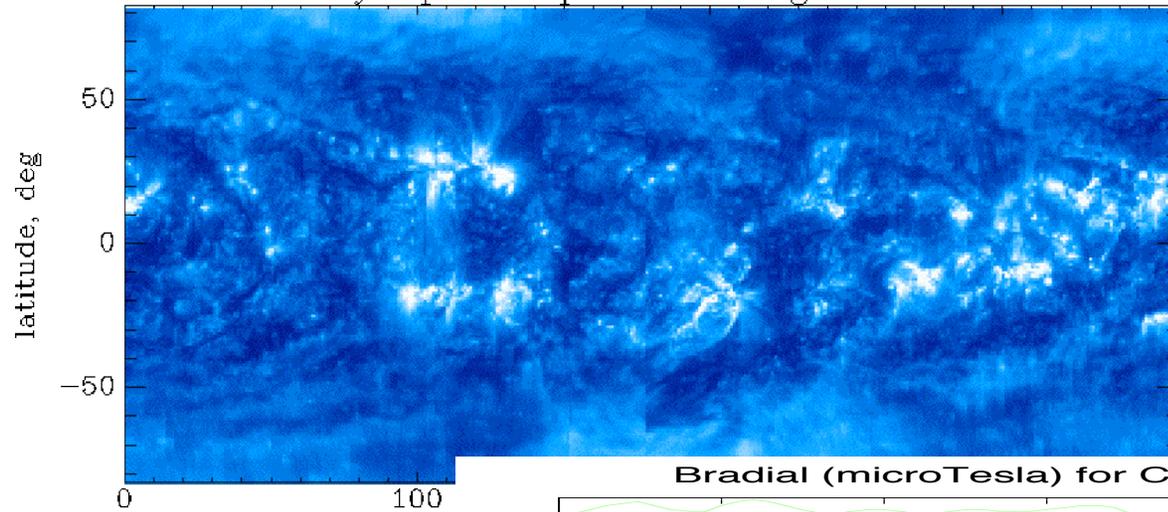
- Assume
  - Photospheric field as boundary
  - Location of open flux in photosphere
- Recognize
  - Magnetic field needs to equilibrate since, low plasma beta  $\rightarrow$  only field can balance latitudinal pressure gradient (Suess et al.)



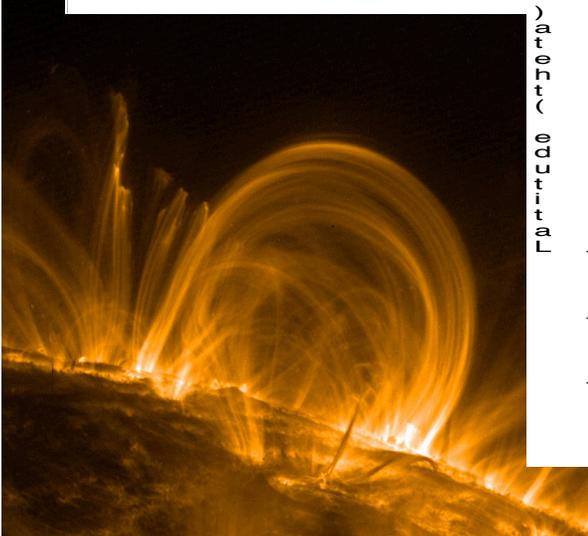
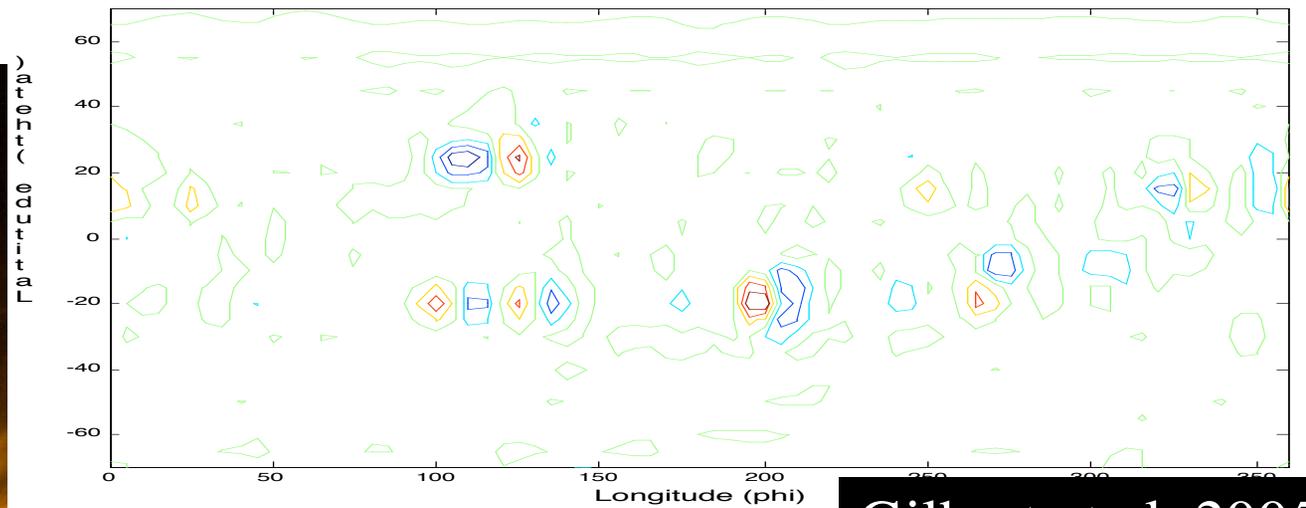
# Photosphere



EIT 171A Synoptic Map for Carrington rotation 1996



Radial (microTesla) for Carrington Rotation 1996

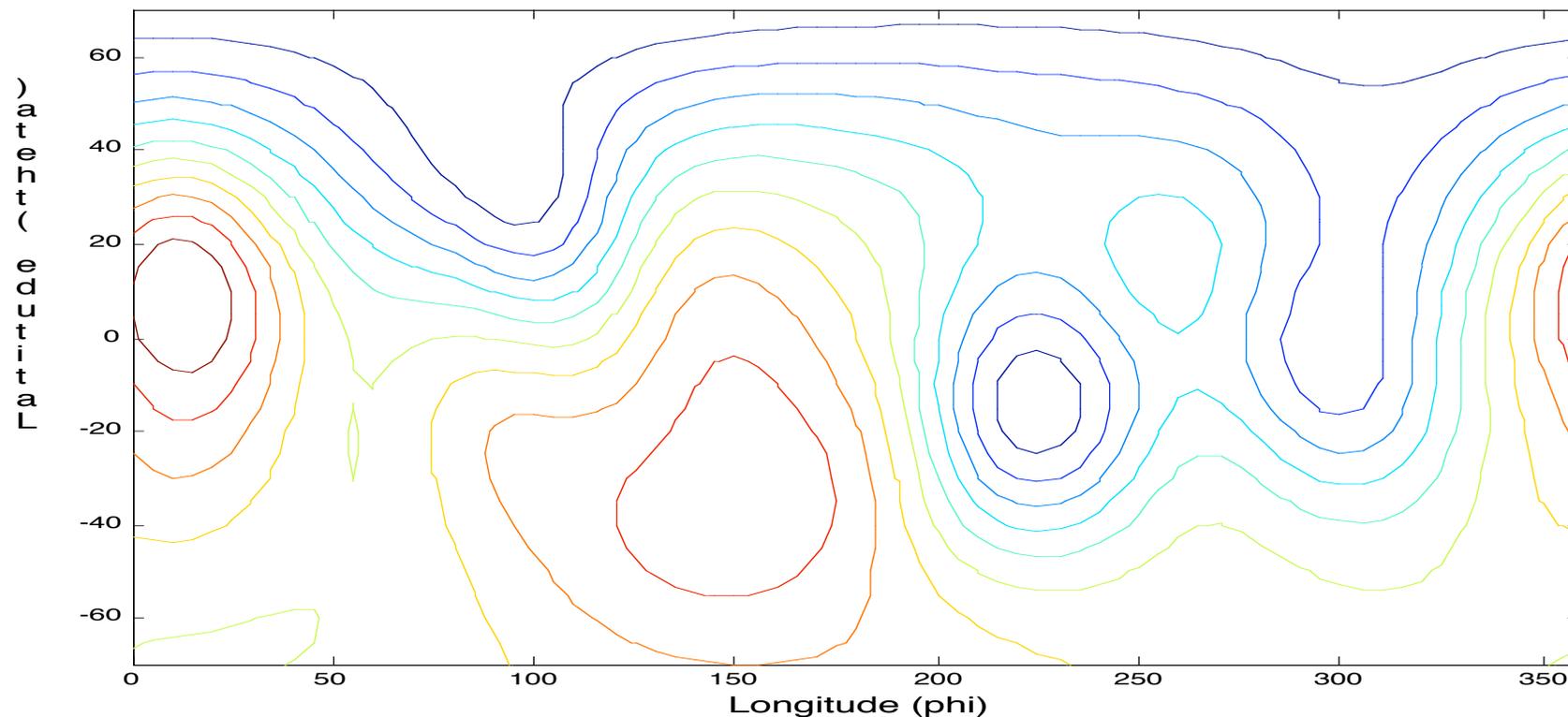


Gilbert et al, 2005.

# Source surface distribution (potential)

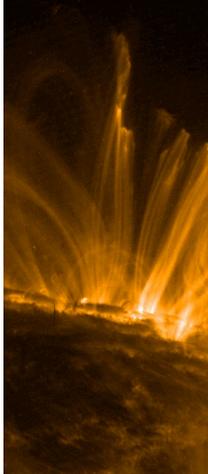
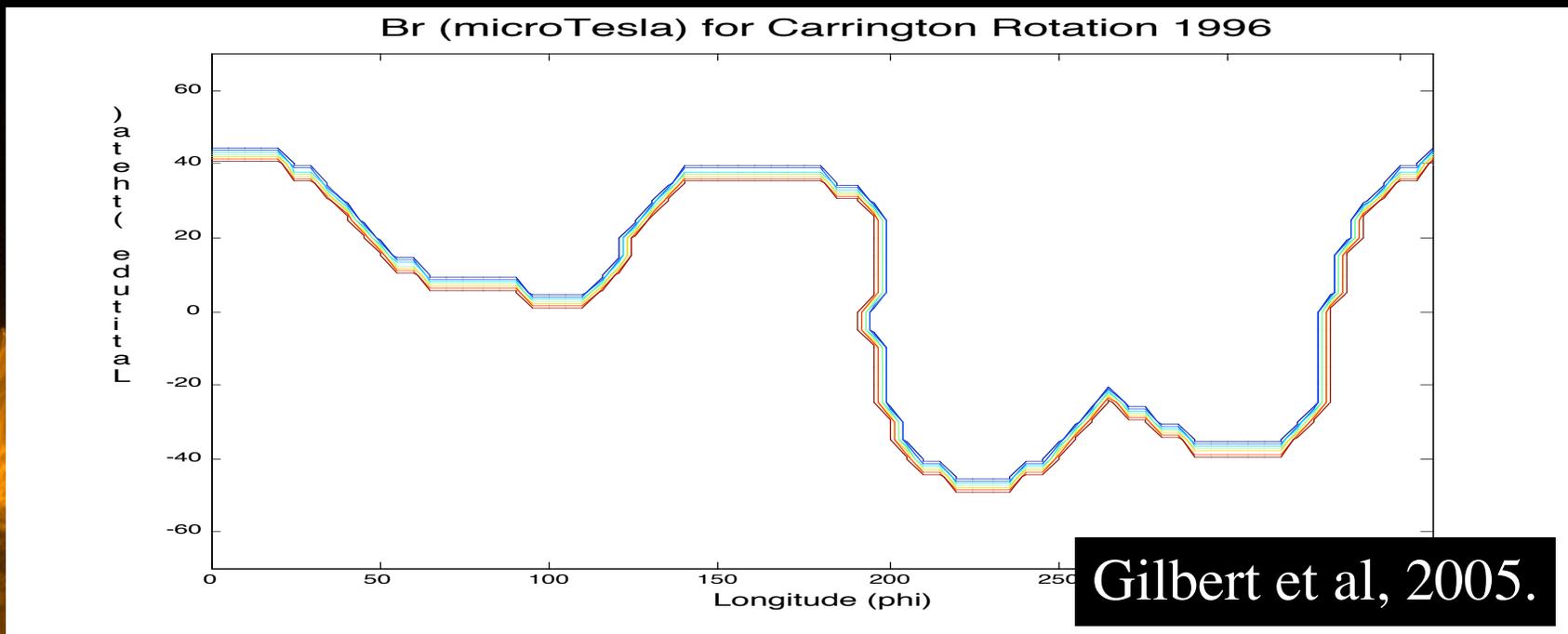
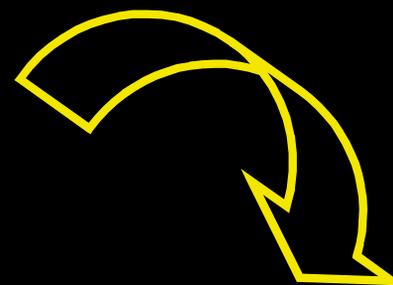
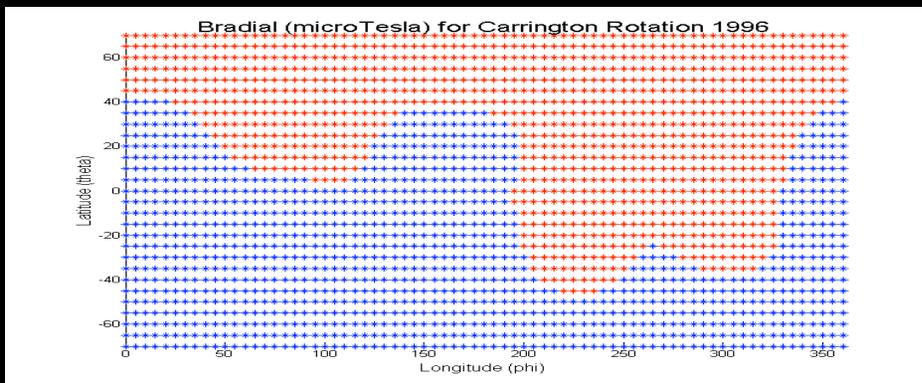


Bradial (microTesla) for Carrington Rotation 1996



Gilbert et al, 2005.

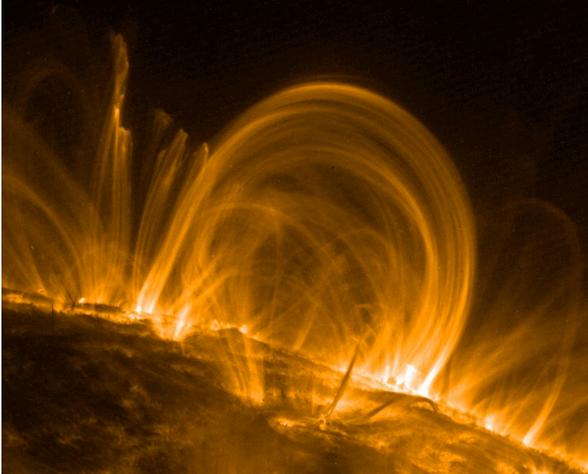
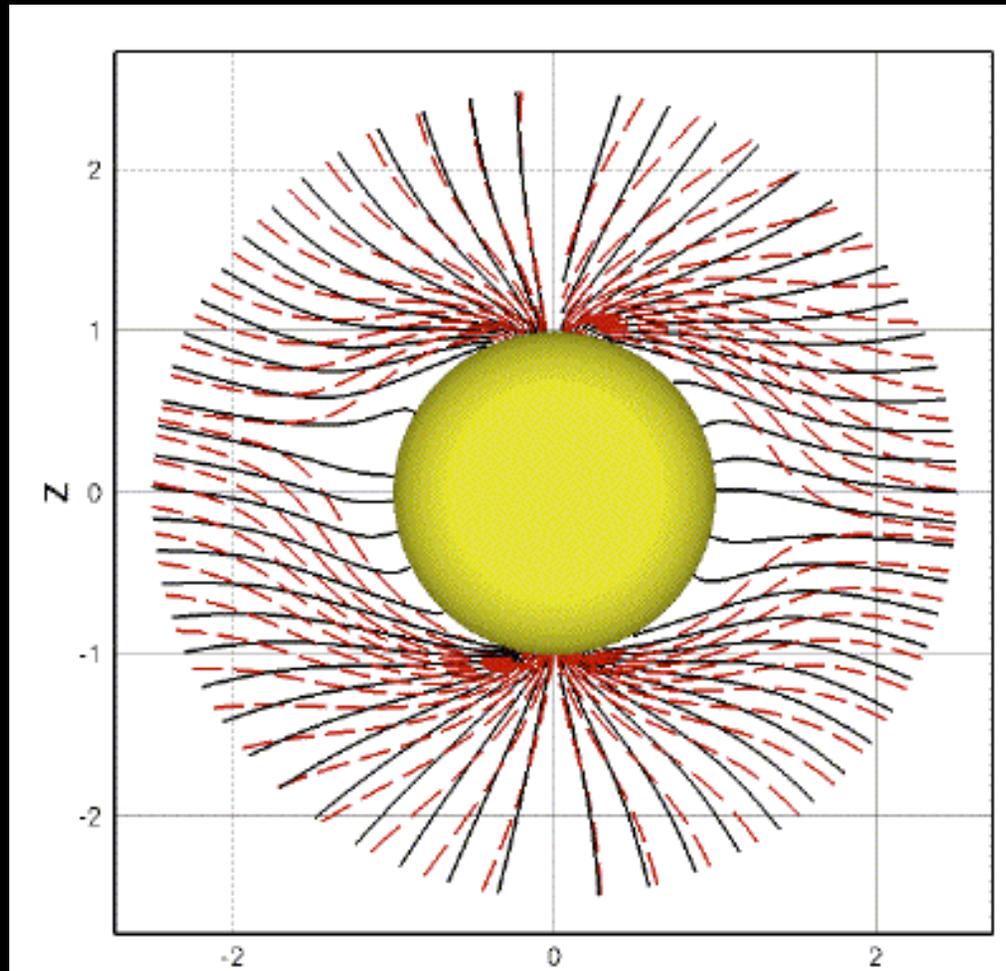
# Diffuse to Equilibrium



# Solar magnetic field expansion

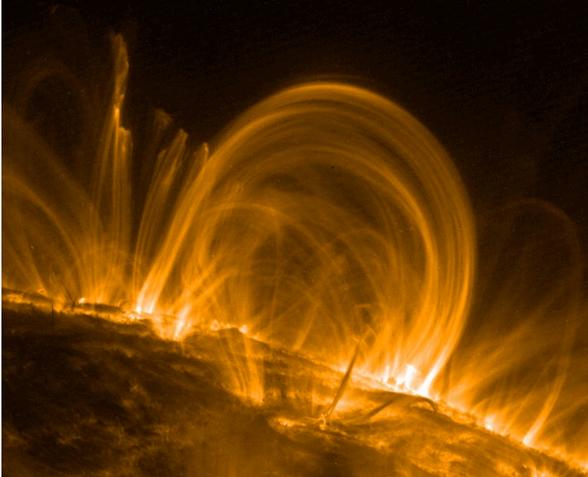


- Open flux at low latitudes in slow solar wind affects overall topology of corona



Gilbert et al., this conference

## 2. Time-dependences?

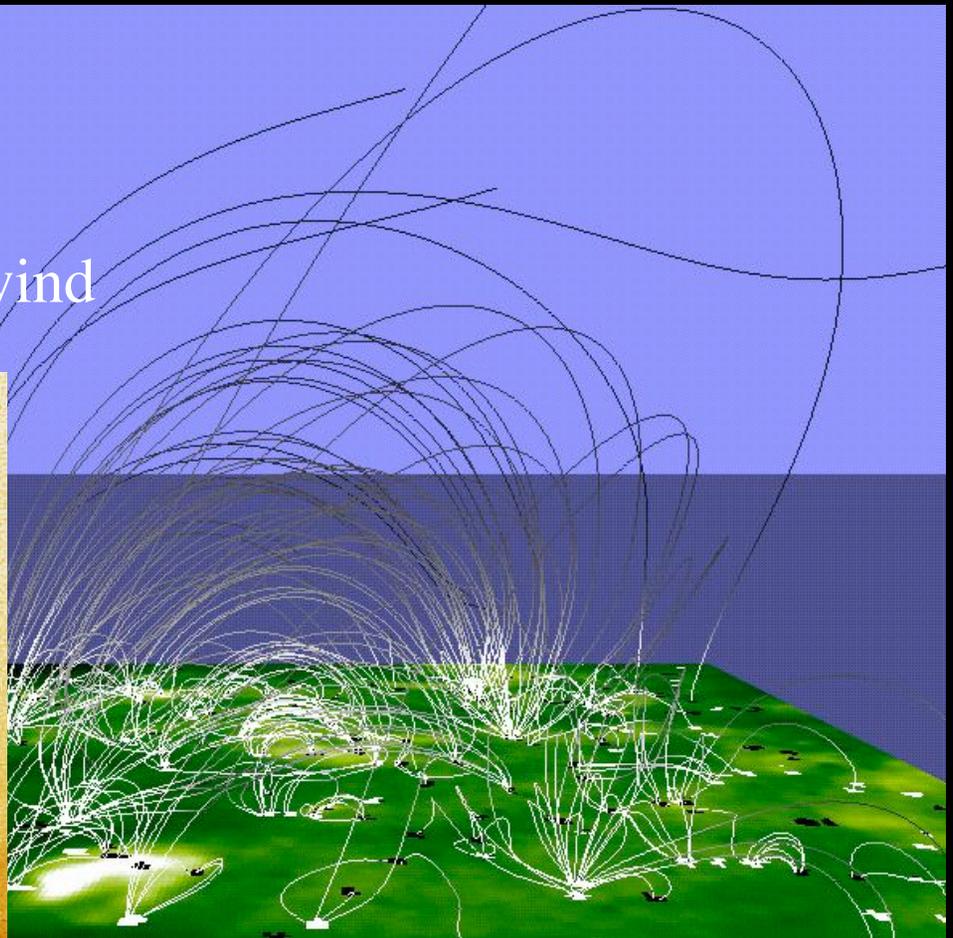
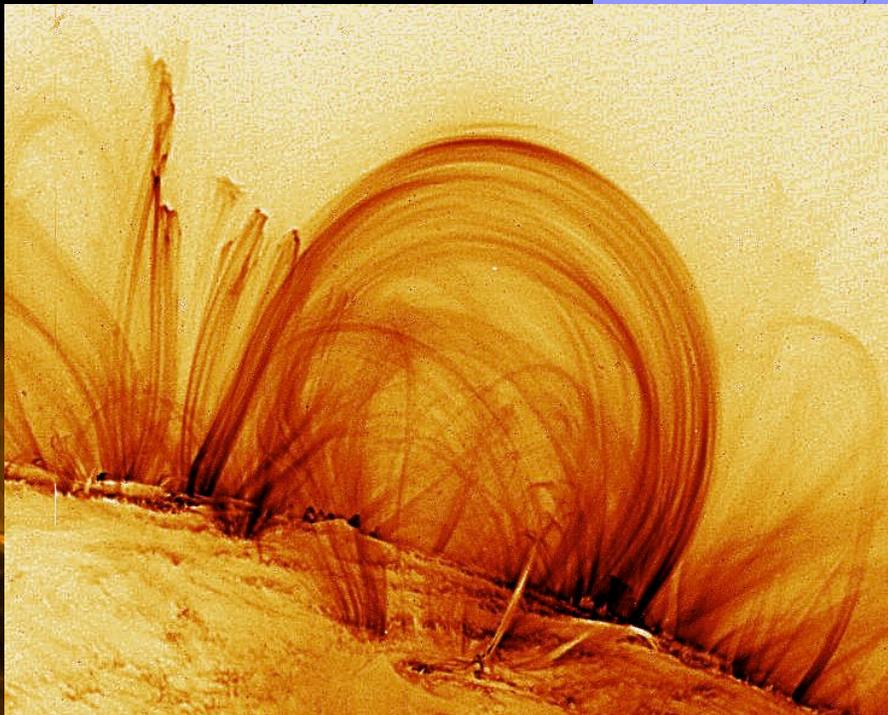




# Magnetic flux evolution

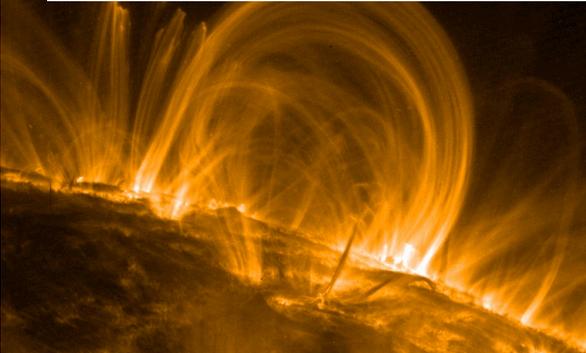
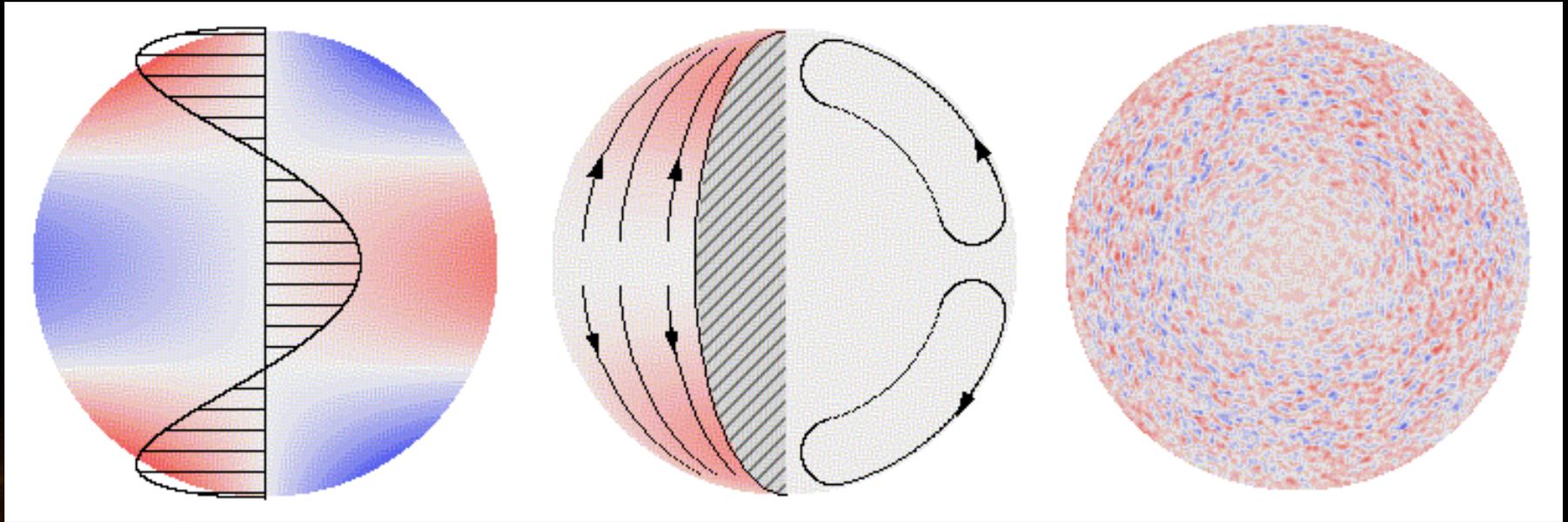
Time-dependent.  
Highly structured.

-> Boundary condition to solar wind





# Surface motions



Images from Stanford Observatory

# Motions -> Heliospheric structure



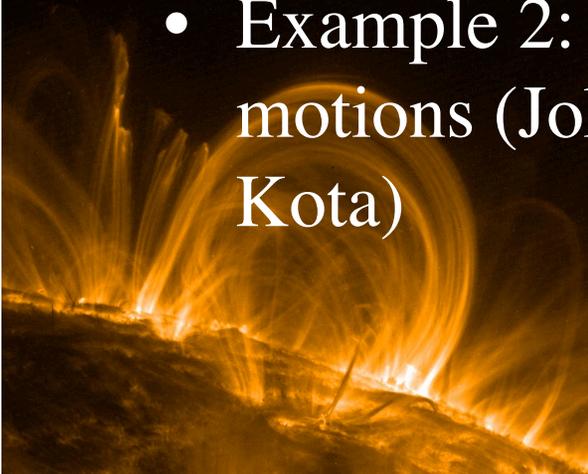
Hollweg and Lee.

$$B_{\perp} = -u_{\perp} (r / r_s) B_r / V$$

- Example 1: Solar rotation

- Example 2: Random motions (Jokipii and Kota)

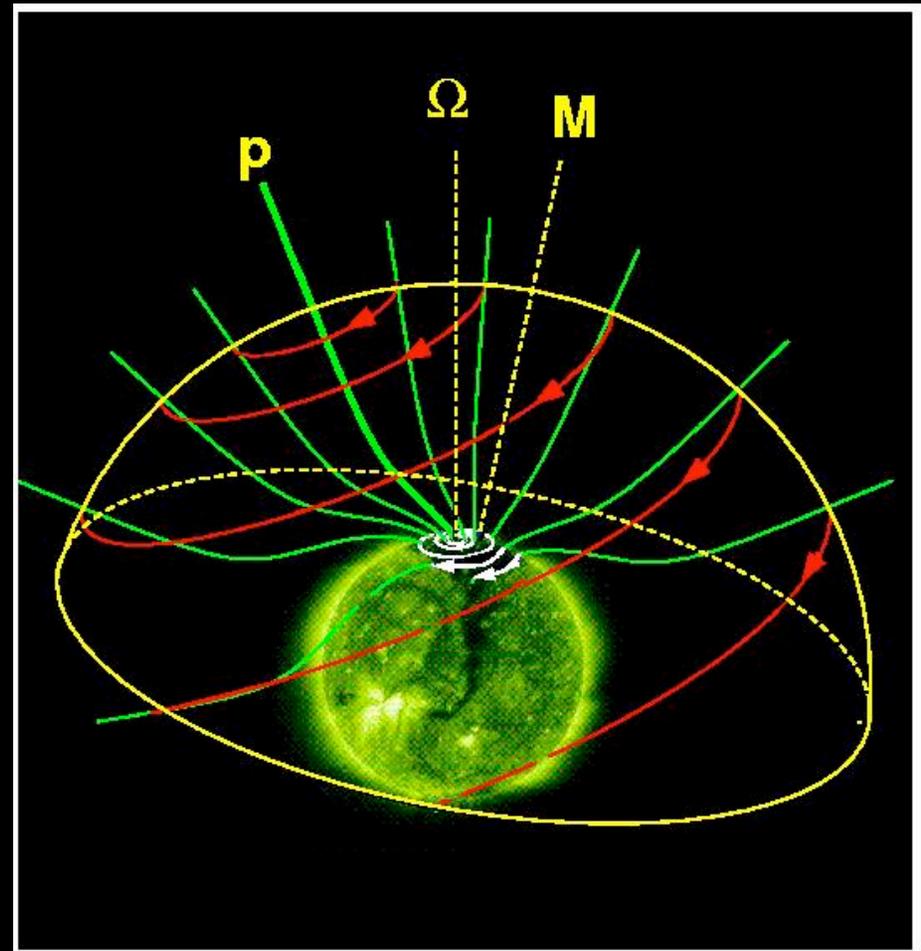
$$\begin{aligned} B_{\perp} &= \Omega r_s \sin \theta e_{\phi} (r / r_s) B_r / V \\ &= -B_r \left( \frac{r \Omega}{V} \right) e_{\phi} \end{aligned}$$

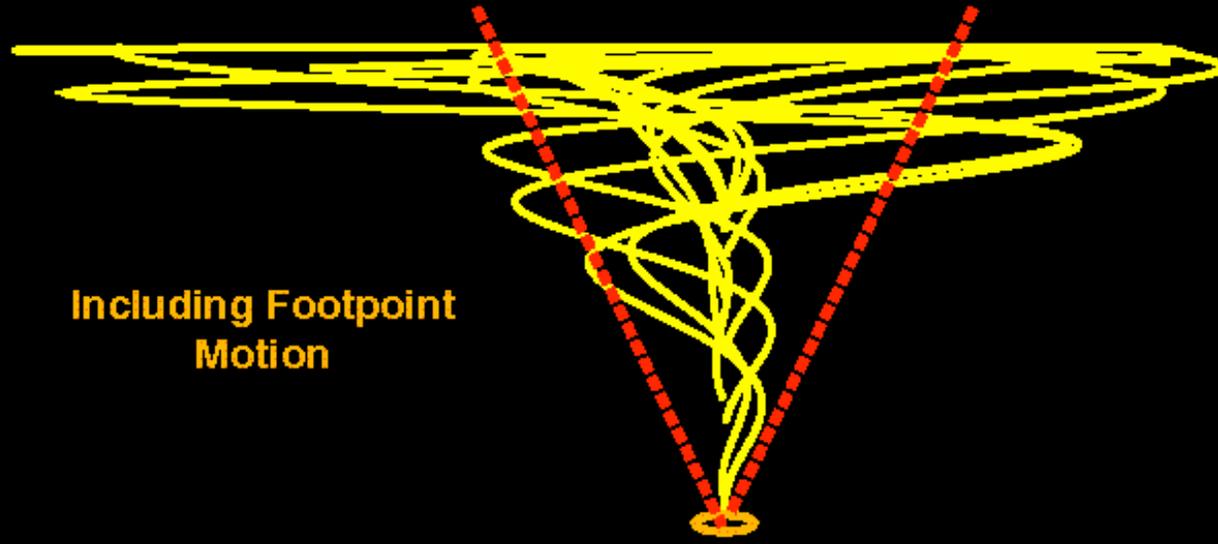




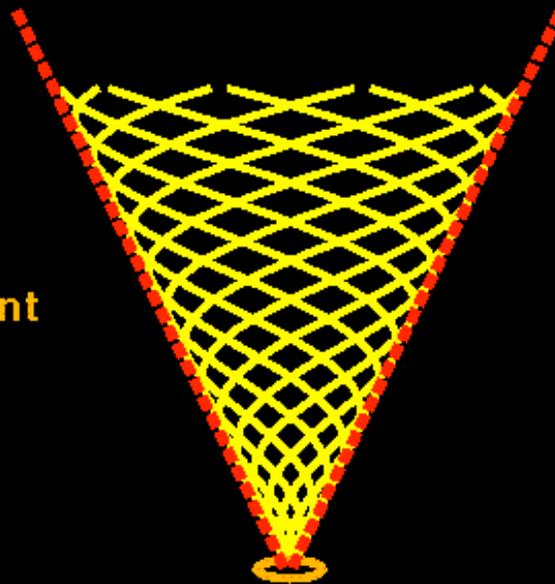
# Large-scale transport

- Fisk, 1996: combination of differential rotation and super-expansion explains large latitude excursions of field lines
- Explains: Forsyth et al., 1995; Zurbuchen et al., 1998; Roelof et al., 1995; Simnett et al., 1995.



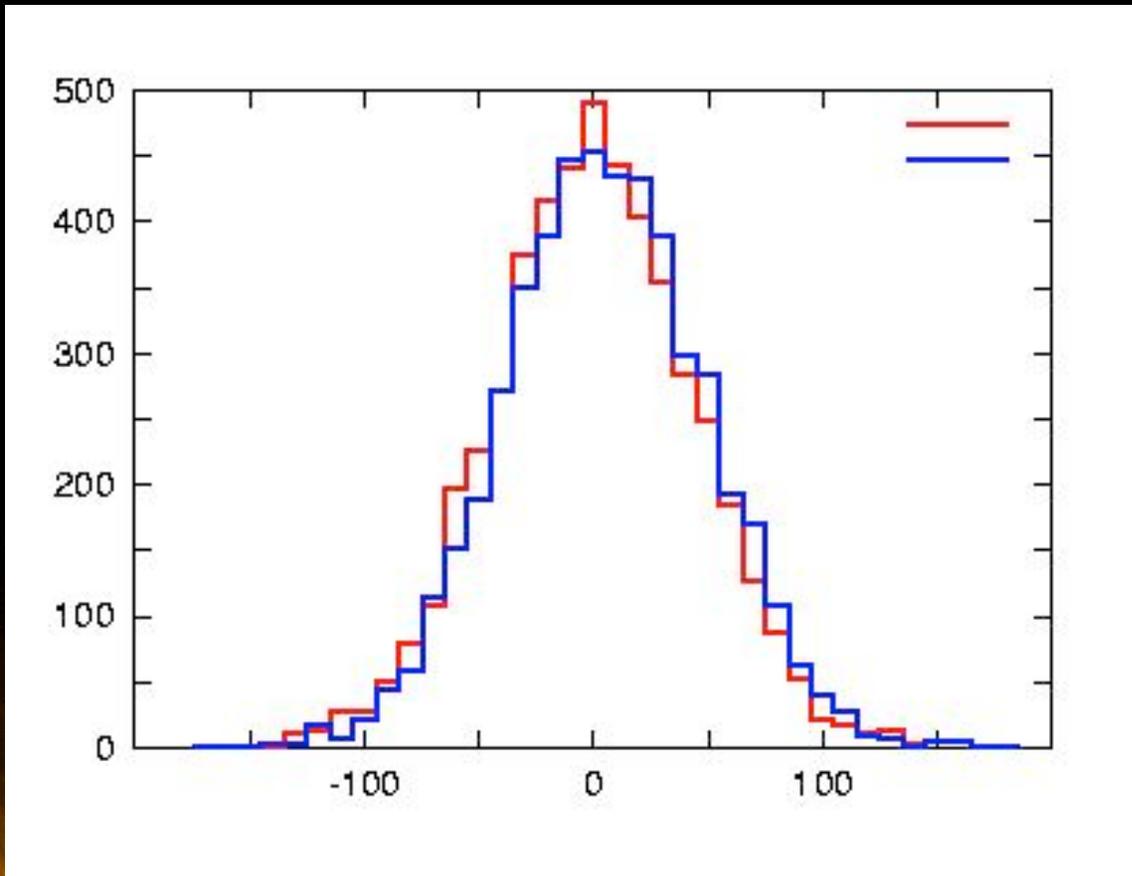


Without Footpoint Motion

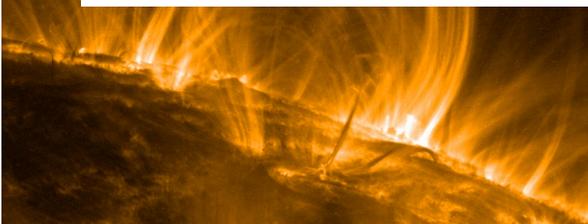




# Comparison



- Only hope: energetic particle measurements
- Correlative measurements.

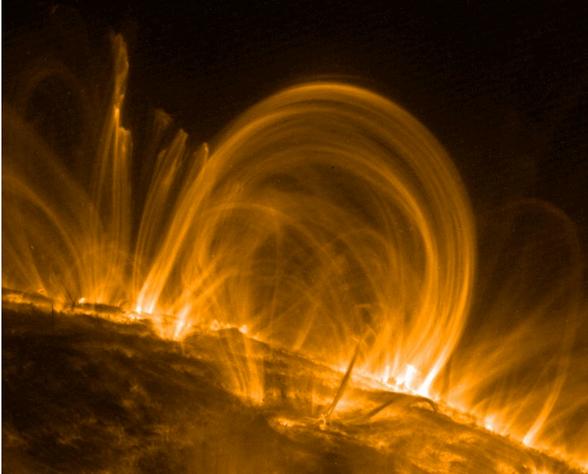
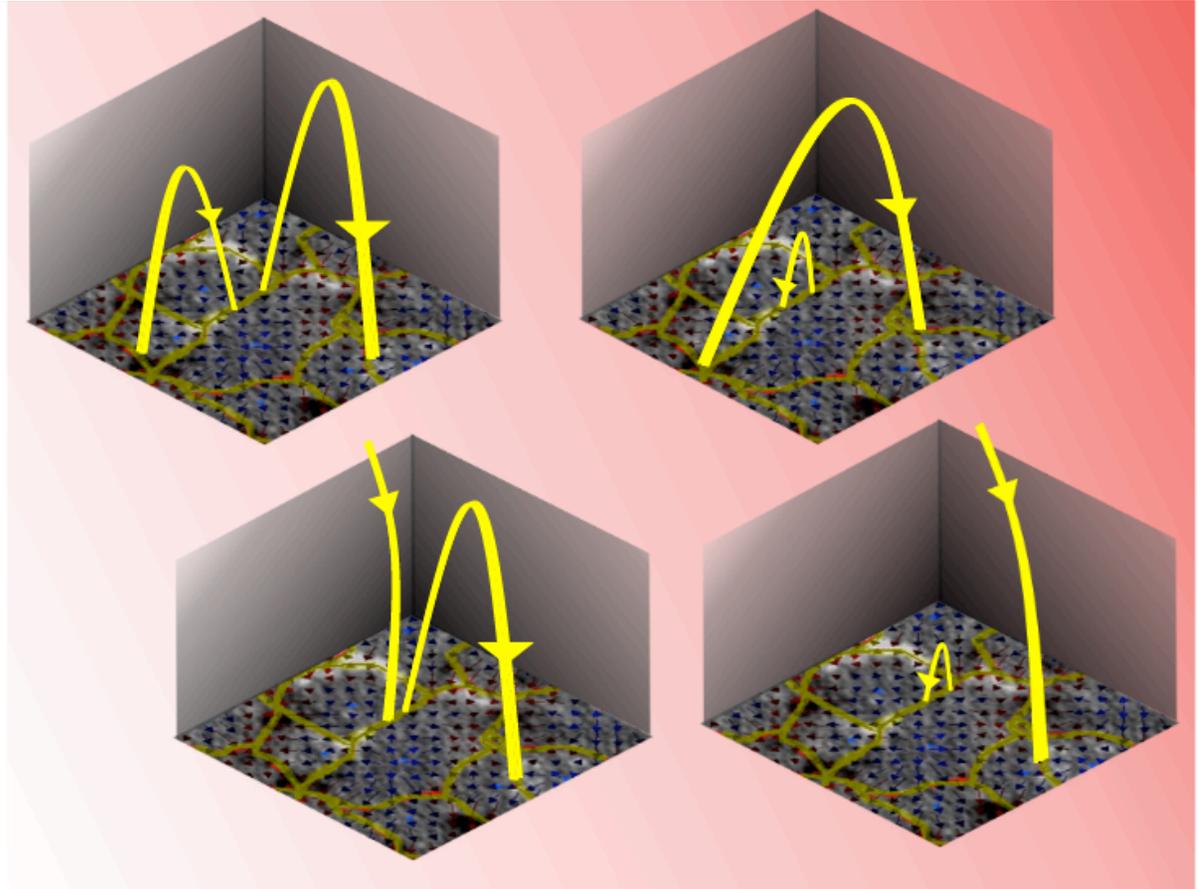


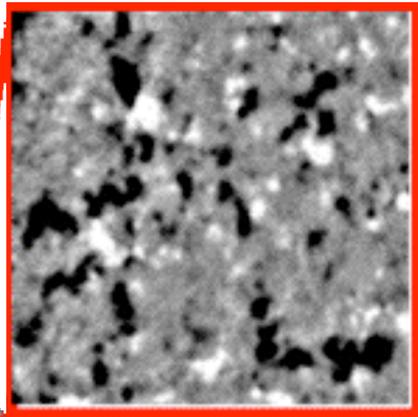
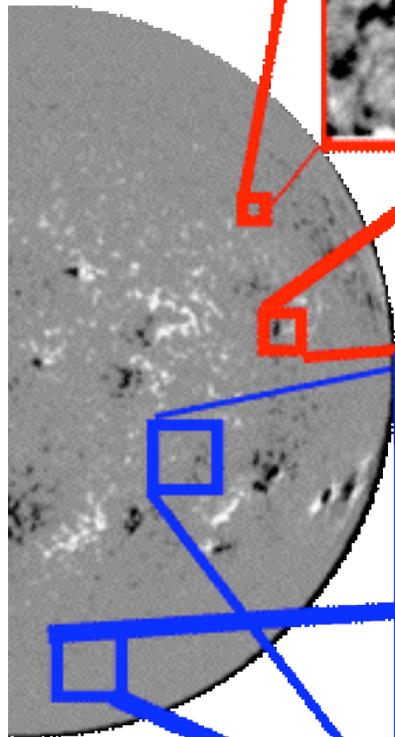
### 3. Open-closed flux interactions



- Loop-loop

- Loop-open

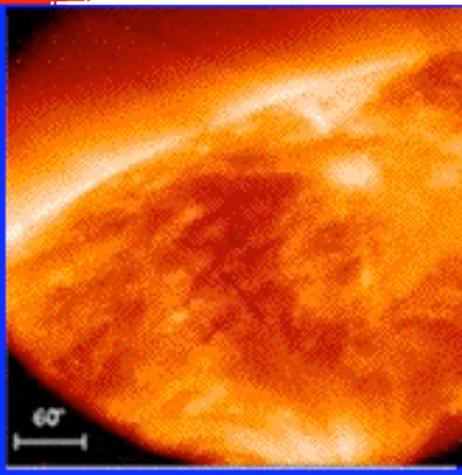




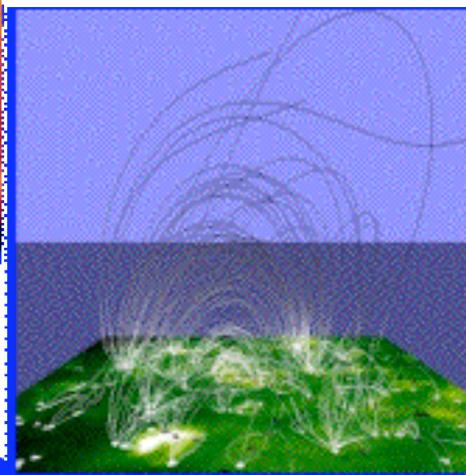
**H-Alpha: 1000 km granules and associated loops**



**X-ray: active region loops**



**EUV: 40,000-400,000 km loops**



**Emerging flux on super-granule scale**

# Diffusion approach



## Diffusion equation

- We need then a diffusion equation [these are diffusive processes]
- In the three-dimensional case the diffusion equation, written in vector form, is

$$\frac{\partial \mathbf{B}_o}{\partial t} = -\nabla \times (\nabla \times (\kappa \mathbf{B}_o) + \mathbf{u}_o \times \mathbf{B}_o) \quad (1)$$

- Which in the case of diffusion along the solar surface, to which the magnetic field is radial, reduces to

$$\frac{\partial B_o}{\partial t} = \nabla^2 (\kappa B_o) - \nabla \cdot (\mathbf{u}_o B_o) \quad (2)$$

- In these two equations,  $\kappa$  is the diffusion coefficient, and it governs the transport. And so our job, to the extent we can, is to specify  $\kappa$ .

Fisk, 2005.

# Coupling

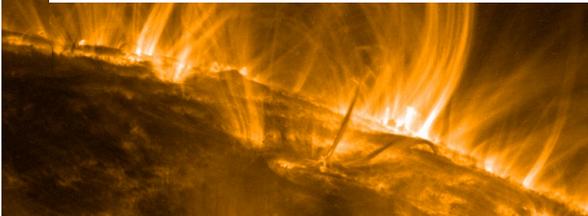


## Diffusion along the solar surface.

- We identified two processes for diffusion along the solar surface. Each is governed by a diffusion coefficient:
- First, open field lines, as with all magnetic flux, diffuses along the solar surface as a result of random convective motions in the network lanes.
- The appropriate diffusion coefficient is

$$\kappa_1 = \frac{\delta h^2}{2\delta t} \quad (3)$$

where again,  $\delta h$  is the linear distance along which the field line is convected in time  $\delta t$ .



Fisk, 2005.

# Solar wind heating



- Calculate Poynting flux injected in each reaction.
- For given relation between mass and Poynting flux, and thermal model
- Determines solar wind speed.

Fisk, 2003.

Gloeckler, Zurbuchen, Geiss, 2003..



# Summary



- Breakthrough research
  - Heating of open and closed corona (includes solar wind acceleration)
  - Interactions between closed and open corona
- Breakthrough technologies
  - Observe the Sun up close
  - Learn how to observe coronal B

