The Flux Transport Model

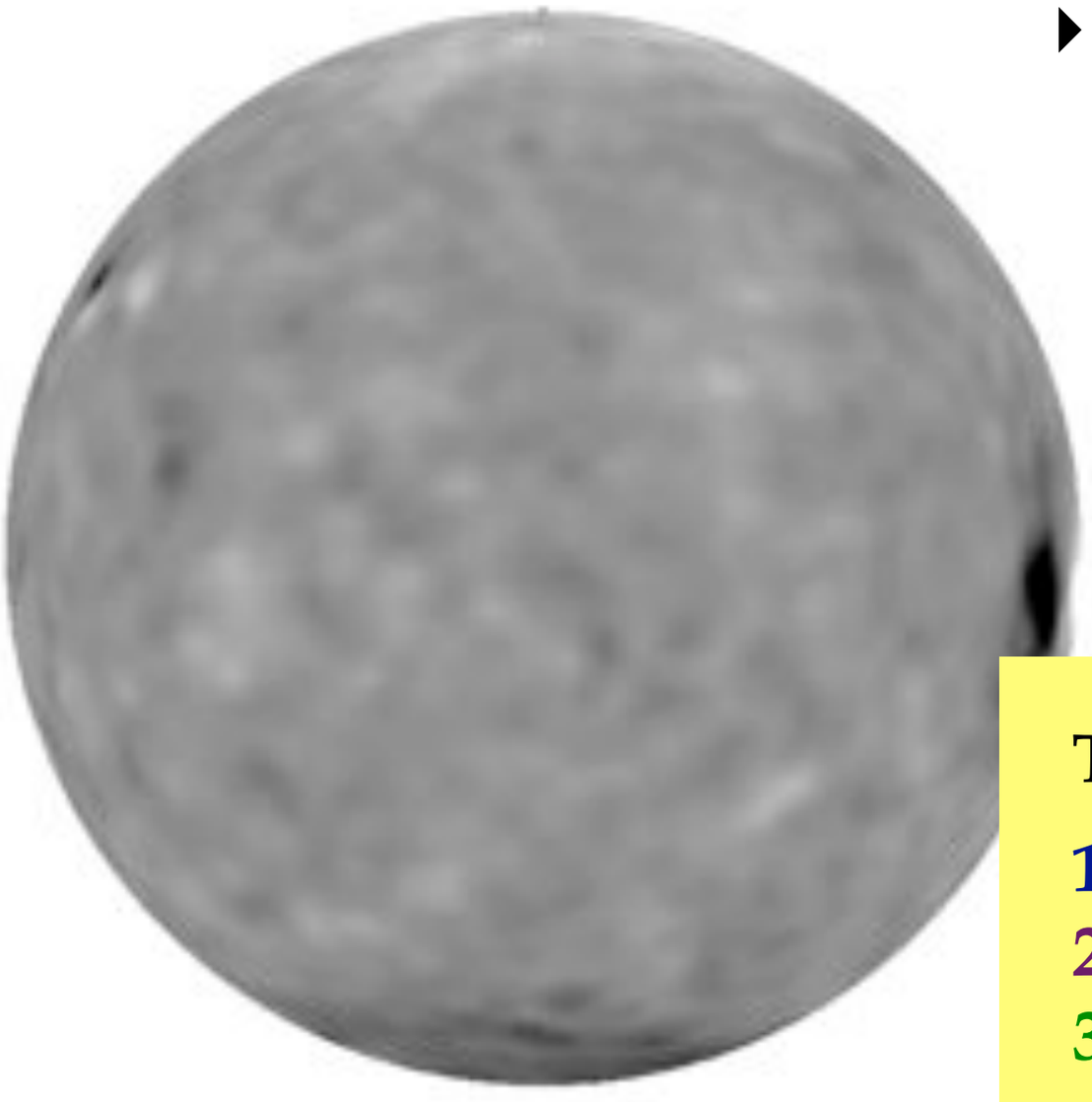
& Its Relevance to Space Weather & Climate

Anthony Yeates (Durham University, UK)

NSO Workshop 26, New Mexico, May 2012

Why flux transport?

Understanding the evolution of magnetic flux we see.



Filling observational gaps:

- full Sun coverage
- high latitude fields

Simulating/predicting activity when we don't have magnetograms:

- future
- historical
- other stars

This talk:

1. Standard model
2. Historical reconstruction of open flux
3. New model for coronal field

Standard model

Leighton, *ApJ*, 1964:
supergranulation ⇒ random walk of flux

$$\frac{\partial B_r}{\partial t} = -(\nabla \cdot \mathbf{v})B_r - (\mathbf{v} \cdot \nabla)B_r + D\nabla^2 B_r$$

advection (diff. rotation) diffusion

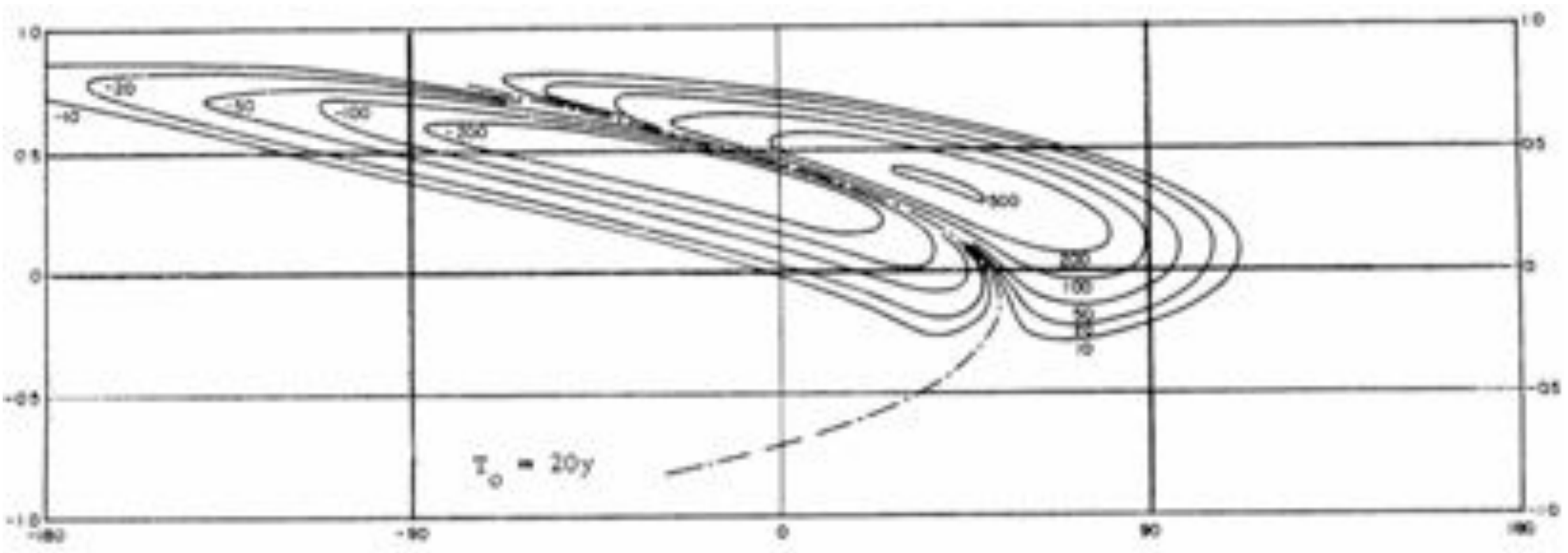
TRANSPORT OF MAGNETIC FIELDS ON THE SUN*

ROBERT B. LEIGHTON
California Institute of Technology
Received June 4, 1964; revised June 25, 1964

ABSTRACT

The dispersal and migration of unipolar and bipolar magnetic regions on the Sun are quantitatively interpreted as a random-walk, diffusion-like process caused by supergranulation convection currents in the Sun's outer layers The time-dependent strength and sign of the polar fields are deduced approximately from the positions, fluxes, and axial tilts of the individual spot groups associated with the sunspot cycle. The well-known predominance of the preceding spot of a group is attributed to a characteristic field configuration which renders *p* spots relatively stable against fragmentation by the supergranulation currents The relation of the random-walk process to the solar cycle is briefly discussed, and the 11-year period is interpreted as the summation of five more-or-less distinct parts

Standard model



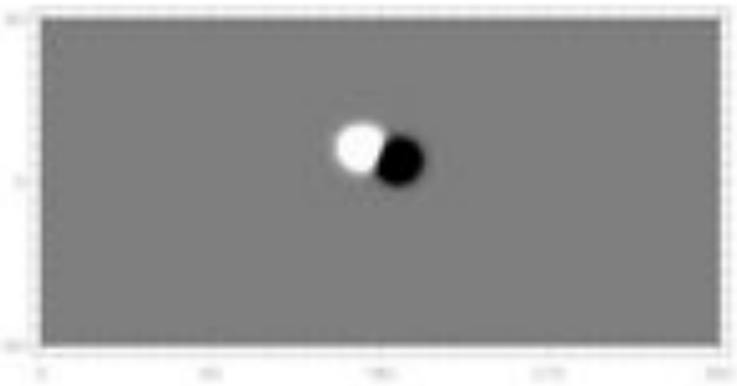
Leighton, *ApJ*, 1964

many bipoles ➔ polar field

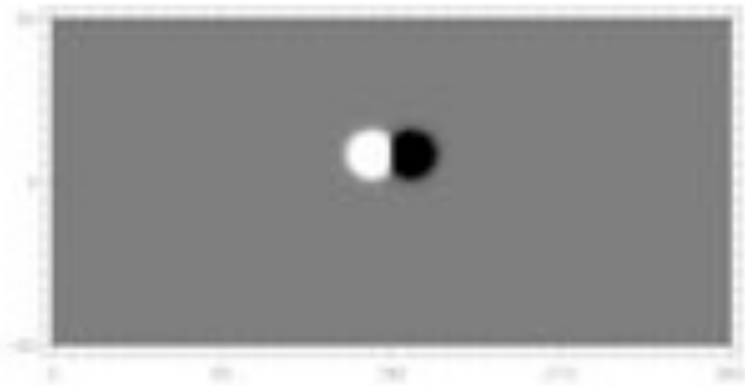
Standard model

Tilt | **No tilt**

saturation 100G

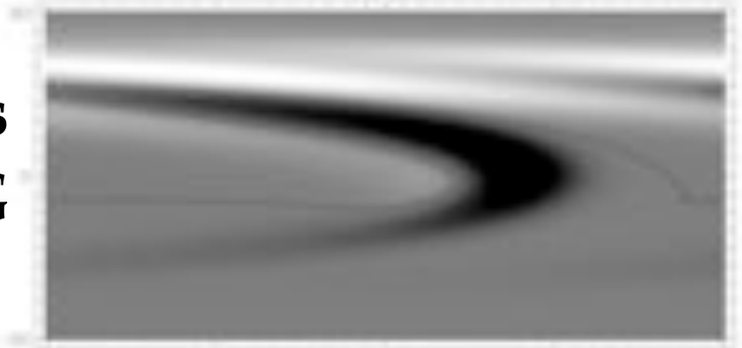


(a)

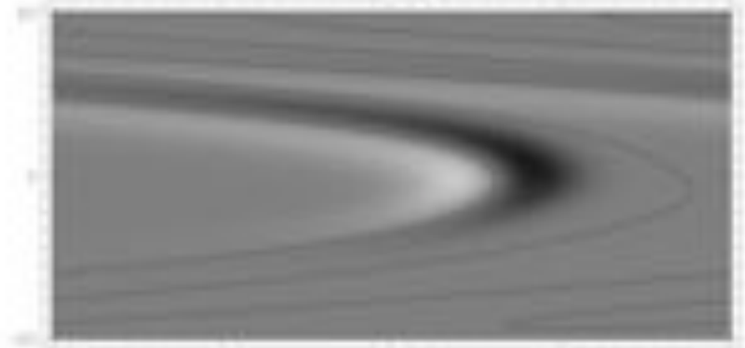


(d)

15 rotations
saturation 10G

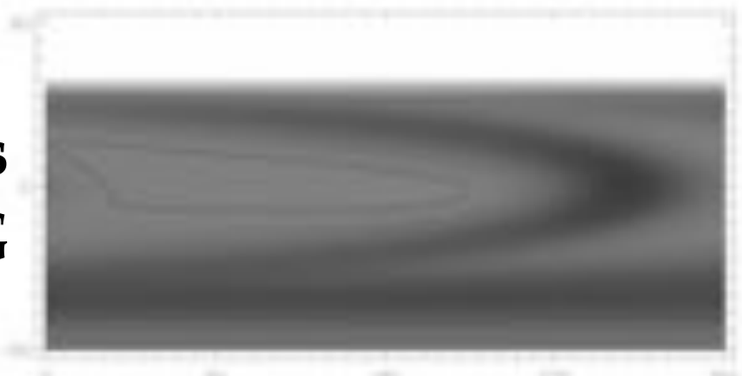


(b)



(e)

30 rotations
saturation 5G



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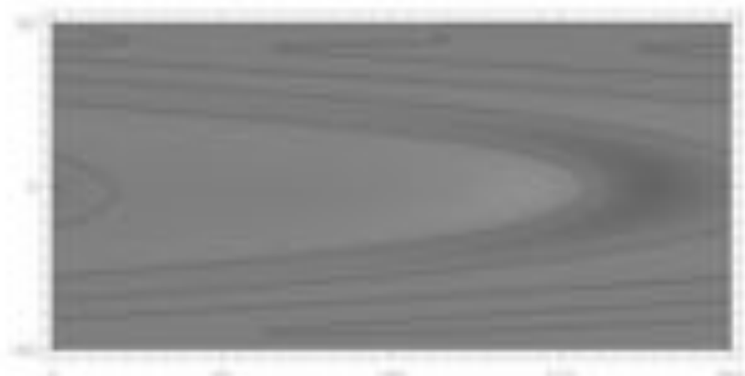
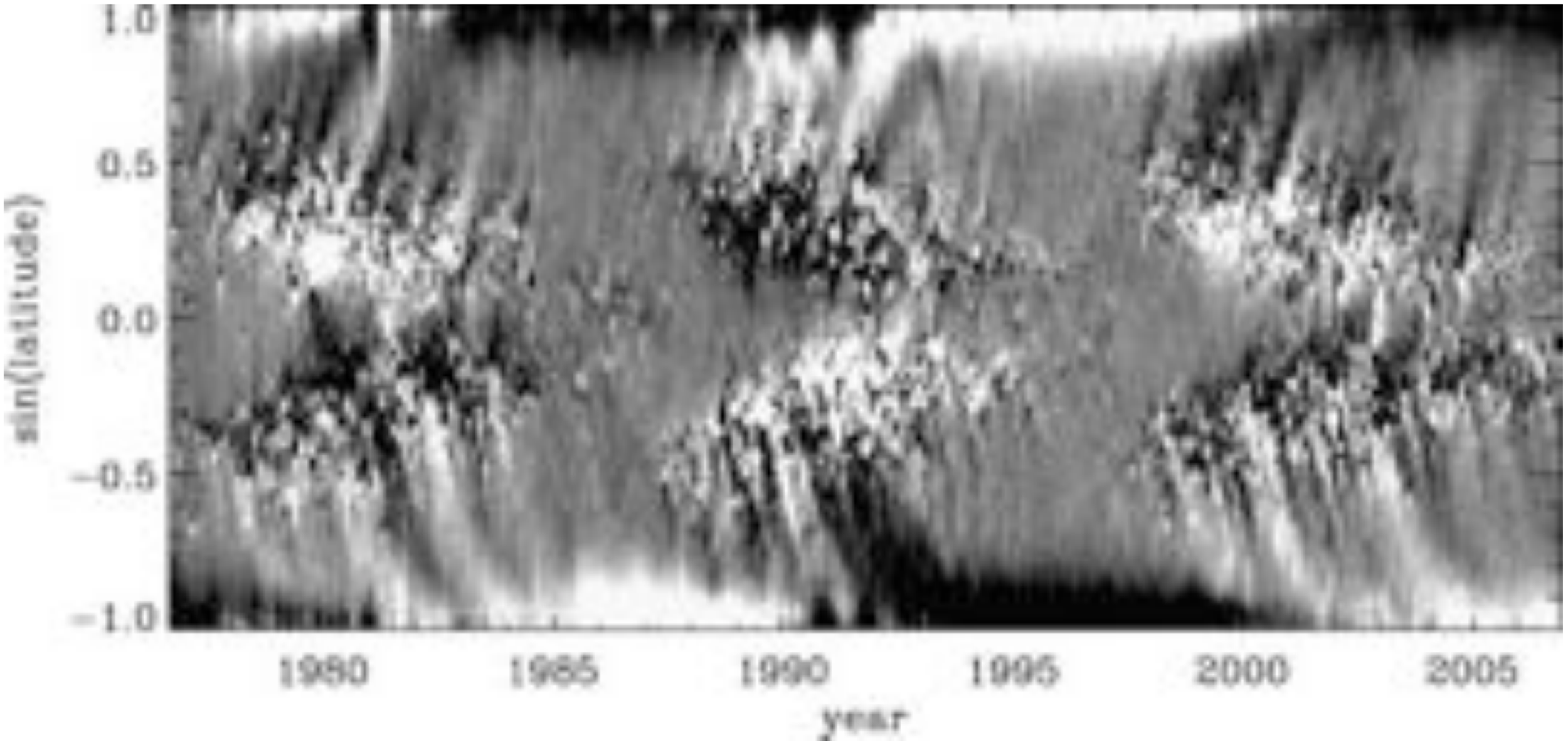


(f)

Standard model



Meridional flow:

1. Reproduces "topknot" polar field
2. Matches poleward surges
3. Allows diffusion coefficient to be reduced to ca. 500 $km^2\ s^{-1}$

Devore, Sheeley & Boris, *ApJ,* 1984
Wang, Nash & Sheeley, *Science,* 1989

Reconstructing past open flux

Motivation: geomagnetic data

A doubling of the Sun's coronal magnetic field during the past 100 years

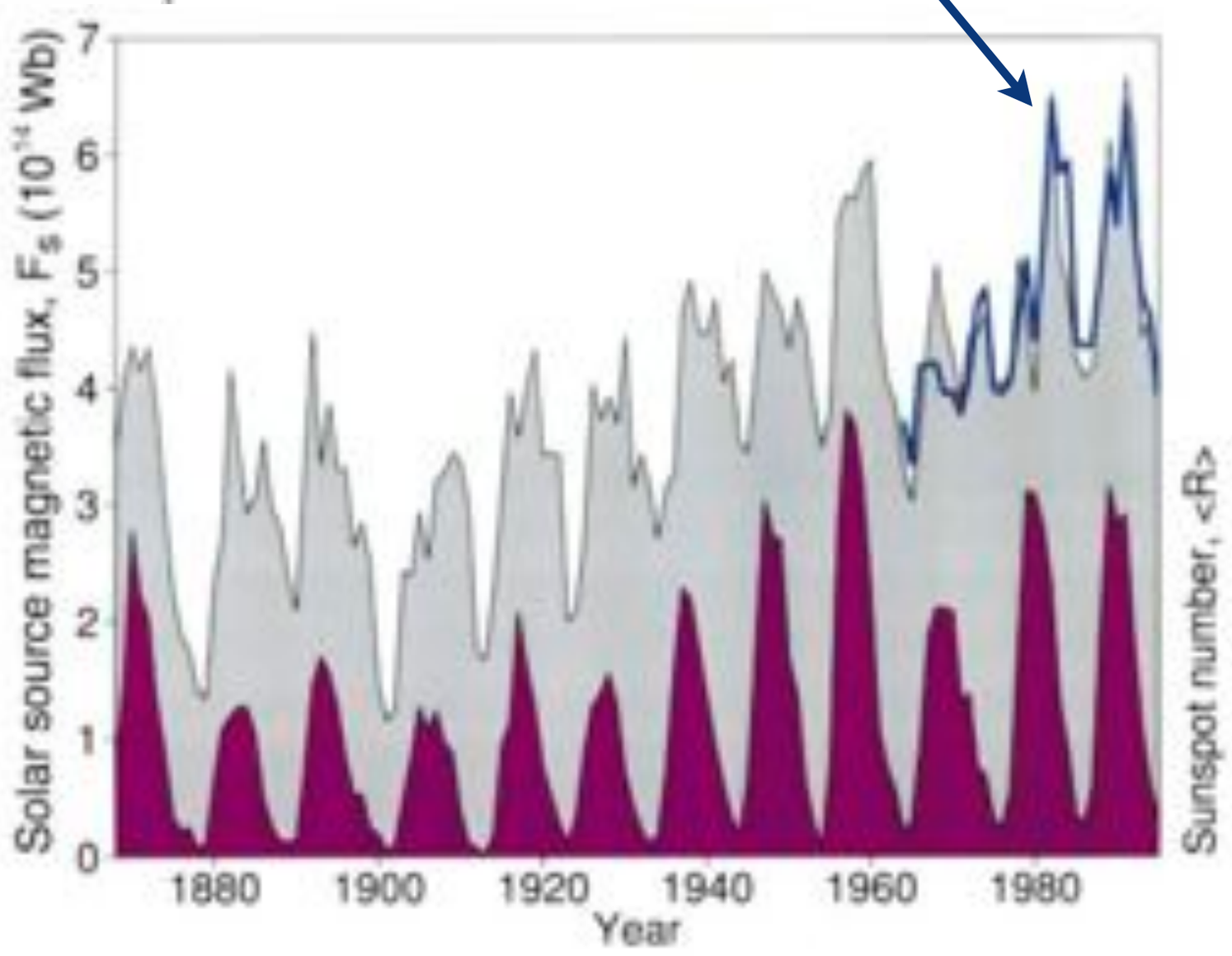
M. Lockwood, R. Stamper & M. N. Wild

World Data Centre C-1 for STP, Rutherford Appleton Laboratory, Didcot OX11 0QX, UK

The solar wind is an extended ionized gas of very hig
conductivity, and therefore drags some magnetic flux
Sun to fill the heliosphere with a weak interplanetar
field[1,2]. Magnetic reconnection—the merging of oppos

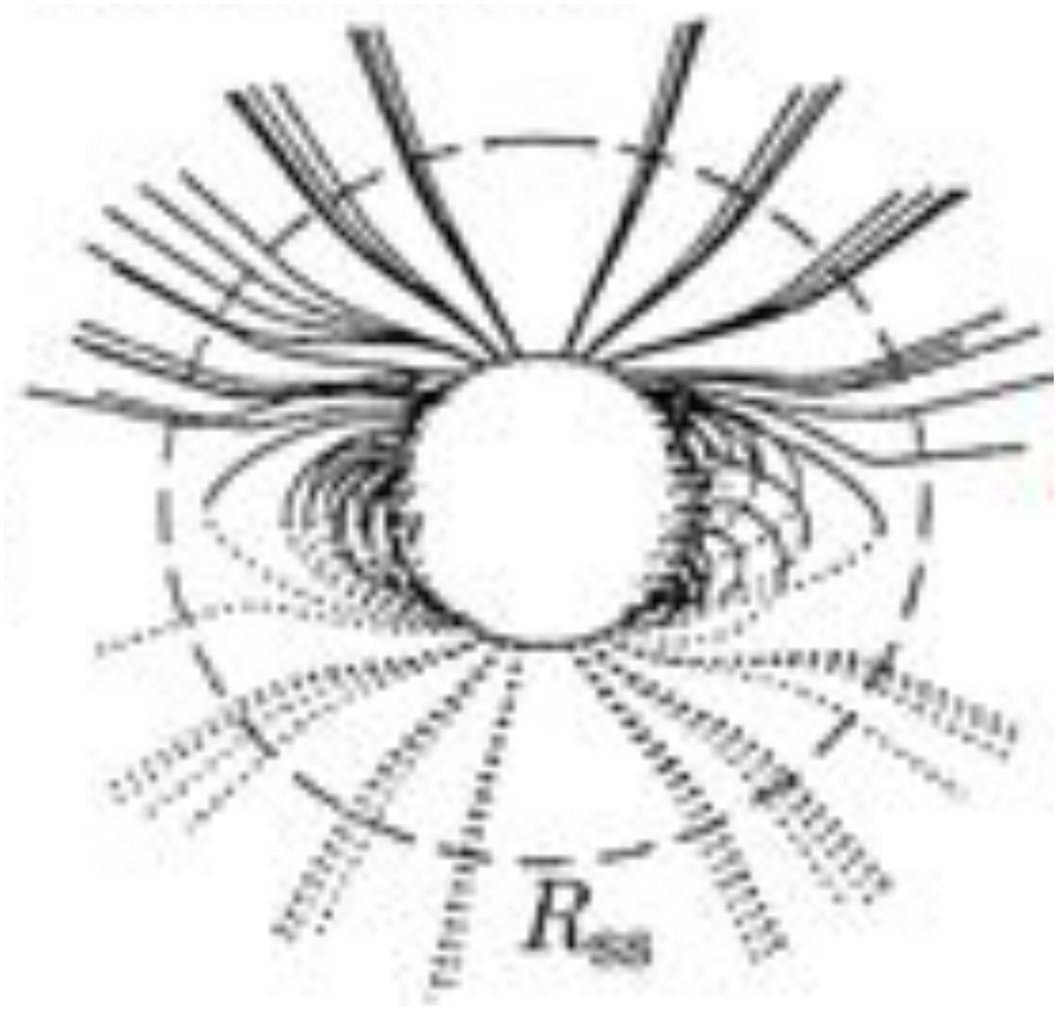
Lockwood, Stamper & Wild, *Nature* 1999

in situ measurements



Reconstructing past open flux

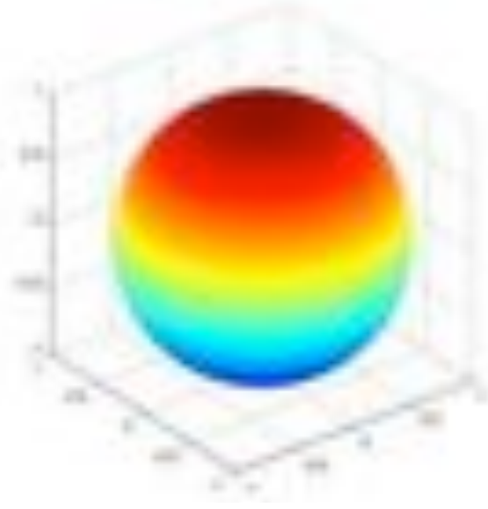
surface flux transport **+ coronal extrapolation** → open flux



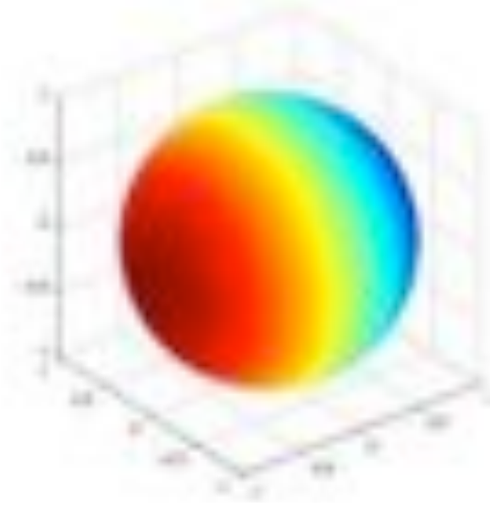
e.g. "Potential Field Source Surface"

Altschuler & Newkirk, *Sol Phys* 1969
Schatten, Wilcox & Ness, *Sol Phys* 1969

axial
(l=1, m=0)



equatorial
(l=1, m=1)

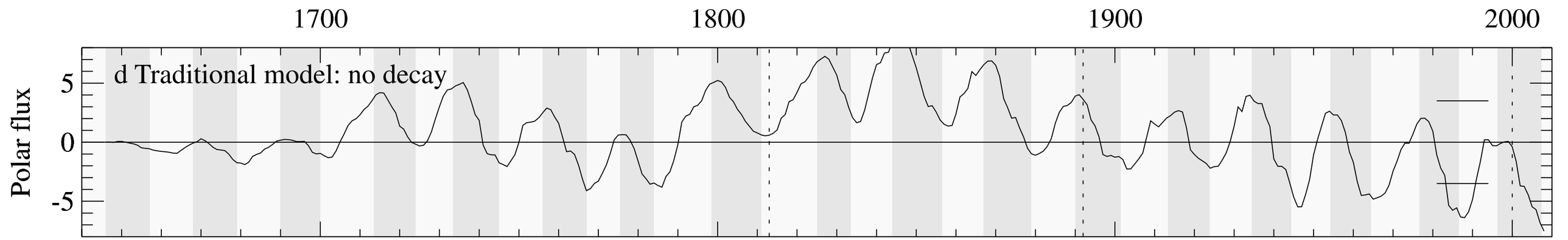


In PFSS model open flux is controlled by dipole components:
Wang, Sheeley & Lean, *ApJ* 2000/02; Mackay, Priest & Lockwood, *Sol Phys* 2002

Reconstructing past open flux

Varying emergence rates ⇒ secular drift of polar fields + non-reversal

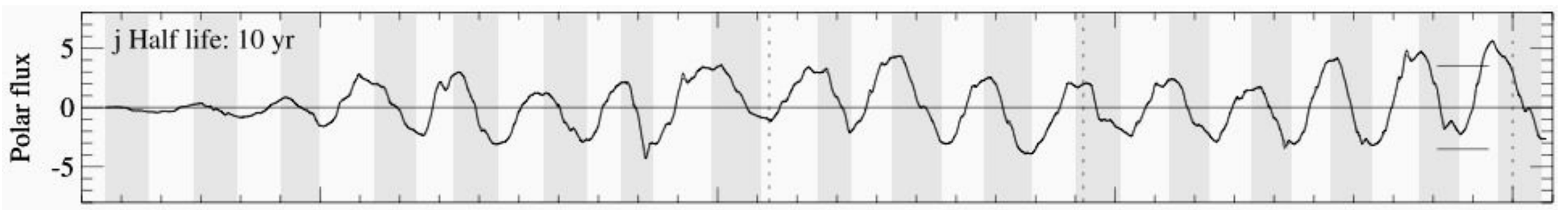
Wang, Lean & Sheeley, *ApJ* 2002, 2005
Schrijver, DeRosa & Title, *ApJ* 2002



Two possible solutions:

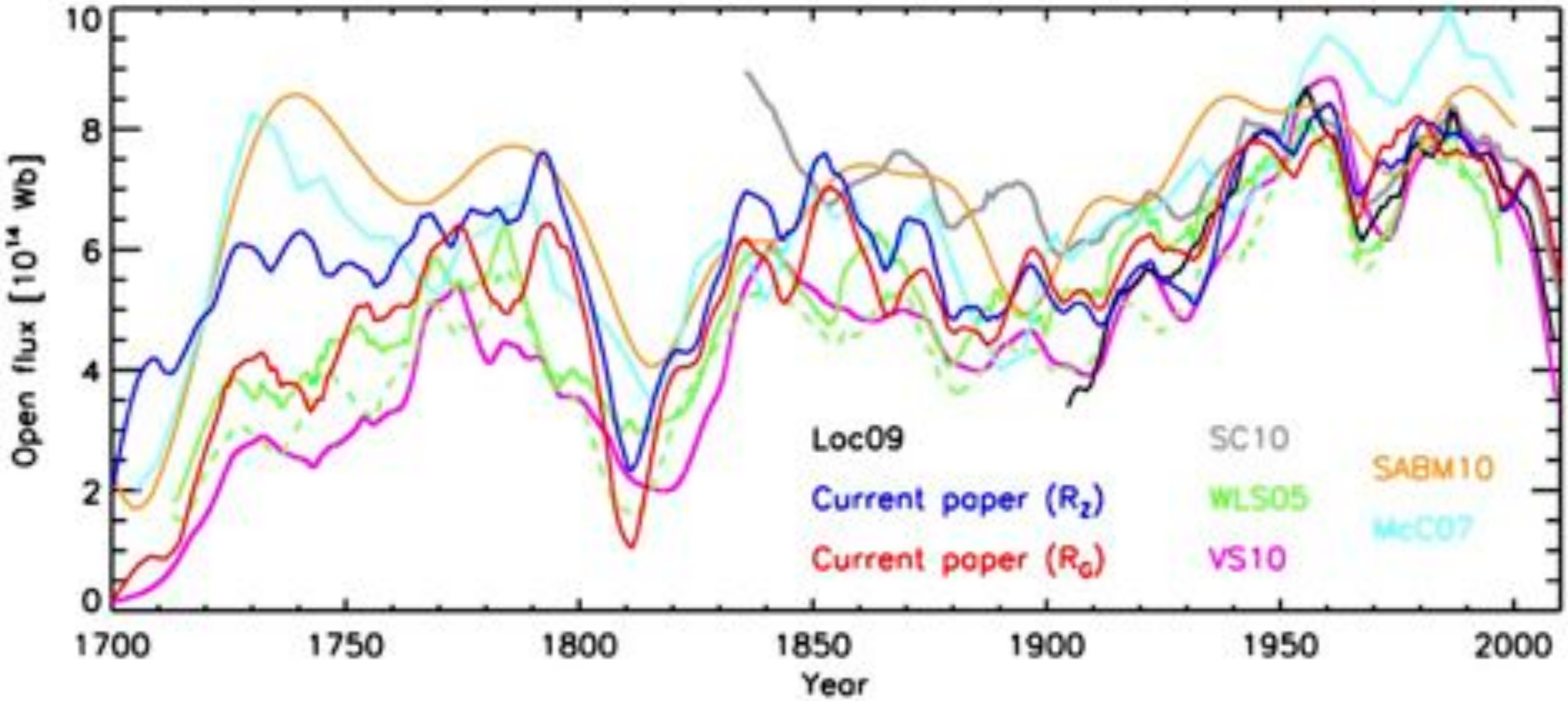
1. Vary model parameters from cycle to cycle (meridional flow, tilt angles)
2. Additional decay term (3D effects)

Schrijver, DeRosa & Title, *ApJ* 2002; Baumann, Schmitt & Schüssler, *A&A* 2006



Reconstructing past open flux

Jiang, Cameron, Schmitt & Schüssler, *A&A* 2011



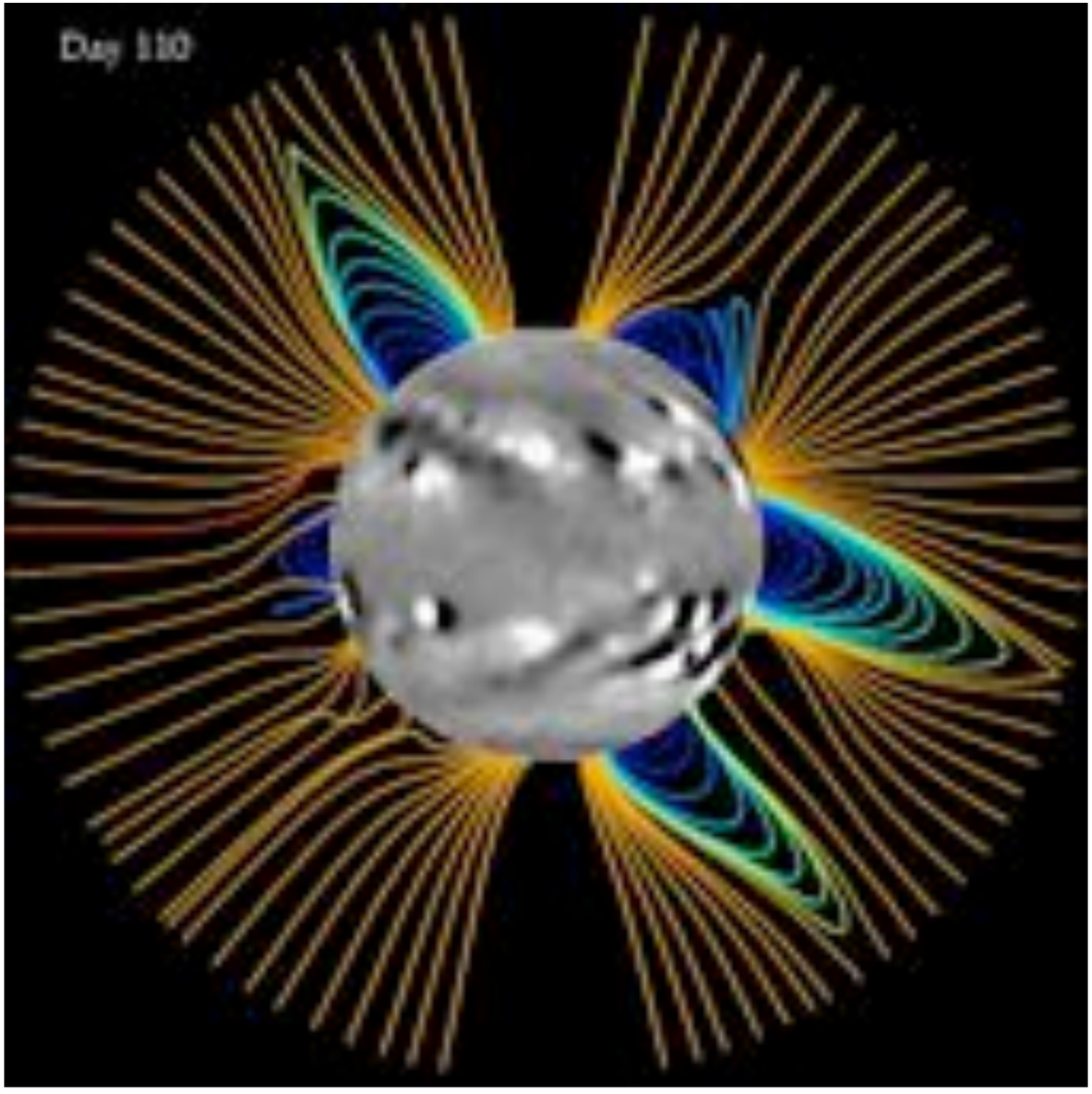
uses Current Sheet Source Surface model - Zhao & Hoeksema, *JGR* 1995

1. Require assumptions about active region properties ⇒ **climate**, not weather
2. Depends on coronal extrapolation model

Non-potential model

surface flux transport +
magneto-frictional relaxation

van Ballegooijen, Priest & Mackay, *ApJ* 2000
Yeates, Mackay & van Ballegooijen, *Sol Phys* 2008



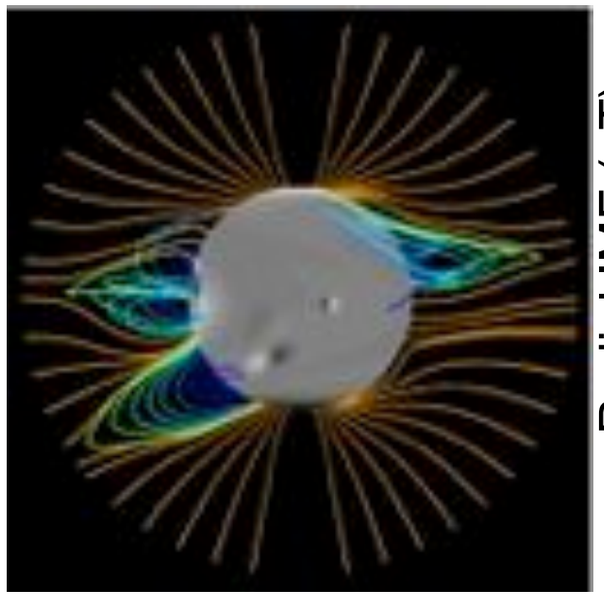
Non-potential model

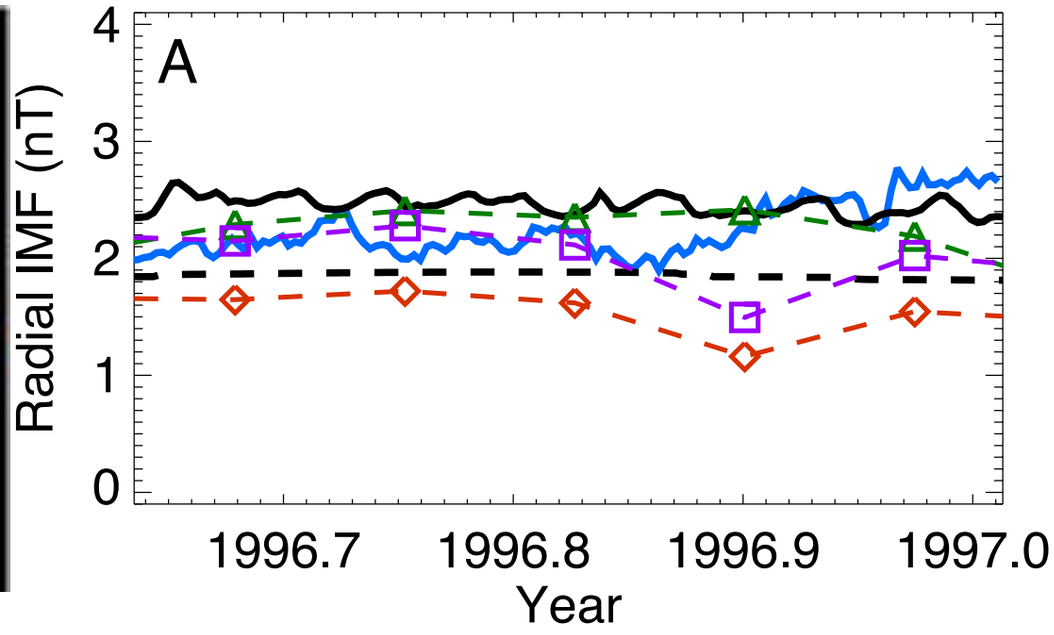
Enhances open flux:

1. background inflation by currents

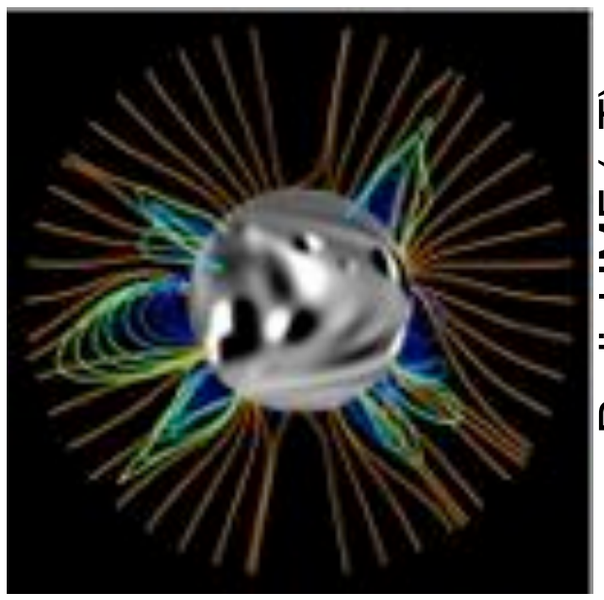
2. fluctuating enhancement by flux rope ejections

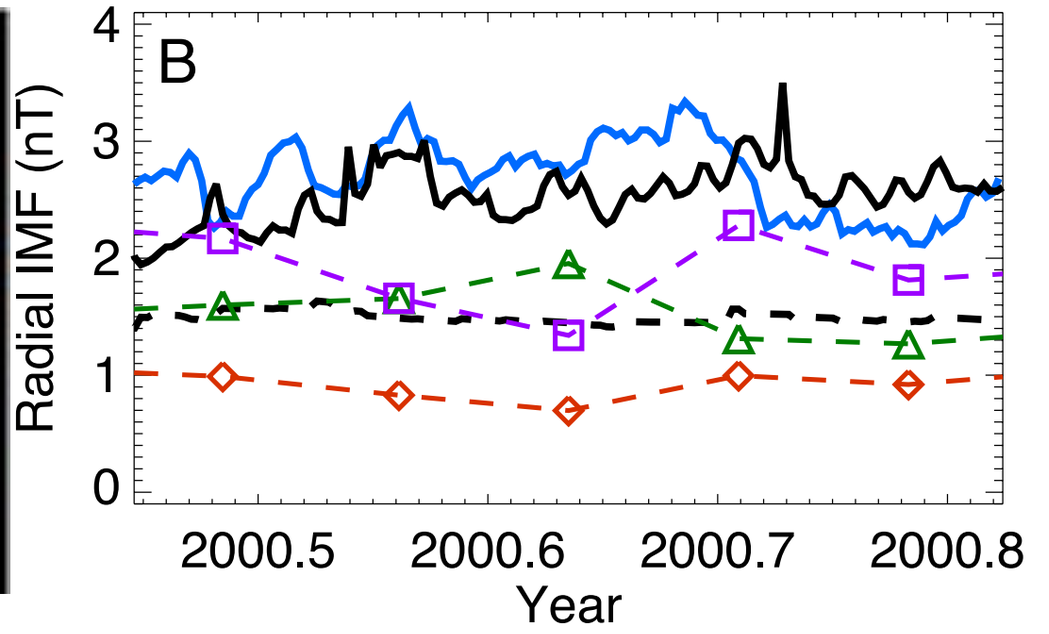
1996





2000





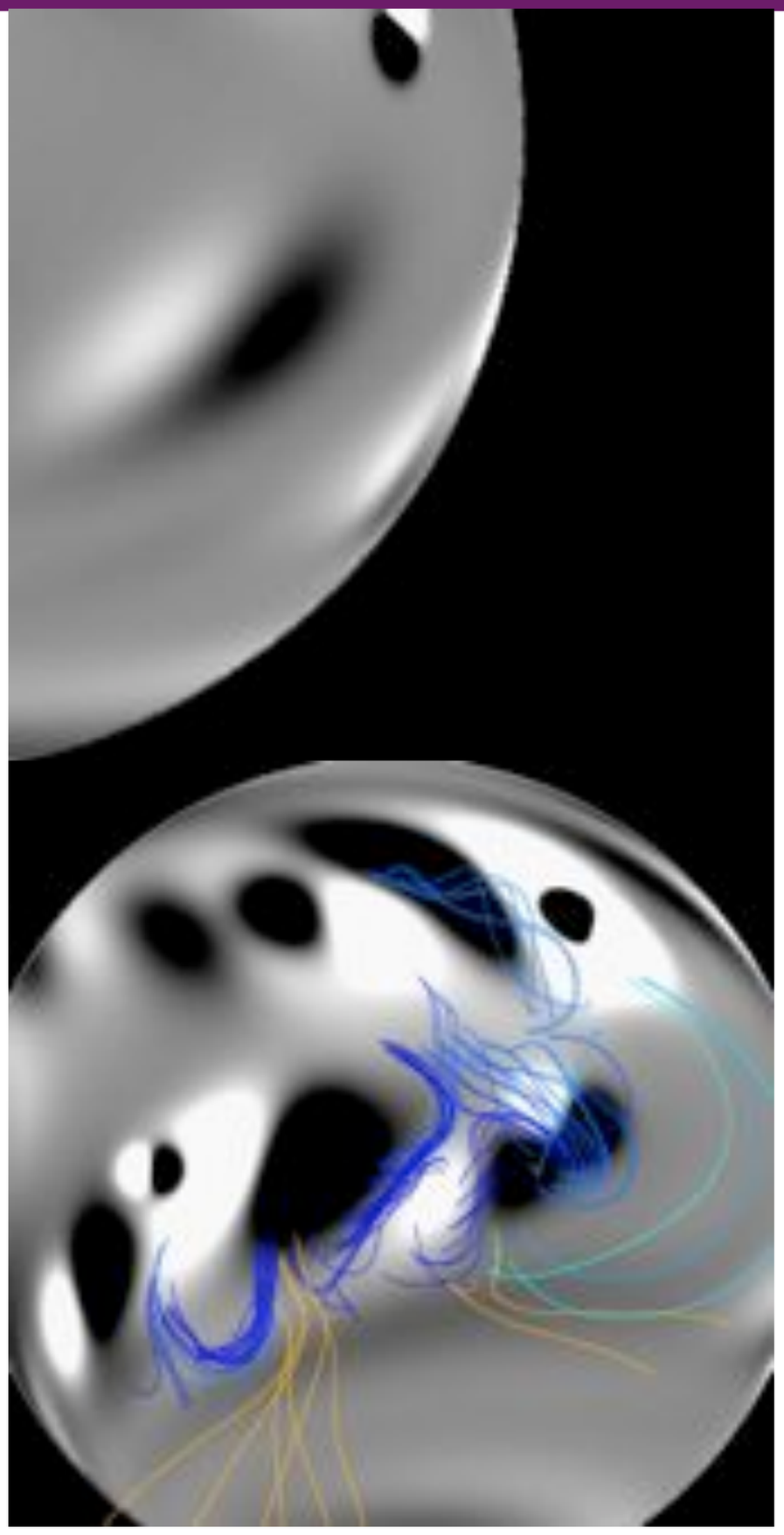
Observed IMF (OMNI2 $|B_x|$)

Non-potential Model

PFSS (simulated, WSOa, WSOb, NSO)

Yeates, Mackay, van Ballegooijen & Constable, *JGR* 2010

Non-potential model



flux rope ejections: towards space **weather**?

Mackay & van Ballegooijen, *ApJ* 2006
Yeates & Mackay, *ApJ* 2009
Yeates, Attrill, Nandy et al., *ApJ* 2010
Yeates, Constable & Martens, *Sol Phys* 2010

but:

1. Only a third of observed CME rate

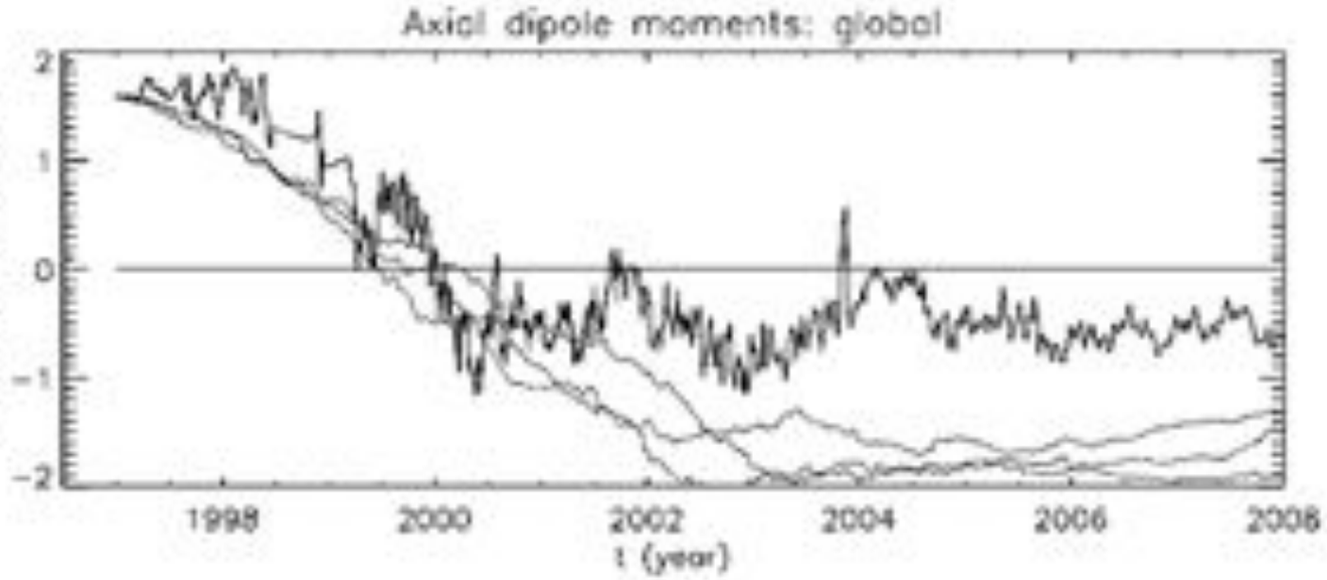
2. Still at statistical level (not detailed enough for individual events, yet)

Magnetogram assimilation:

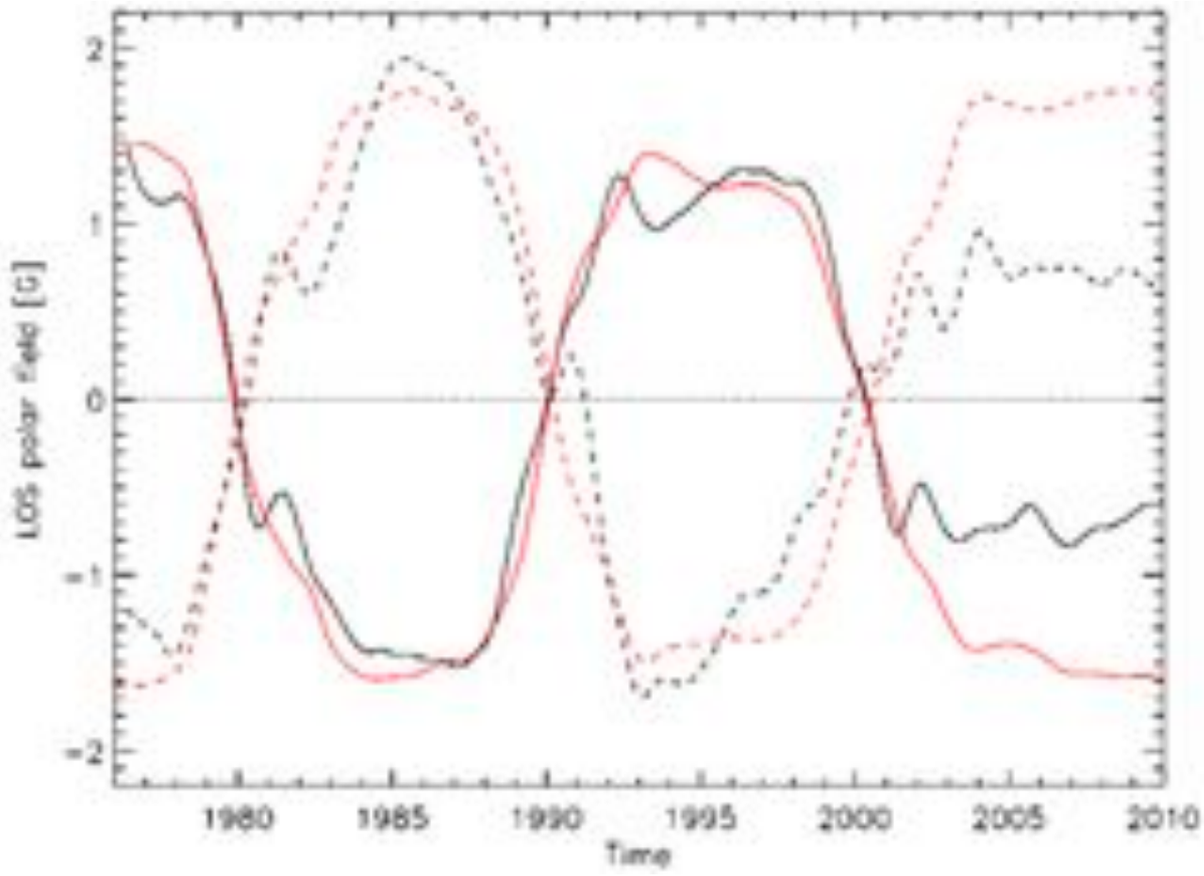
Schrijver, *ApJ* 2001
Mackay, Green & van Ballegooijen, *ApJ* 2011

The future?

Schrijver & Liu, *Sol Phys* 2008



Jiang, Cameron, Schmitt & Schüssler, *Space Sci Rev* 2011



⇒ need to vary model parameters with time

Future focus:

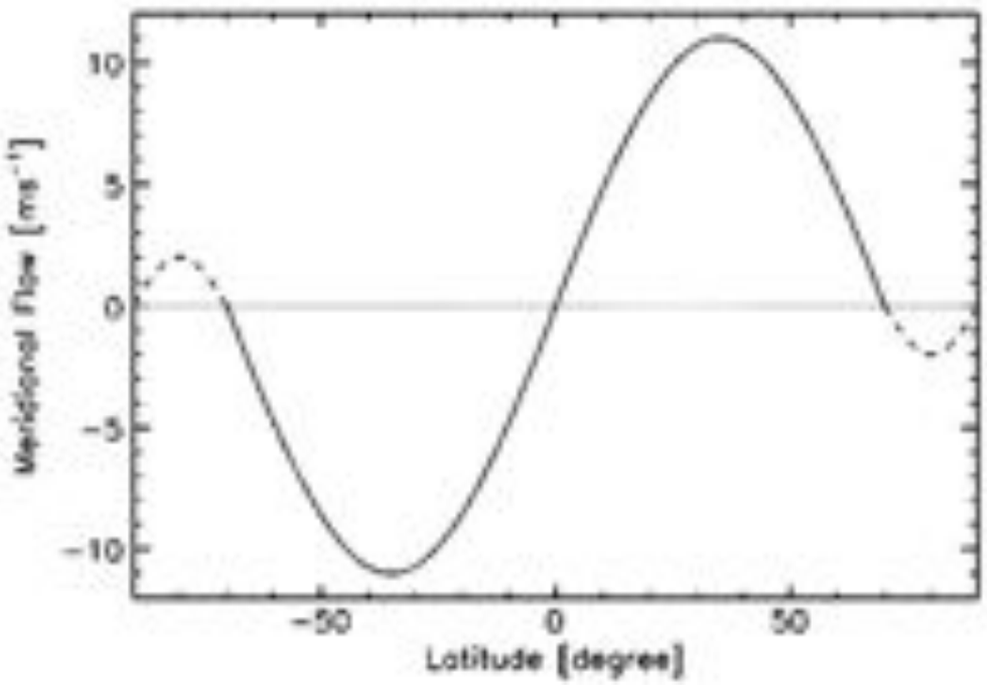
1. Build in these variations **automatically**.
2. Enough detail in coronal models for **real** events.

Further reading

Sheeley, *Living Rev Sol Phys* 2005 - **historical review**

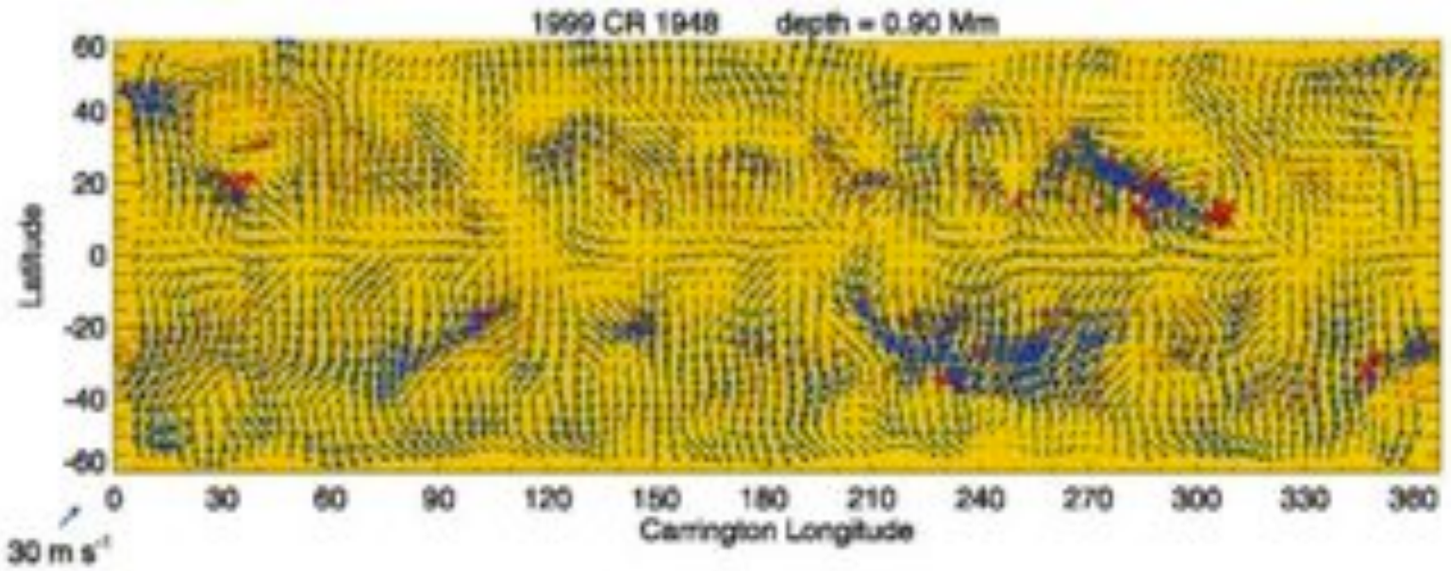
Mackay & Yeates, *Living Rev Sol Phys* (in prep) - **surface/coronal mag fields**

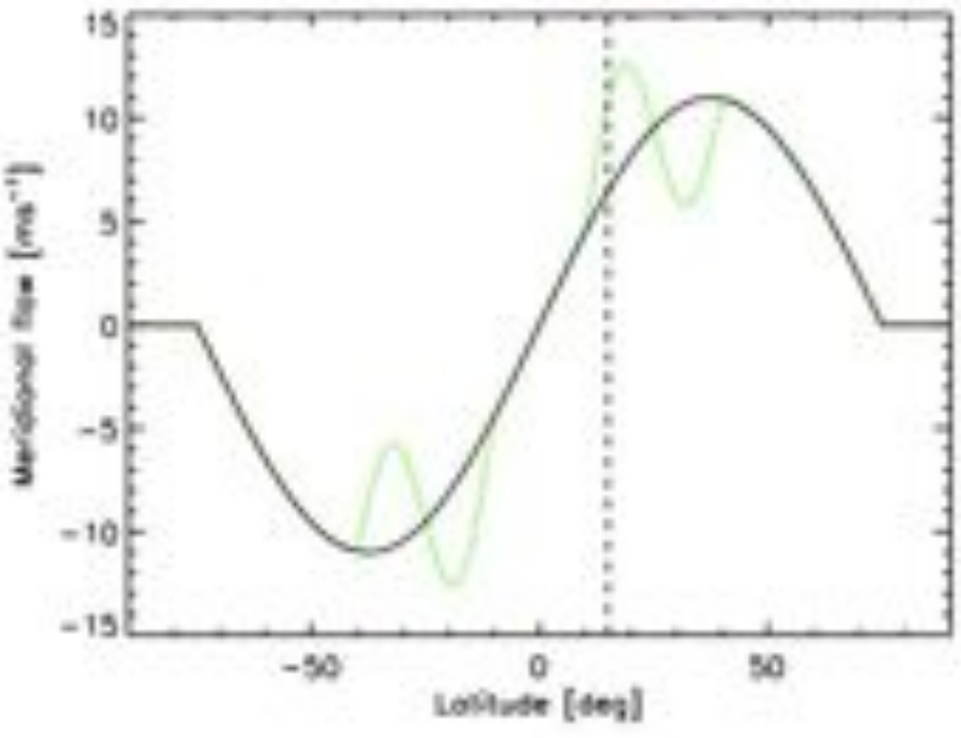
Meridional flow modifications



High-latitude countercell:
Jiang, Cameron, Schmitt & Schüssler, *ApJL* 2009

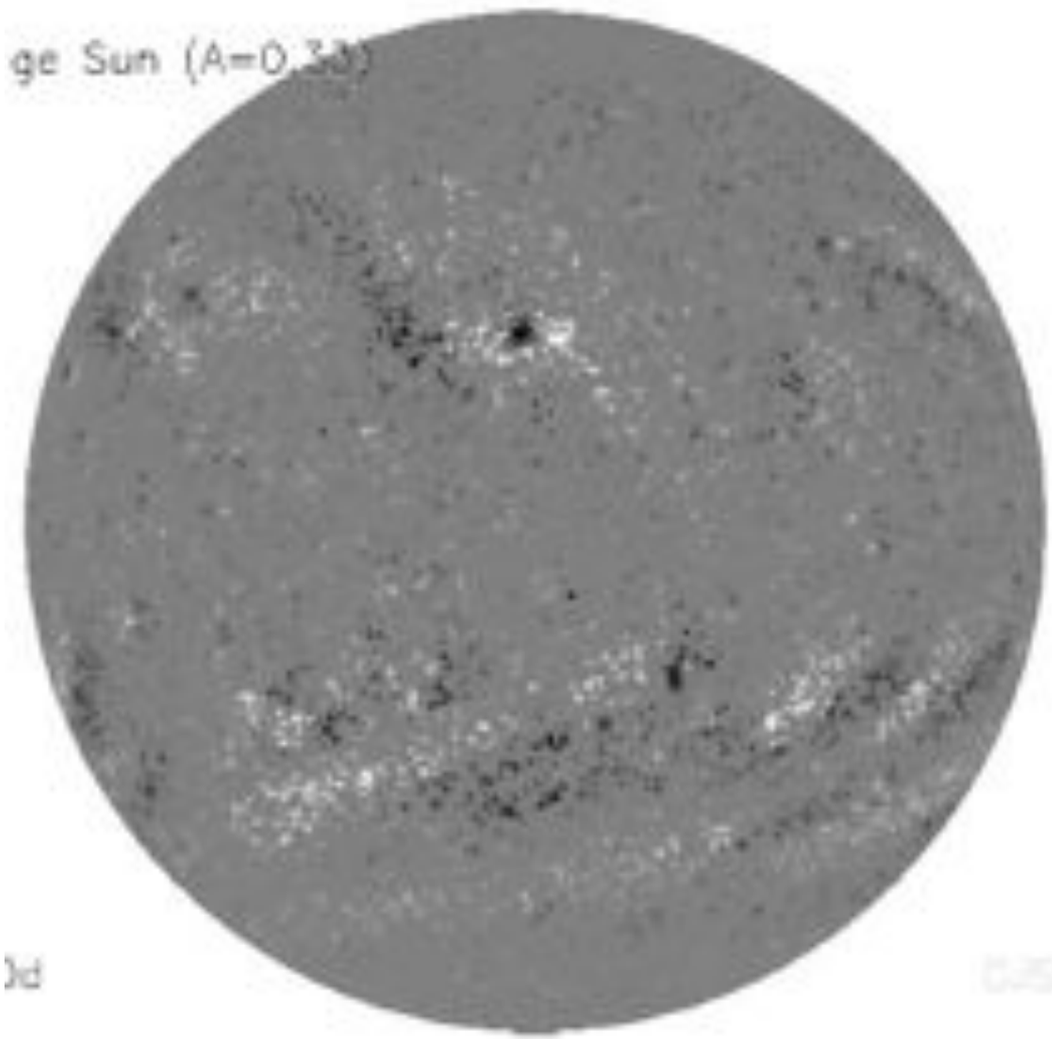
Inward flow towards active regions:
DeRosa & Schrijver, *Proc SOHO18* 2006





Latitudinal inflows:
Jiang, Isik, Cameron, et al., *ApJ* 2010;
Cameron & Schüssler, *ApJ* 2010

Magnetogram assimilation



Schrijver, *ApJ* 2001

Mackay, Green & van Ballegooijen, *ApJ* 2011