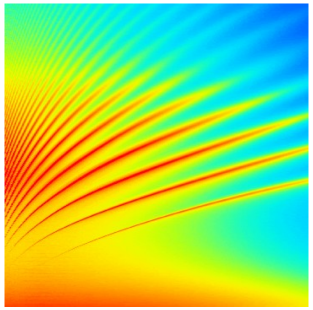
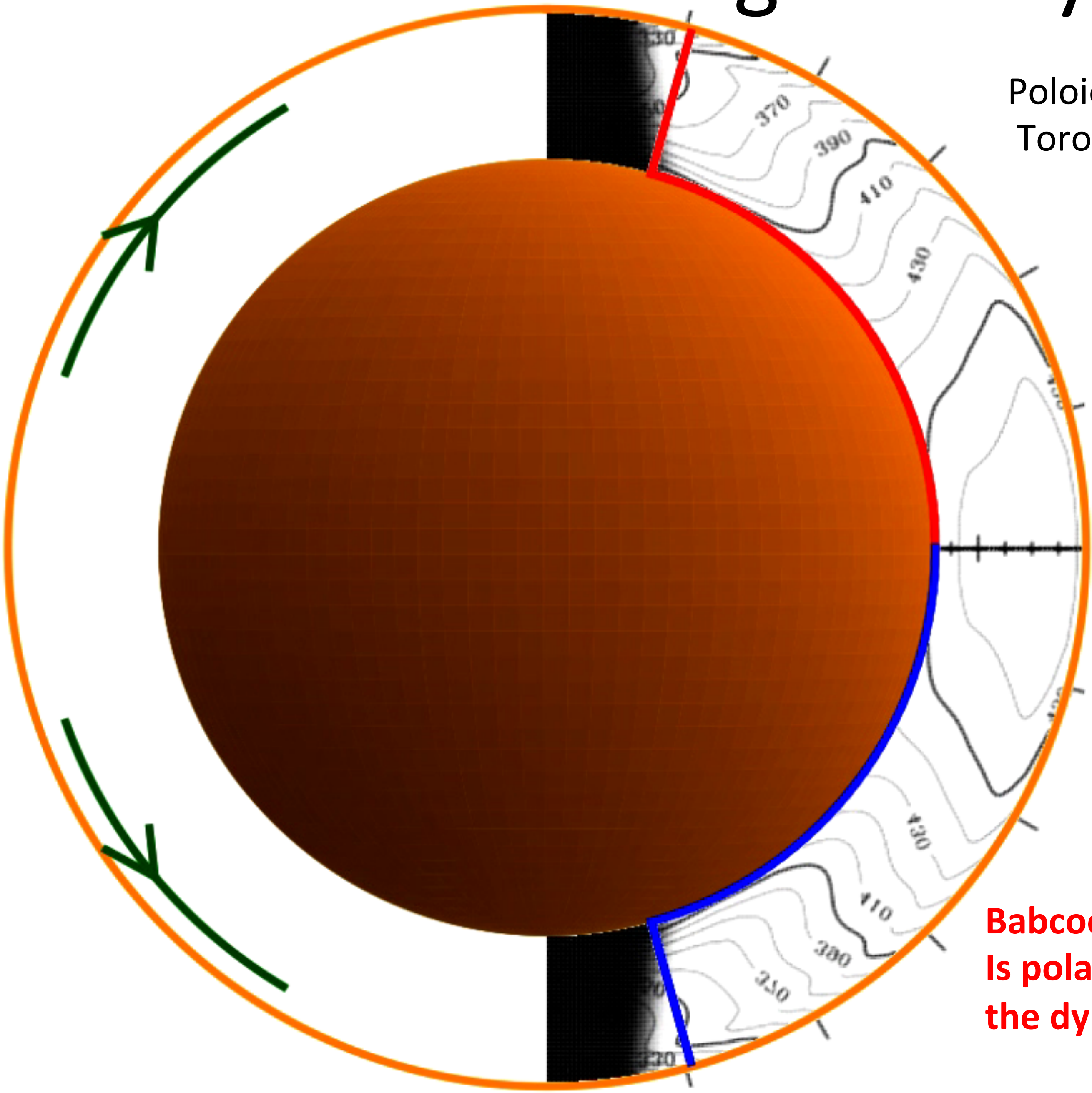
Observational constraints on the global solar dynamo

Robert Cameron & Manfred Schüssler

(Jie Jiang, Dieter Schmitt, Emre Isik, Laurent Gizon)



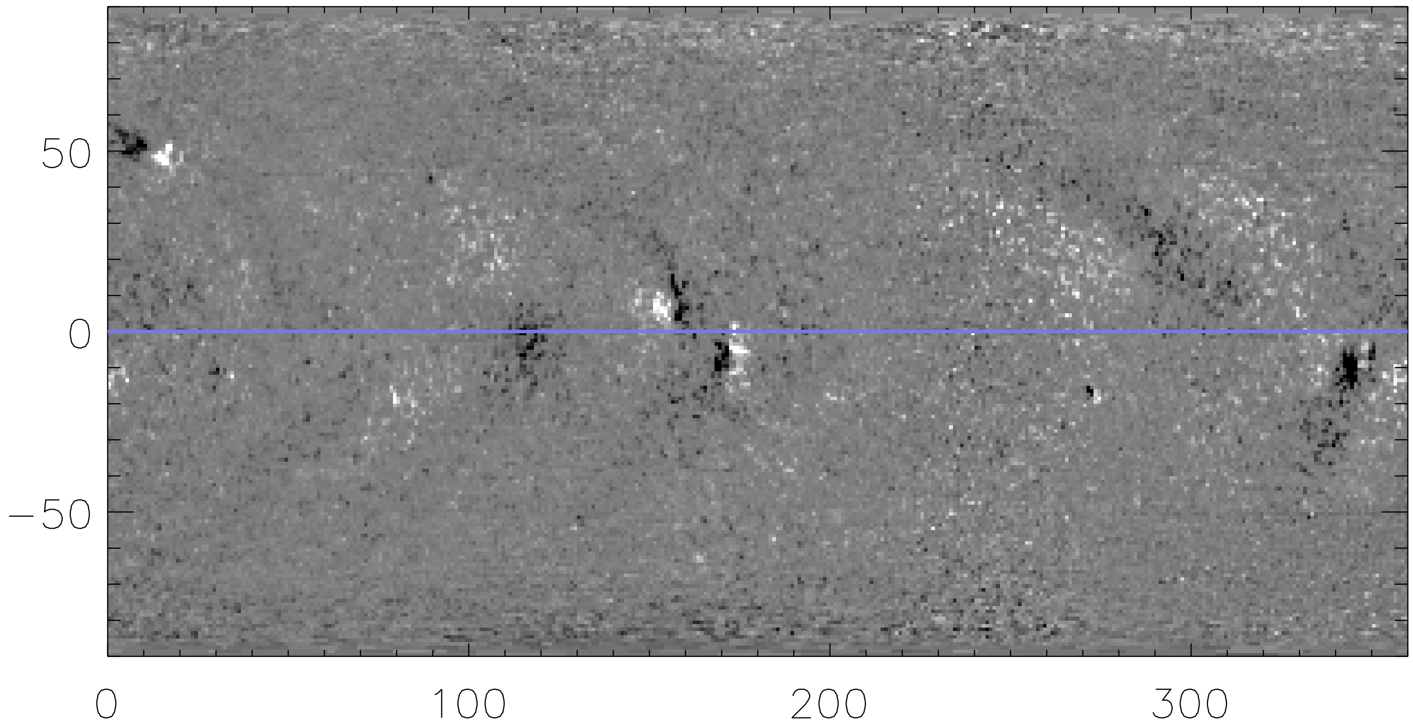
Babcock-Leighton Dynamo



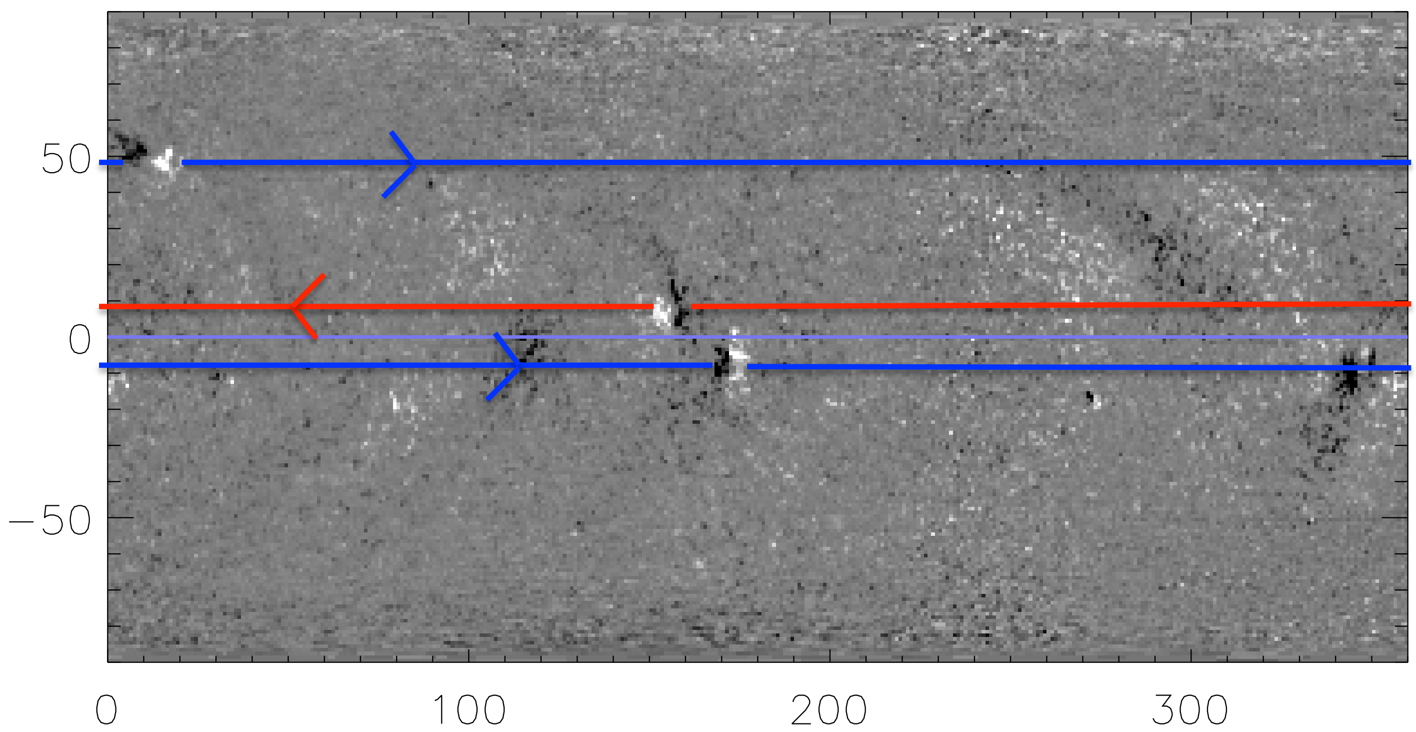
Poloidal to Toroidal
Toroidal to poloidal

Babcock-Leighton key question:
Is polar field is <u>*the*</u> poloidal field of the dynamo

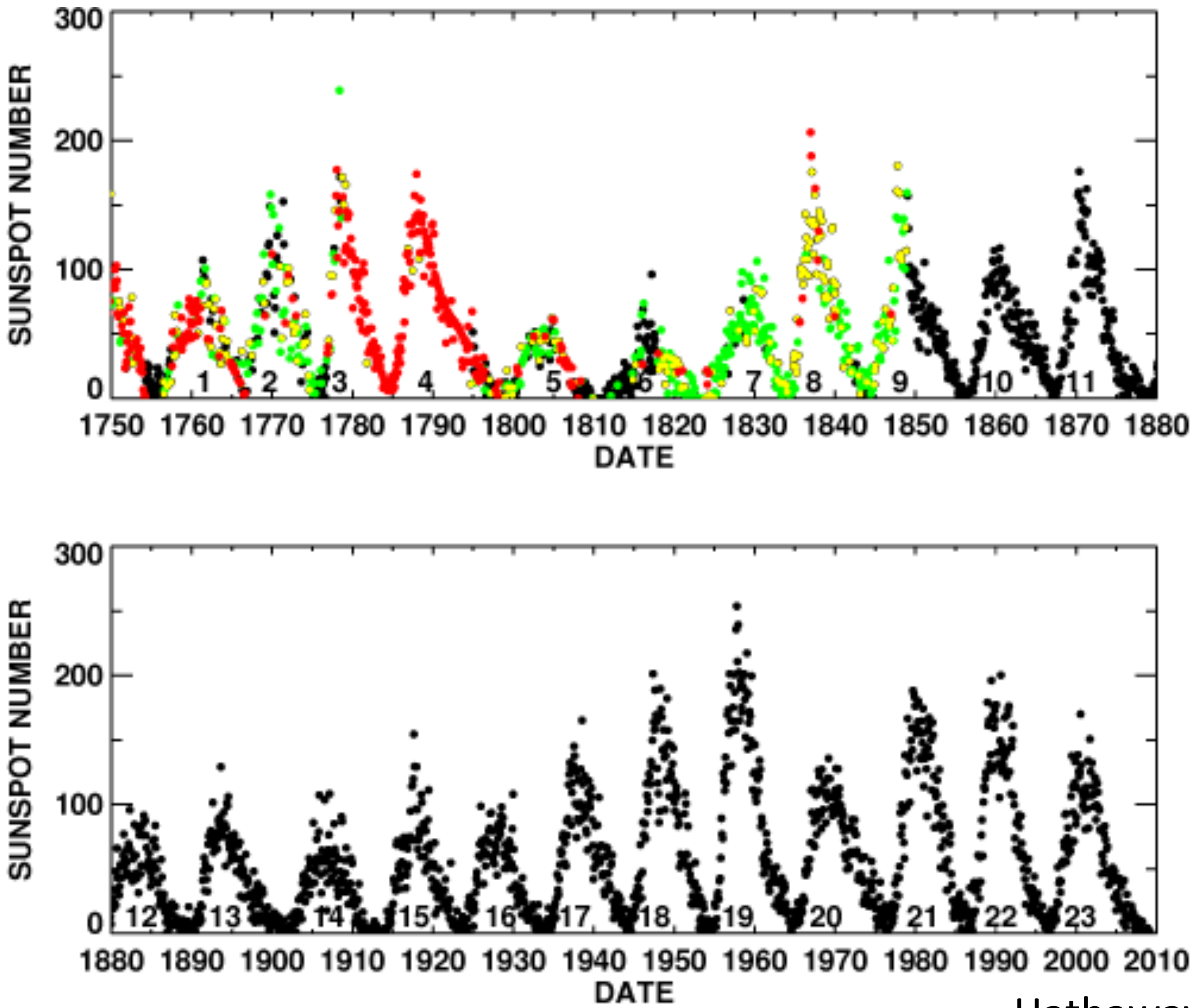
Sunspots (and unsigned flux) are a measure of toroidal flux



Sunspots (and unsigned flux) are a measure of toroidal flux



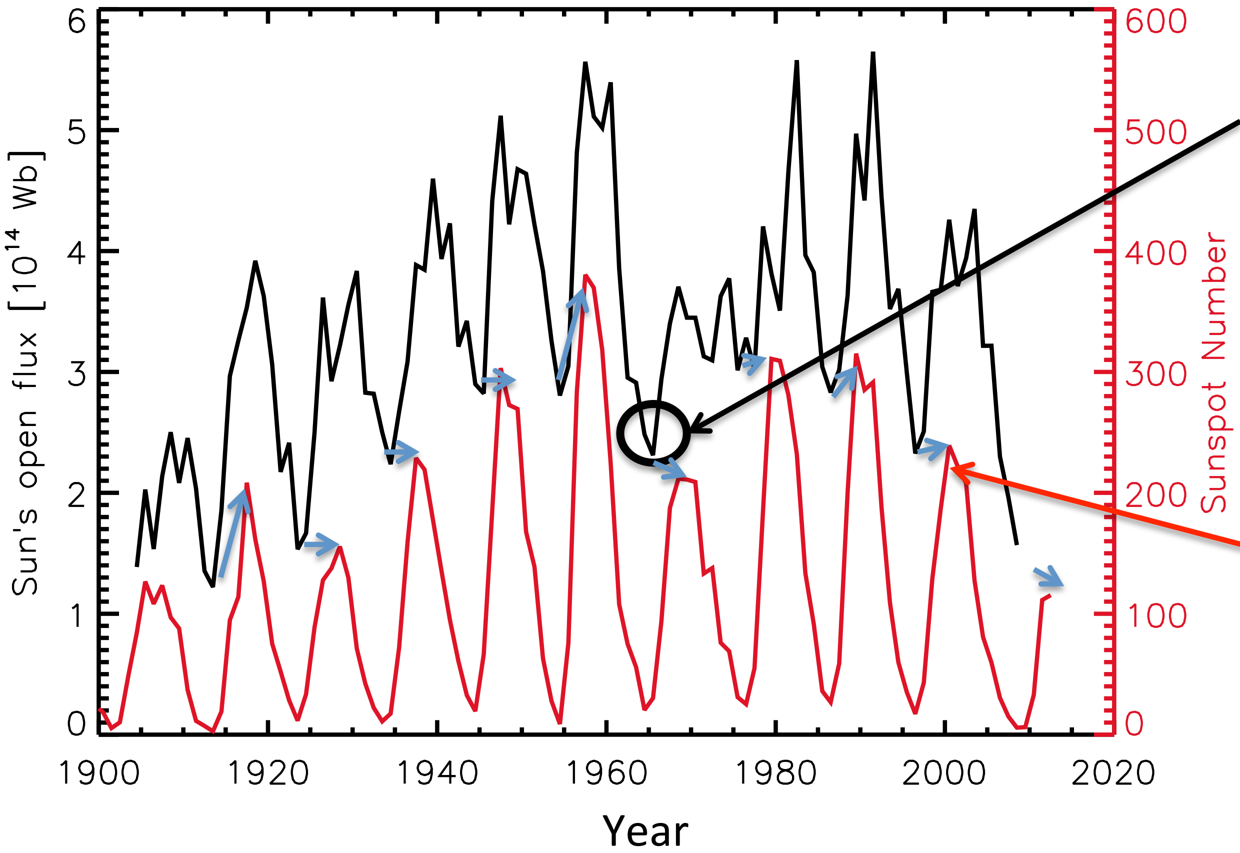
The number of sunspots (a measure of the toroidal field) varies from cycle to cycle.



Hathaway, Living reviews

Babcock-Leighton key feature: Polar field is *the* poloidal field of the dynamo

What do observations say?



At minimum, the Sun's open flux comes form its poles

Sunspot number (measure of toroidal field)

after Wang and Sheeley (2009).

Babcock-Leighton key feature: Polar field is ***the*** poloidal field of the dynamo

The axial dipole moment near minimum is strongly correlated with the strength of the next cycle

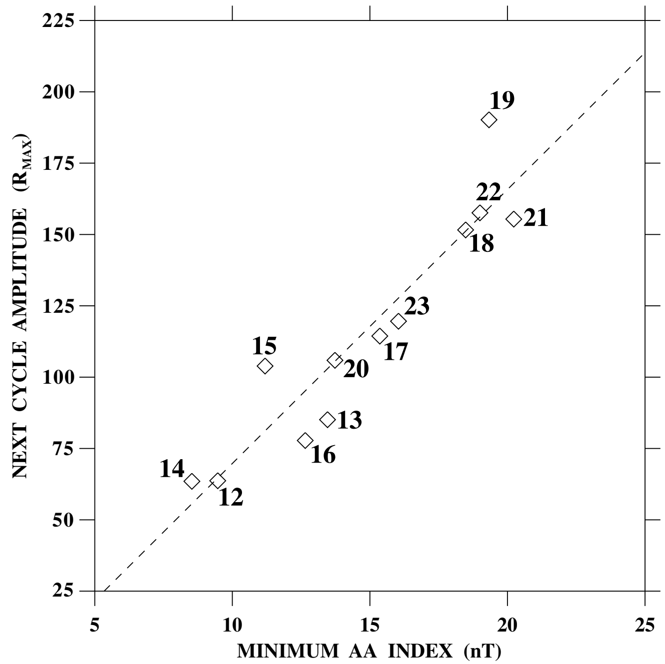


Figure 2. Scatter plot of maximum yearly sunspot number R_{max} vs. lowest yearly value of the *aa* index near the preceding sunspot minimum, for cycles 12–23. Dashed line represents a linear least-squares fit to the data.

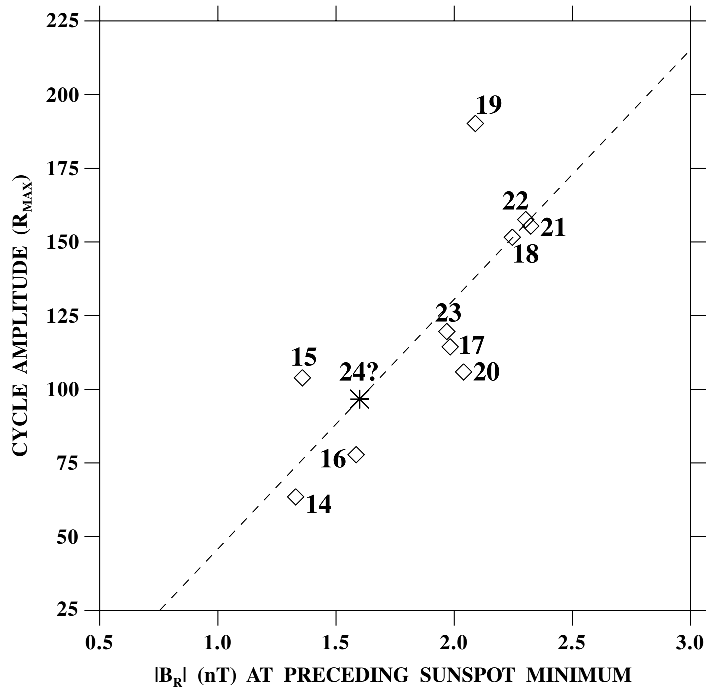


Figure 5. Scatter plot of maximum sunspot number R_{max} vs. radial IMF strength at the preceding sunspot minimum, derived from the *aa* index as described in Rouillard et al. (2007). Dashed line represents a least-squares fit to the annually averaged data.

Wang and Sheeley (2009).

So polar field is at least strongly correlated with *the* poloidal field of the dynamo

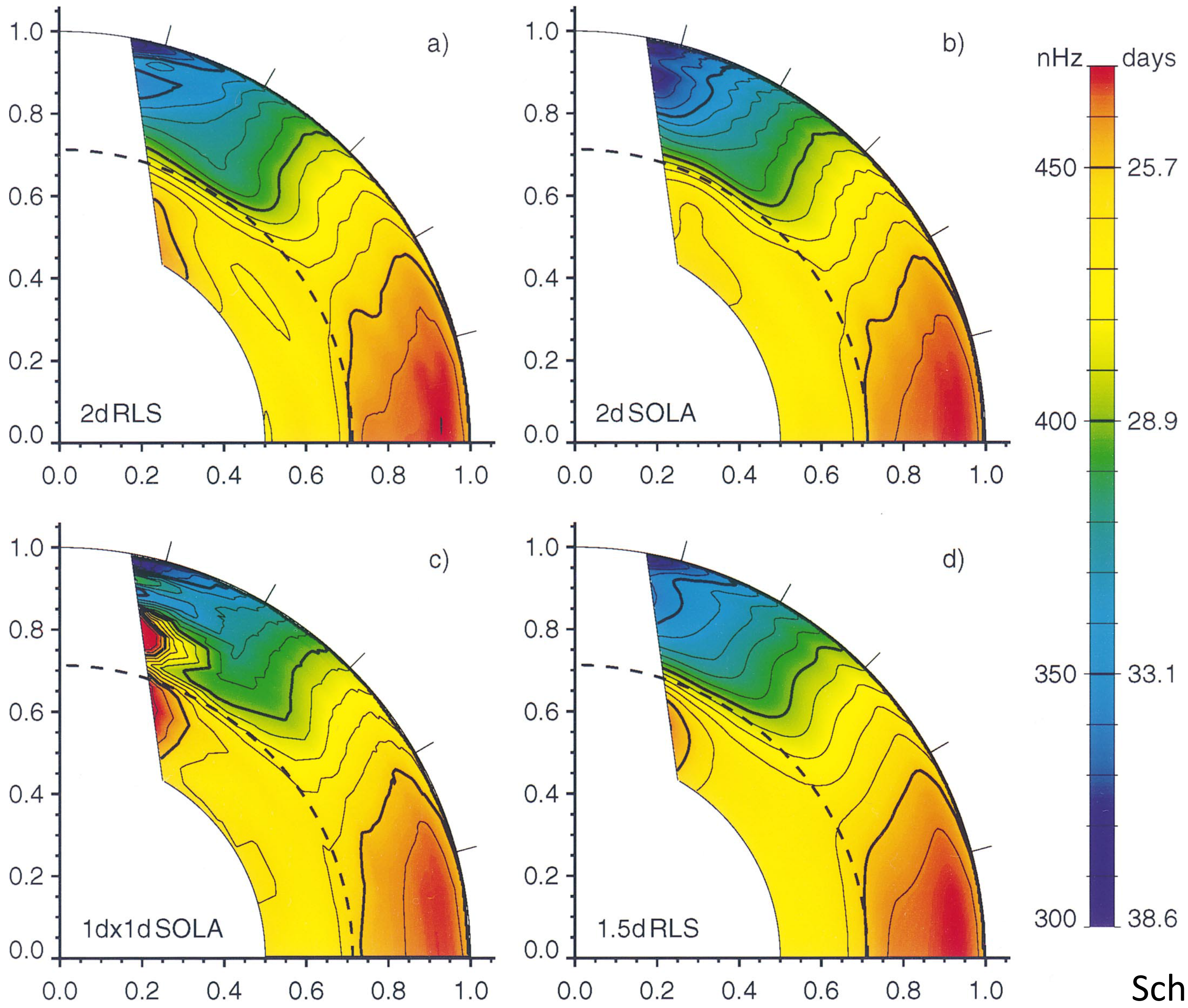
Summary

- The polar fields are highly correlated with the activity level of the next cycle

How much toroidal flux is produced in each hemisphere?

How much toroidal flux is produced by the Babcock-Leighton mechanism?

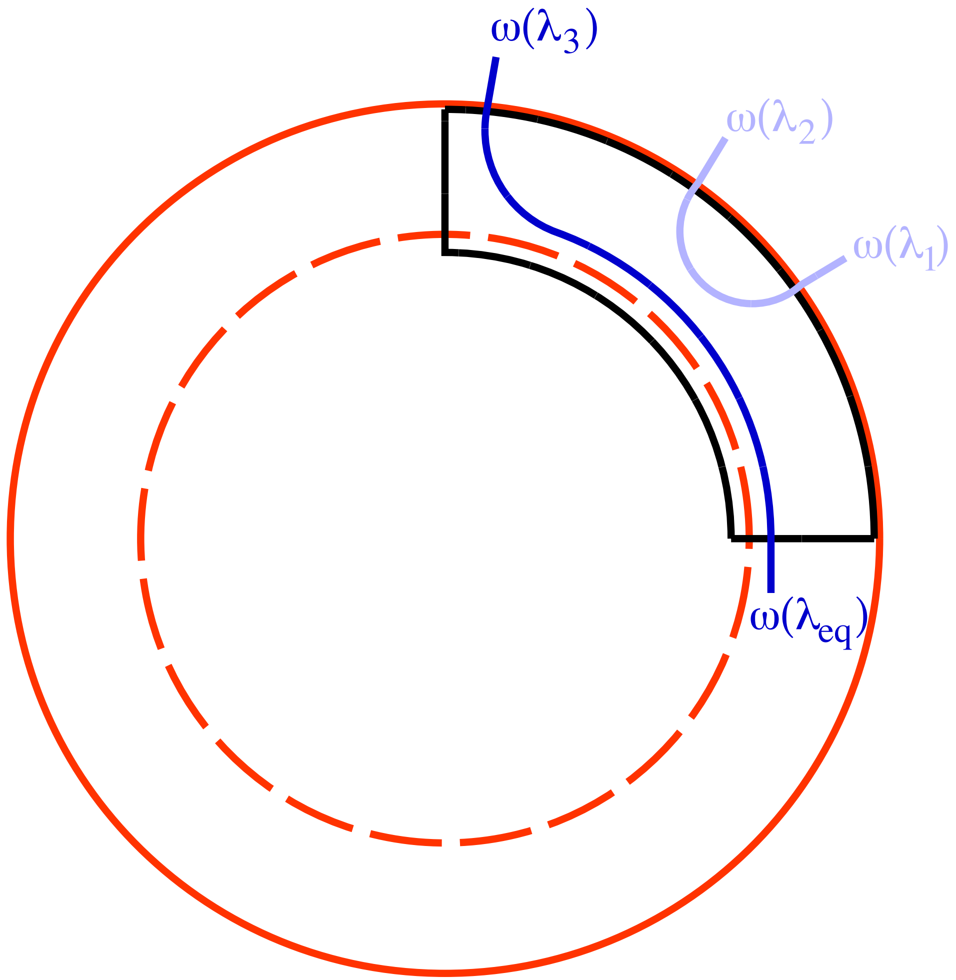
Solar differential rotation



Schou et al 1998

Babcock-Leighton key feature: Polar field is *the* poloidal field of the dynamo

How much toroidal field is generated by differential rotation and the polar fields?

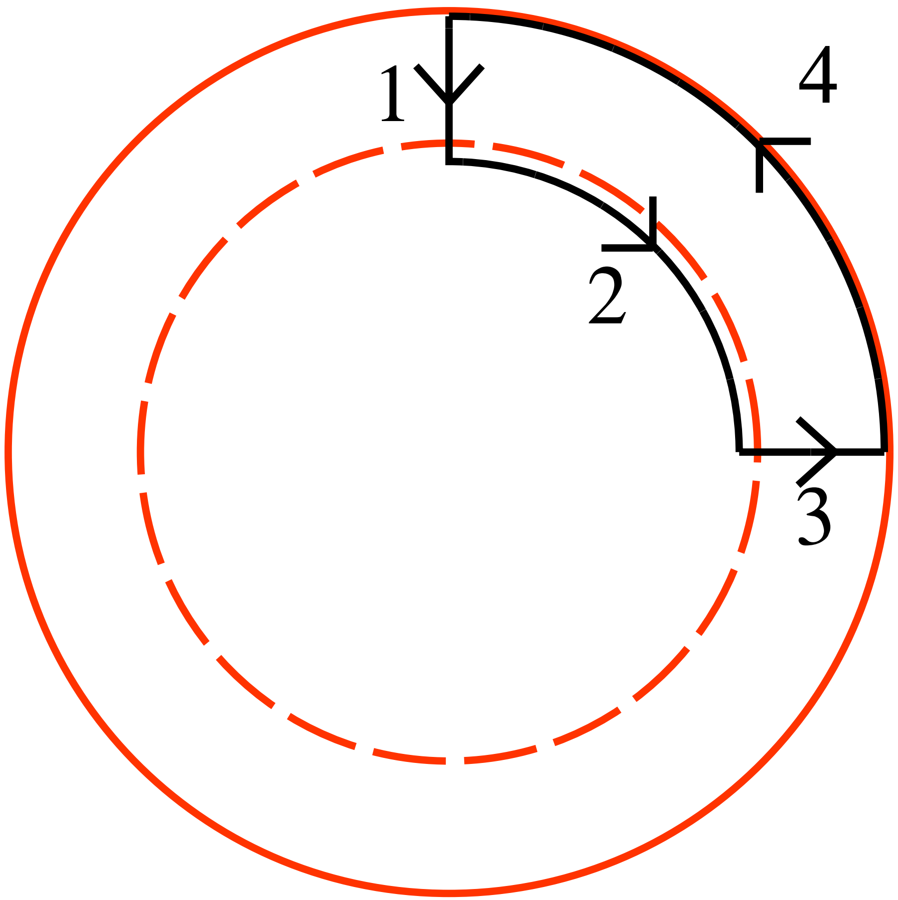


$$\frac{\mathrm{d}\Phi_{\mathrm{tor}}^{\mathrm{N}}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\int_{\Sigma} B_{\phi}\mathrm{d}S\right) = \int_{\delta\Sigma}(\mathbf{U}\times\mathbf{B} + \langle\mathbf{u}\times\mathbf{b}\rangle - \eta\nabla\times\mathbf{B})\cdot\mathrm{d}\mathbf{l}$$

$$\frac{\partial}{\partial t}\left(\int_{\Sigma} B_{\phi}\mathrm{d}\Sigma\right) = \int_{90}^{0}(U_{\phi}B_{r})\,|_{r=R\odot}\, R_{\odot}\mathrm{d}\theta + D_{eq}^{ax}$$

Cameron & Schüssler (in prep)

How much toroidal field is generated by differential rotation and the polar fields?



Work in reference frame rotating at the Rate of the equator.

Induction Equation,

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} + \langle \mathbf{u} \times \mathbf{b} \rangle - \eta \nabla \times \mathbf{B})$$

Stokes Theorem

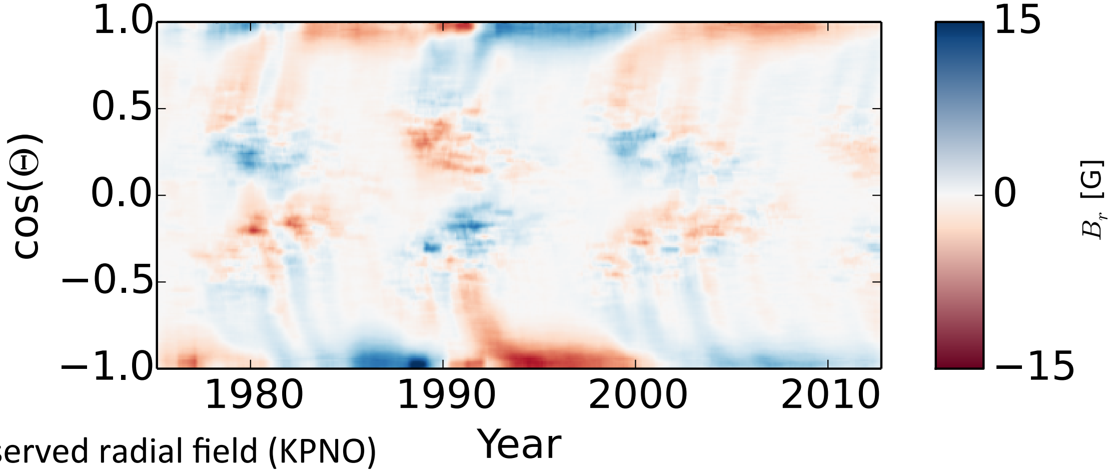
$$\frac{\mathrm{d}\Phi^{\mathrm{N}}_{\mathrm{tor}}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\int_{\Sigma} B_{\phi}\mathrm{d}S\right) = \int_{\delta\Sigma} (\mathbf{U} \times \mathbf{B} + \langle \mathbf{u} \times \mathbf{b} \rangle - \eta \nabla \times \mathbf{B}) \cdot \mathrm{d}\mathbf{l}$$

1: $U_\theta = U_\phi = 0$, $B_\theta = B_\phi = 0$ =>Integrand 0
2: $B_\theta = B_\phi = B_r = 0$ =>Integrand 0
3: $U_\theta = U_\phi = 0$ =>Integrand 0
4: $B_\theta = B_\phi = 0$ =>Integrand $= U_\phi B_r$

$$\int_{\delta\Sigma} (\mathrm{uxb}) \cdot \mathrm{d}(\delta\boldsymbol{\Sigma}) = \ , D^{ax}_{eq}$$

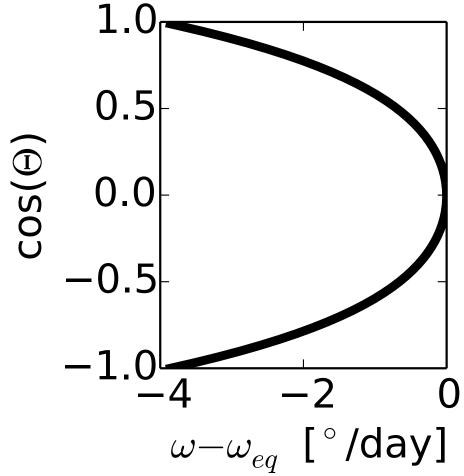
$$\frac{\partial}{\partial t}\left(\int_{\Sigma} B_{\phi}\mathrm{d}\Sigma\right) = \int_{90}^{0} (U_{\phi}B_{r}) \mid_{r=R\odot} R_{\odot}\mathrm{d}\theta + D^{ax}_{eq}$$

The integrand

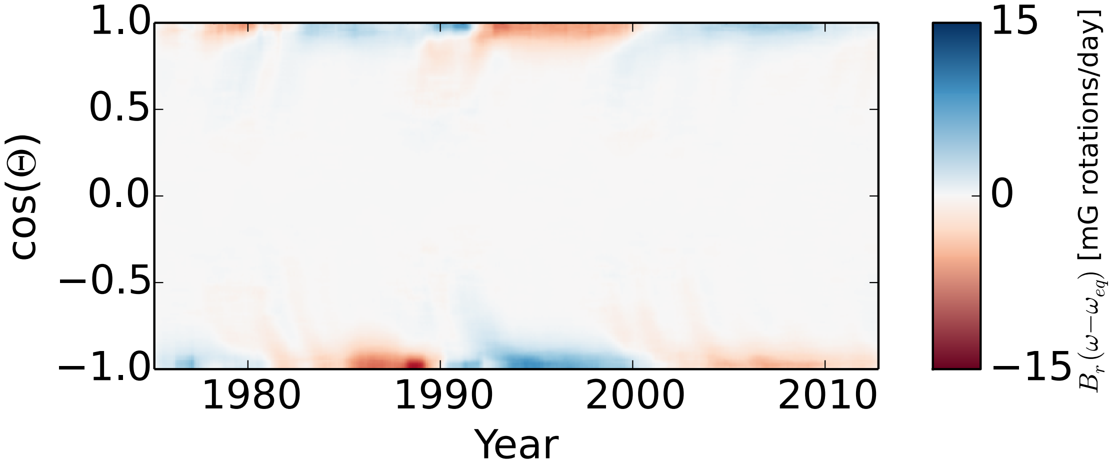


Observed radial field (KPNO)

X



Observed latitudinal differential rotation

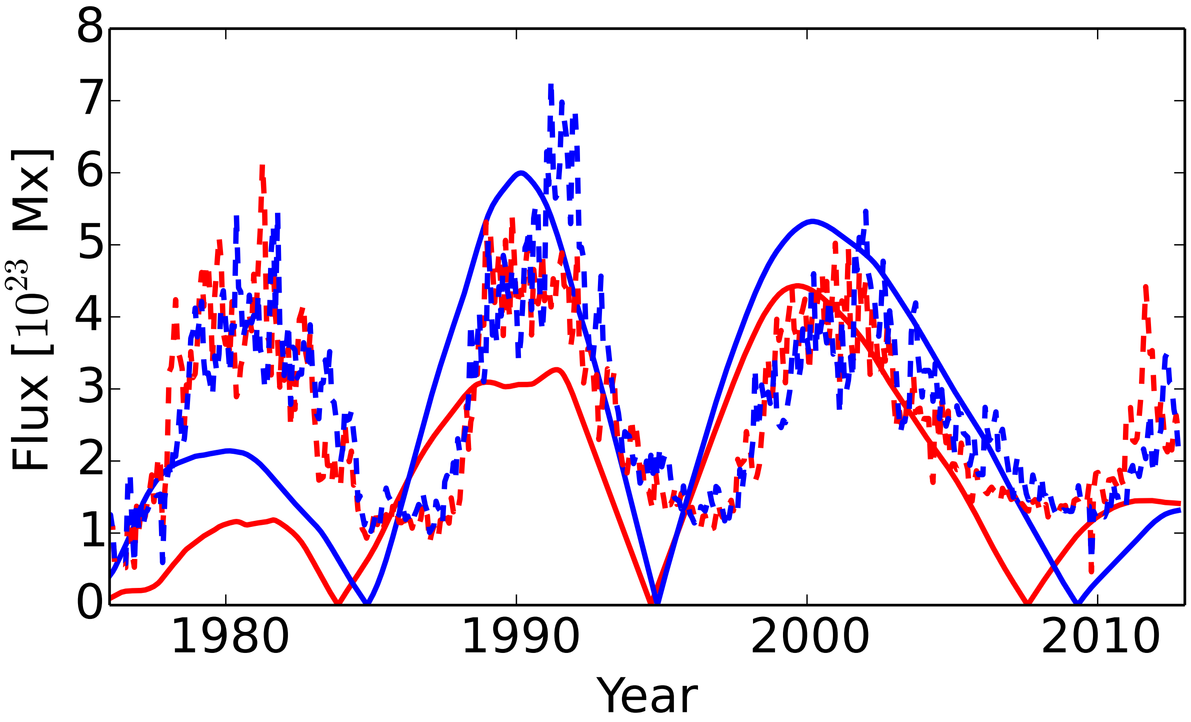


Time derivative
of toroidal flux

Cameron et al (in prep)

$$\frac{\partial}{\partial t}\left(\int_s B_\phi ds\right) = \int_0^{90} \left(U_\phi B_r\right)|_{r=R\odot}\, d\theta + D_{eq}^{ax}$$

$$D_{eq}^{ax} = 0,$$



Toroidal flux northern hemisphere

Toroidal flux southern hemisphere

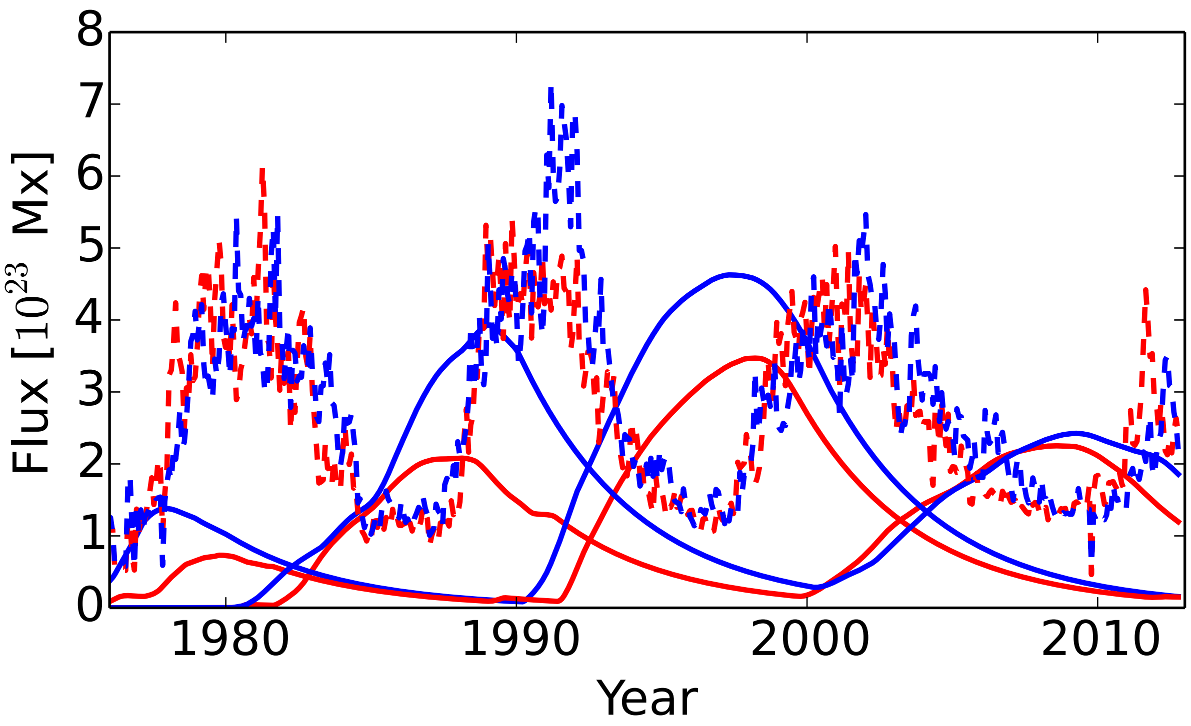
Surface unsigned radial flux northern hemisphere

Surface unsigned radial flux southern hemisphere

Based on KPNO synoptic magnetograms

Cameron & Schüssler (in prep)

$$\frac{\partial}{\partial t}\left(\int_s B_\phi ds\right) = \int_0^{90} \left(U_\phi B_r\right)|_{r=R\odot}\, d\theta + D_{eq}^{ax}$$



, D_{eq}^{ax} Exponential decay
E-folding time 4 yr,

Toroidal flux northern hemisphere

Toroidal flux southern hemisphere

Surface radial flux northern hemisphere

Surface radial flux southern hemisphere

Recall sunspots (& their flux) are a measure of the toroidal field

Based on KPNO synoptic magnetograms

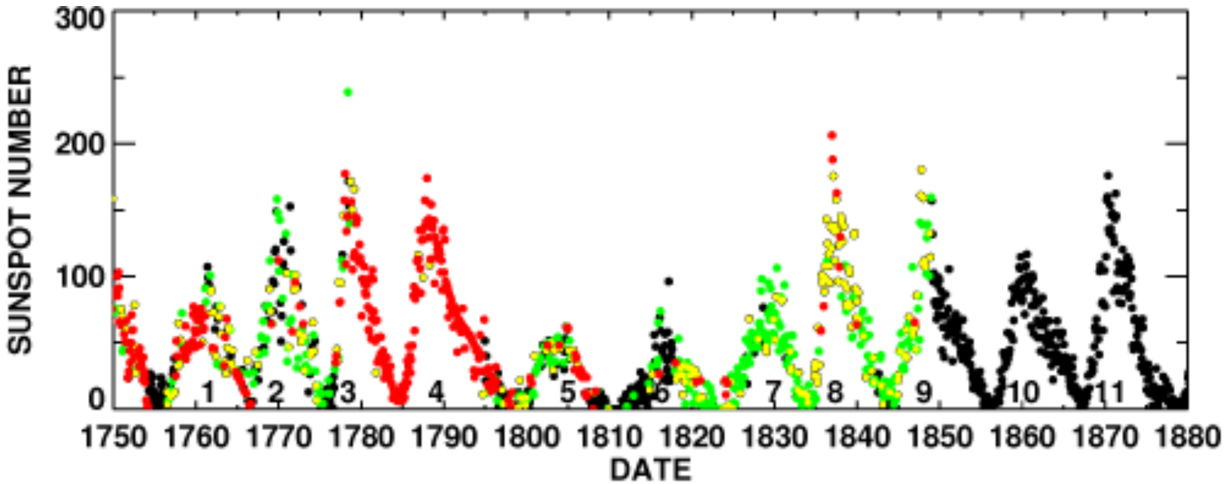
Summary

- The polar fields are highly correlated with the activity level of the next cycle

- All of the net toroidal flux in each hemisphere is produced by the winding up of the polar fields.
- This produces a net toroidal field of about 5×10^{23} Mx/Hem in a cycle
- This is about equal to the unsigned radial flux from the active regions
- Most sunspots groups throughout cycle obey Hale's Law (which suggests toroidal field involved in the global dynamo is mainly of one sign).

- Both these points provide independent strong support for the Babcock-Leighton dynamo.

What causes the modulation of solar activitiy from cycle to cycle?



Hathaway, Living reviews

The modulation occurs before the magnetic field reaches the poles.

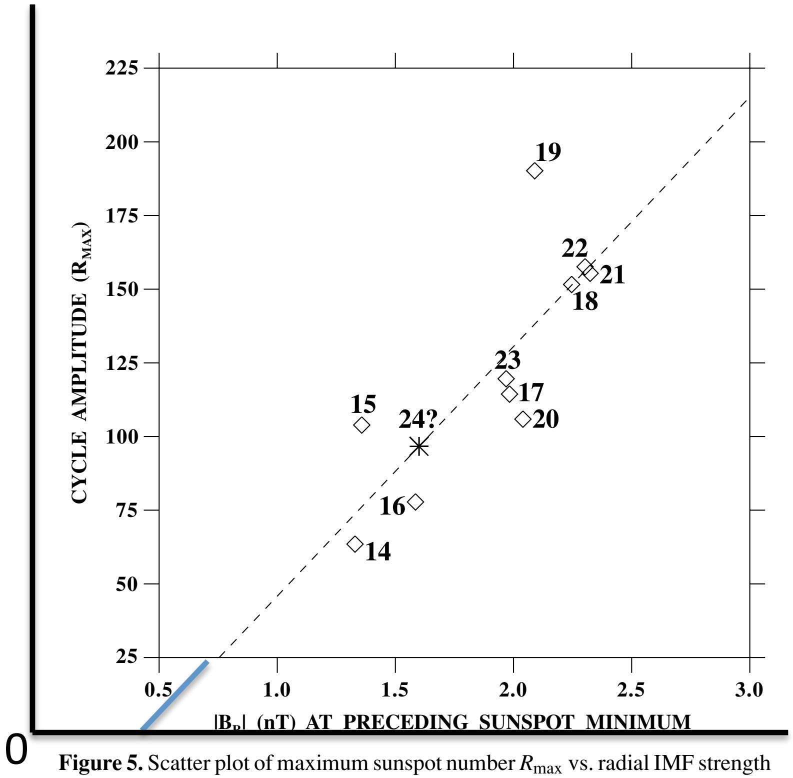
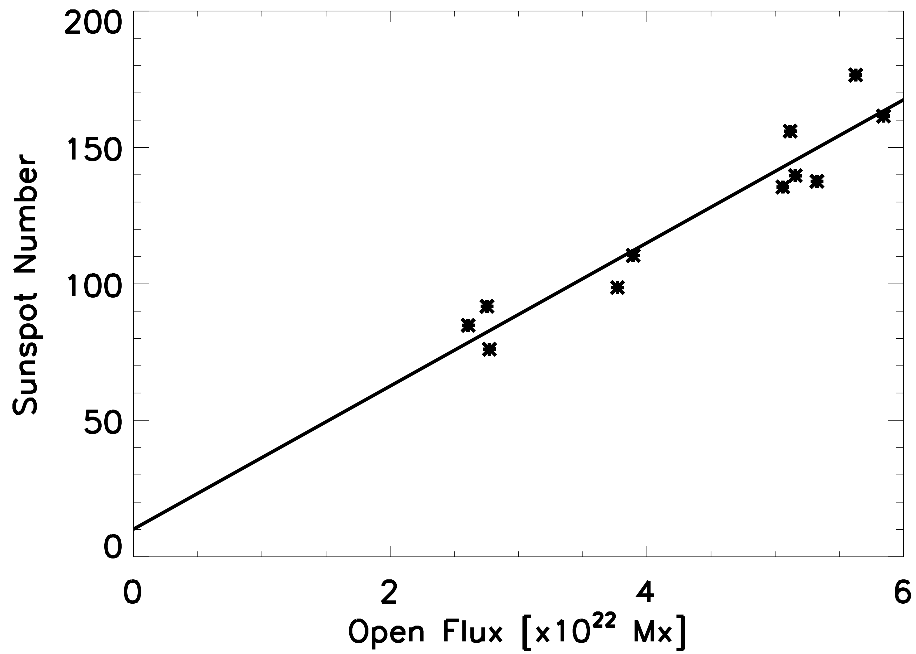


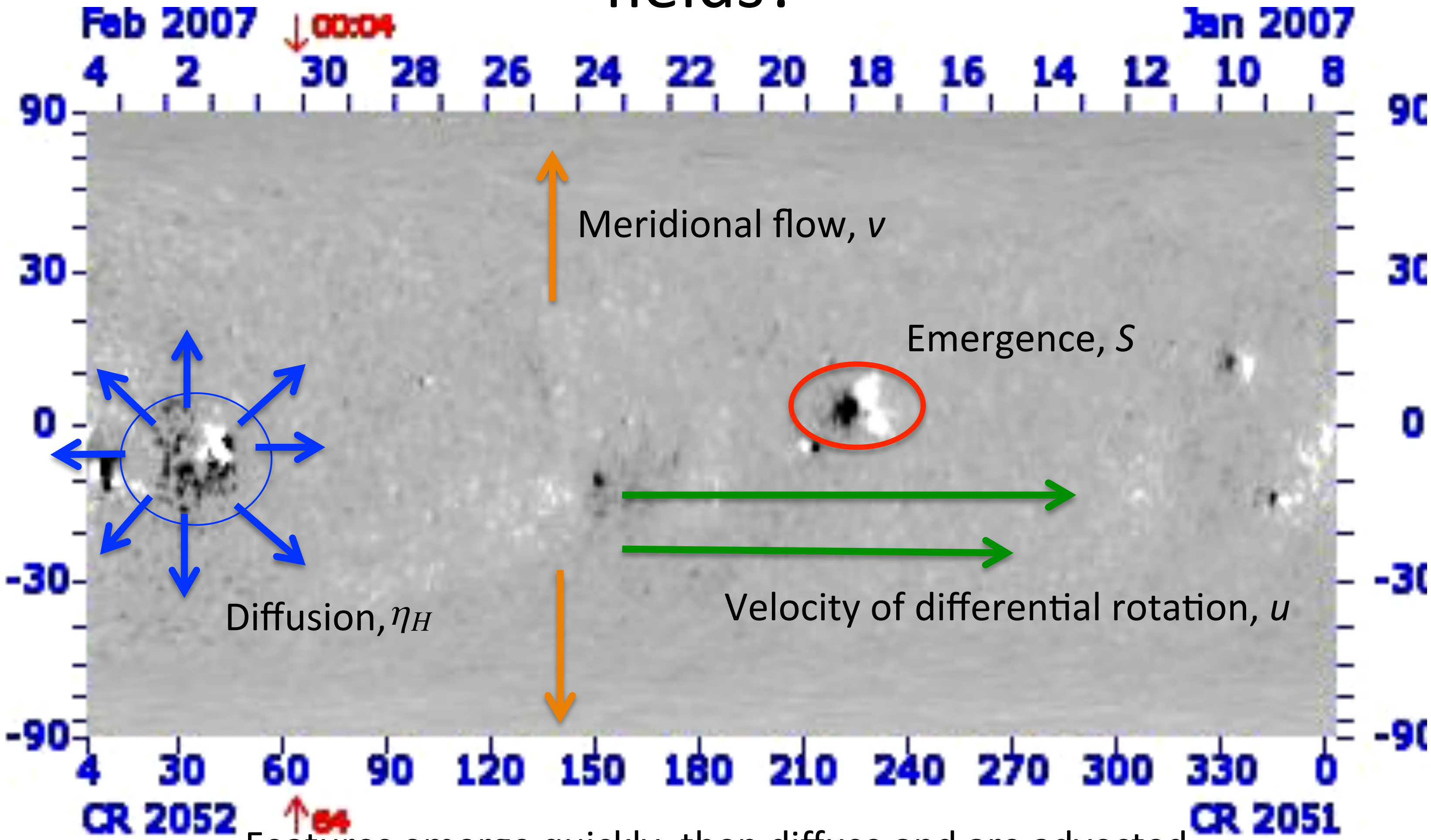
Figure 5. Scatter plot of maximum sunspot number R_{max} vs. radial IMF strength at the preceding sunspot minimum, derived from the *aa* index as described in Rouillard et al. (2007). Dashed line represents a least-squares fit to the annually averaged data.

Wang and Sheeley (2009).



Can also see same effect in pairs of cycles.

What determines the strength of the polar fields?

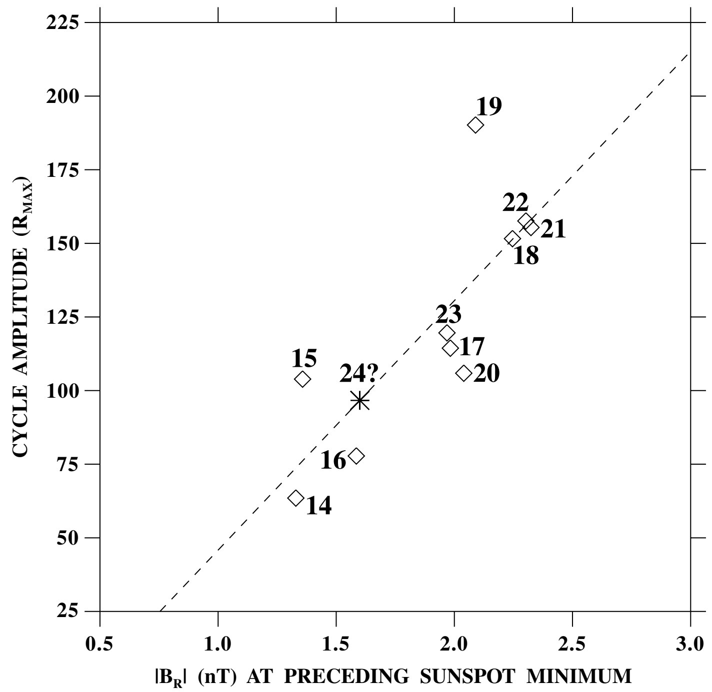


Features emerge quickly, then diffuse and are advected.

$$\frac{\partial B_r}{\partial t} = - - \frac{1}{R_\odot \sin\theta}\frac{\partial u B_r}{\partial \phi} - \frac{1}{R_\odot \sin\theta}\frac{\partial}{\partial\theta}\left[v B_r \sin\theta\right]$$
$$+ \eta_H \left[\frac{1}{R_\odot^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial B_r}{\partial\theta}\right) + \frac{1}{R_\odot^2 \sin^2\theta}\frac{\partial^2 B_r}{\partial\phi^2}\right]$$
$$+ S(\theta, \phi, t)$$

Leighton 1964, Schatten 1972
DeVore, Sheeley & Boris 1984
Wang, Nash & Sheeley 1989
etc.

Comparison of dipolar field
(observations vs model)



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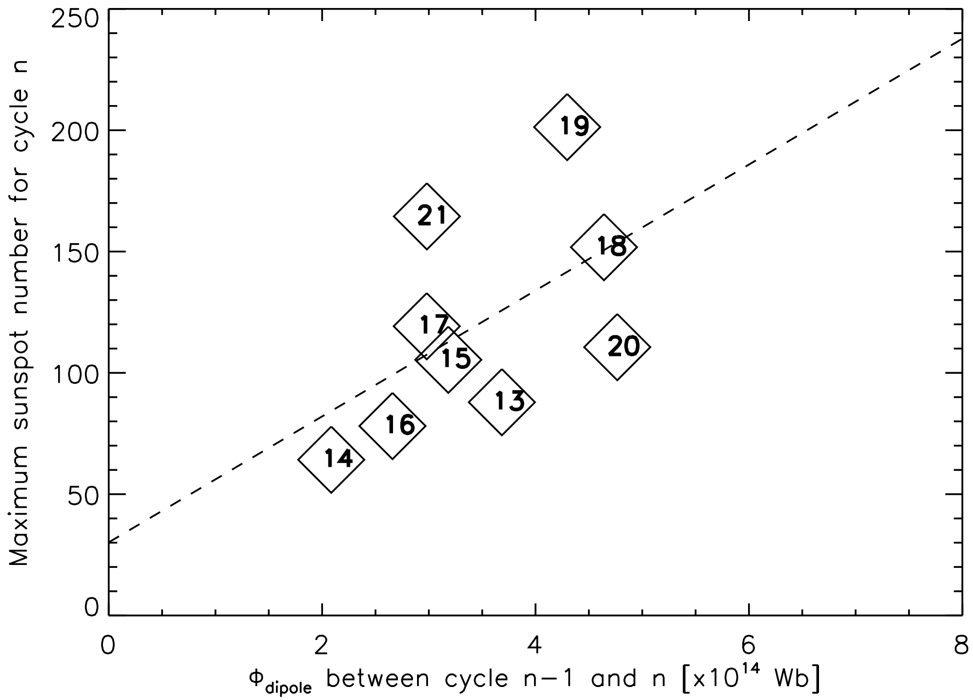
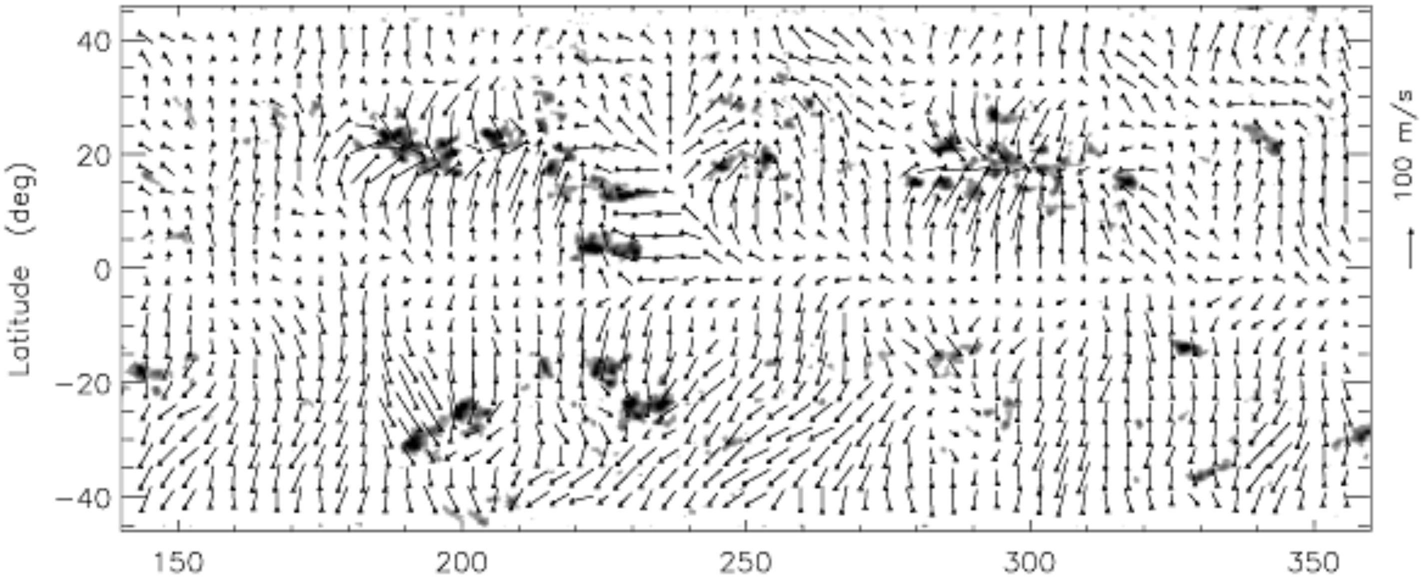
Observations
(Wang and Sheeley 2009)



Results from SFT model without inflows
(Cameron and Schuessler 2012)

Not included above: flow variations?

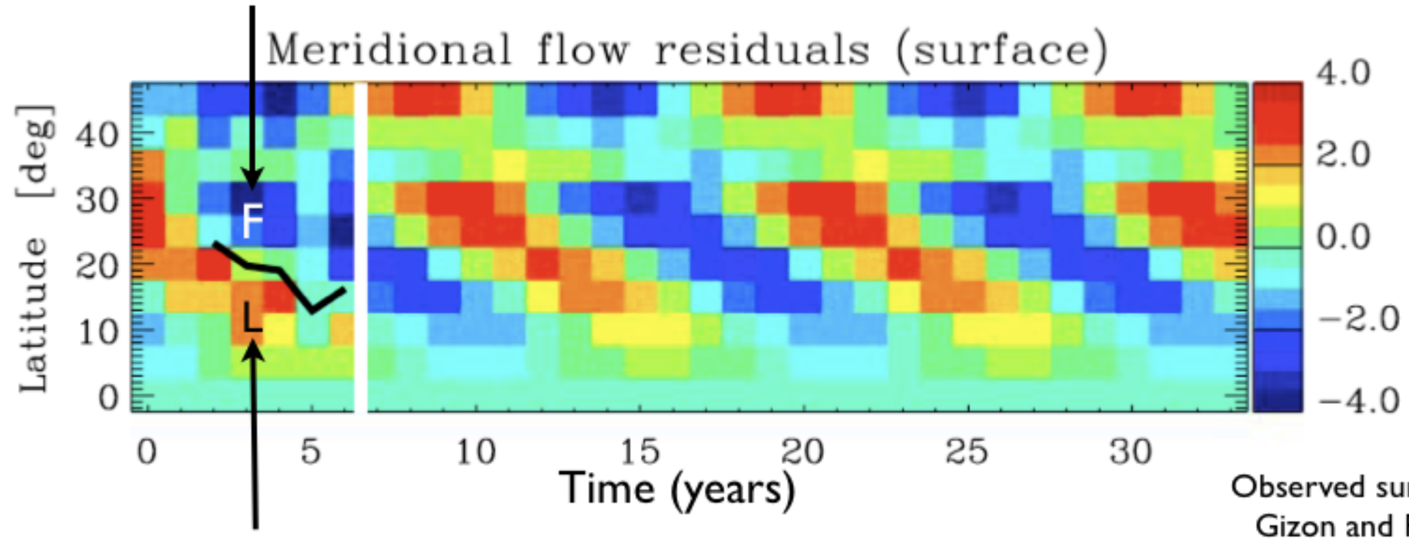


Active regions drive flows

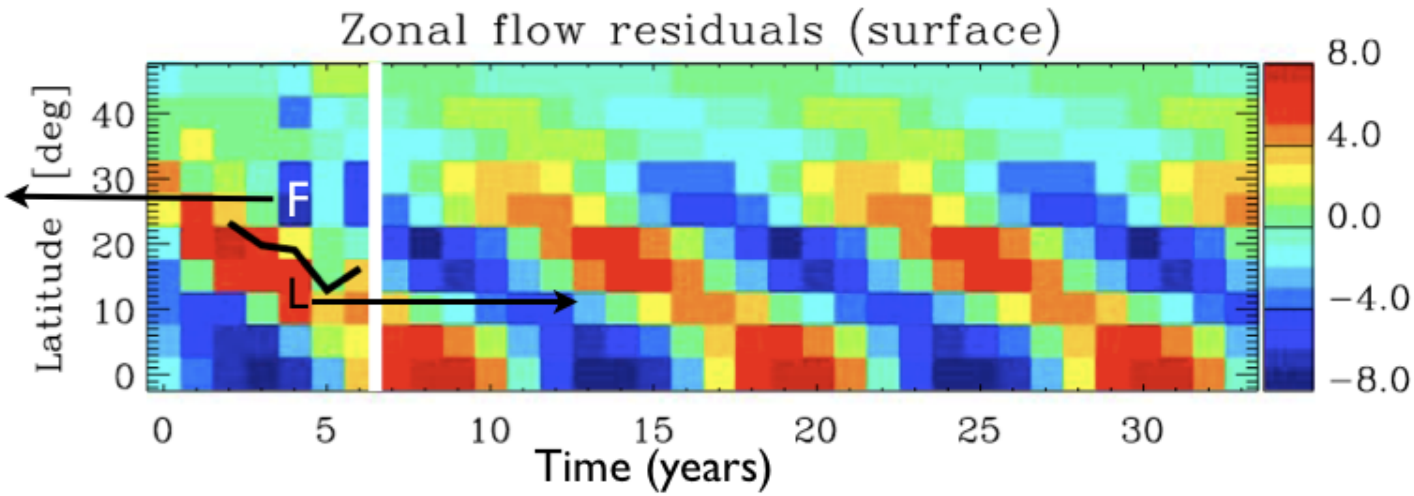
Gizon et al 2001

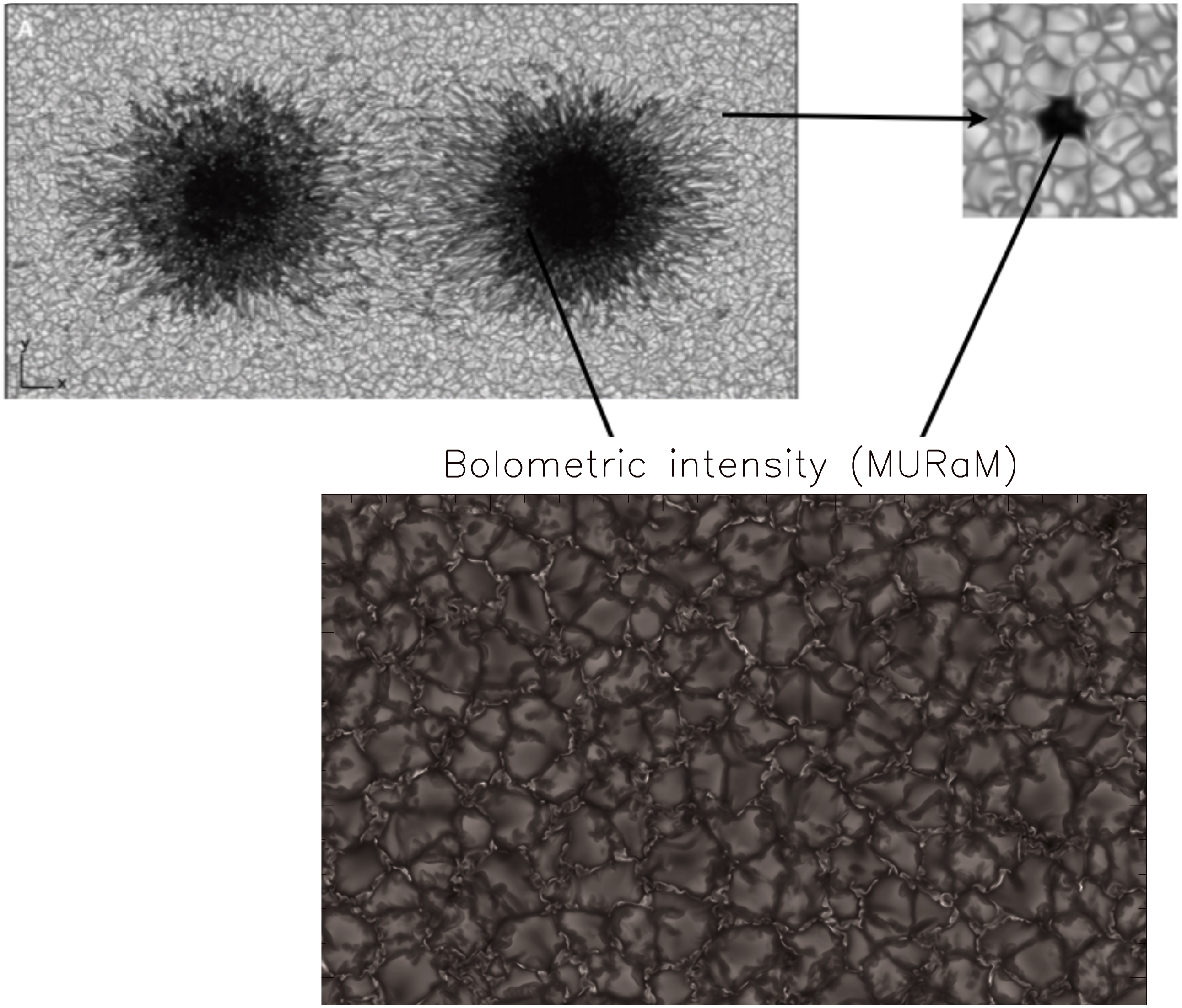
But we know the flow is time dependent

This *should* be included in the model.

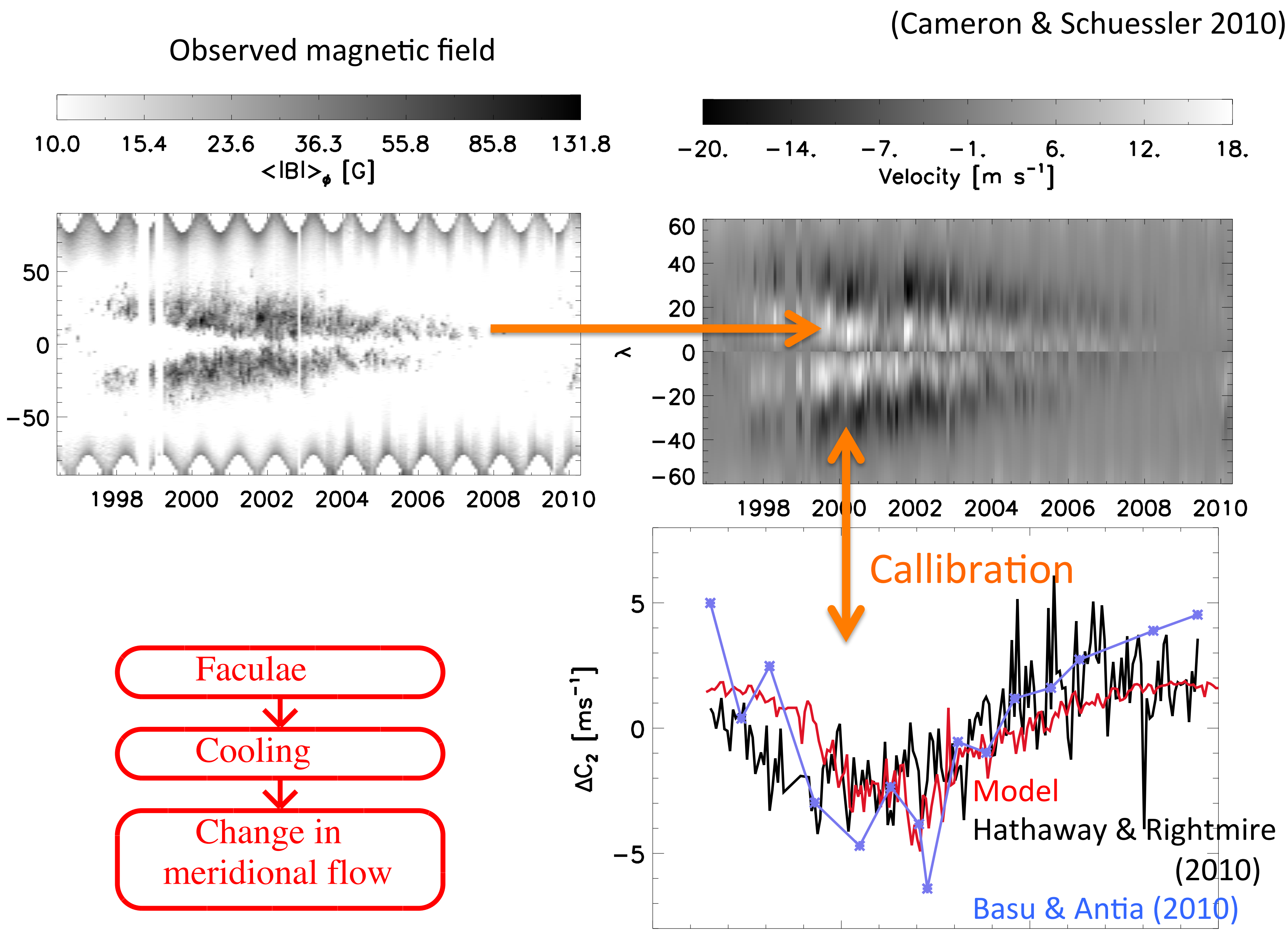


Observed surface flows from Gizon and Rempel (2008)





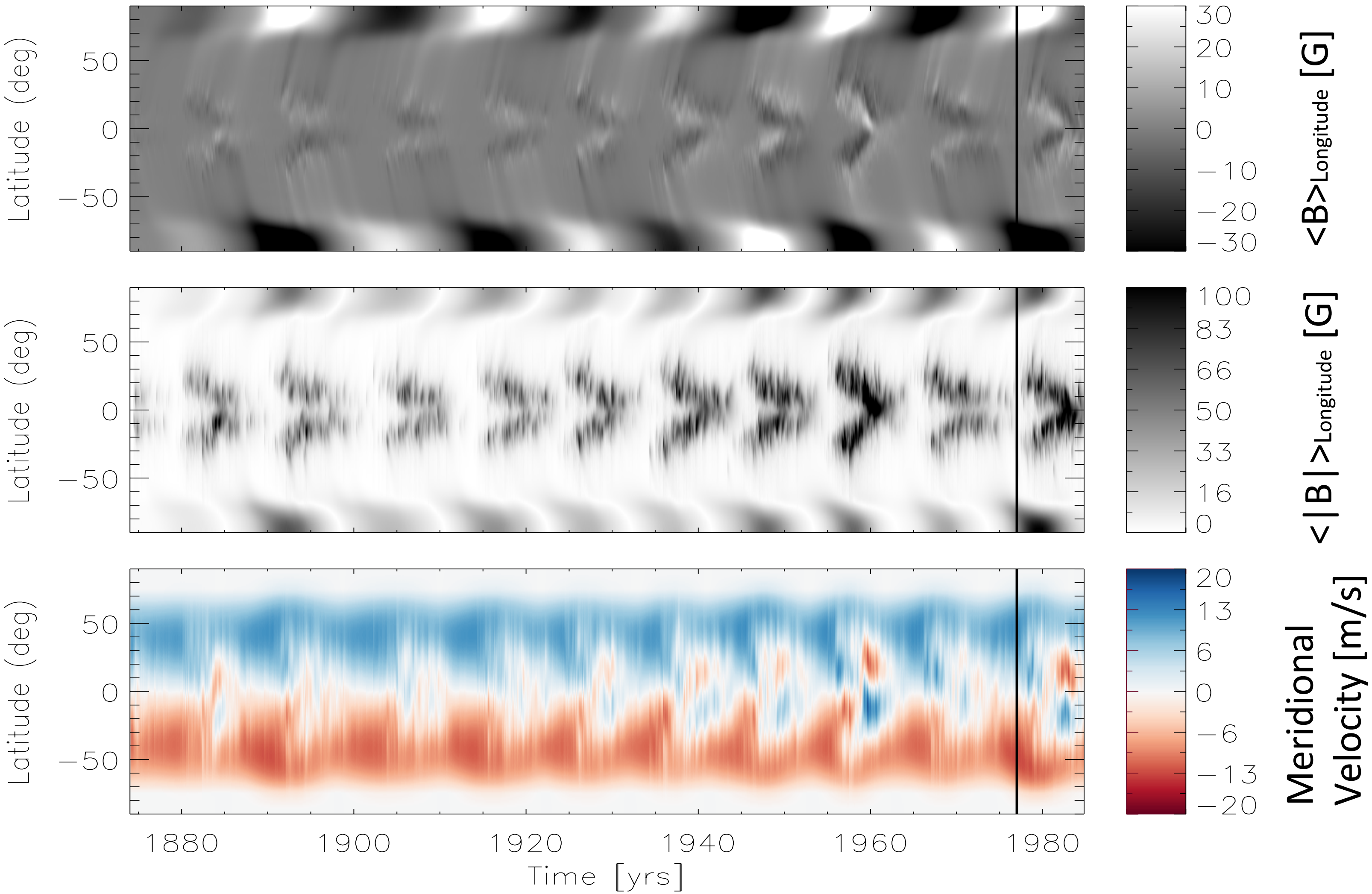
activity related radiance changes


(Cameron & Schuessler 2010)
Observed magnetic field
10.0 15.4 23.6 36.3 55.8 85.8 131.8
<|B|>$_\phi$ [G]
50
0
−50
1998 2000 2002 2004 2006 2008 2010
−20. −14. −7. −1. 6. 12. 18.
Velocity [m s^{-1}]
60
40
20
λ
0
−20
−40
−60
1998 2000 2002 2004 2006 2008 2010
Callibration
5
0
−5
ΔC$_2$ [ms^{-1}]
Model
Hathaway & Rightmire (2010)
Basu & Antia (2010)
1995 2000 2005 2010
Faculae
Cooling
Change in meridional flow

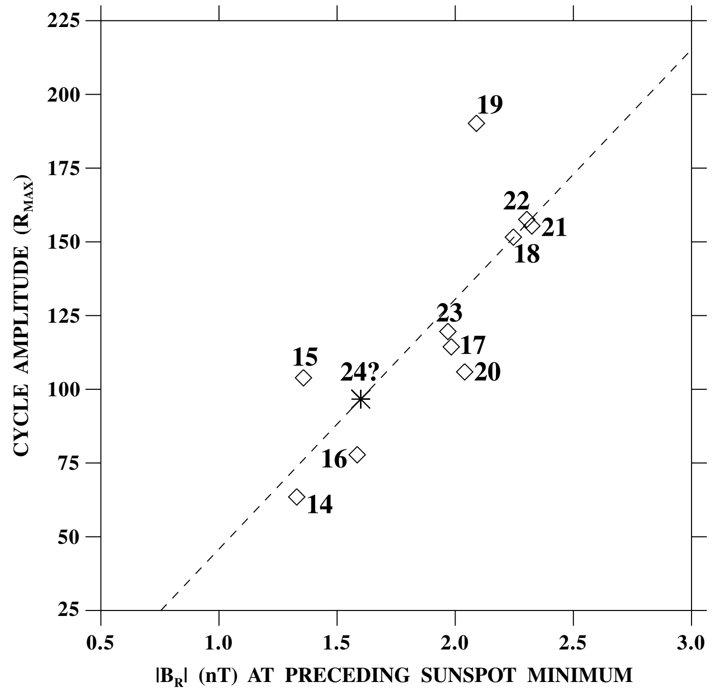
Spruit (2003)

Non linear SFT model, including Waldmeier effect and the inflows into the active regions

Cameron and Schüssler (2012)



Comparison of dipolar field
(observations vs simulations with inflows & Waldmeier effect)



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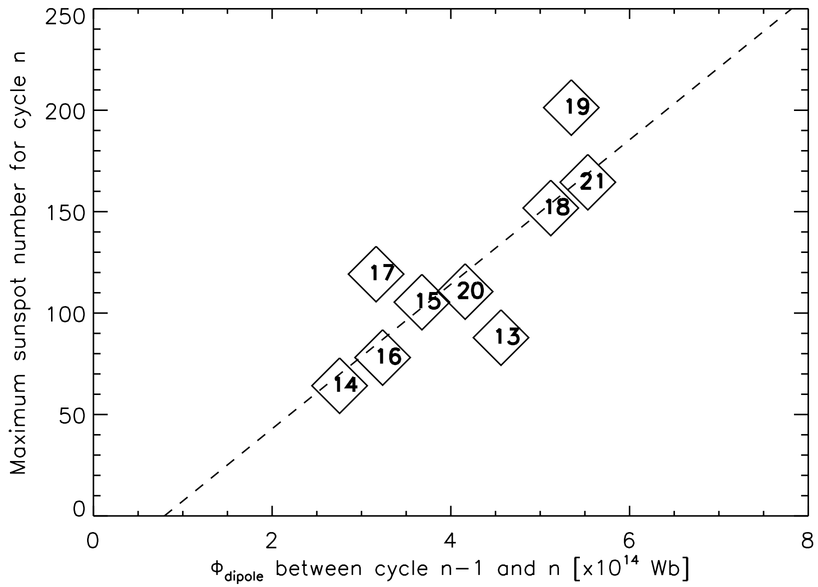
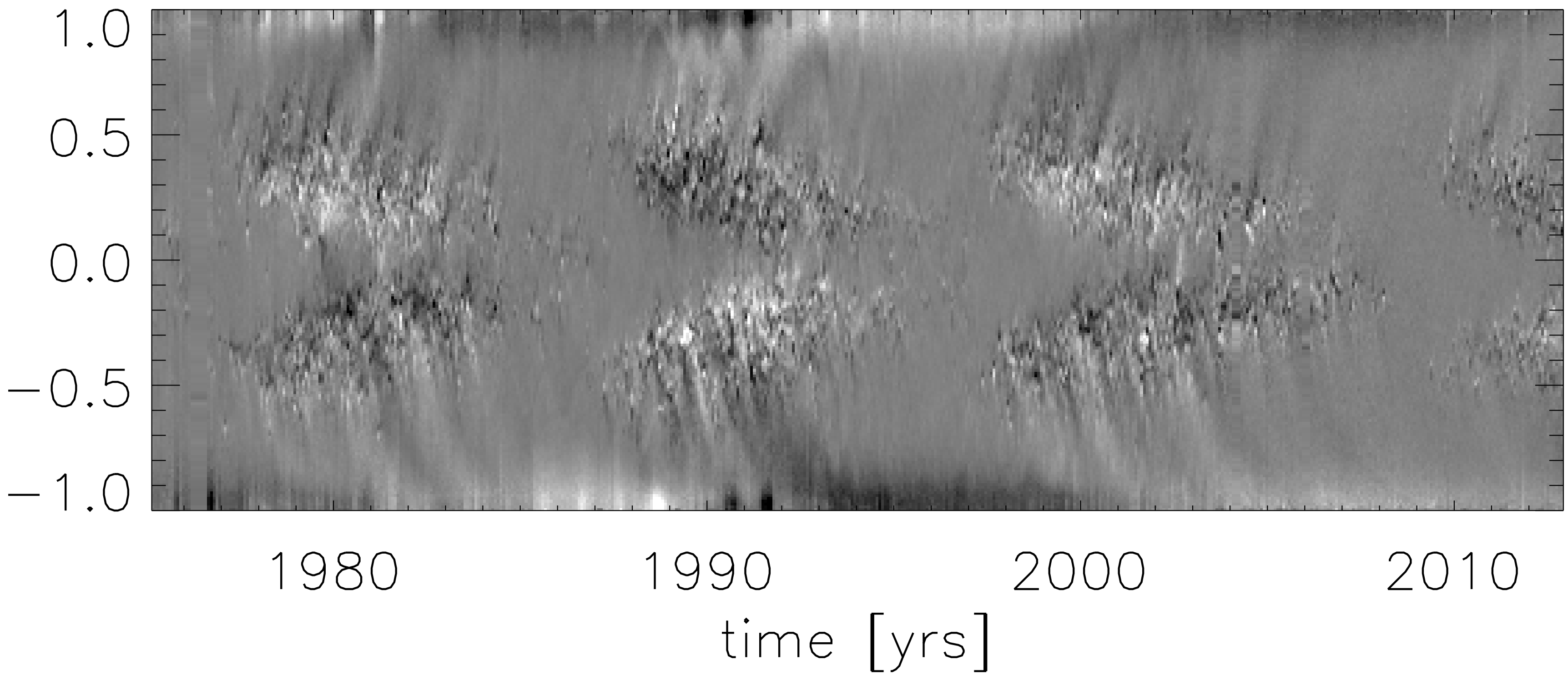
Observations
(Wang and Sheeley 2009)



Results from SFT model including Waldmeier effect and inflows
(Cameron & Schüssler 2012)

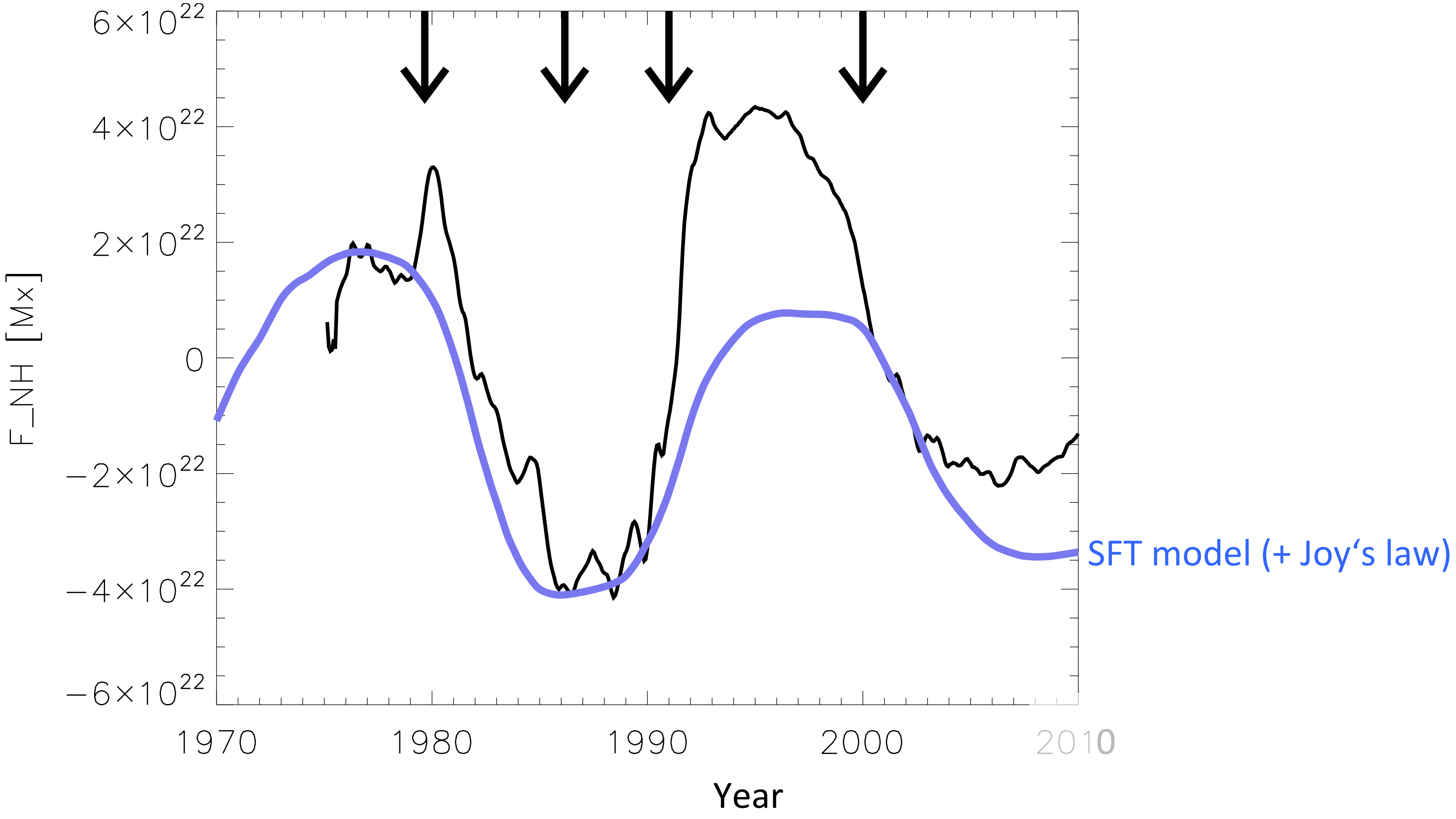
We have regular synoptic magnetograms since cycle 21, and so can find what else the model is missing.

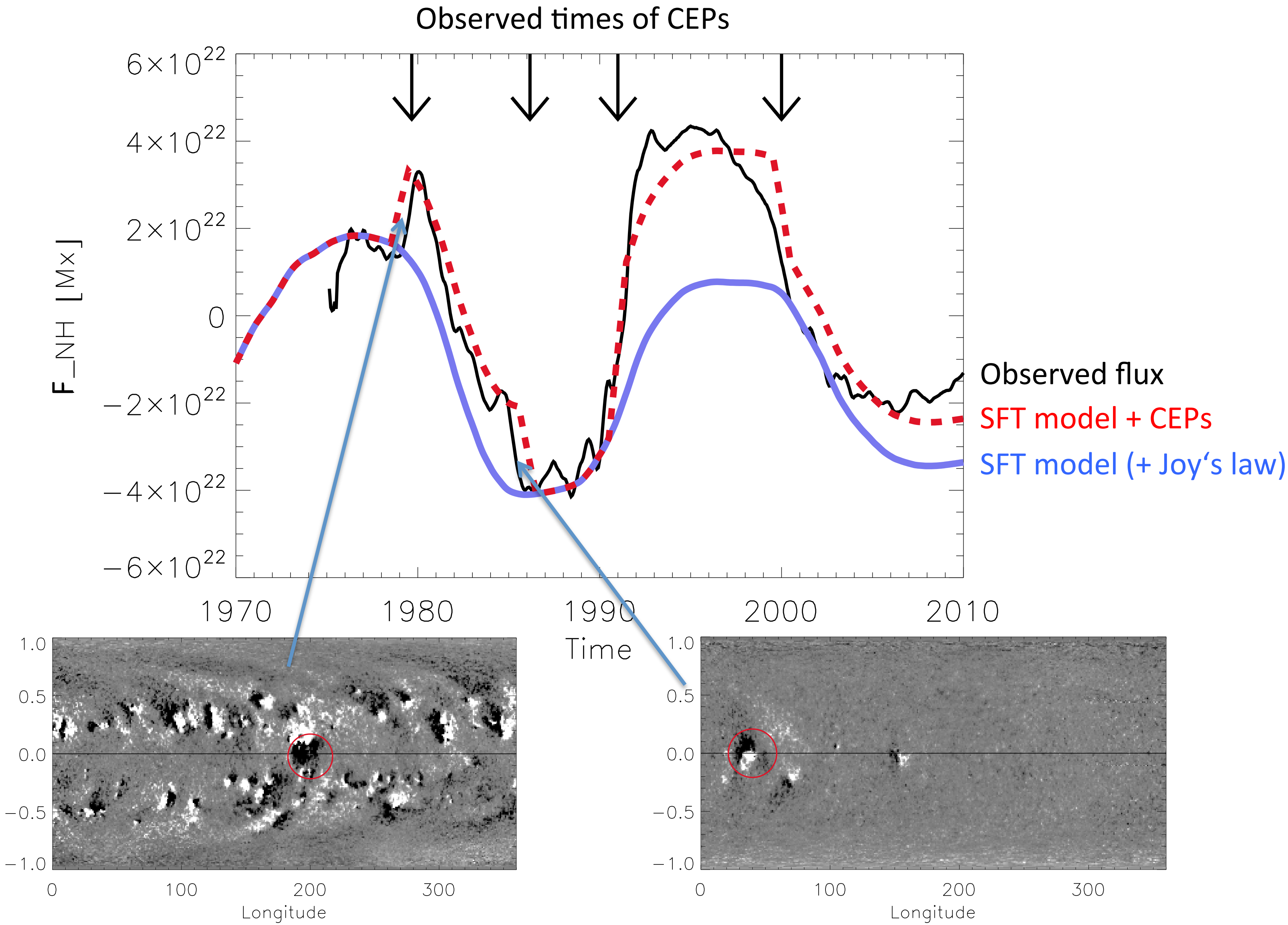
Observations of the radial magnetic field from cycles 21 onwards



What determines the polar fields (or e.g. axial dipole moment)?

Flux in the northern hemisphere: observations & SFT model



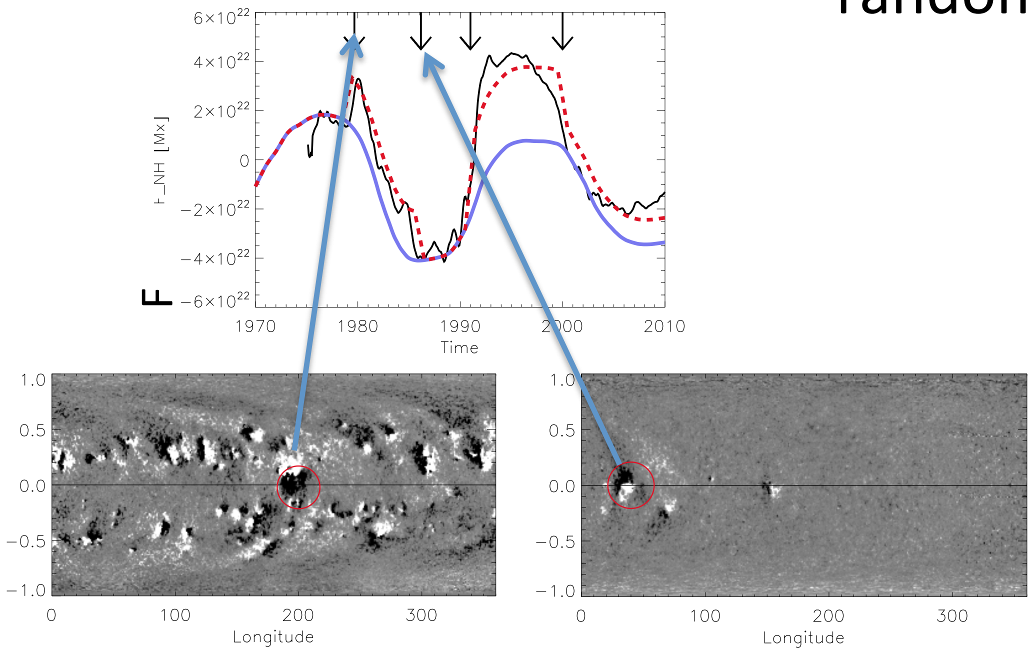


Cameron et al (submitted)

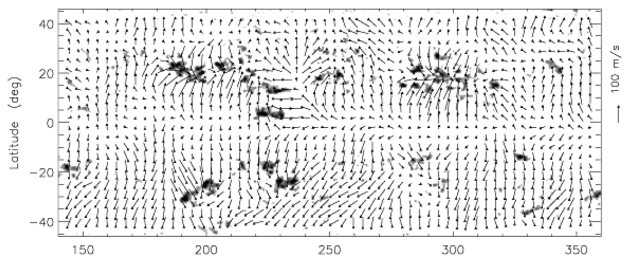
Emergence of highly tilted large groups near or across the equator is a large source of randomness.

Summary of activity modulation.

- Cross Equatorial Plumes are a substantial source of randomness



- Inflows are a substantial nonlinearity



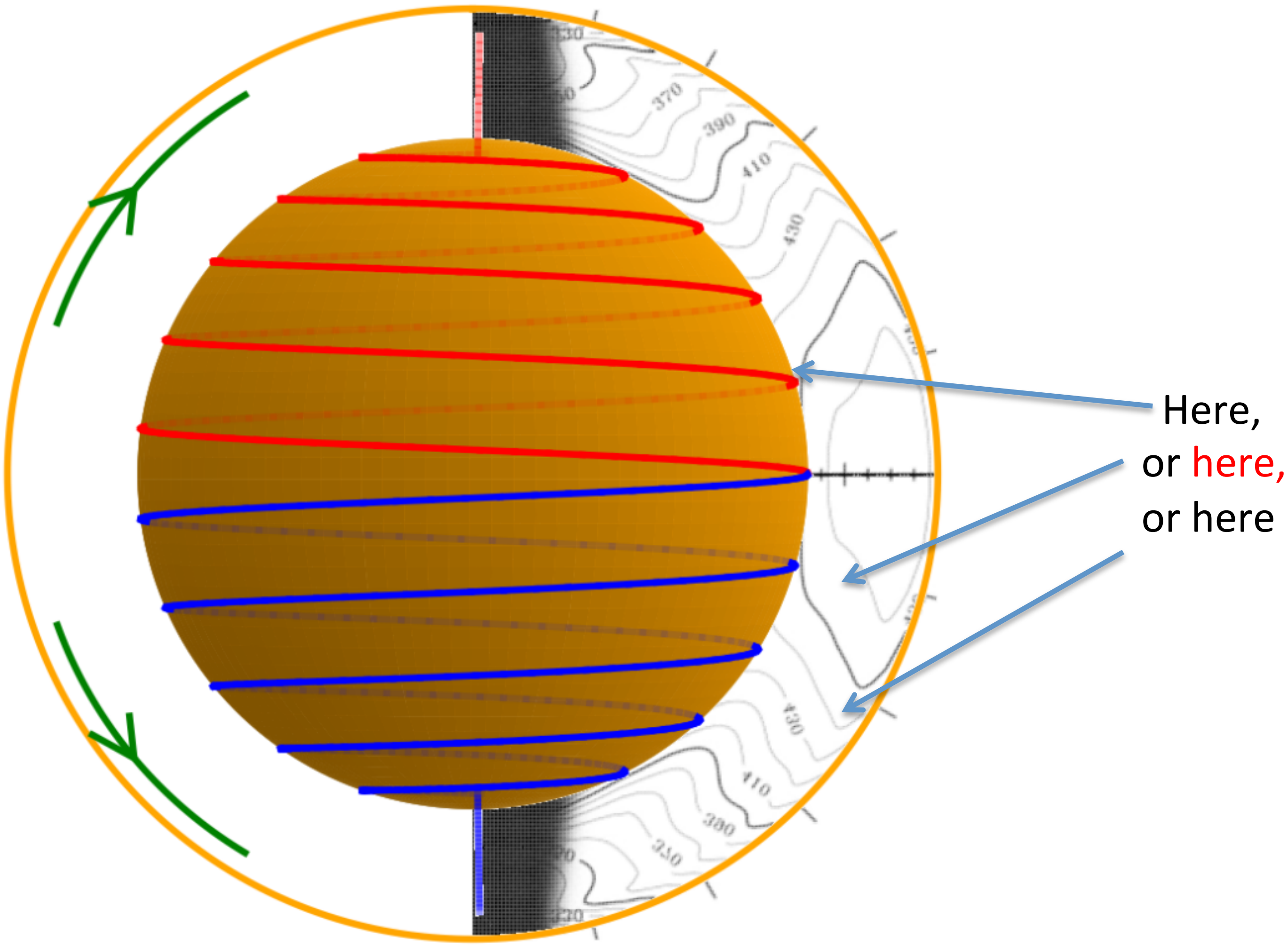
- Together these are enough to explain the observed variability from 1874 onwards.

Conclusions

- Observations strongly support Babcock-Leighton model
- Inflows are sufficient to explain observed nonlinearity
- Cross-Equator Plumes are sufficient to explain randomness.

Open questions:

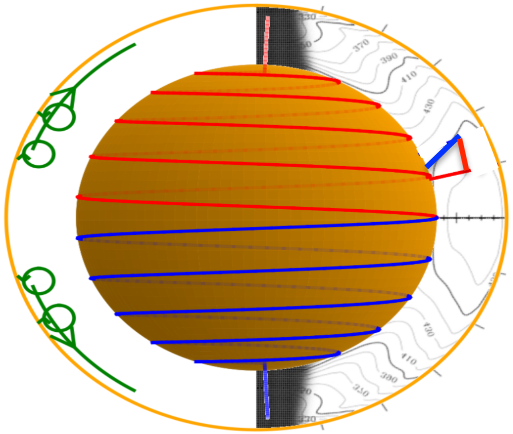
1. Where is the toroidal field stored?



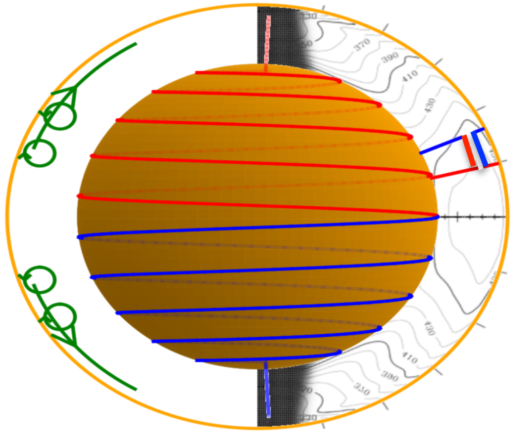
(Detecting changes in the flows or structure associated with the solar cycle)

How does the emergence process of active regions fit in?

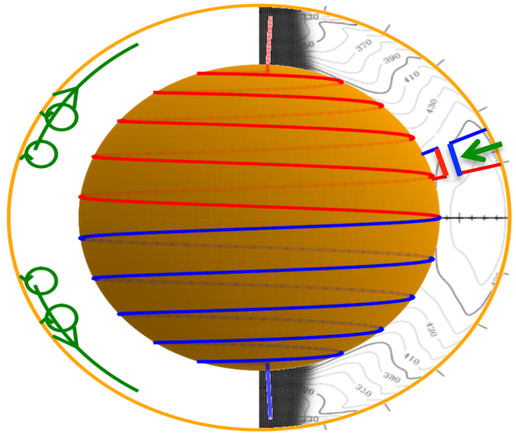
Standard picture, possibly/probably wrong in subsurface detail.



Eruption, Coriolis force
(detecting flows
before emergence?)



Dynamic disconnection
(sunspot seismology?)



Pumping
(measuring correlations
in the flow?)