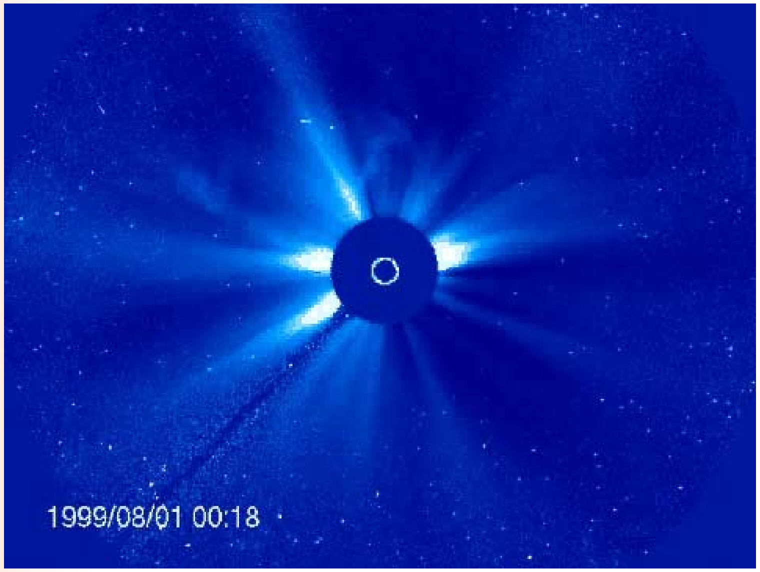
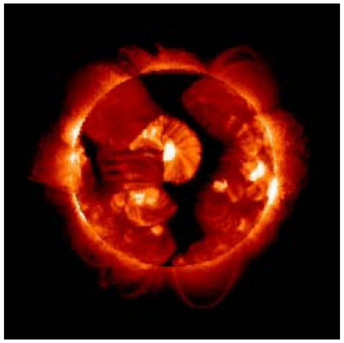
Tutorial: The magnetic Connection between the Sun and the Heliosphere





Karel Schrijver

The connection between Sun and Earth …

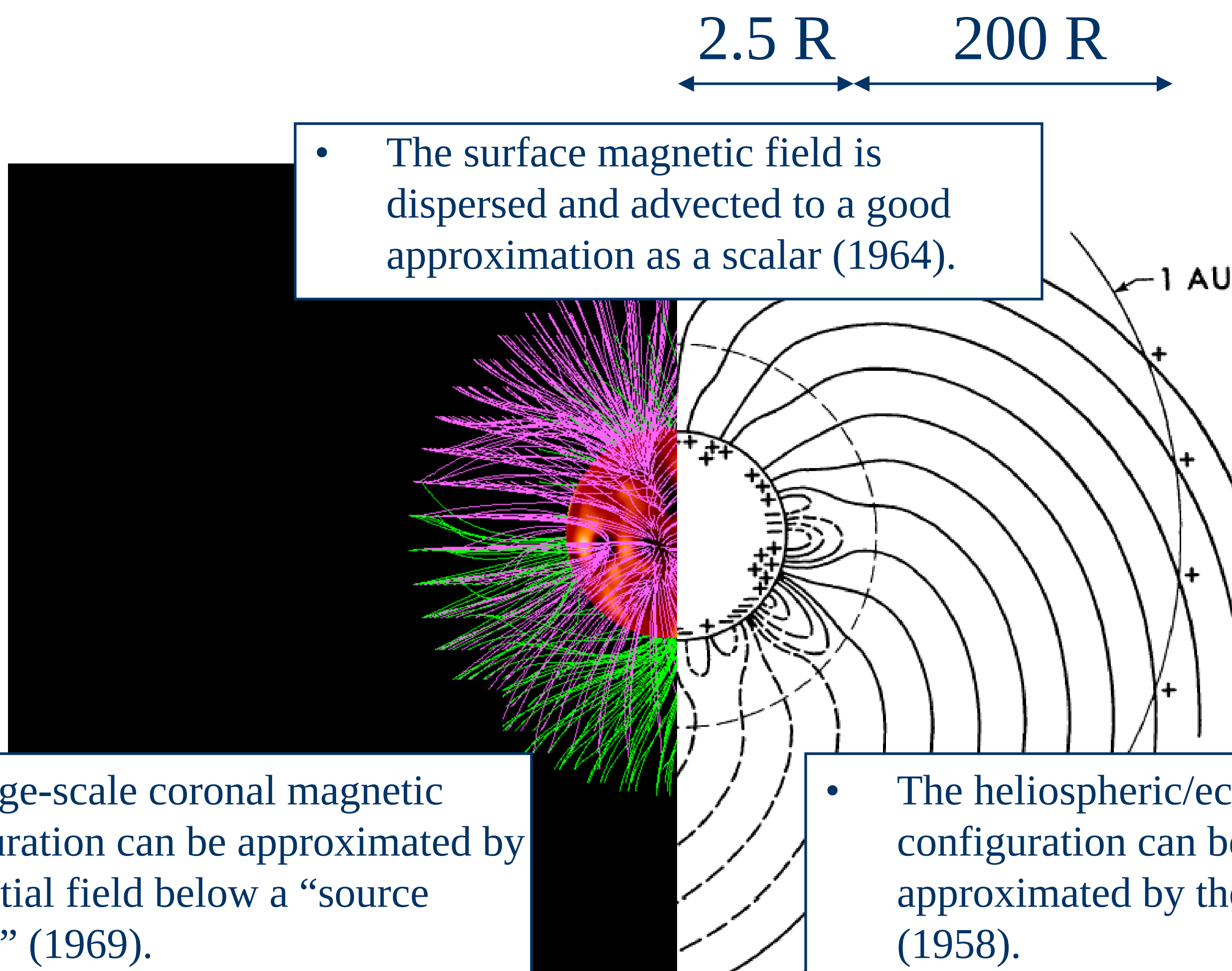
The problem:

Focus of this presentation

Overview

- From ideal to real …
- Five pieces of the puzzle:
  1) The "streamer belt" of a model Sun
  2) Evolution of the Sun-heliosphere coupling
  3) Source regions of the solar wind
  4) Forecasting the quiescent solar wind
  5) Powering the solar wind (and the corona)
- Conclusions and some questions

An ideal world: solar/heliospheric model



- The surface magnetic field is dispersed and advected to a good approximation as a scalar (1964).

- The large-scale coronal magnetic configuration can be approximated by a potential field below a "source surface" (1969).

- The heliospheric/ecliptic magnetic configuration can be reasonably approximated by the "Parker spiral" (1958).

Simulation of the solar cycle

Visualizing the evolution of the solar wind source domains, as seen in a ‘corotating’ frame, over 1-1.5 magnetic cycles:

Surface view	Surface grid	Source-surf. grid
Equatorial	Equatorial	Equatorial
40° North	40° North	40° North
90° North	90° North	90° North

Surface ϕ-θ map and neutral line:

Streamer belt still: From ‘Earth’:

Streamer belt envelope (27-d syn. Bartels frame):

Simulating photospheric activity

Flux emergence

Random stepping

Diff. Rot. & Merid. flow

Flux frag-mentation

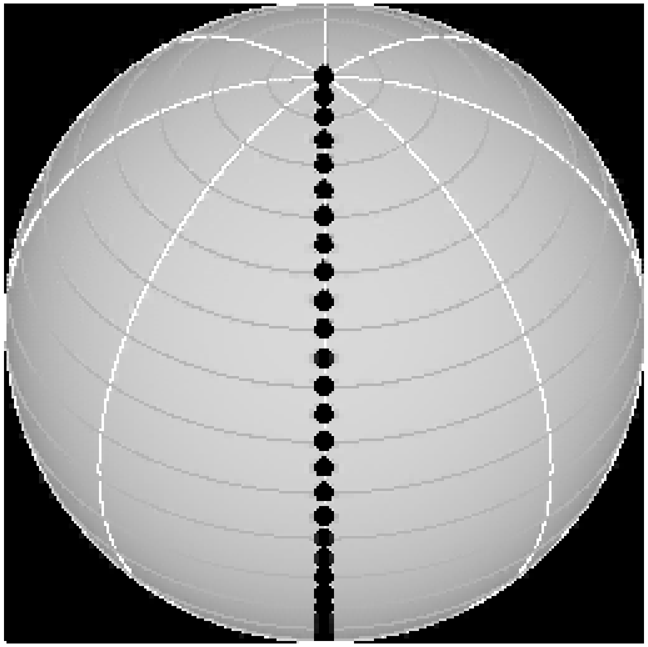
Collision & cancelation

Relatively recent essential additions:

- magneto-convective coupling
- magneto-chemistry: fragmentation and collisions
- ephemeral-region population

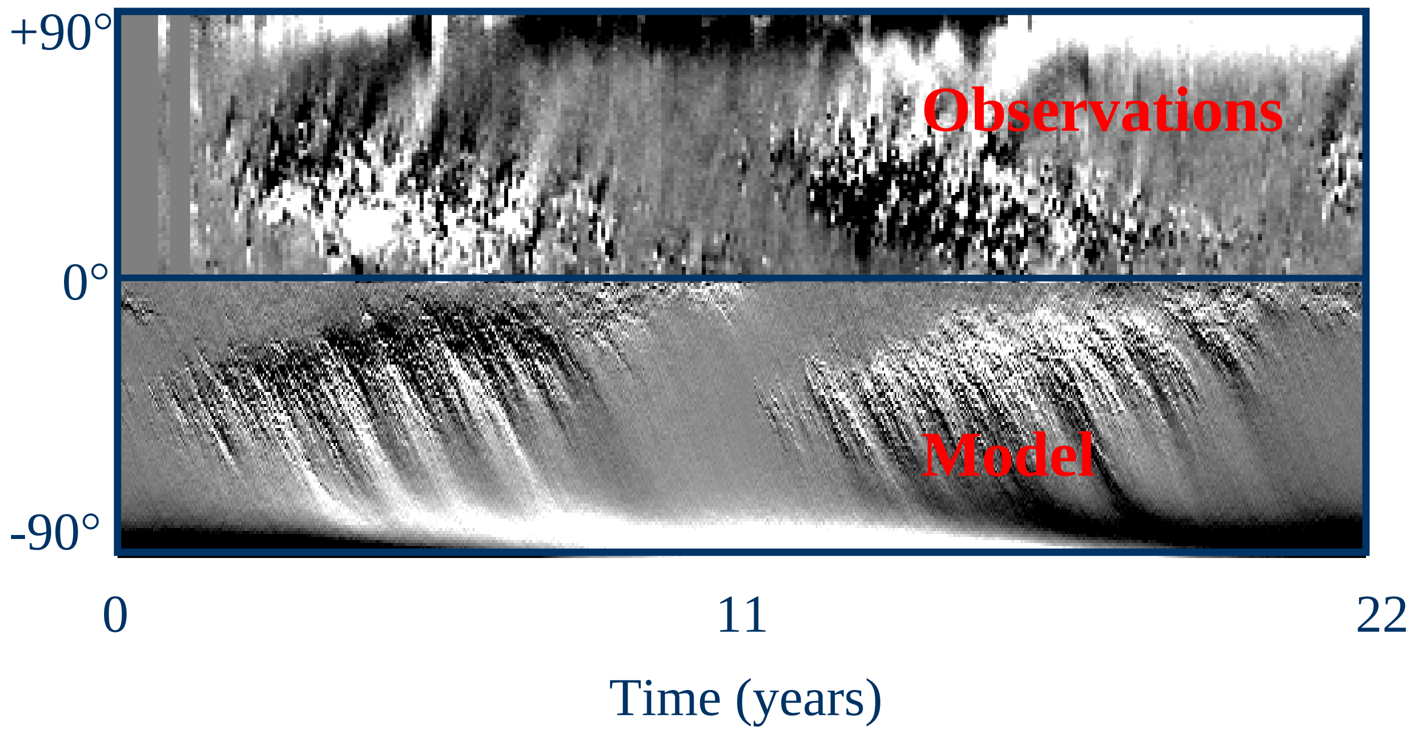
Effects of large-scale flows

Differential rotation and meridional flow only,
as viewed from 40°N



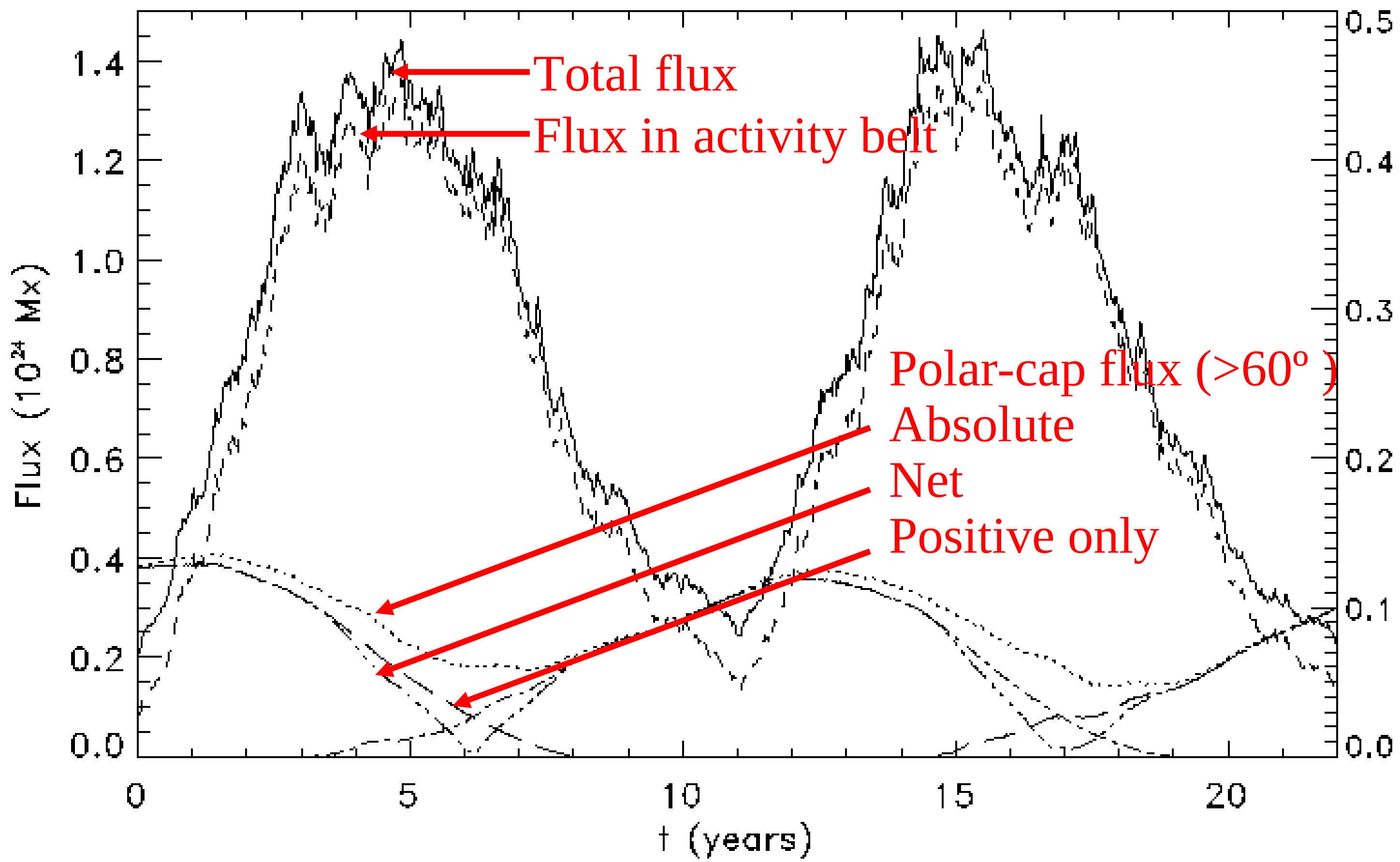
Large-scale solar field

- Large-scale solar field depends on source function, dispersal, meridional flow, and differential rotation



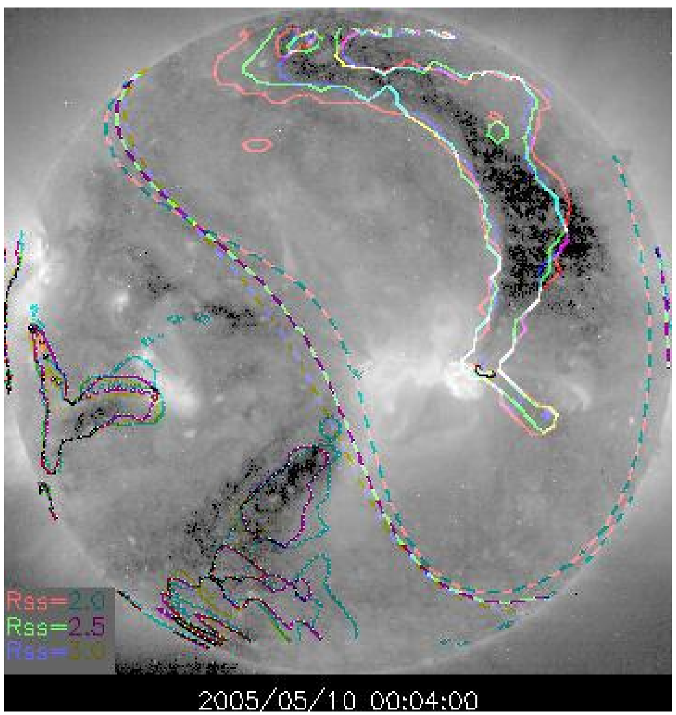
- Good approximation of large-scale flux patterns, including polar fields

The Sun through the cycle

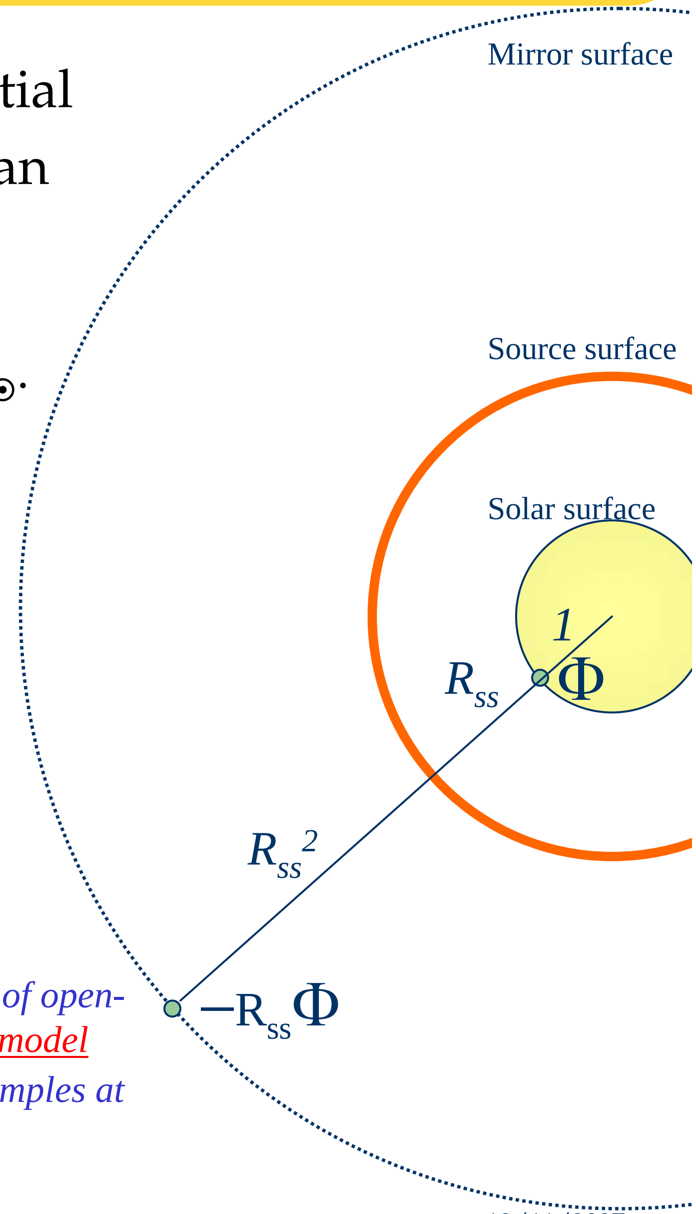


PFSS model and coronal holes

- The large-scale coronal field is mostly potential
- It can be approximated remarkably well by an *electrostatic model:*
  - charge distribution on the solar photosphere
  - within a perfectly conducting sphere of ~5 $R_\odot$.

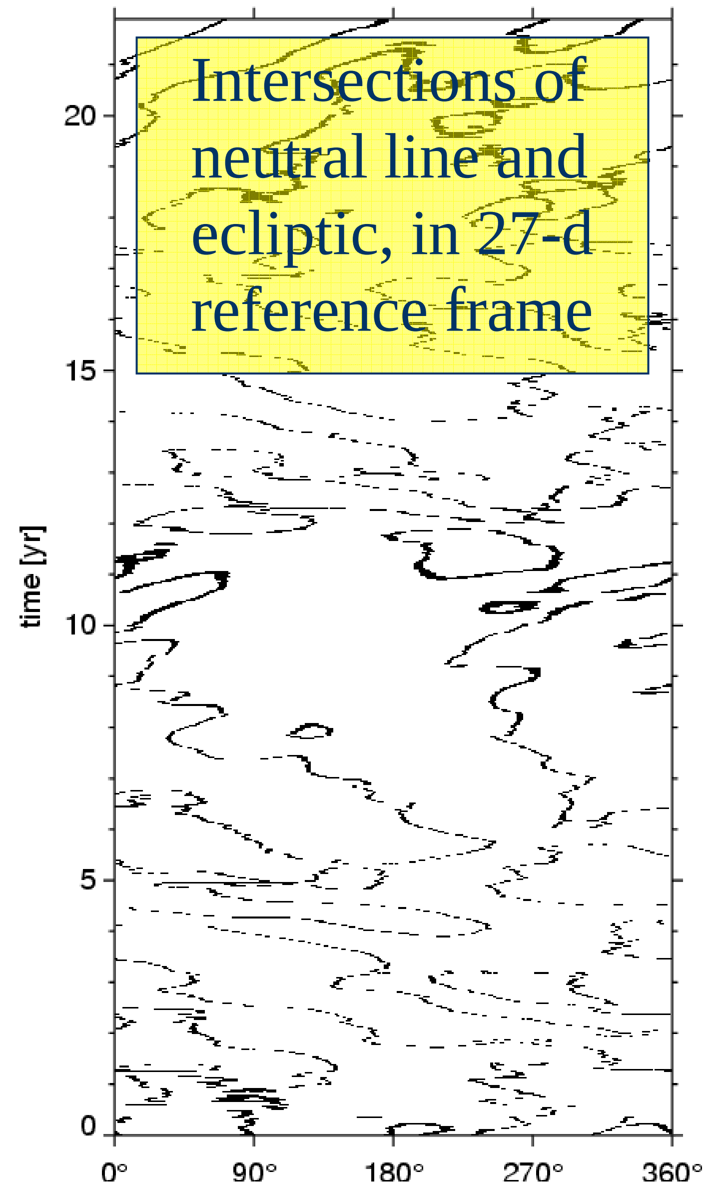


SOHO/EIT 284Å with overlay of open-field boundaries from a PFSS model for different R_{ss} (see other examples at www.lmsal.com/forecast).

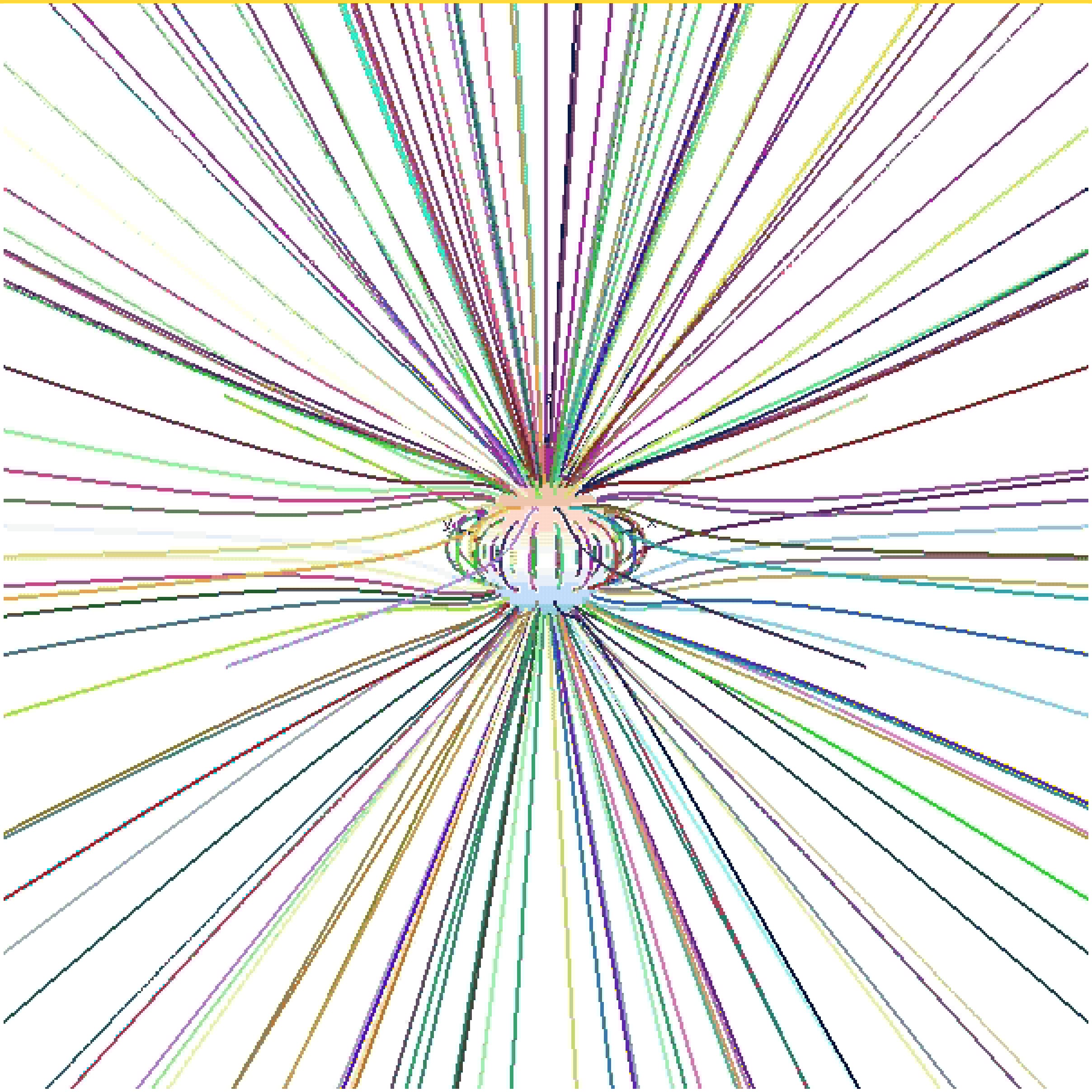


The "current sheet" for a model Sun

- The neutral line drifts around a 27-d synodic rate, as observed. *No magic needed!*
- Model:
  - One neutral line 90% of the time.
  - One additional polarity island: 10% of the time
  - Only ~30 islands throughout a full magnetic cycle.
  - Islands commonly pinch off from, and re-merge with, the neutral line.
  - Very few islands form at cusp: *the quiescent corona rarely blows bubbles.*



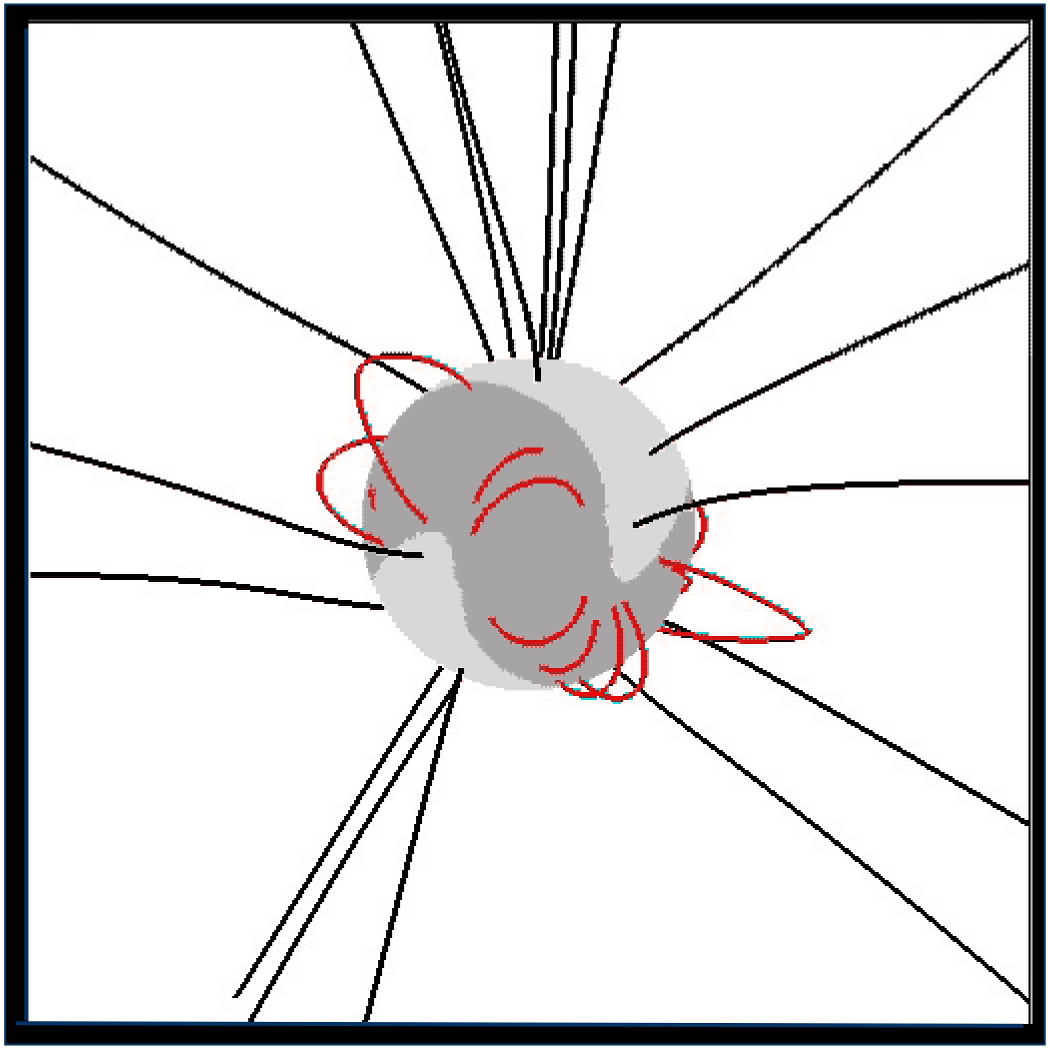
MHD sim. shows disconnected field in current sheet



Flux emergence in a dipolar field

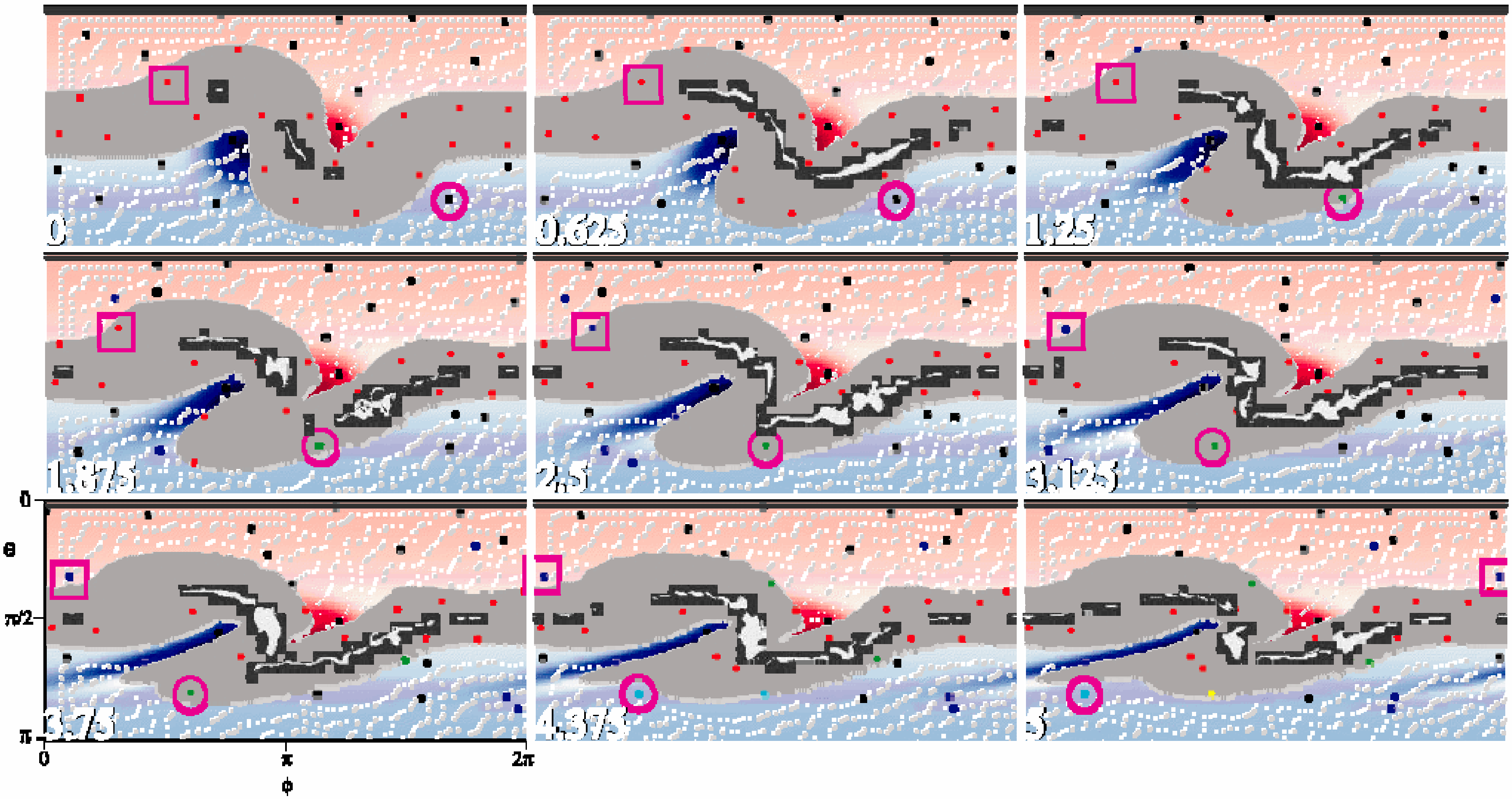
Courtesy Pete Riley

MHD sim. shows disconnected field in current sheet



MHD simulations by Lionello et al. (2005; ApJ 625, 463).

MHD sim. shows disconnected field in current sheet



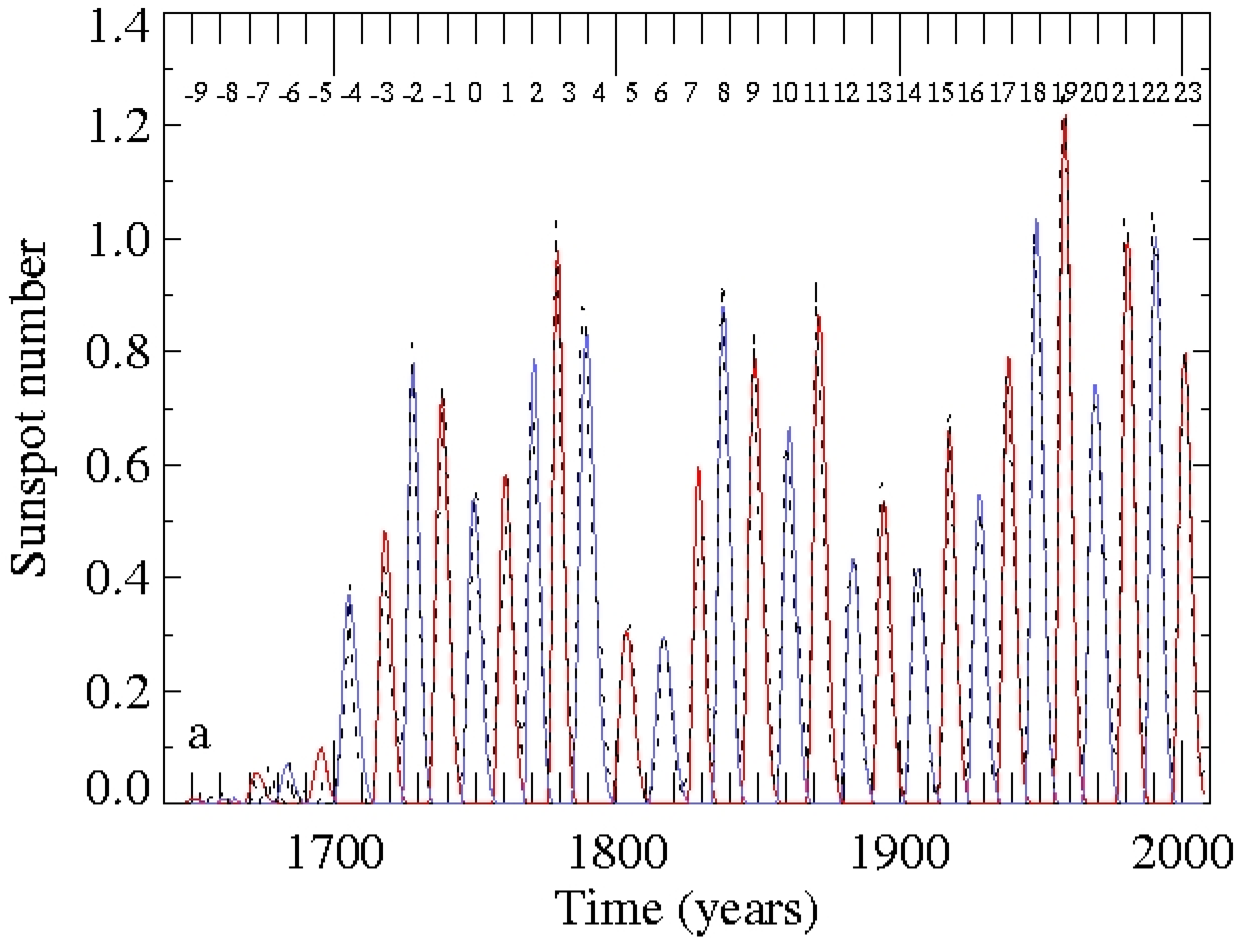
Red: initially closed ; Blue: opened field
Black: initially open ; green/cyan/yellow: successive openings/closings
Circled: foot point of field line that closes and reopens
Boxed: foot point of field line that opens

White areas: field is not connected to the Sun at 30 solar radii (Lionello et al., 2005; ApJ 625, 463).

All Such regions are adjacent to the current sheet.

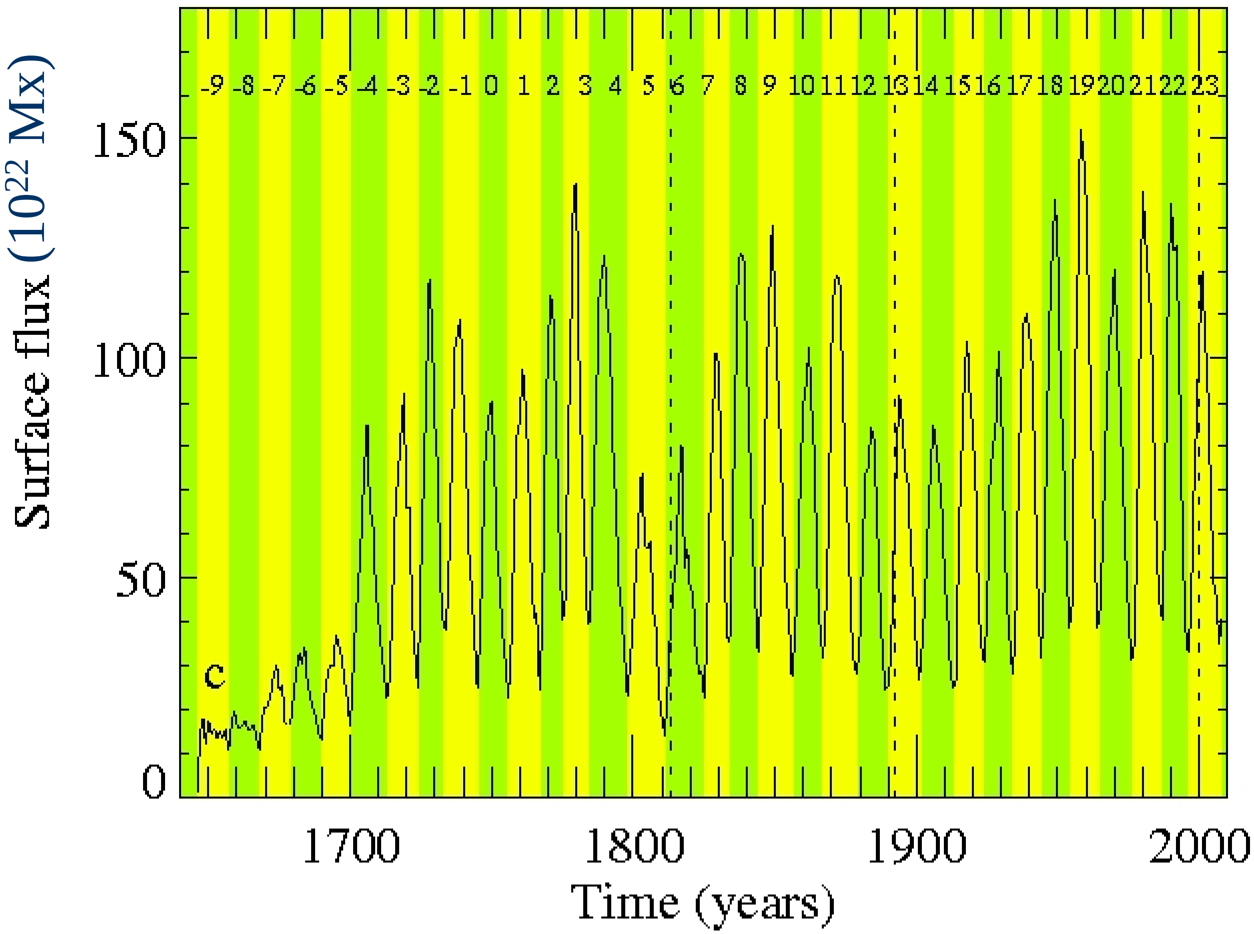
Sunspot cycles: history and approximation

Successive cycles often differ strongly:



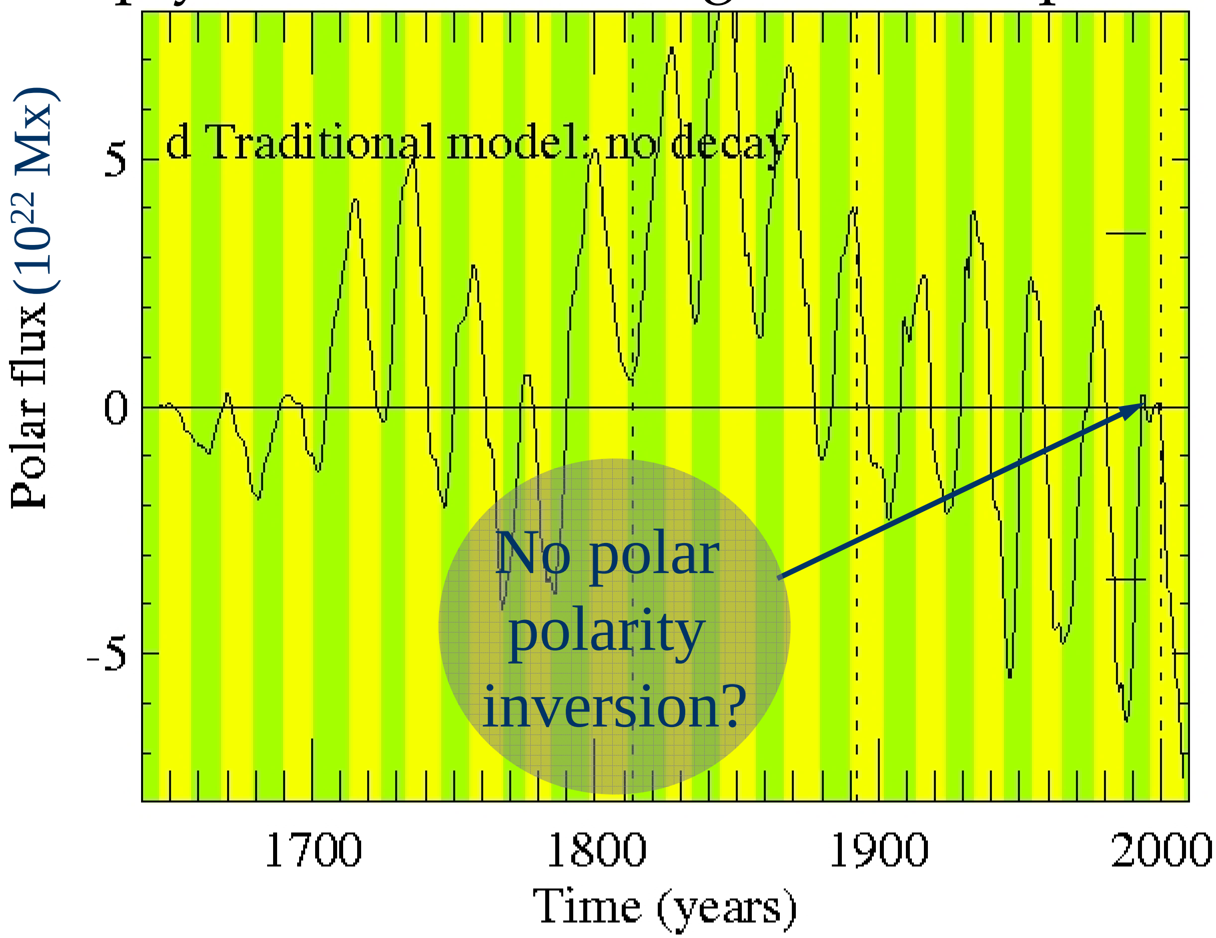
Total flux on the Sun: cycle-to-cycle modulation

Consequently the total flux on the Sun is modulated:



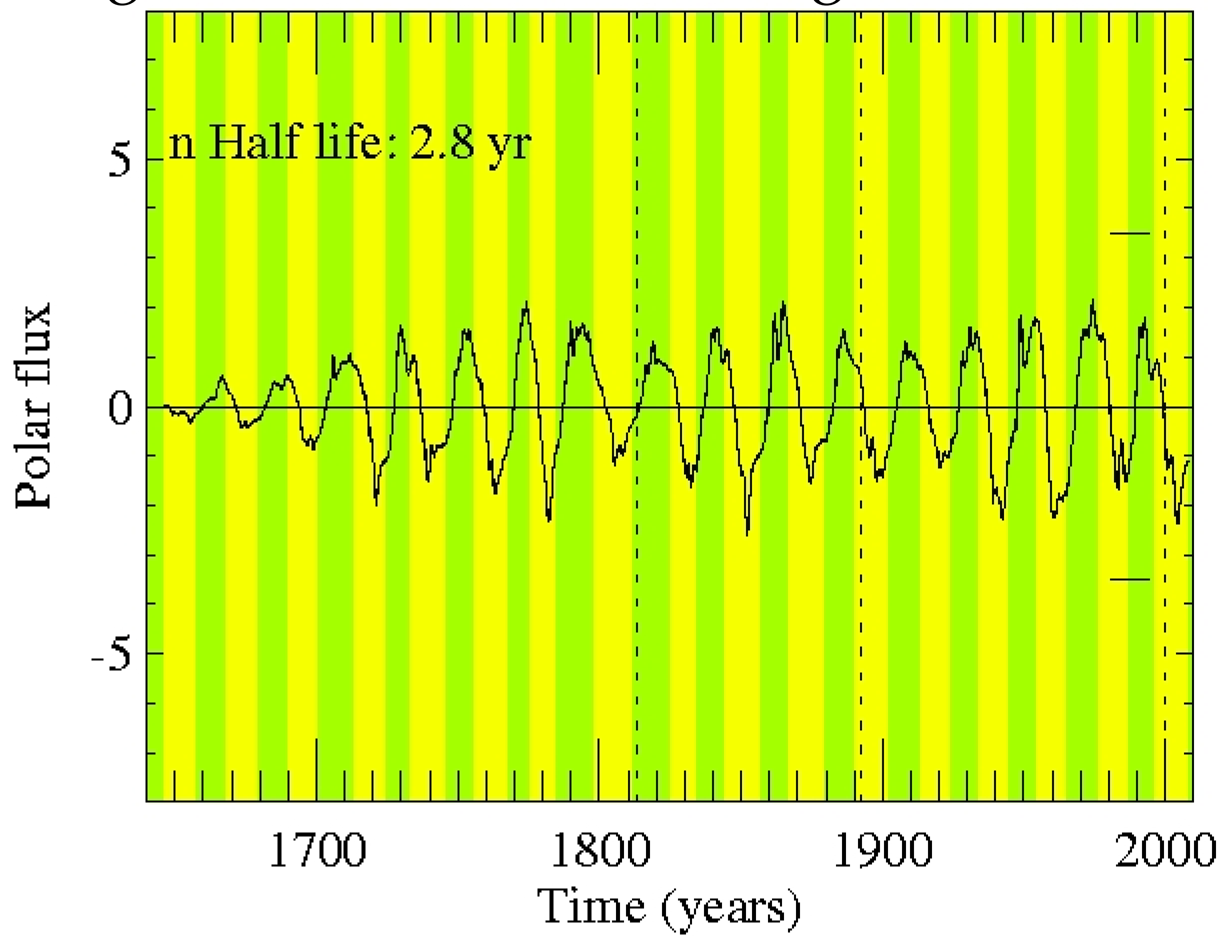
Polar-cap (>60°) absolute flux

And the polar-cap field "capacitor" does not simply alternate in strength or even polarity:



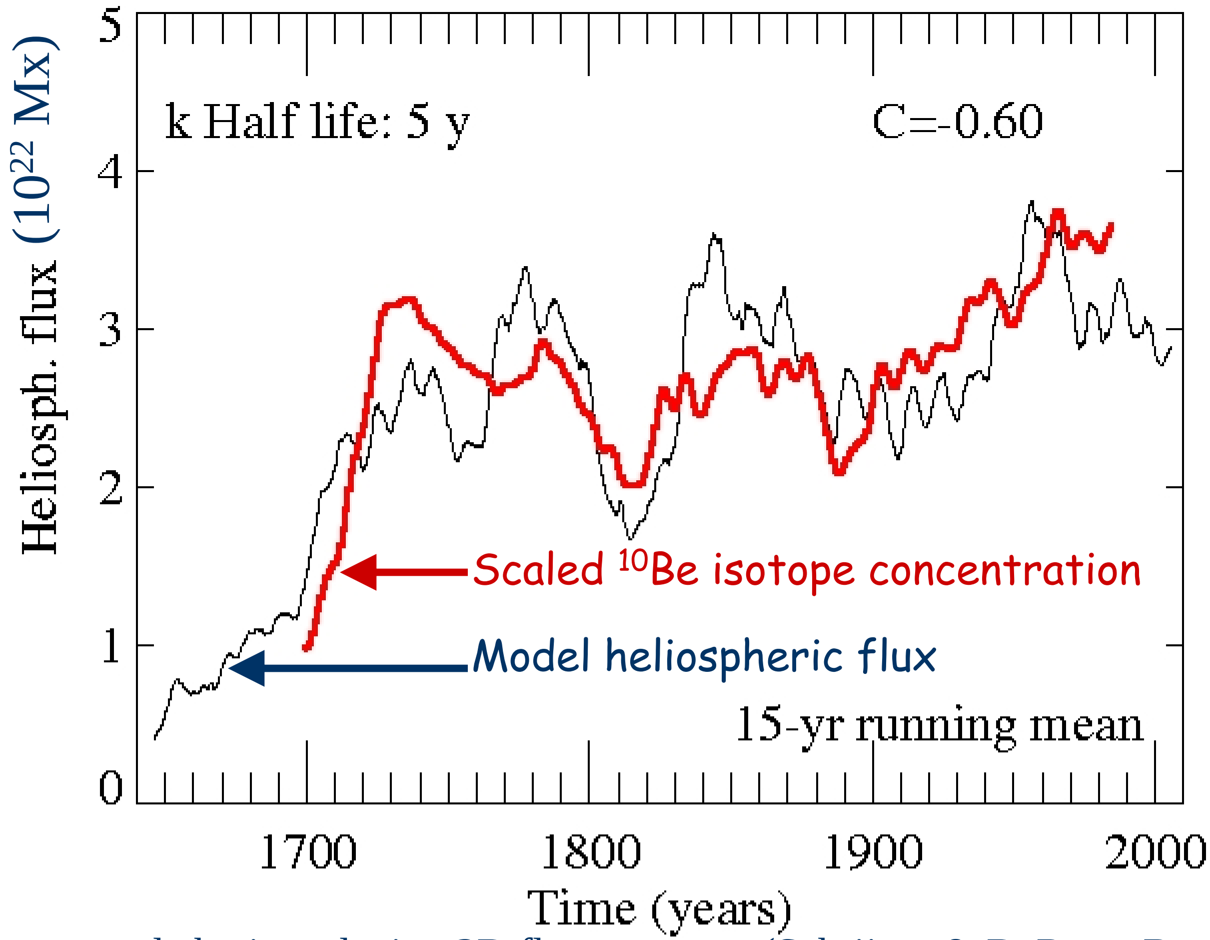
What if flux "decayed" by, e.g., 3D transport?

The polar-cap flux behavior signals something is missing from our understanding:



What if flux transport were modified?

With polar-cap behavior 'regularized'*, the heliospheric and cosmic-ray fluxes are roughly *anti*-correlated:



* For example by introducing 3D flux transport (Schrijver & DeRosa, Baumann et al.) or by modulating flux transport (Wang et al., Schrijver et al.).

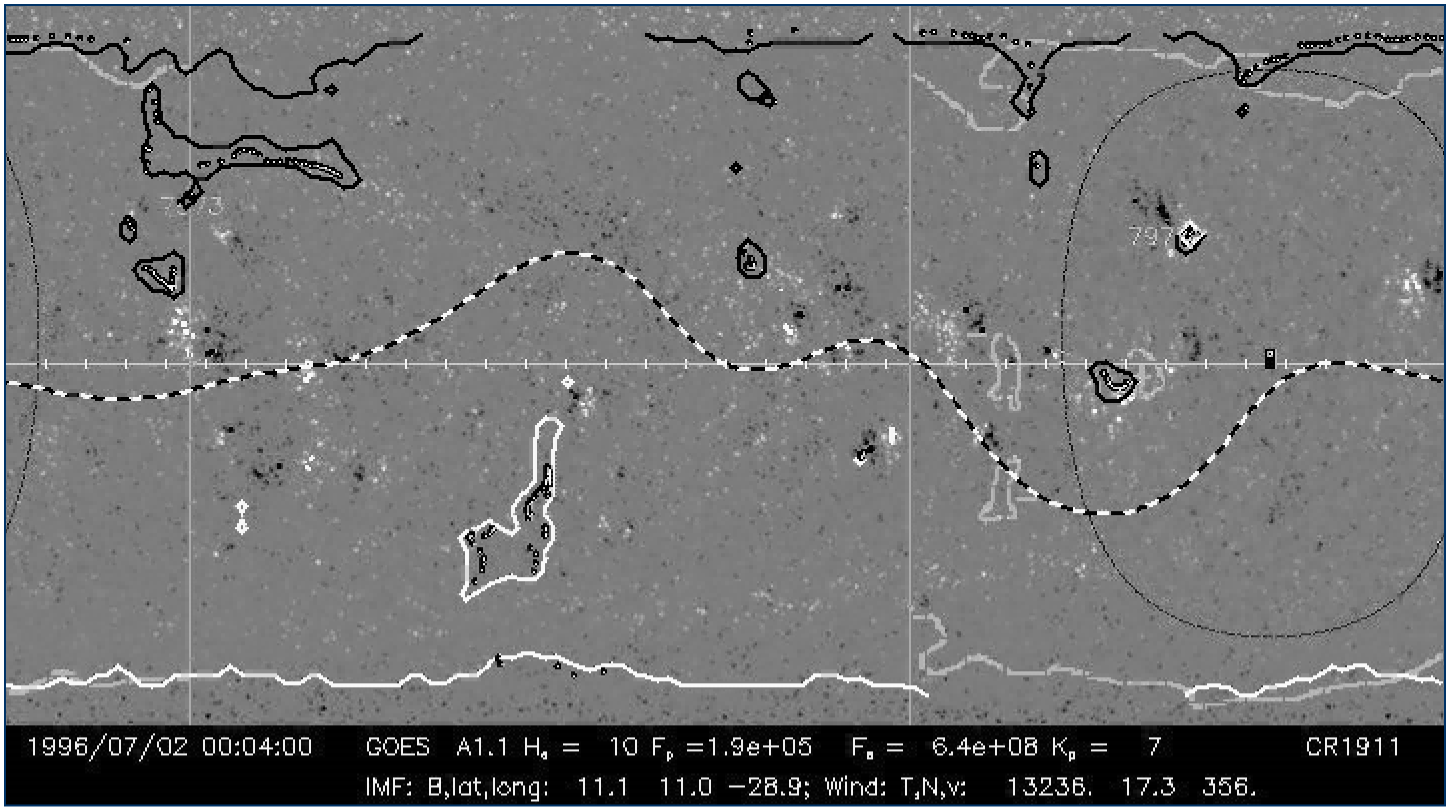
Source regions of the solar wind

Perspective changes over the past few years:

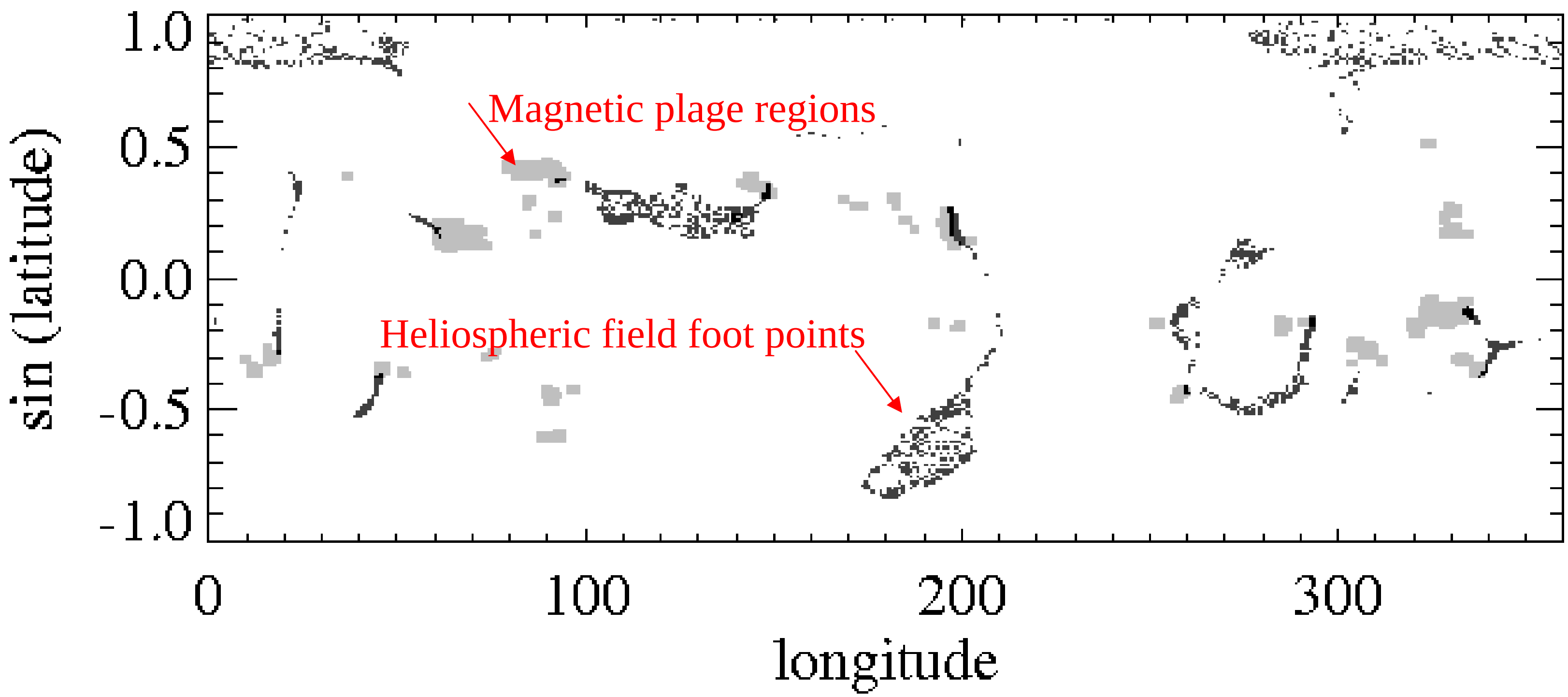
- Much of the IMF is rooted in active regions (even sunspots).
  - Luhmann et al., 2002, JGR 107, 10.1029
  - Neugebauer et al., 2002, JGR 107, A12, 13-1
  - Schrijver and DeRosa, 2003, SPh 212, 165
  - Wang and Sheeley, 2003, ApJ 587, 818
- Heliospheric field from up to a dozen source regions at cycle maximum (may be connected by thin channels).
- Much of the slow wind originates in the ARs whose fields generally lie near the cusp at low (i.e., IMF) latitudes.

Data assimilation into a global model

Assimilating ("inserting")
magnetograms into the model:

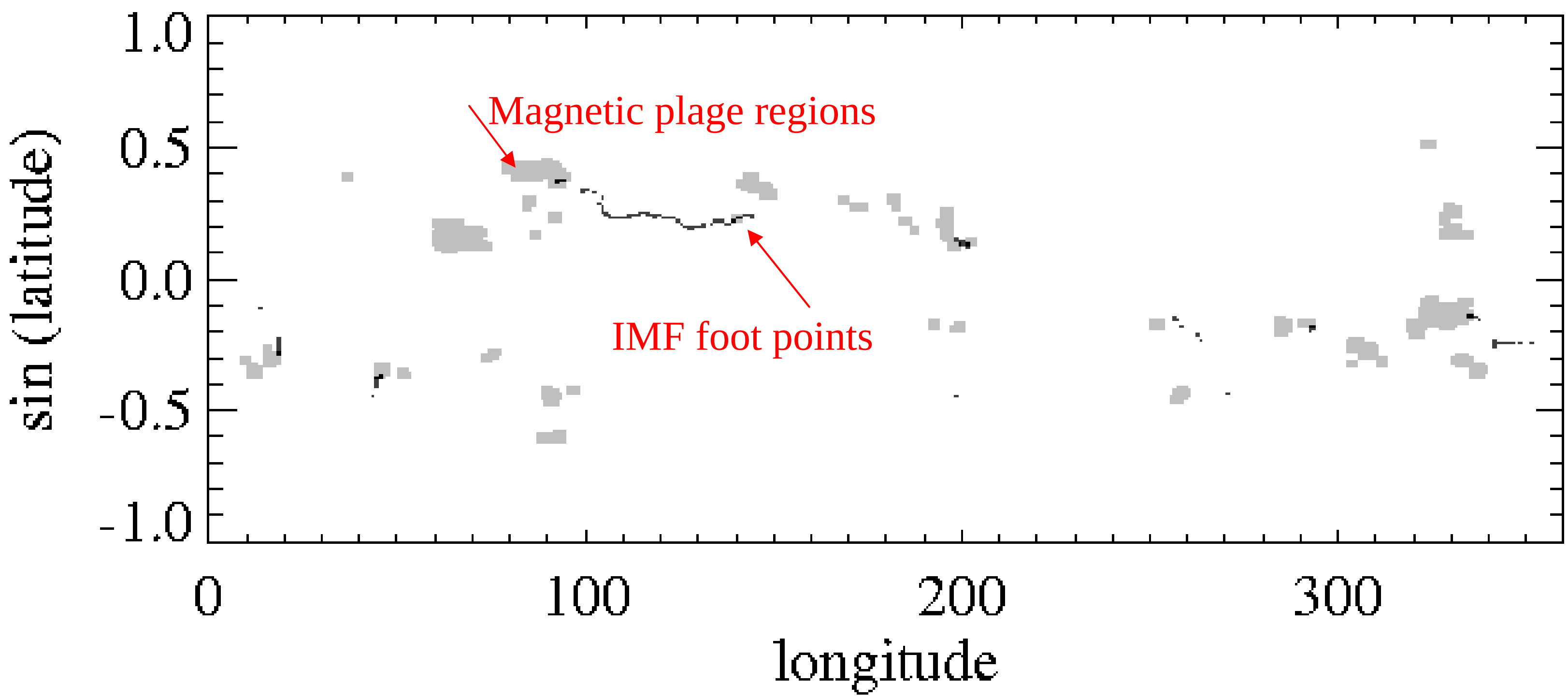


“Sources” of heliospheric field



- ✓ Heliospheric field originates in coronal holes
- ✓AND in active regions!

"Sources" of the IMF

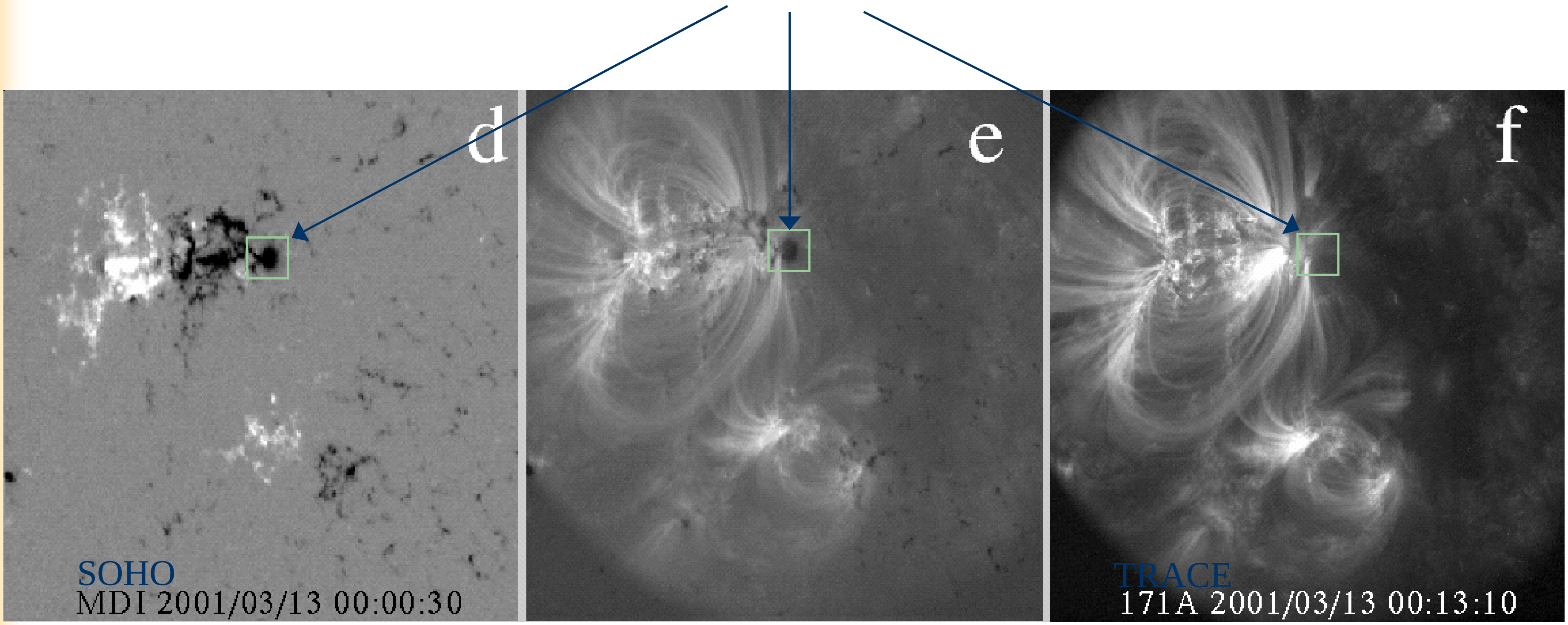


✓ IMF originates in coronal holes over unipolar network AND in young and mature active regions!

Sources of heliospheric field

At solar maximum, 30-50% of the interplanetary magnetic field connects directly to active regions (incl. sunspots)

Model: field open to the heliosphere



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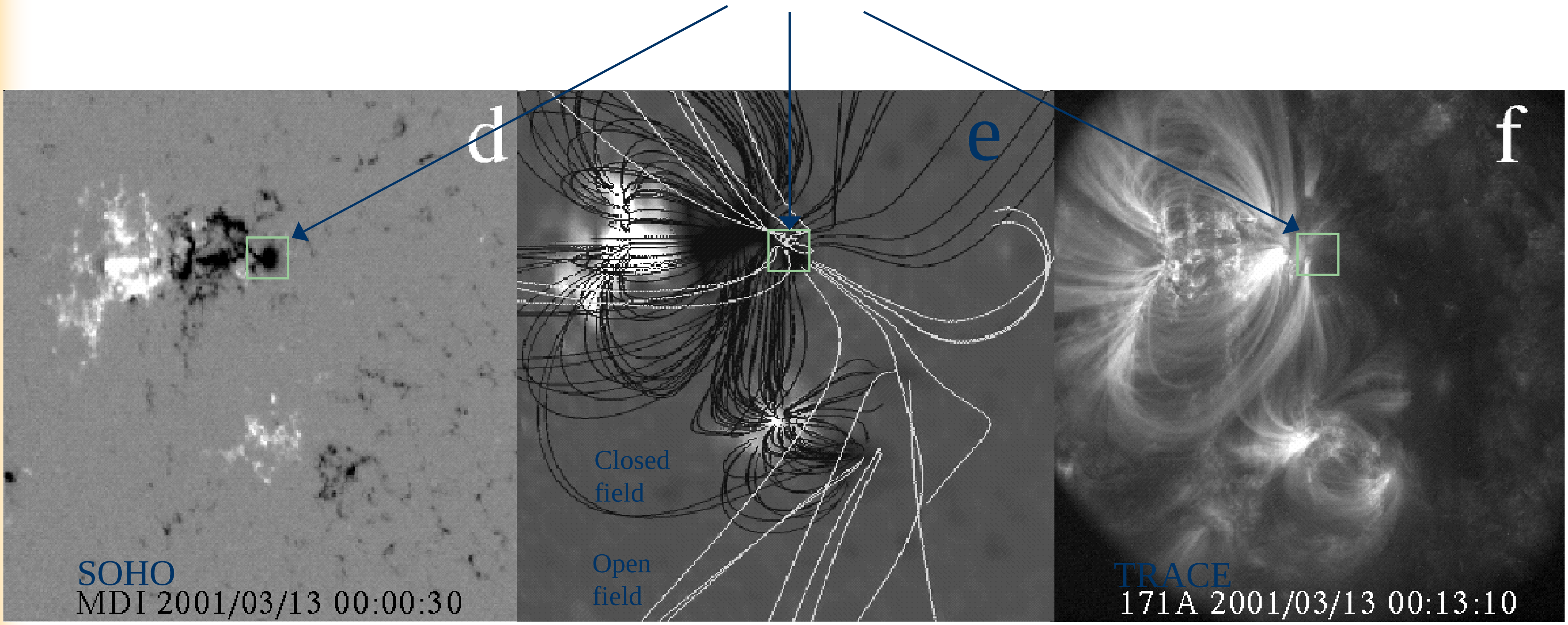
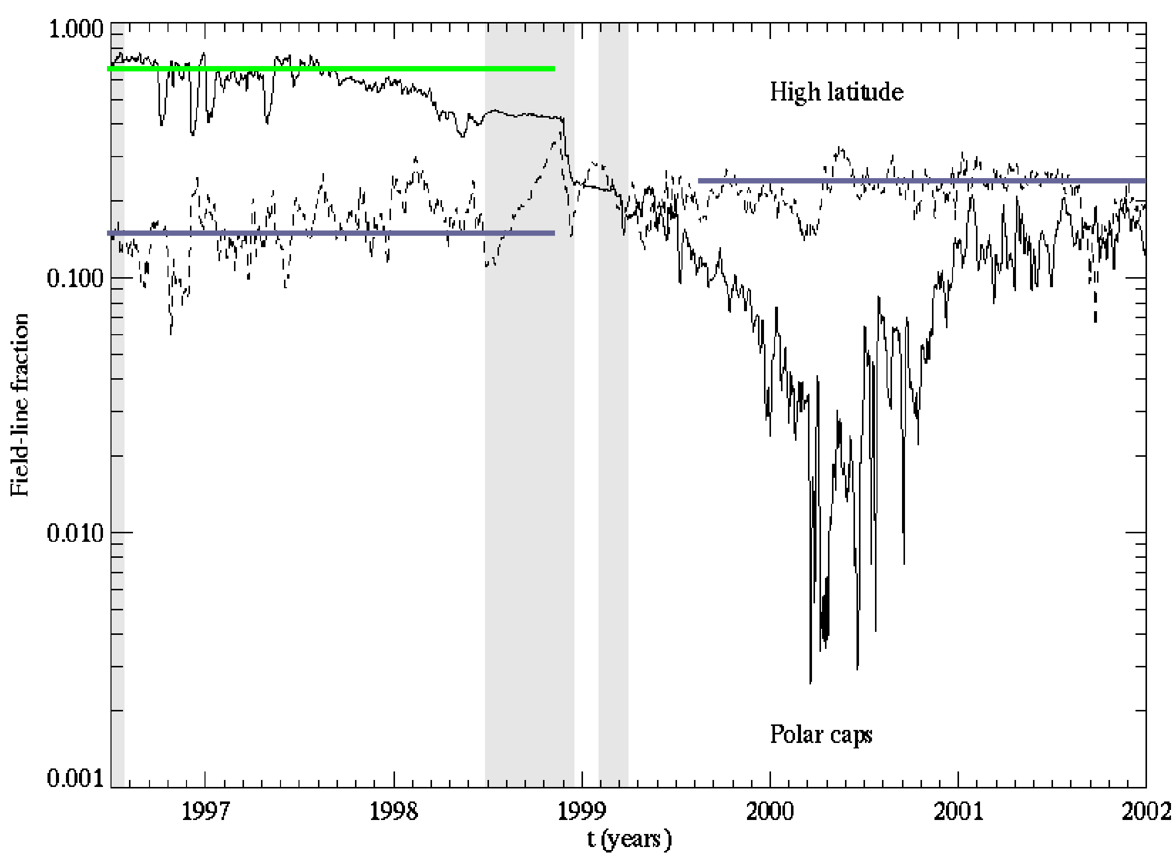


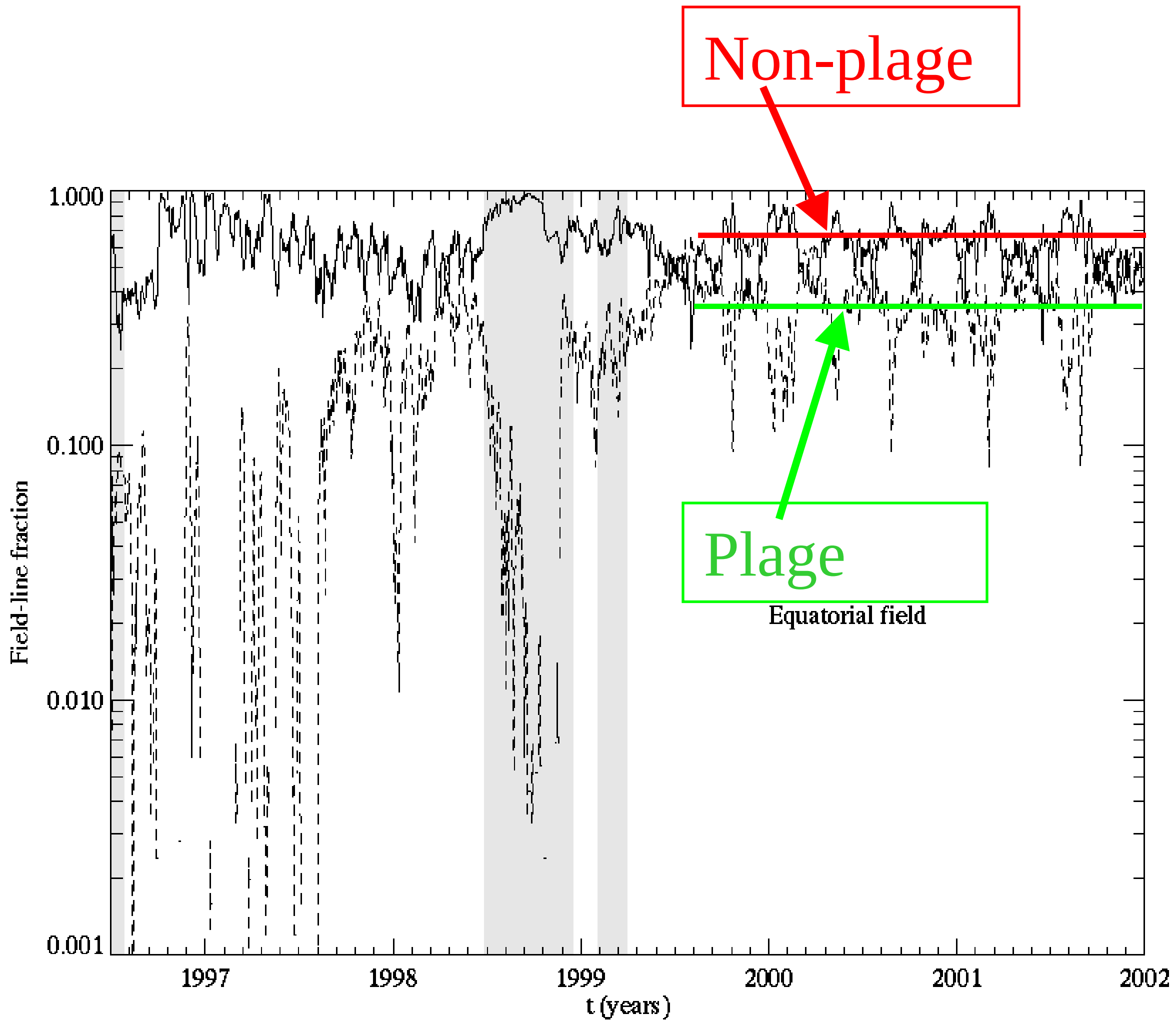
Sources of heliospheric field
(all directions from the Sun)

- Latitudes above 30 degrees contribute 20 to 80% of the total heliospheric flux.

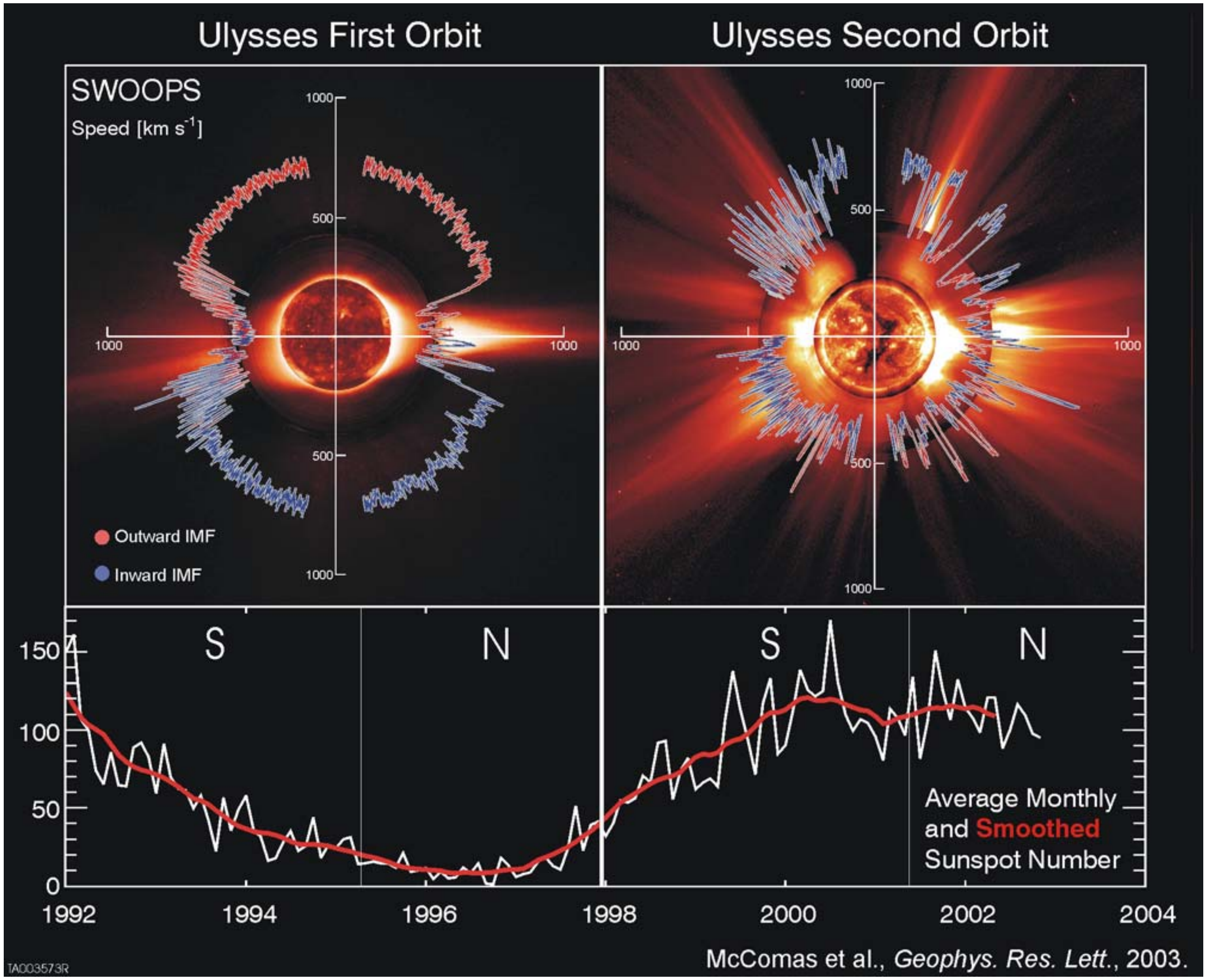


IMF: plage vs. activity belt

- Latitudes above 30 degrees contribute no more than 40% of the IMF
- Some 30-50% of the IMF at cycle maximum originates in magnetic plages.

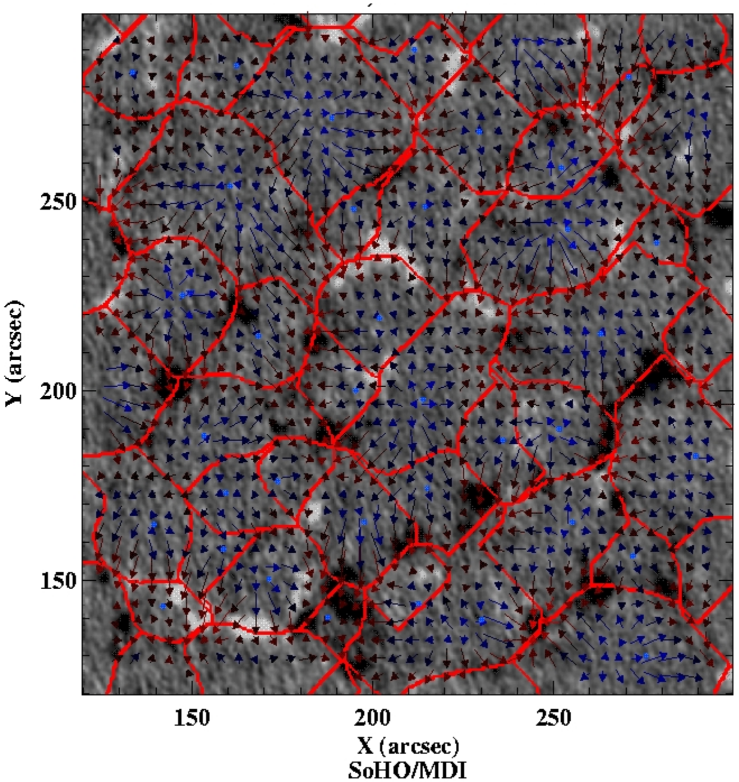


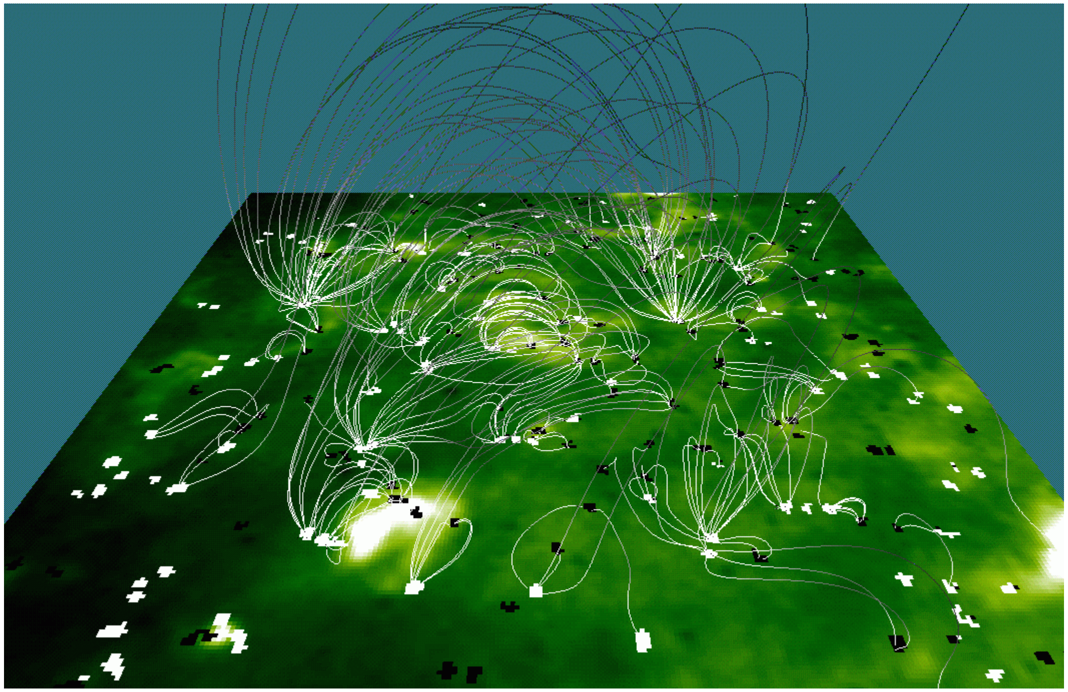
Streamers and the solar wind



How important is the small stuff (I) ?

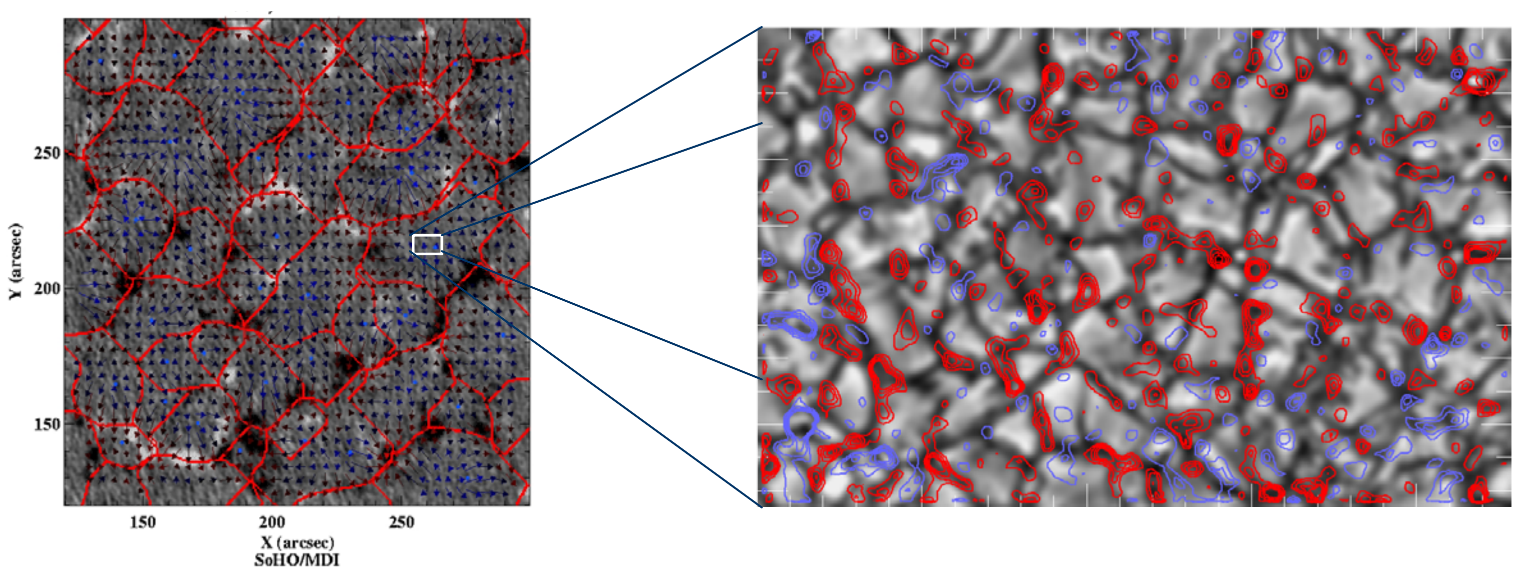
- Quiet-Sun "magnetic carpet":
  - *Large-scale patterns survive for months* or more
  - *Network flux concentration survive for at most a few days*, and magnetic connections much less than a day, owing to emergence of many small bipoles ("ephemeral regions")



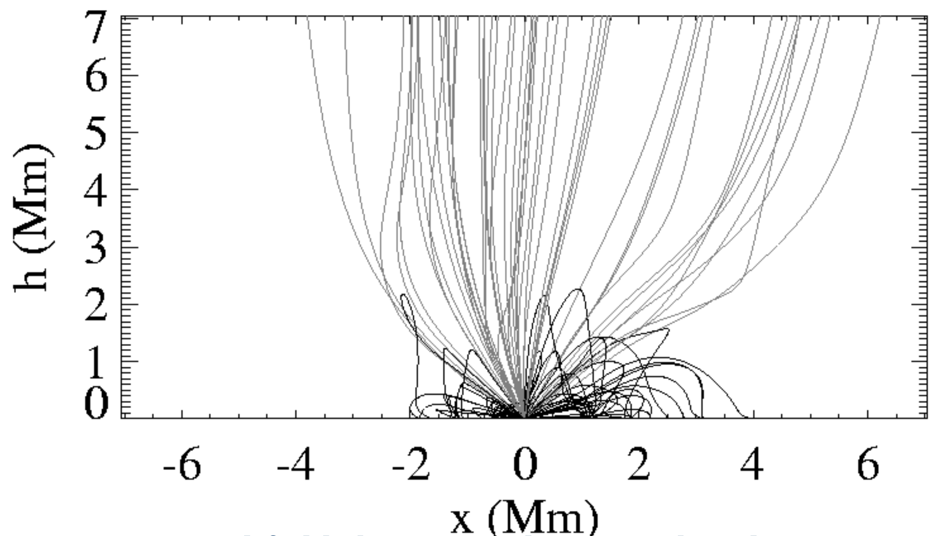


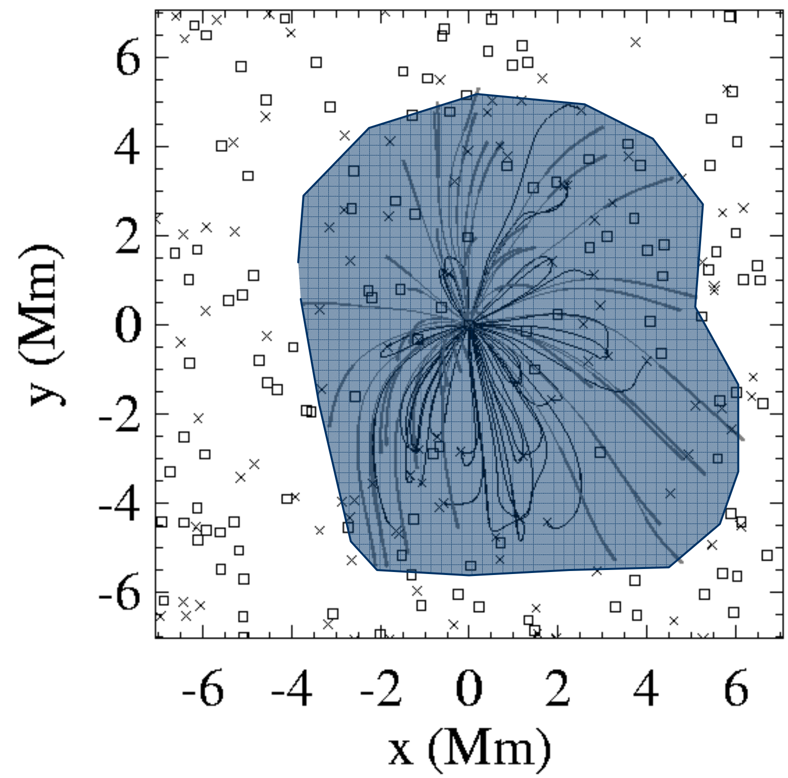
How important is the small stuff (II) ?

- A “magnetic canopy” was thought to separate the strong network field from essentially field-free regions around the network in a closed-vault geometry. But then:
  - “Weak field” away from the network discovered in the mid 70s
  - Maybe “weak field,” but lots of flux: ~5 — 50 Mx/cm^2 , on average ~20 Mx/cm^2
  - Maybe not “weak,” but merely “small”: $10^{16\text{-}17}$Mx compared to $10^{18\text{-}19}$Mx?



Photosphere-corona connection





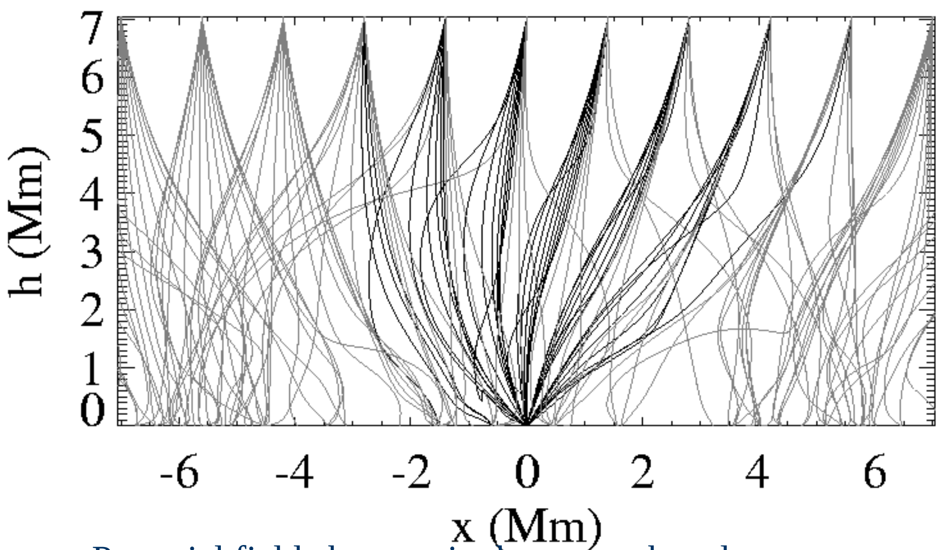
Potential field above unipolar network and mixed-polarity intranetwork; side and top view

- The “intranetwork field” steals flux from the network, so that
- the field geometry is inconsistent with the classical canopy concept, while
- the <u>connectivity into corona & heliosphere changes on minute-to-hours time scale</u>!

Oh, and much of the quiet-Sun corona is not low-β!

(Schrijver and van Ballegooijen, 2005; also Hansteen …)

Photosphere-corona connection



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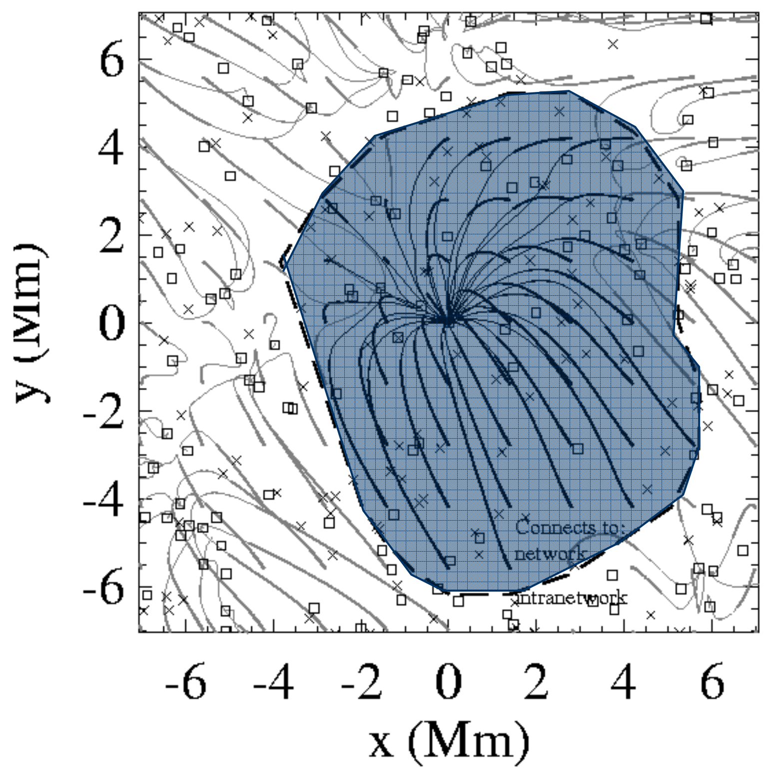

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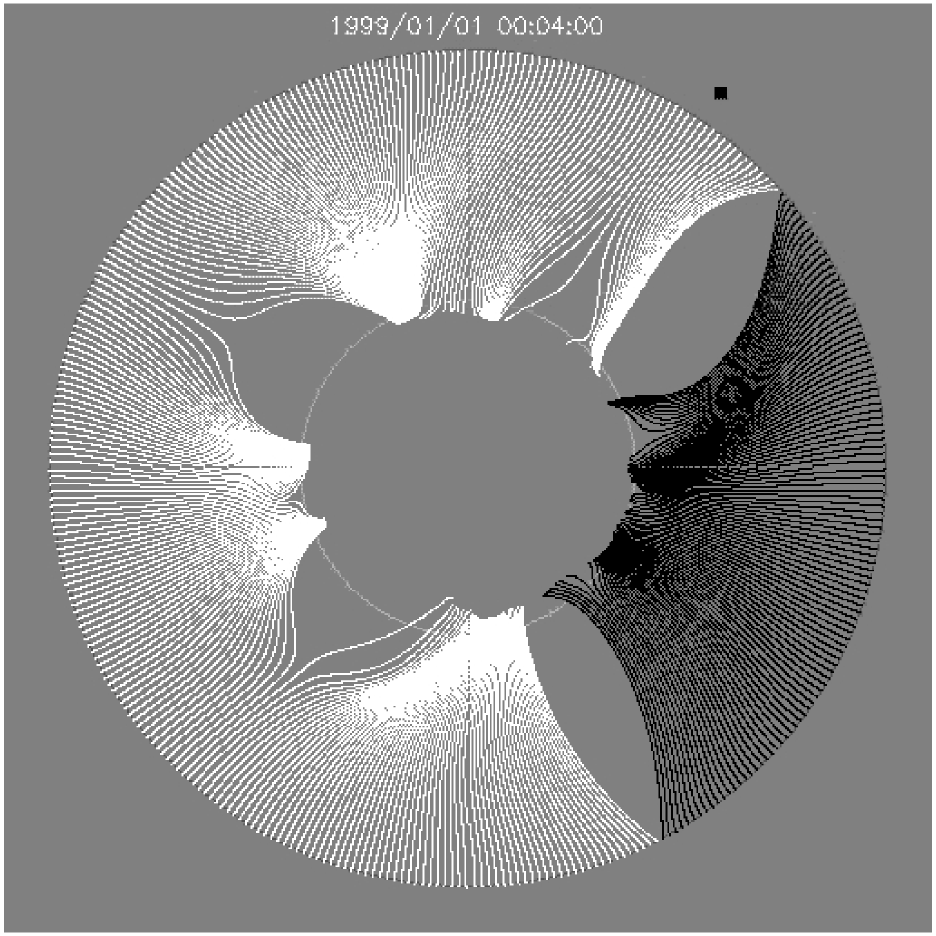
- the field geometry is inconsistent with the classical canopy concept.

'Incomplete knowledge' :

Having observations of only ¼- ⅓ of the solar surface introduces substantial uncertainties (2nd half of the movie) not seen in a model with perfect knowledge (1st half of the movie).



Note the substantial field deflections from the sub-solar point ■ to the photosphere!

Forecast accuracy: wind speeds / base field strength

The polarity pattern of the heliospheric field is forecast accurately more than a month into the future.

Not surprising: this pattern is dominated by the largest scales, which evolve slowly.

Around spot maximum, the source strength of the source-surface heliospheric field can be forecast accurately only a few days ahead of time, because (a) active regions evolve quickly, and (b) active regions are seen too late.

Forecast accuracy:polarity of the IMF

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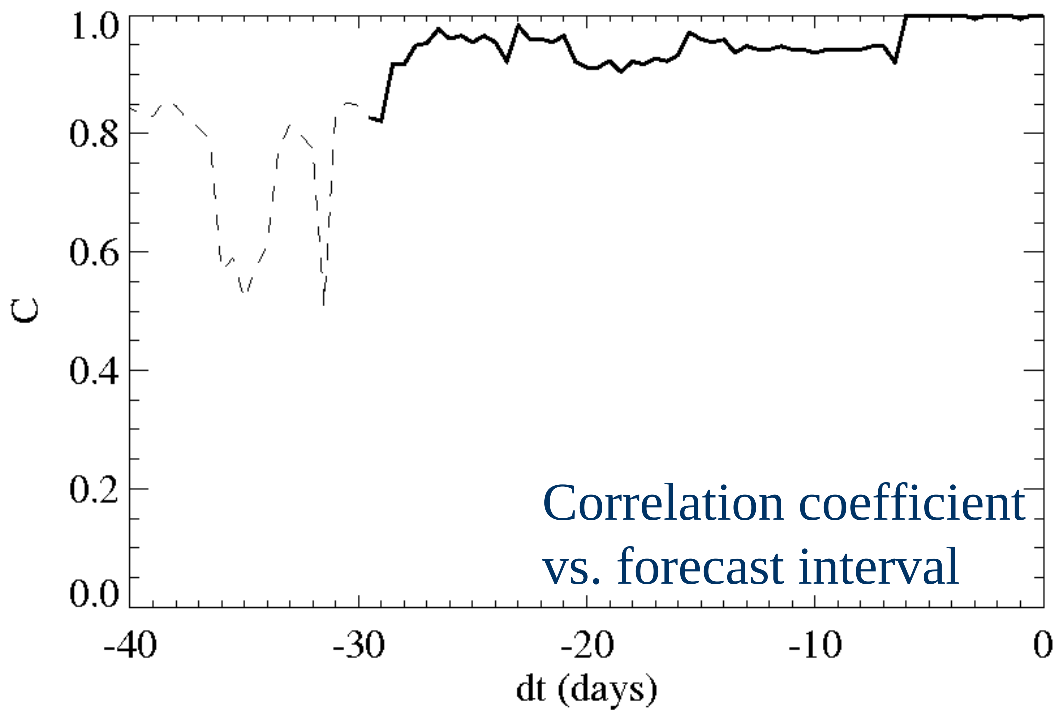

Correlation coefficient vs. forecast interval

Forecast accuracy: wind speeds / base field strength

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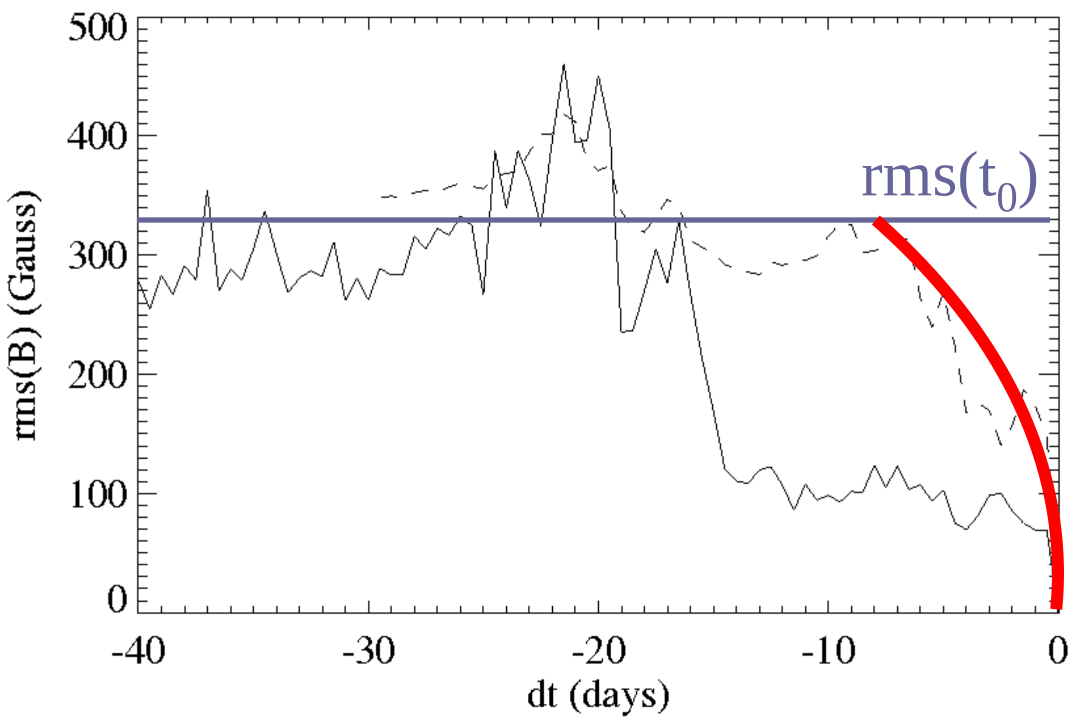
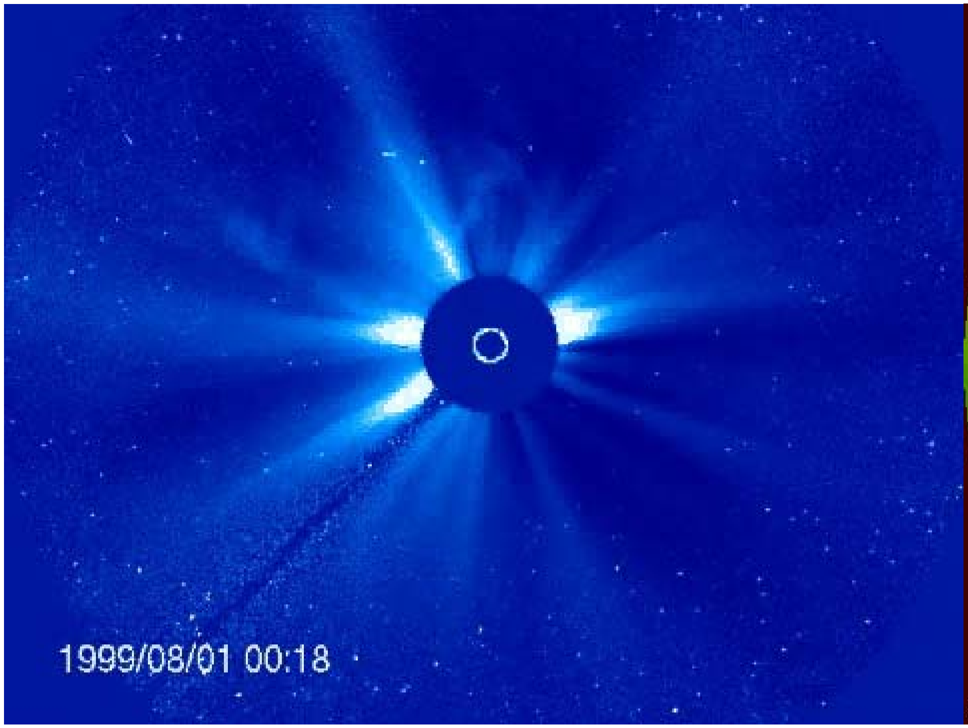
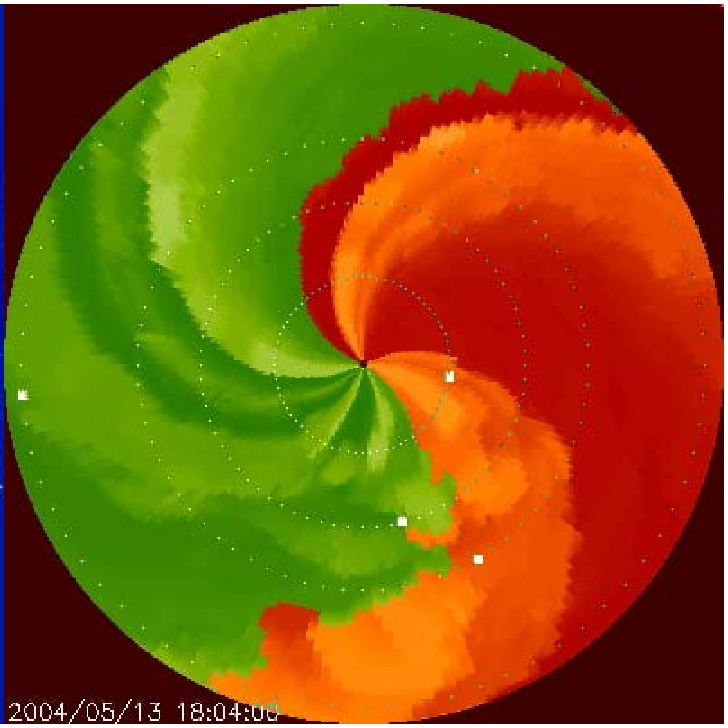


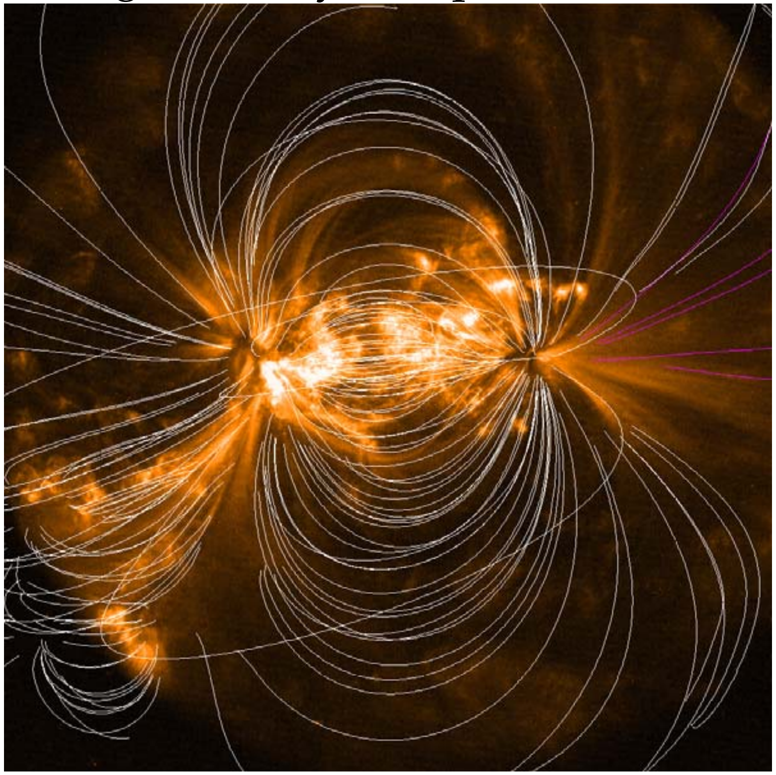
The extended stellar atmosphere

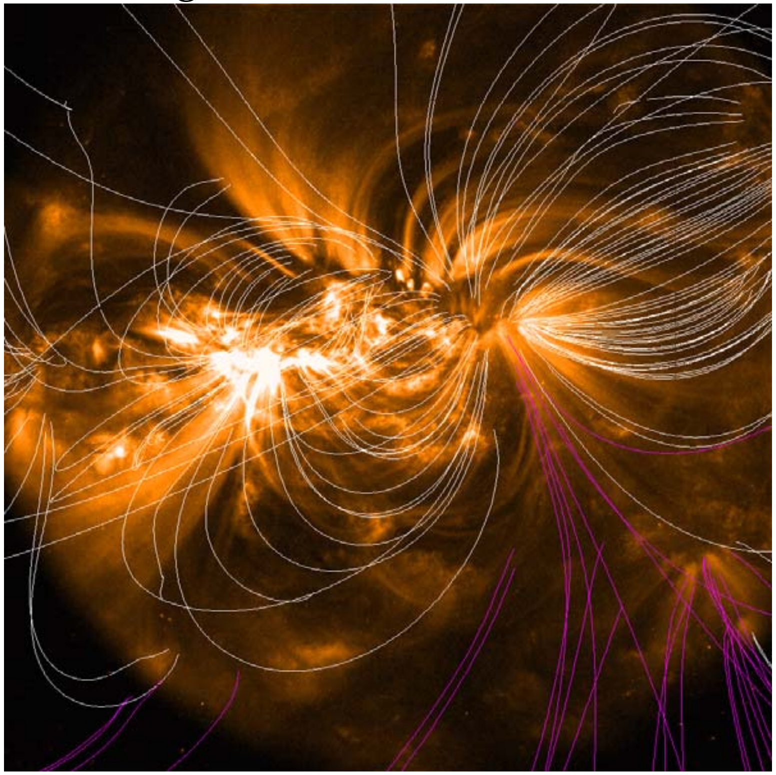




PFSS – MHD modeling and solar-wind models

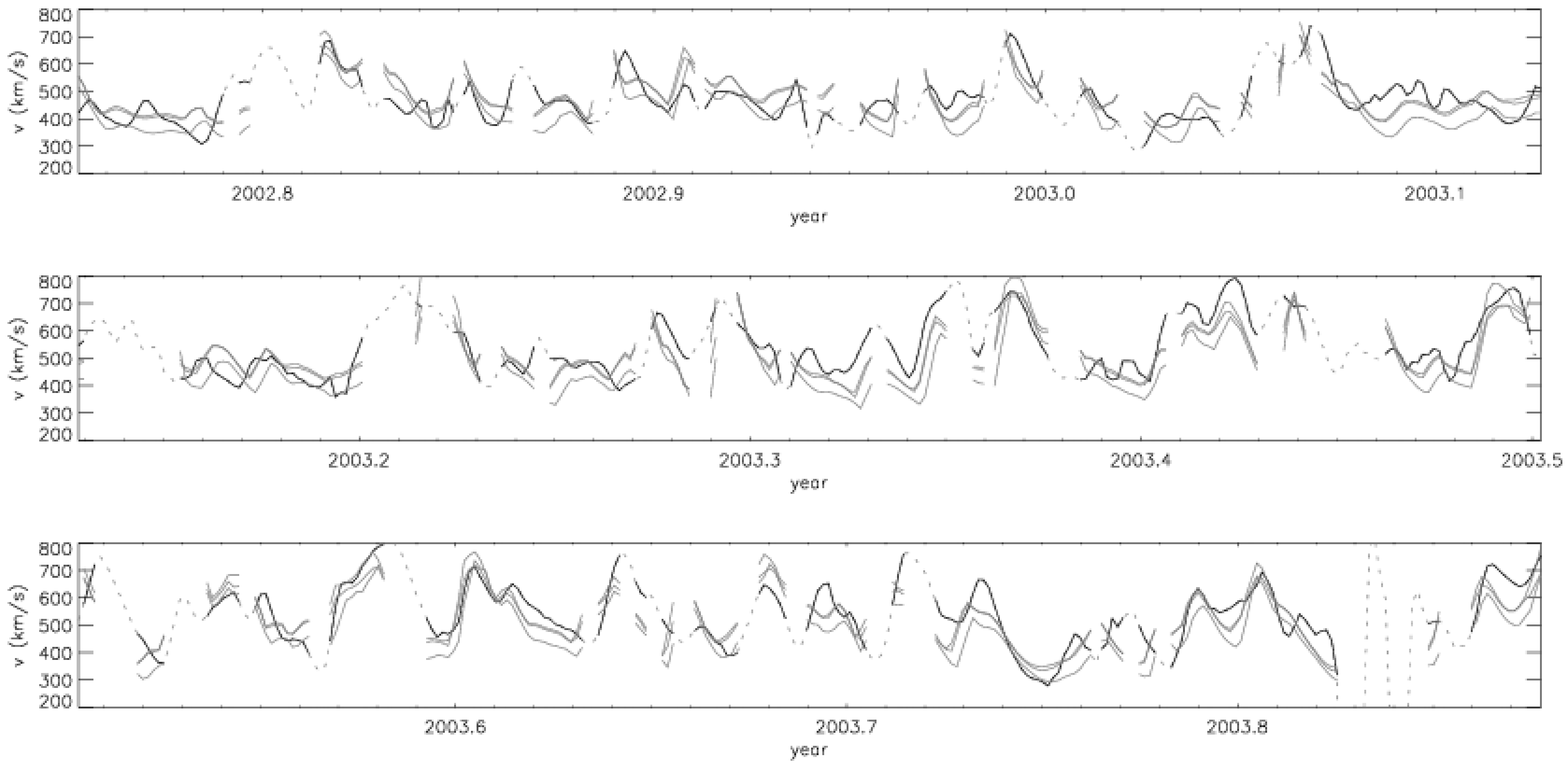
- Cycle maximum: 30-50% of the IMF from ARs,
- significantly non-potential ~10-30% of the regions on the surface,





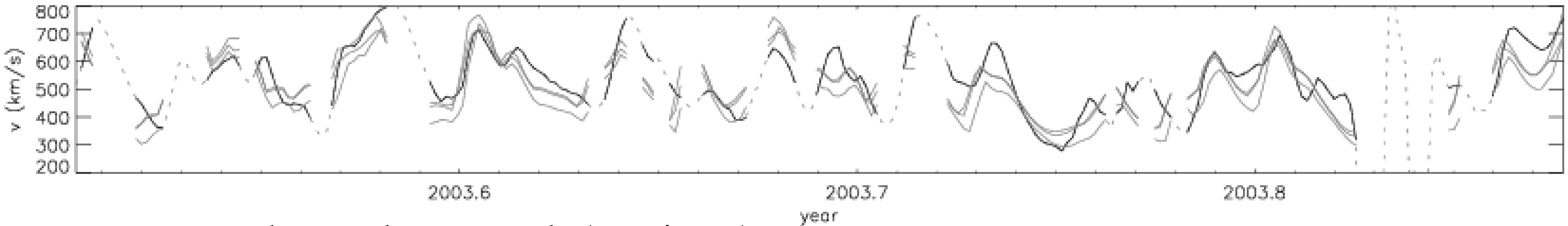
- with the wind perturbed by wide-angle CMEs ~15-20% of the time (during non-potential phases of ARs), and
- inadequate knowledge of much of the solar surface:
- <u>PFSS source-region mapping must fail ~20% of the time.</u>

Wang-Sheeley/Arge-Pizzo wind modeling …



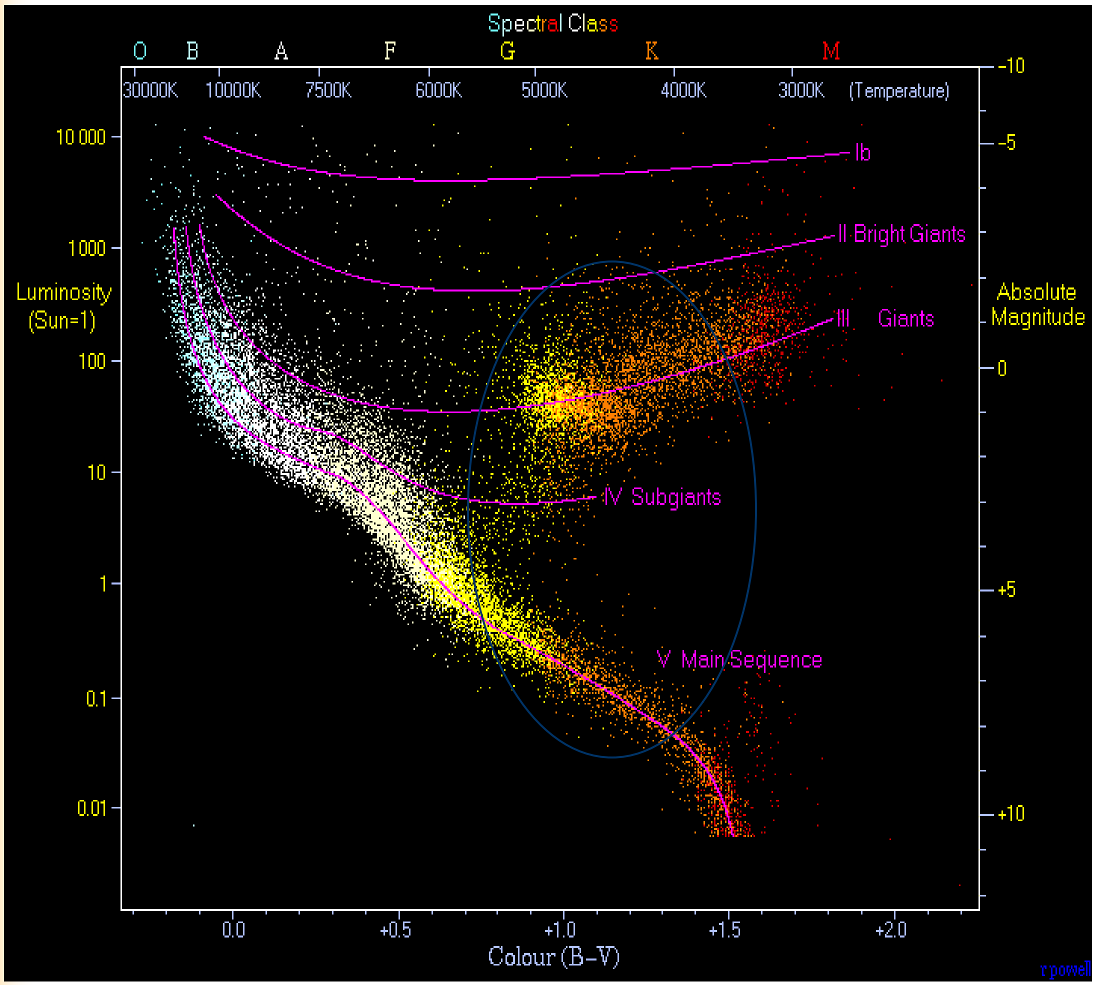
Wang-Sheeley/Arge-Pizzo wind modeling …

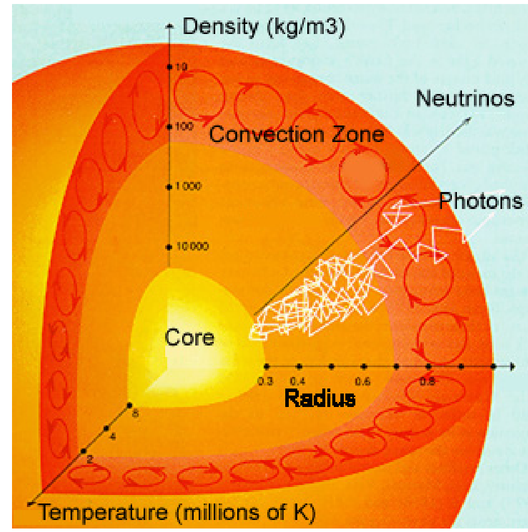
- Arge/Pizzo (2000) model:
  - Arge/Pizzo – *<u>field expansion (ratio of base to source-surface field strengths)</u>*:
    C=0.34-0.39 for 3-yr for sunspot numbers 10-25
  - Our model – *<u>base flux density over average source-surface flux density</u>*:
    C=0.38 for 3-yr for sunspot numbers 30-115.
    Eliminate the worst 17%, then C=0.71



  - Wind speed: $v = a + b\ (B_{ss} / B_{ph})^c$
    - Arge/Pizzo: **a=270km/s, b=410km/s, c=0.4**
    - Our model: **a=280 ± 40km/s, b=1000 ± 200km/s, c=0.49 ± 0.10**
      (Note: b is sensitive to magnetogram resolution)
  - Wind interaction: $v_{ij} = [\ (v_i^{-d} + v_j^{-d})/2\ ]^{-1/d}$
    - Arge/Pizzo: **d=2**
    - Our model: **$d \in [-2,2]$ – unconstrained!**

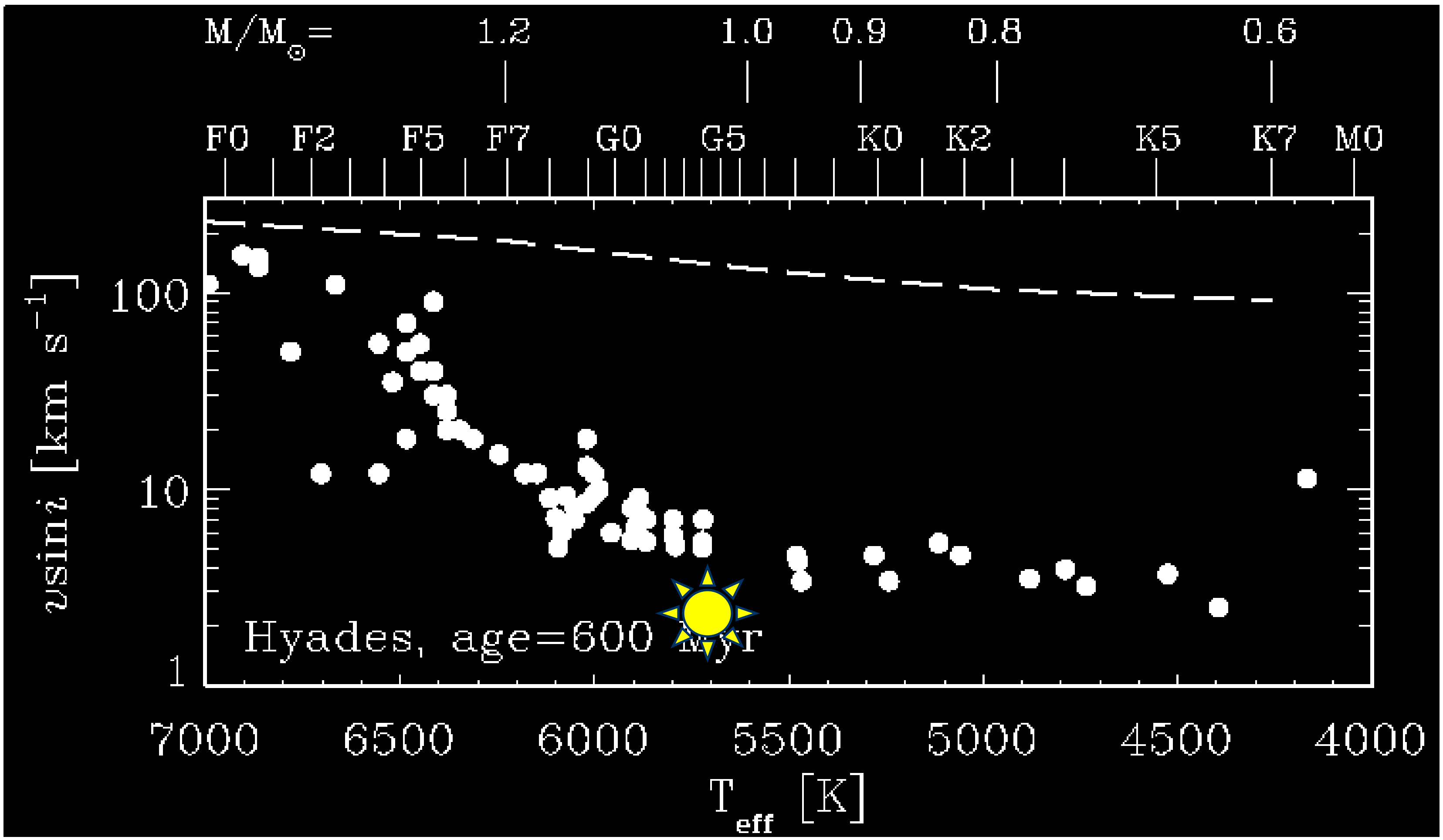
Solar-like activity





All rotating stars with convective envelopes exhibit atmospheric magnetic activity.

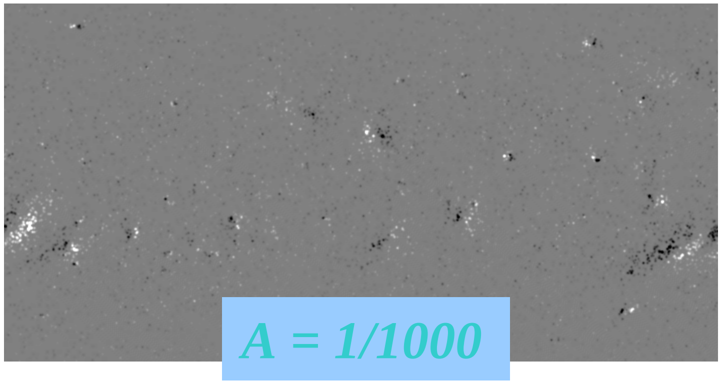
Rotation and age

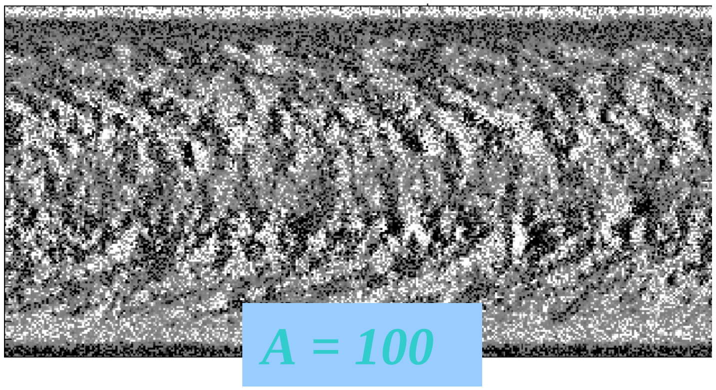


Simulating other stars

Hypothesis:

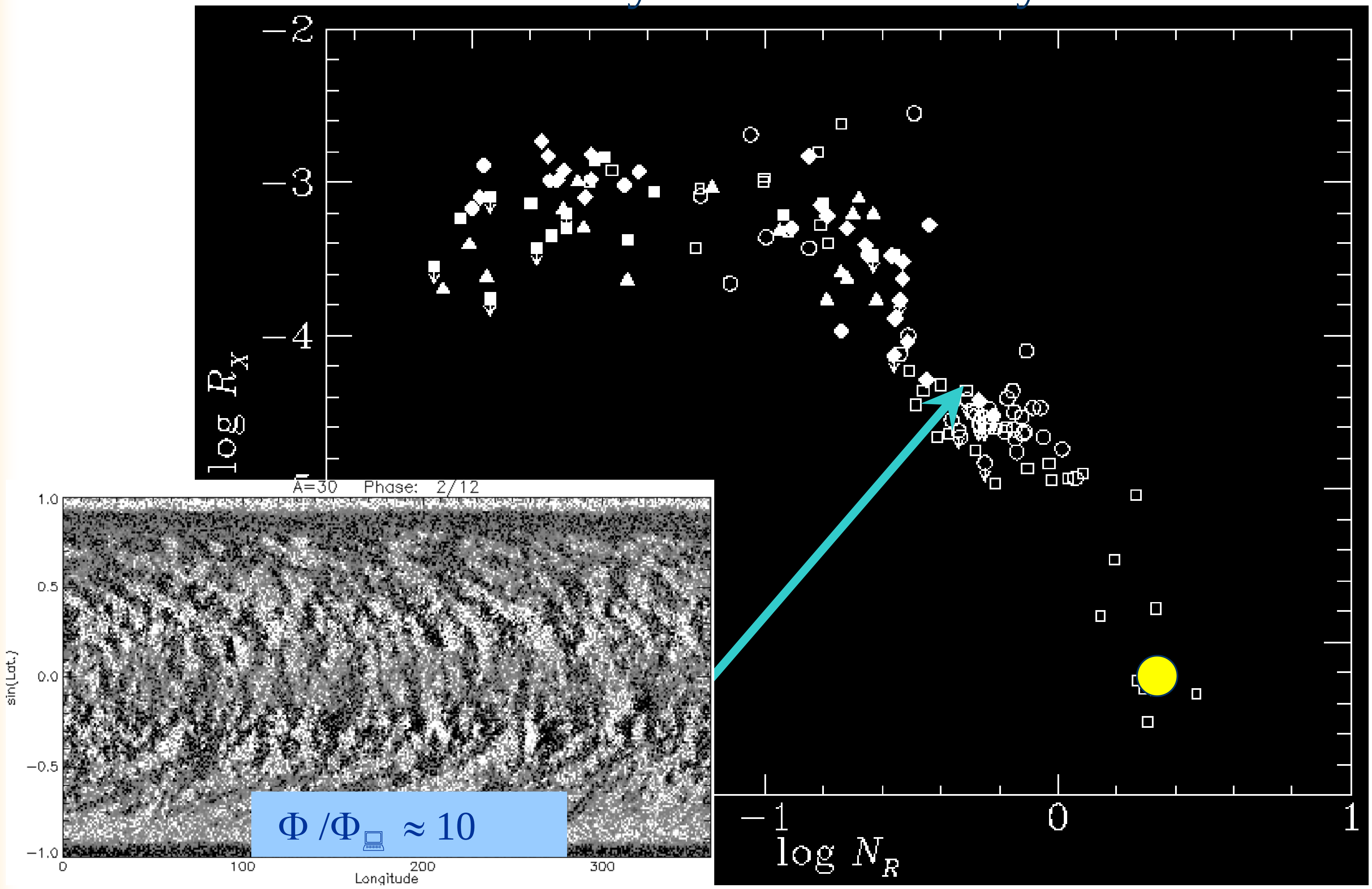
Stellar dynamos are like that of the Sun, *except for the frequency of active-region emergence*





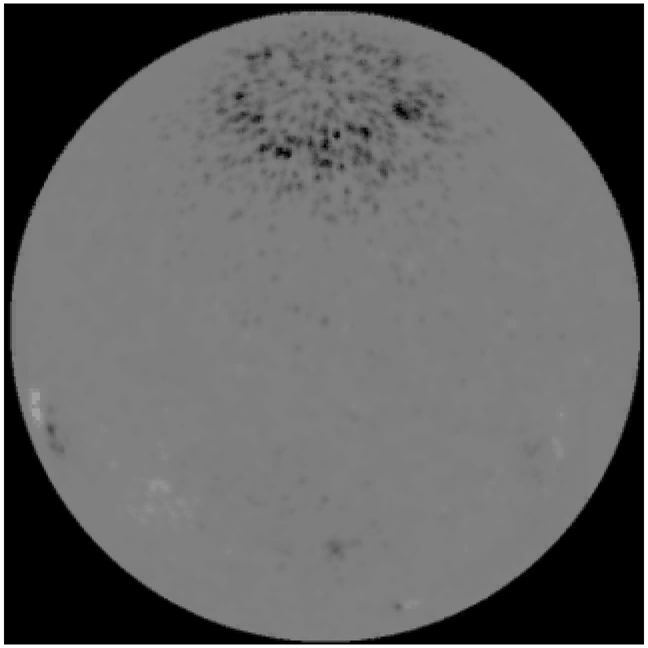
Activity, rotation, and saturation

A star at 30x solar rate of flux injection is of merely moderate activity:



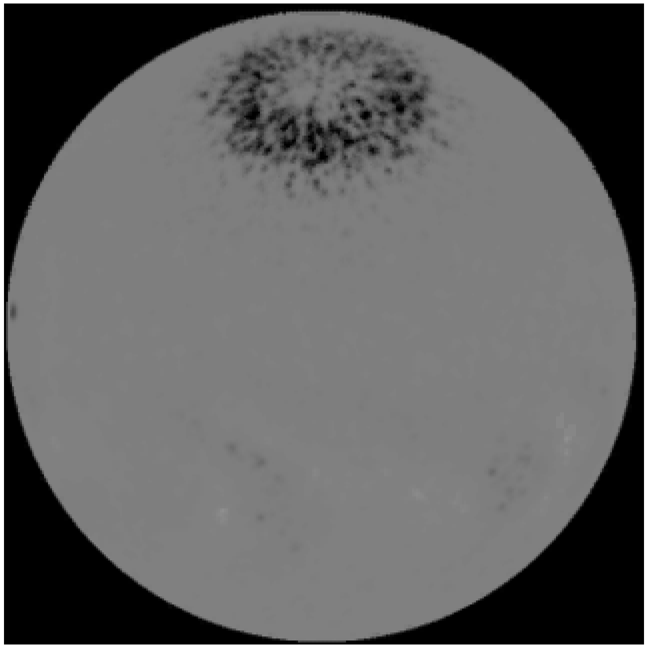
Simulations of activity

Simulated "Sun" from 40°N:



Present Sun

Active star (30x higher rate of flux injection), from 40°N:

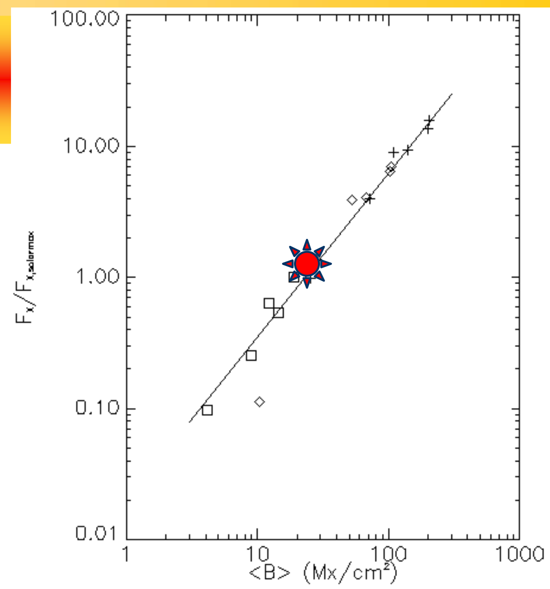


Young Sun at ~500 Myr?

Wind from the once and future Sun

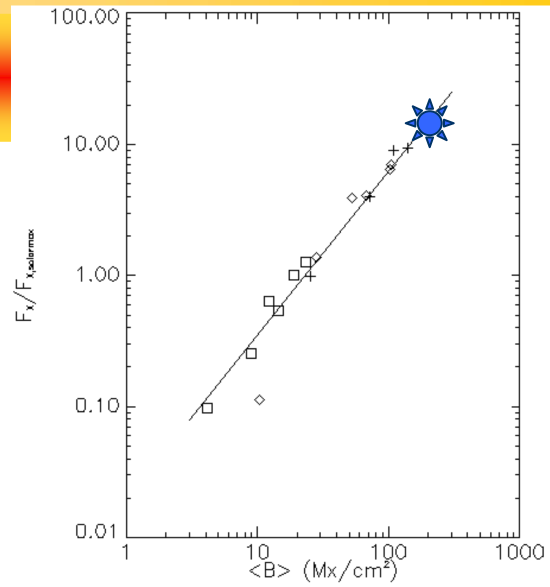
- Combination of solar and stellar observations constrains mass loss and angular momentum loss of the Sun in the distant past and future, and
- raises the question whether the mechanism which drives the wind also contributes significant power to (long) loops.

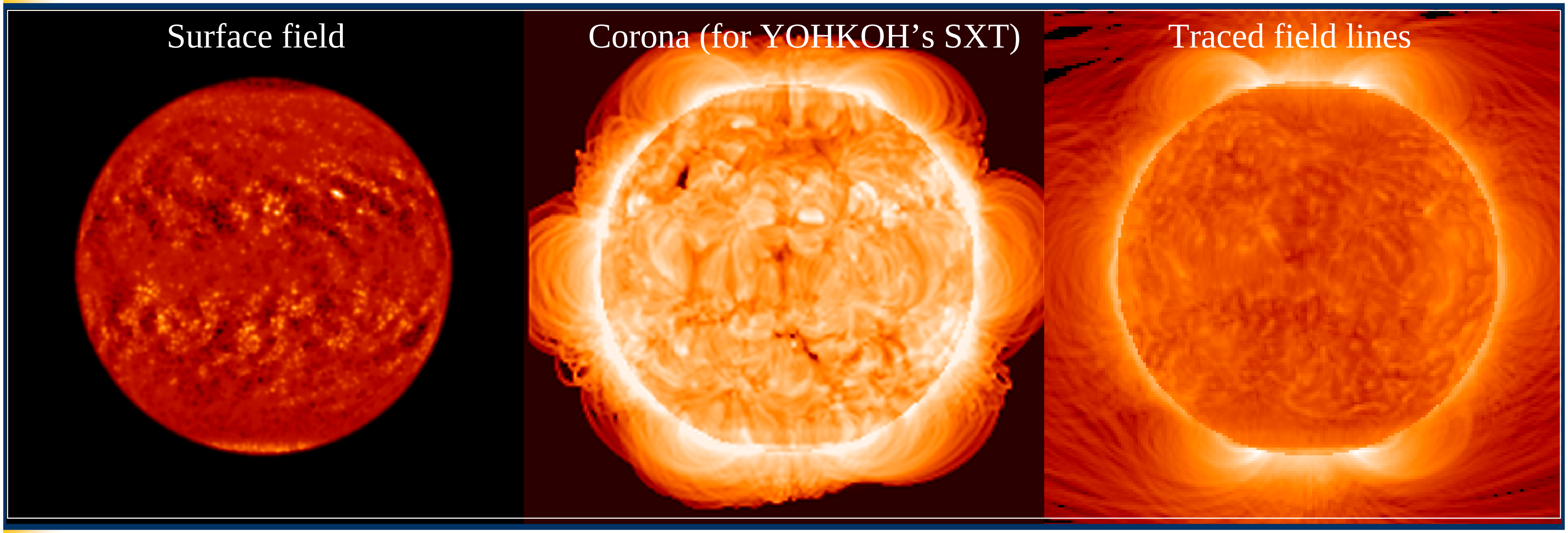
Sun-like star



Cycle maximum

30x solar emergence rate

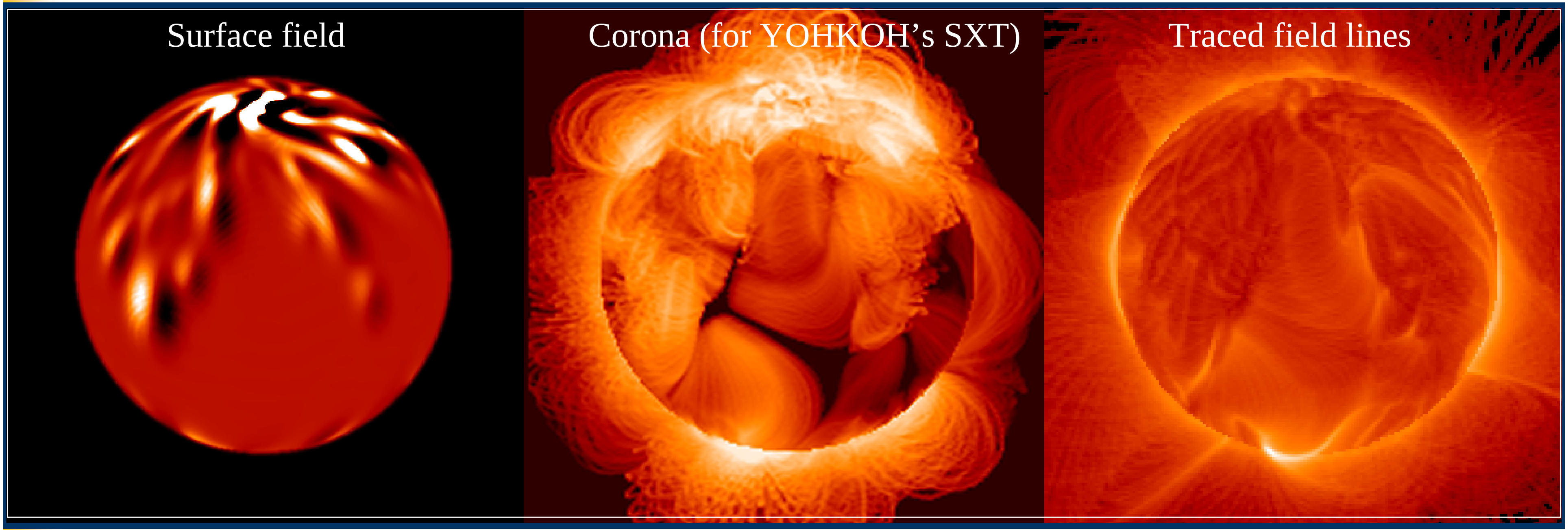




AB Dor – like star

Simulated magnetic field on a star like AB Dor (K0V, 15pc, 20-30Myr, P=0.51d), just prior to “cycle maximum”

by MacKay, Jardine, Collier Cameron, Donati, Hussain (2004)



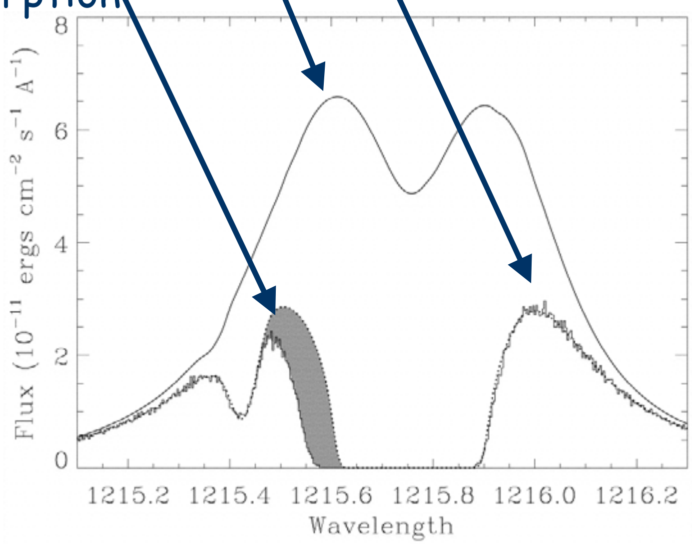
Asterospheres

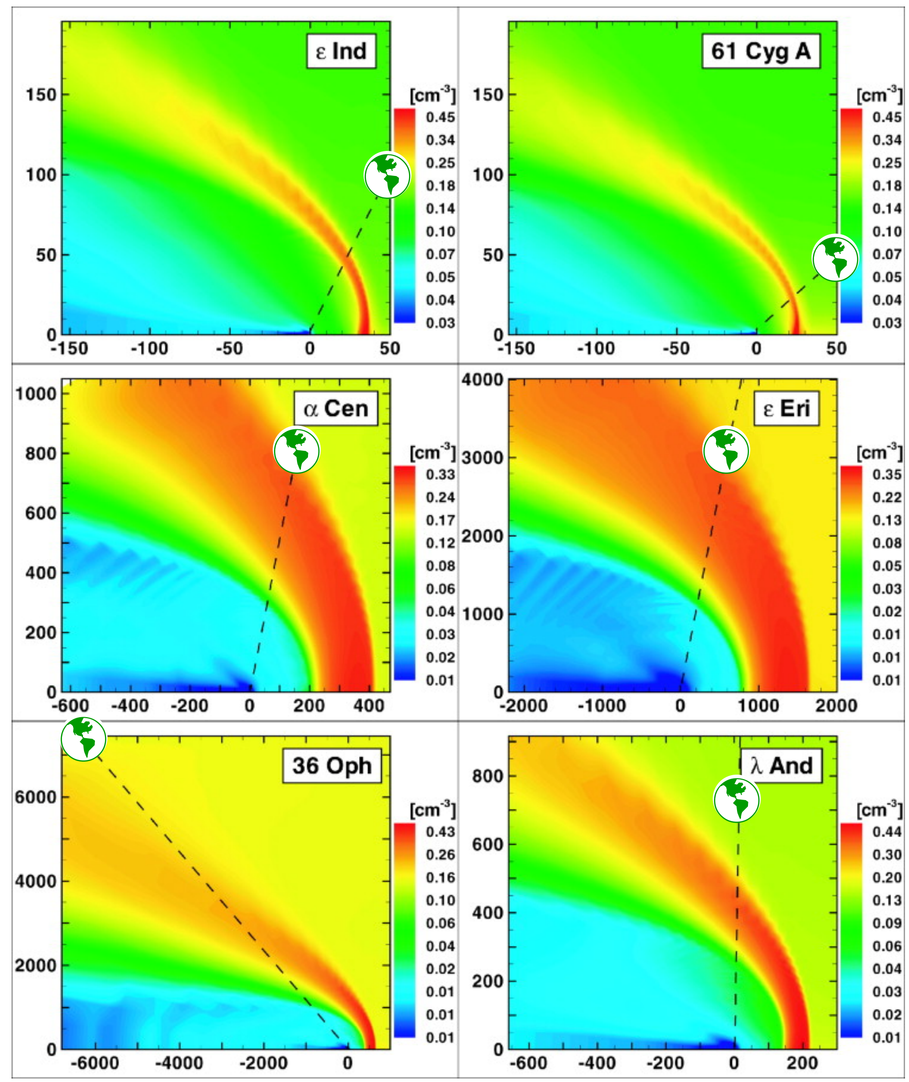
Combine observed Ly α profiles with models of wind-ISM inter-action to derive mass loss rates:

Observed after inter-/ circumstellar absorption

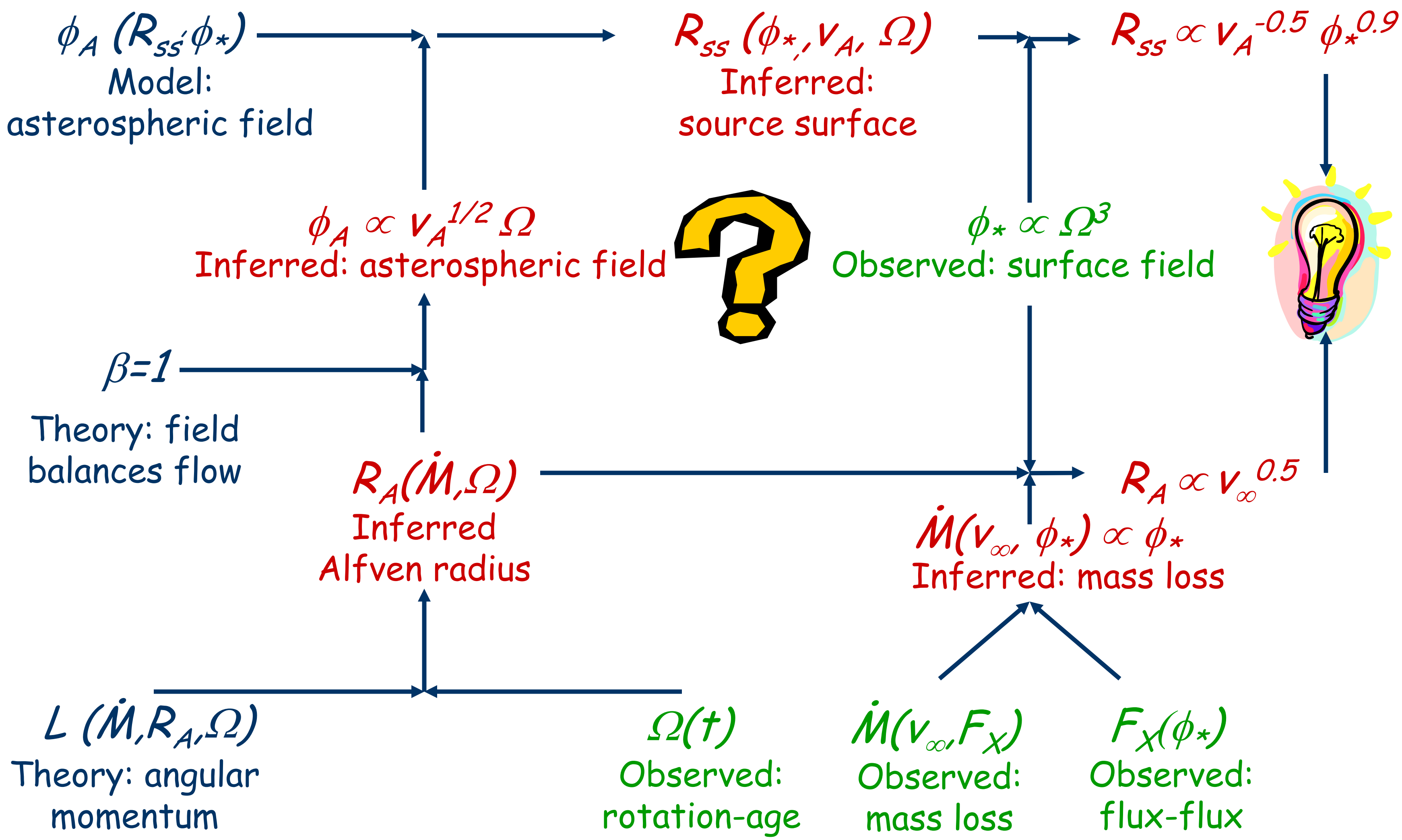
Model stellar profile

Asterospheric absorption





The mystery of magnetic braking



The mystery of magnetic braking

$R_{ss} \propto v_A^{-0.5}\ \phi_*^{0.9}$

$\phi_A \propto v_A^{1/2}\ \Omega$
Inferred: asterospheric field

$\phi_* \propto \Omega^3$
Observed: surface field

$R_A \propto v_\infty^{0.5}$

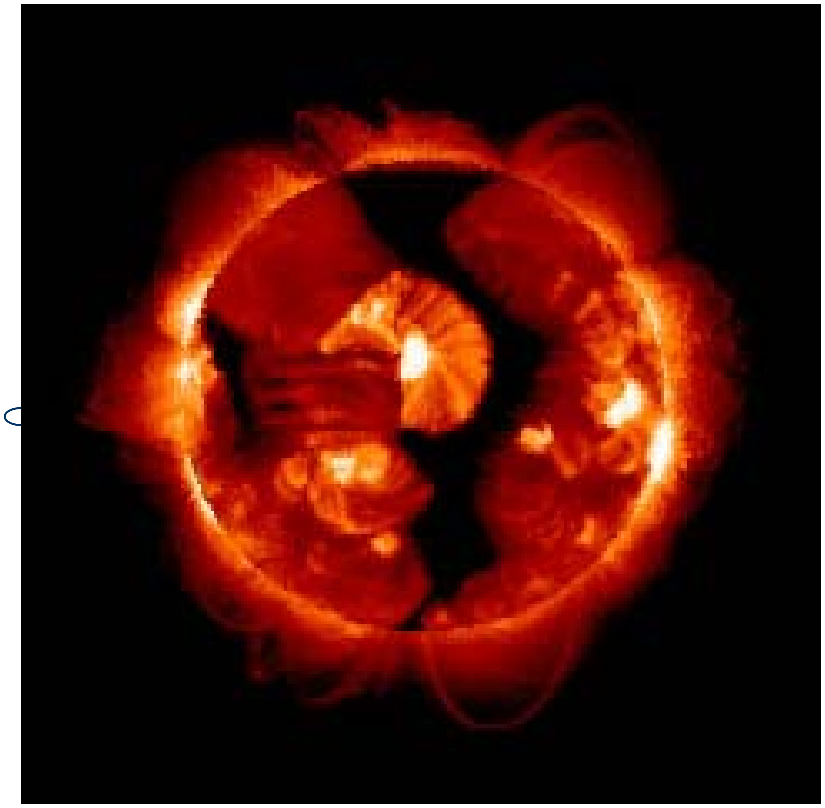
$\dot{M}(v_\infty, \phi_*)\ v_\infty^2 \propto \phi_*\ v_\infty^2$
Inferred: wind power

Q: Why do surface and asterospheric fields scale differently with activity?

A: Coronal field is forced open *lower* as activity decreases
(causes: field expansion in a dipolar geometry and wind acceleration).

Powering the corona and the solar wind

Simulation: braiding-induced heating



Extra heating possible needed for long loops = power needed for wind

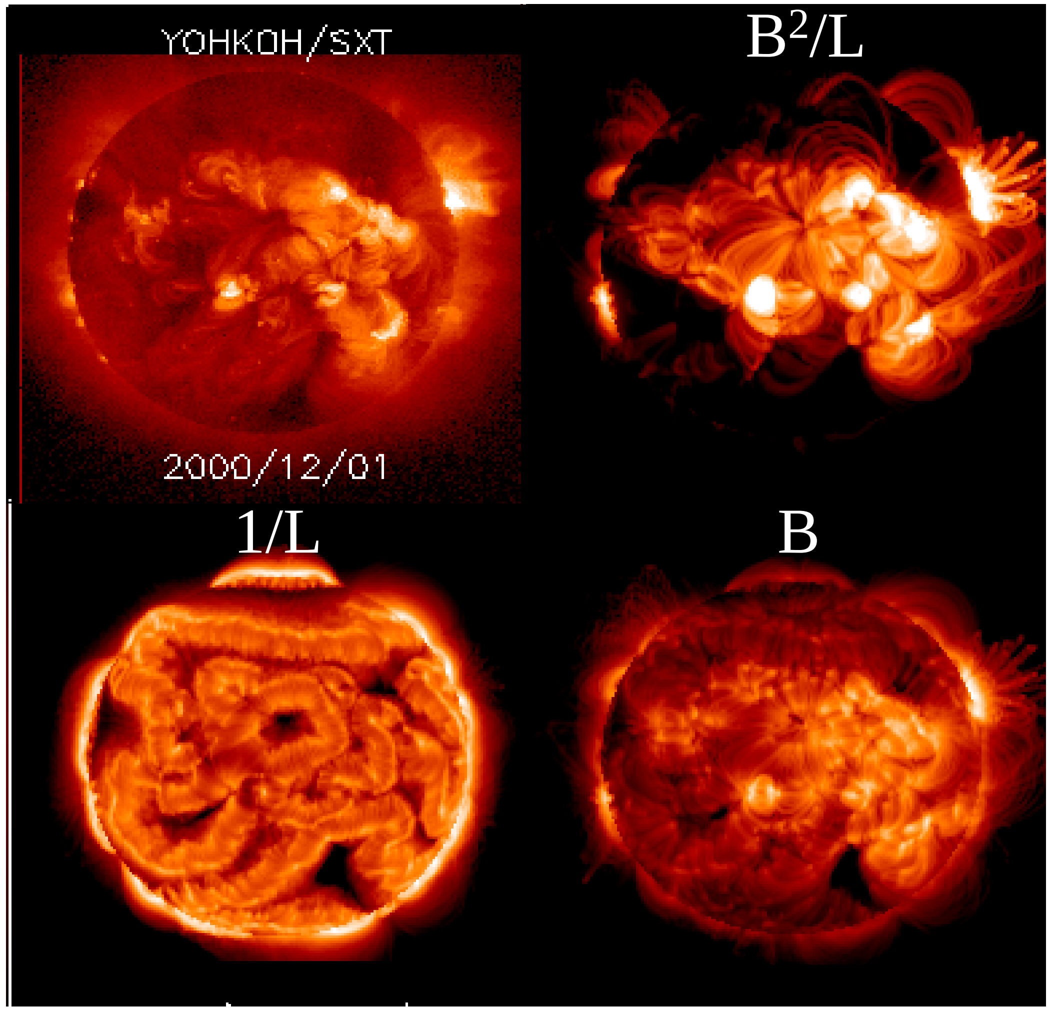
- Model solar corona, based on observed magnetic field, rendered for YOHKOH/SXT Al/Mg filter
- Heating power into loops (ApJ 615, Nov. 1, 2004):

$$F_H = 8 \times 10^4 B^{1.0\pm0.3}(10^{10}/2L^{1.0 \pm 0.5} + 1) \quad ergs/cm^2/s$$

Heating and coronal appearance

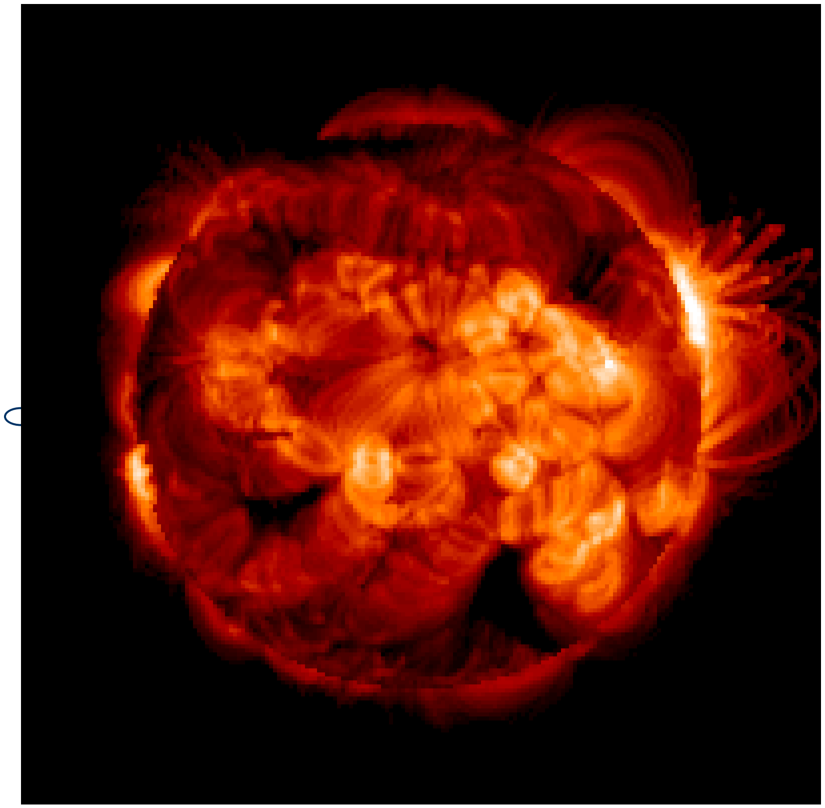
The appearance of the corona depends on the properties of coronal heating.

These sample images show some of the "worst-fit" cases.



Powering the corona and the solar wind

Simulation: braiding-induced heating



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Conclusions and some questions

- PFSS-like modeling works well most of the time.
- Reconnection through the neutral-line/current-sheet can likely take care of the evolution of the heliospheric flux.
- Much of the IMF connects directly to ARs (& spots).
- Much of the fast wind is likely rooted in dynamic small-scale field. *What does that imply for , e.g., the Solar Probe?*
- Does the wind driver also dominate in long closed loops?
- How best to improve understanding of wind driver(s)? At least, improve our understanding of photosphere-heliosphere coupling
  - better coverage of the full sphere (Sentinels & FarSide); inclusion of major current systems in active-region coronae (Solar-B, SDO, & GBO); long-term sampling of inner heliosphere (IHS, Orbiter); improved understanding of polar-cap behavior (Orbiter); …