Solar Cycle Propagation, Memory, and Prediction
Insights from a Century of Magnetic Proxies

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Work performed in collaboration with:

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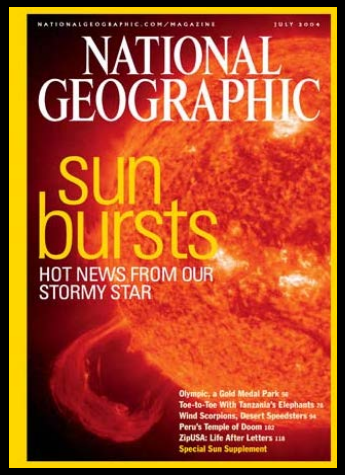
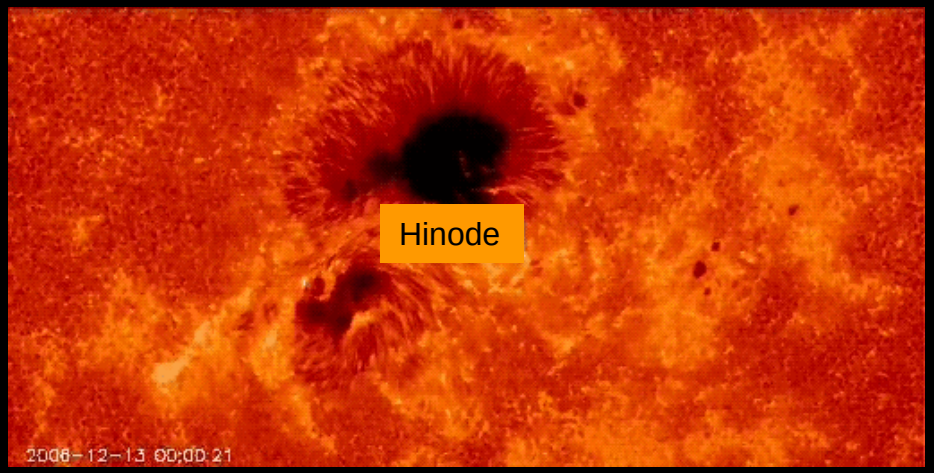
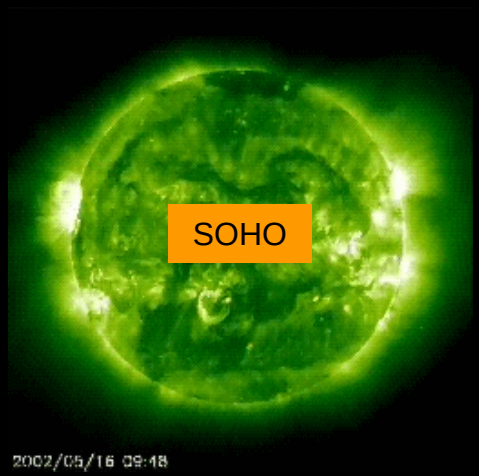
SOLAR CYCLE PREDICTION

One of the main practical goals of solar physics

Why do we want to predict the solar cycle?

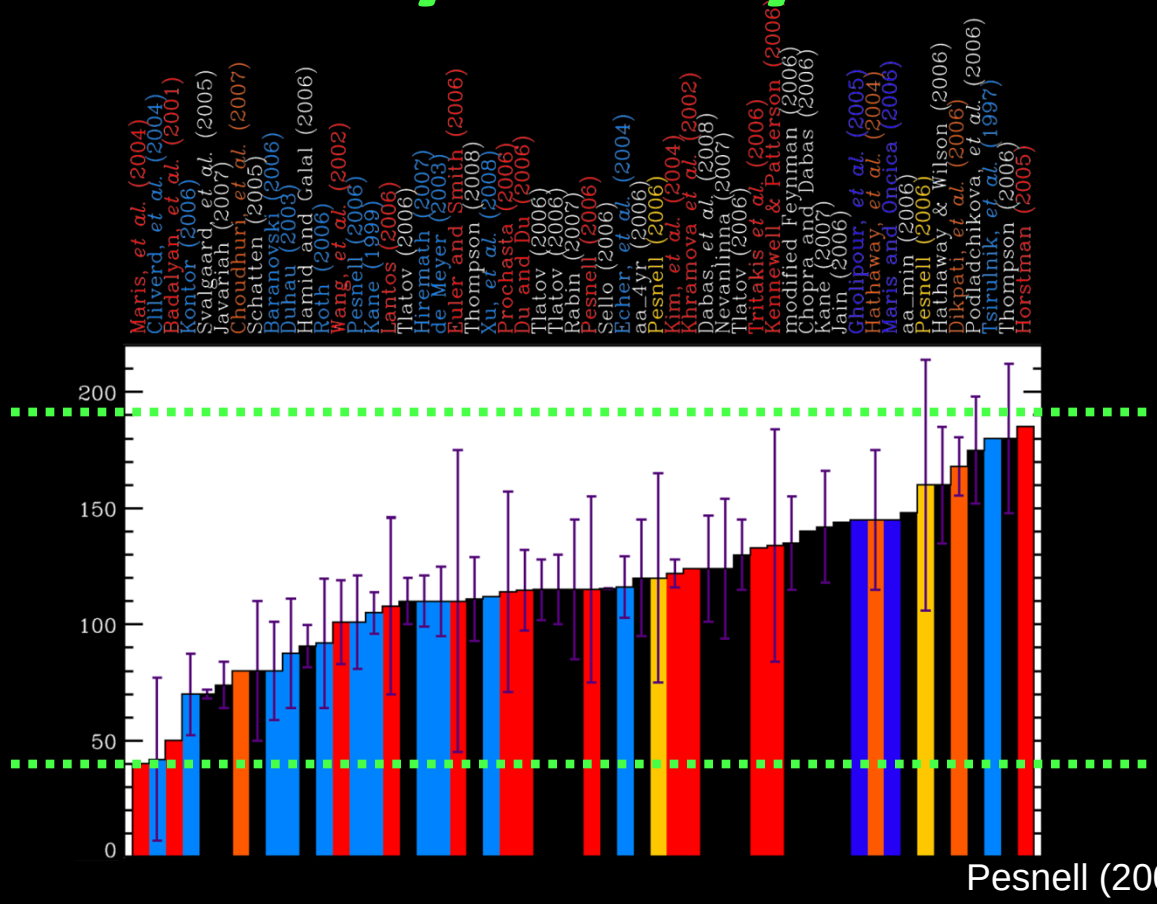






- Solar storms generate severe space weather.
  - They originate within sunspot magnetic structures (modulated by the solar cycle).
- The cycle also modulates several important heliospheric quantities (for example solar irradiance and cosmic ray flux).
  - Long term variation is relevant for Earth's climate system.

Predictions exist, but we their results vary widely…



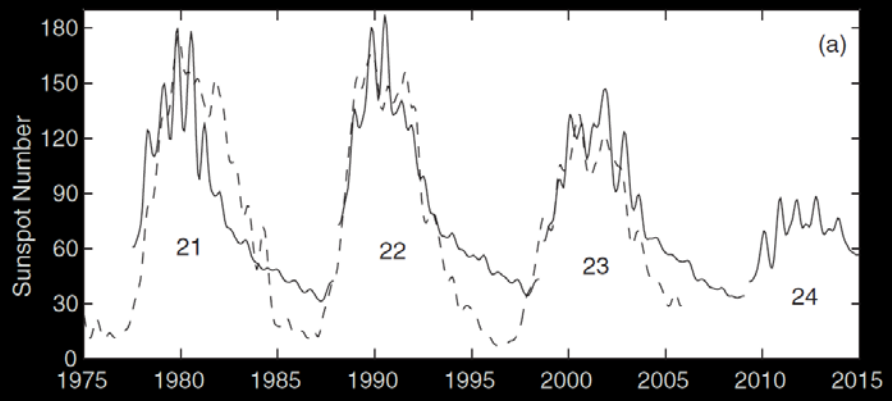
Pesnell (2008)

Range of predictions for this cycle (24) spans the entire range of all sunspot cycles directly observed!

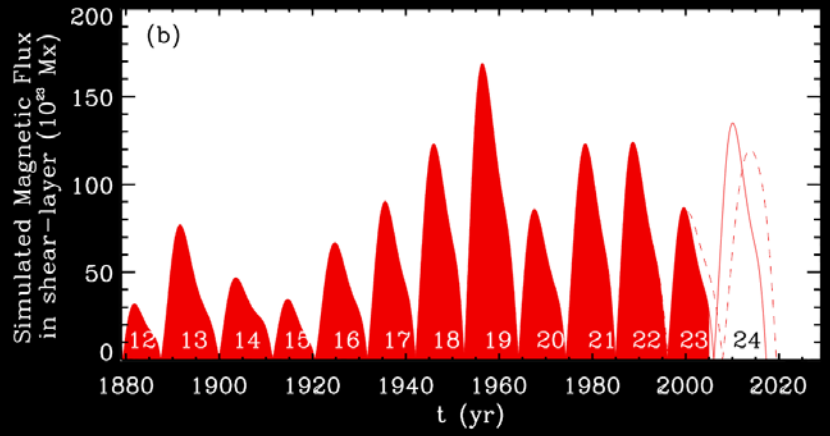
Types of solar cycle predictions

- Statistical/mathematical analysis of past sunspot data.
- Precursors: quantities that define the coming cycle early.
- Solar dynamo models.
  - Understanding of the dynamo mechanism required

Dynamo-based Predictions



Choudhuri et al. (2007)



Dikpati et al. (2006)

- Choudhuri et al. predict a weaker solar cycle 24.
- Dikpati et al. predict a stronger solar cycle 24.

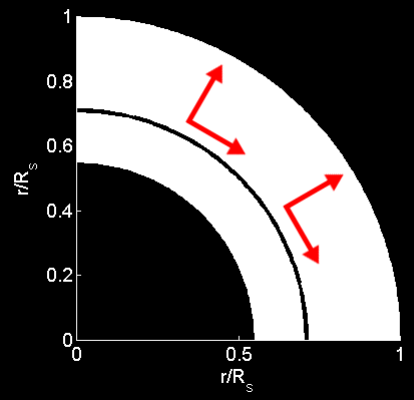
Why the difference?

SOLAR CYCLE UNDERSTANDING AND DYNAMO-BASED PREDICTIONS

Current understanding of the solar cycle

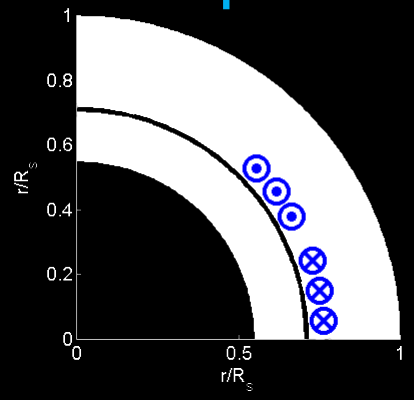
Poloidal

r - θ



Toroidal

ϕ

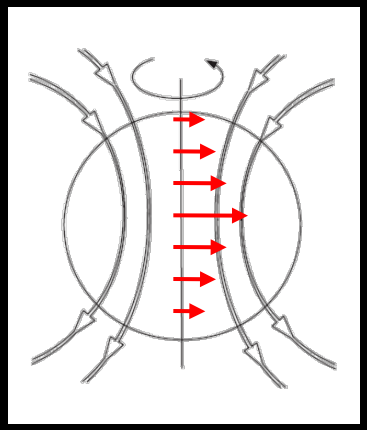


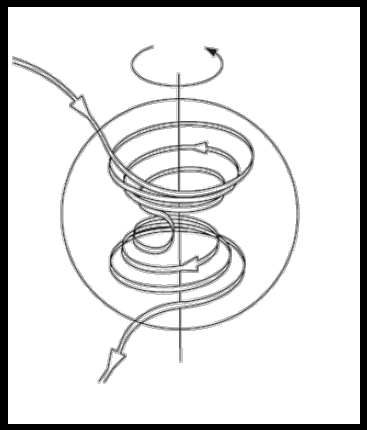
Current understanding of the solar cycle

Poloidal
$r - \theta$

Differential Rotation

Toroidal
ϕ





Credit: J. J. Love

Current understanding of the solar cycle

Poloidal

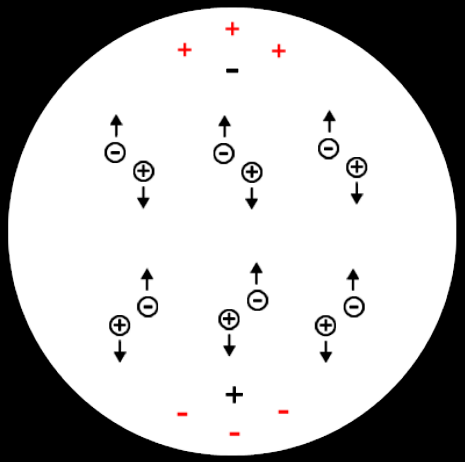
$r - \theta$

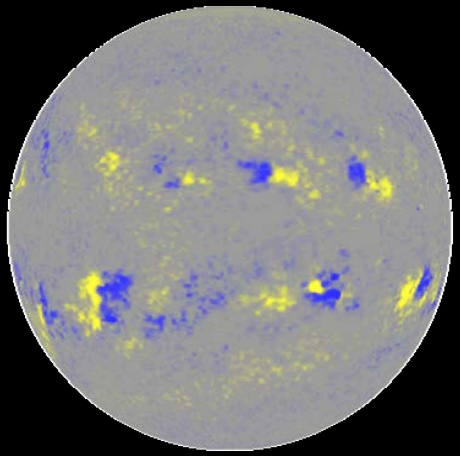
Differential Rotation

Emergence and Decay of Tilted Active Regions (Sunspots)

Toroidal

ϕ





Current understanding of the solar cycle

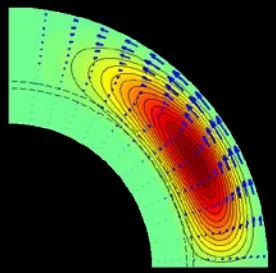
Poloidal
$r - \theta$

Differential Rotation

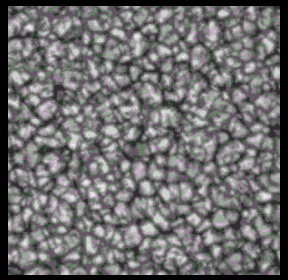
Toroidal
ϕ

Emergence and Decay of Active Regions (Sunspots)

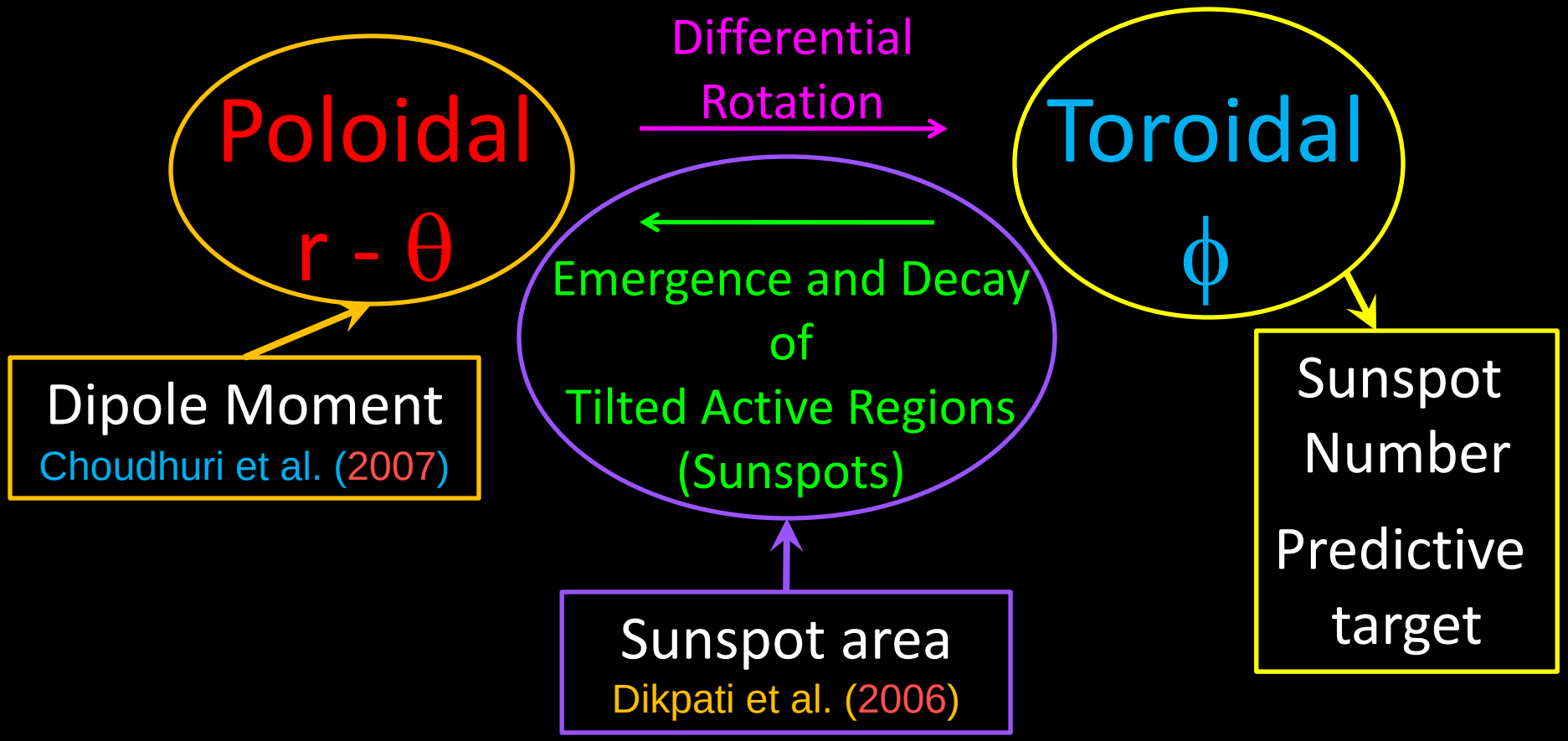
Meridional Flow



Turbulent Diffusivity



The first important difference between dynamo-based predicitons is the type of solar data assimilated:



The second important difference is the nature of flux transport:

Dominated by
Turbulent Diffusion
Choudhuri et al. (2007)

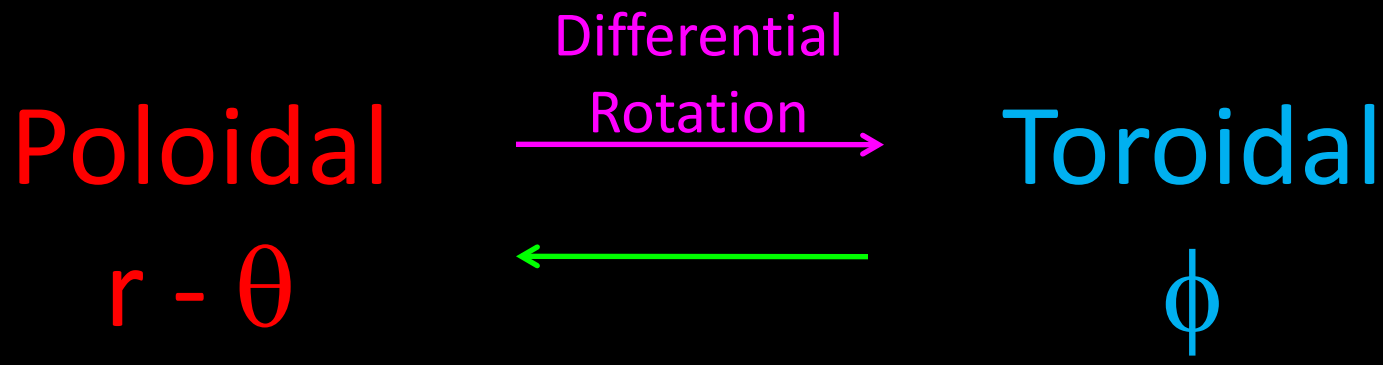
Dominated by
Meridional flow
Dikpati et al. (2006)

- Different flux transport regimes have different intrinsic memory.

- Studied by introducing randomness in the poloidal field creation process.

Yeates, Nandy & Mackay. (2008)

The second important difference is the nature of flux transport:



- The the poloidal field at minimum (Pf_n) should correlate well with the next cycle's toroidal field at maximum (Tf_{n+1}) (Schatten et al. 1978).
- It is possible that more than one cycle's magnetic field is playing a role in determining (Dikpati et al. 2006; Pf_n -> Tf_{n+1}, Tf_{n+2}, Tf_{n+3})

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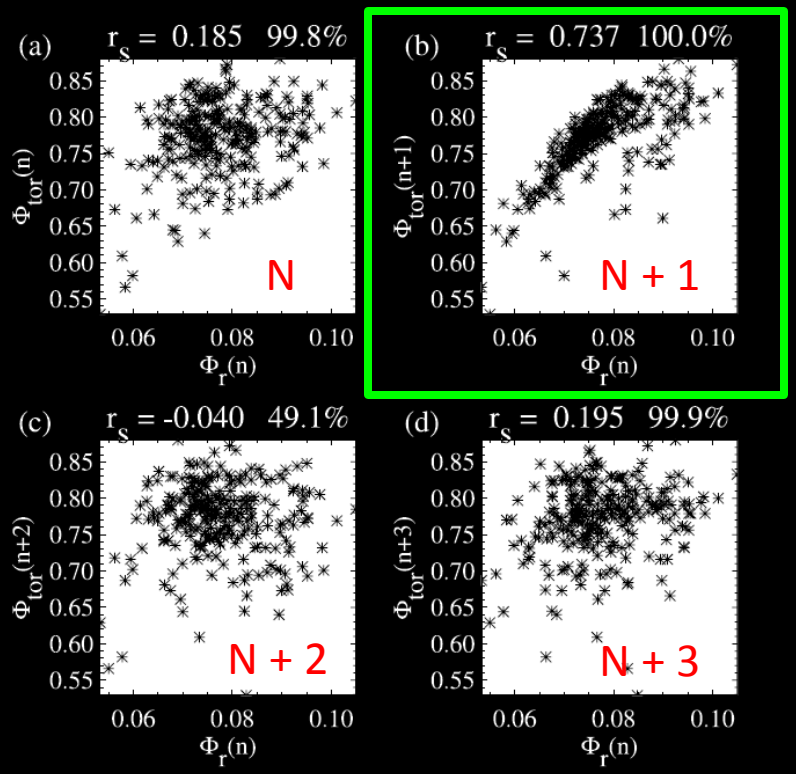
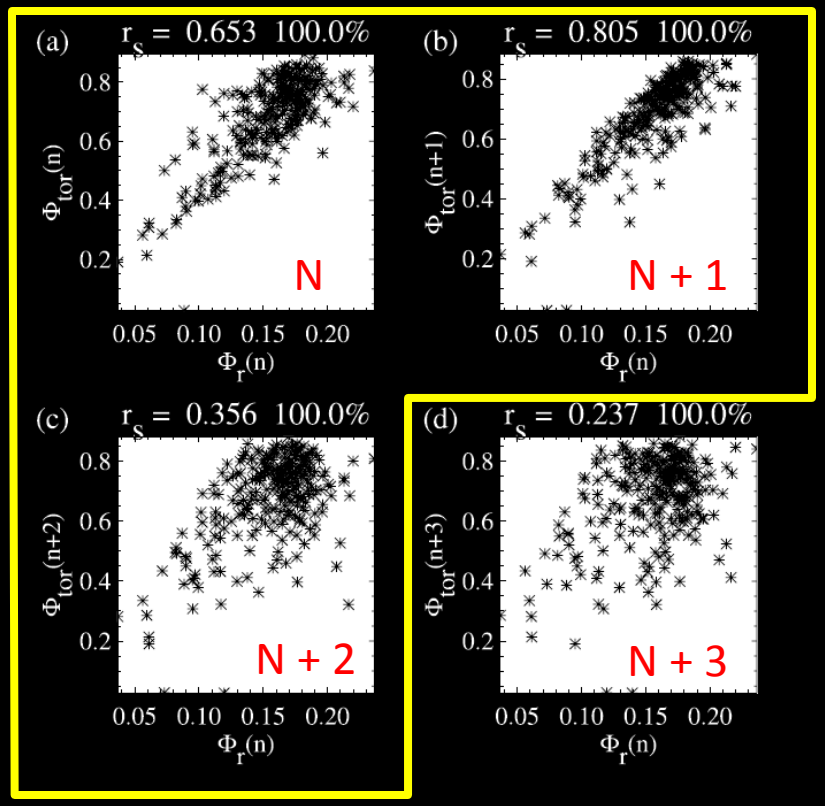


Dominated by
Meridional flow
Dikpati et al. (2006)



- What are the roles of polar fields and sunspots in the propagation of the cycle? Is our current understanding valid?

- Does the cycle have short-term or long-term memory?

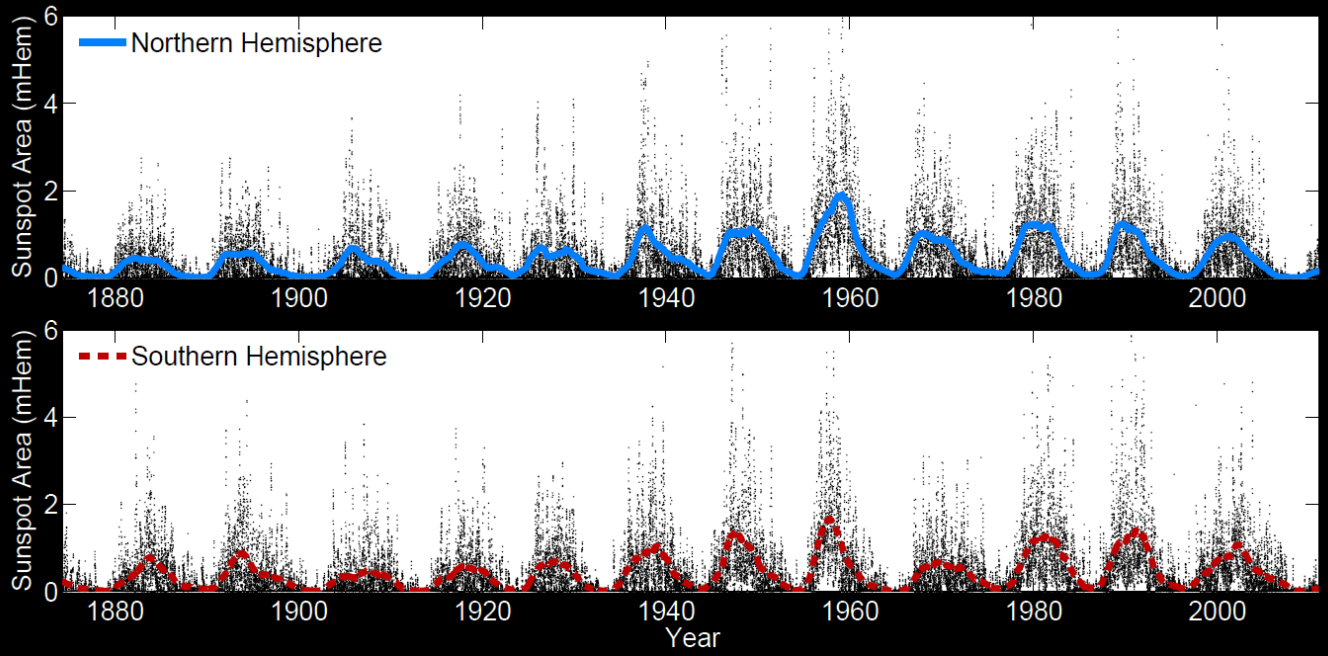
CONSOLIDATION OF A CENTURY OF MAGNETIC PROXIES

Muñoz-Jaramillo, Sheeley, Zhang & DeLuca, *ApJ*, **753**:146, 2012

Magnetic data only spans four cycles so we need to use proxies

? Poloidal $r - \theta$ ⟶ ⟵ Toroidal ϕ ✓

We use the sunspot area database of Balmaceda et al. (2009) as our toroidal field proxy



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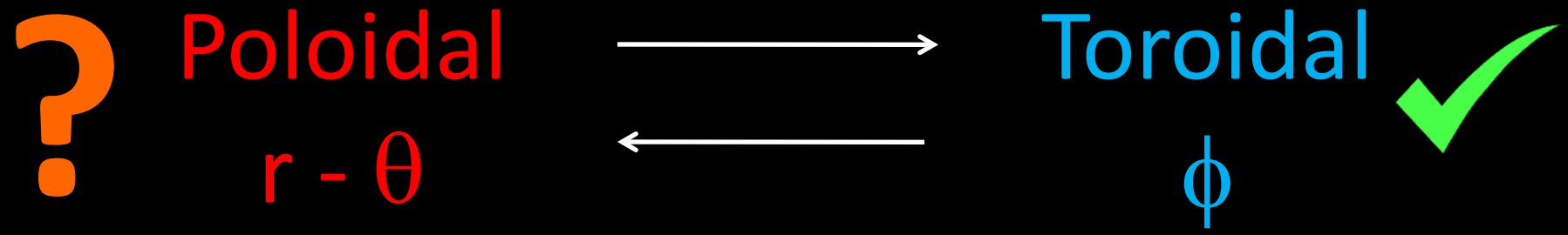
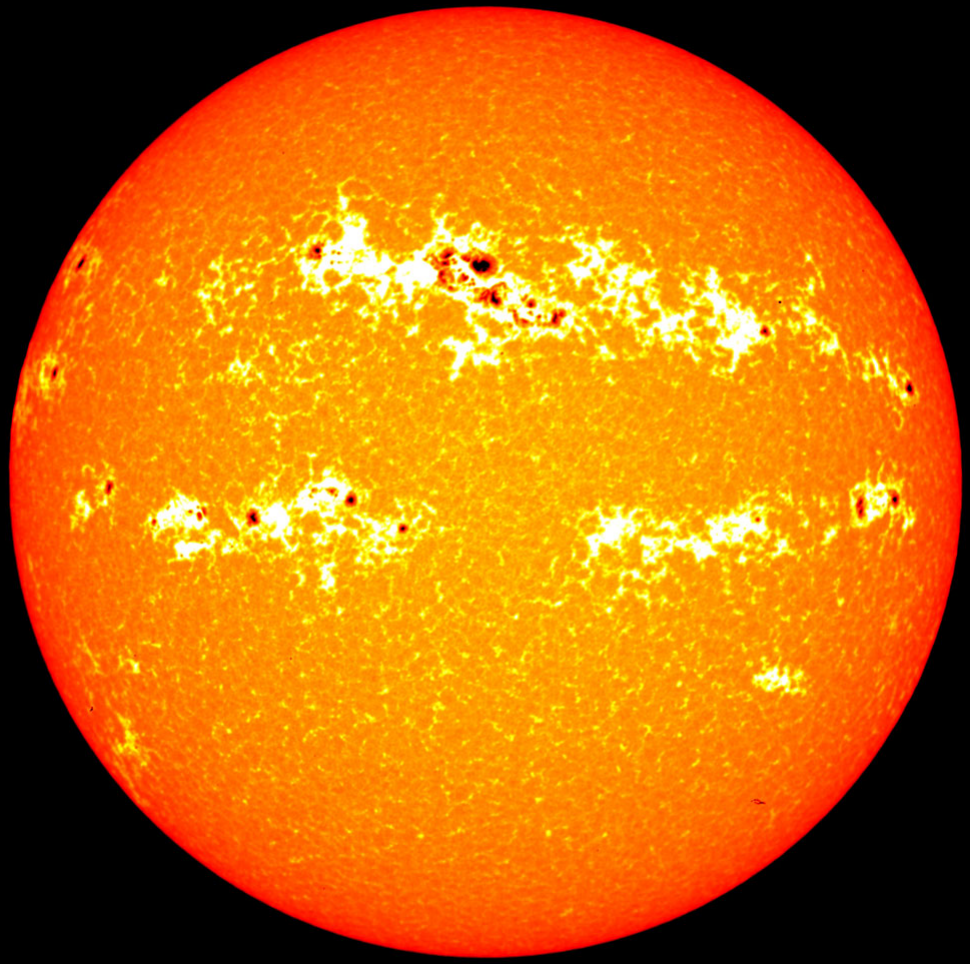


- If our understanding of the cycle is correct, the solar polar fields should be a good proxy for the poloidal field (Schatten et al. 1978).
- Used as a precursor to predict solar cycle 25 (Schatten 2005, Svalgaard & Cliver 2005).
- We need a proxy for the polar fields akin to sunspots.

NEIL SHEELEY'S FACULAR DATA

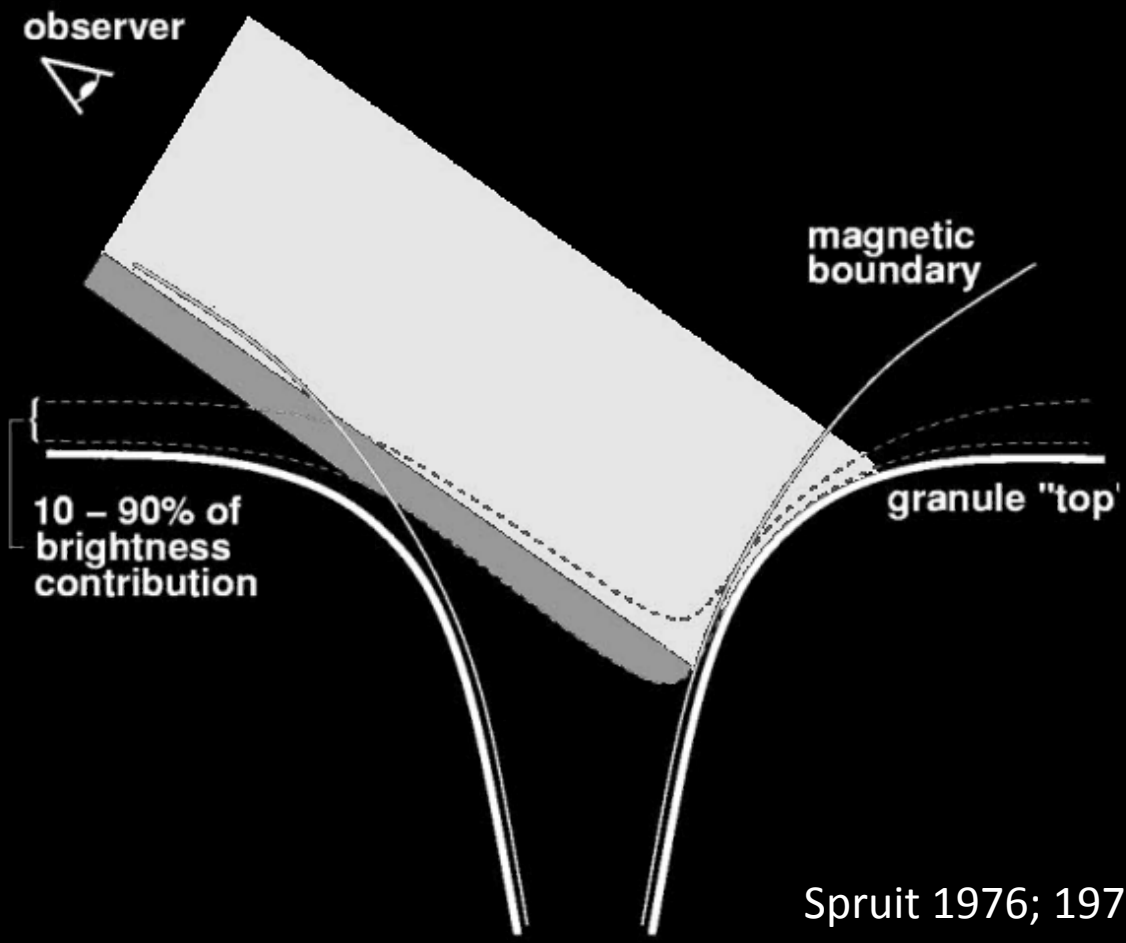
An invaluable treasure

Photospheric patches which are brighter than the surrounding quiet Sun



Credit: NASA/Goddard/SORCE

They are believed to be associated with concentrations of magnetic field

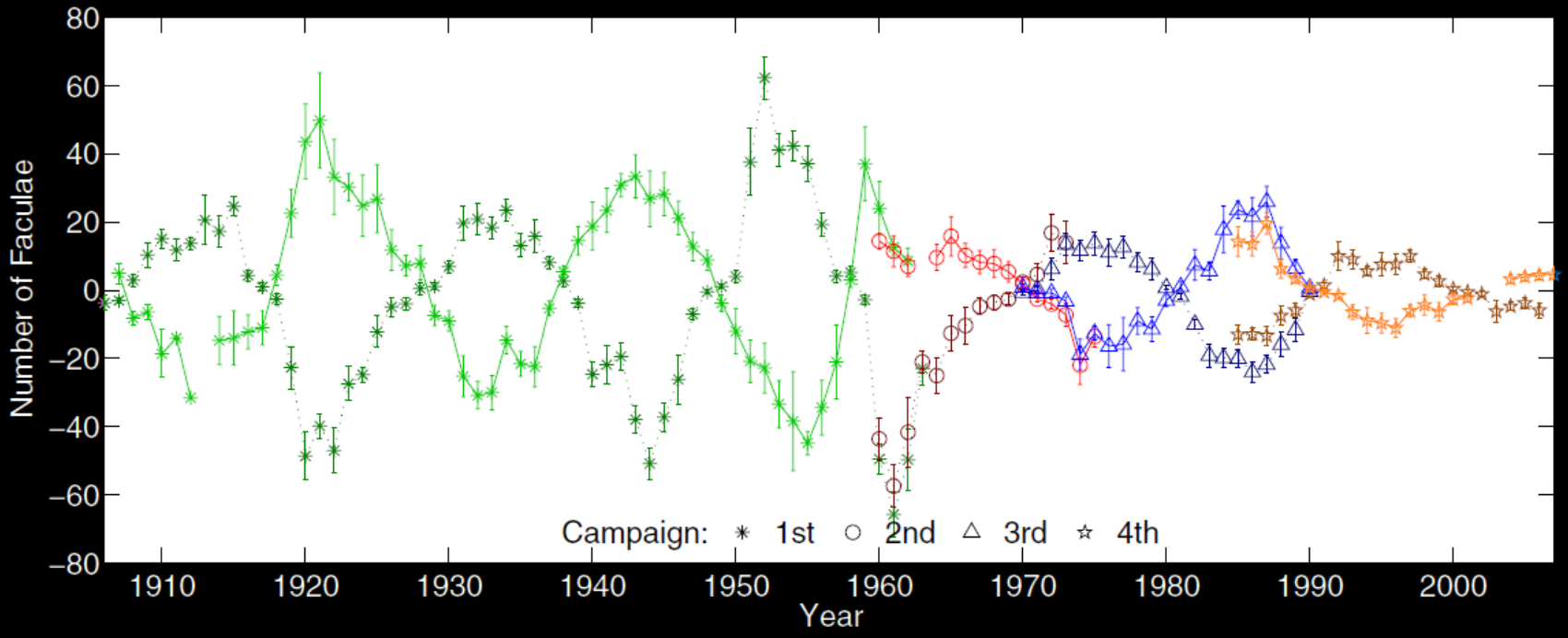


Spruit 1976; 1977; Keller et al. 2004

Neil Sheeley has counted a century's worth of polar faculae in four data reduction campaigns (1966, 1976, 1991, 2008)

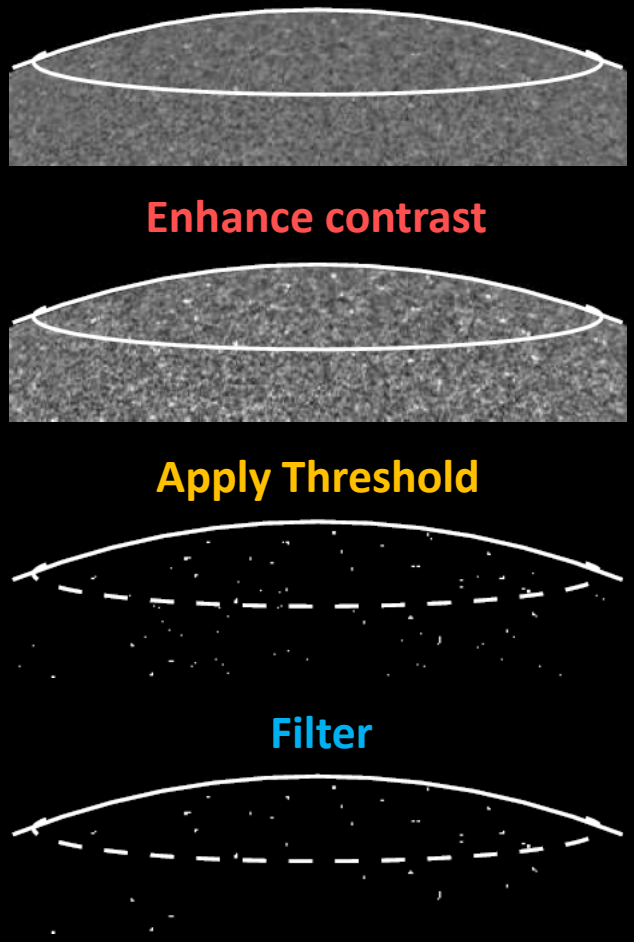
- Using plates for daily integrated sunlight of the Mount Wilson Observatory.
- Best plates were chosen to maximize polar coverage (Feb-Mar for South and Aug-Sep for North).
- Plates were marked and then randomized in time and orientation.
- Polar Faculae were counted by hand and averaged for each time interval.

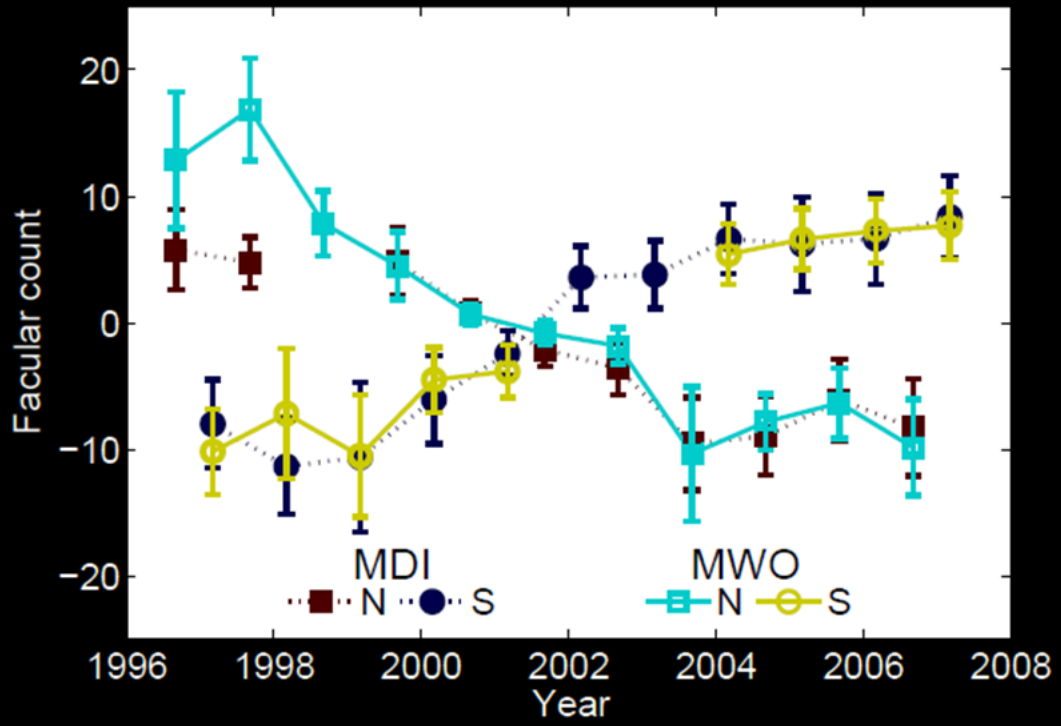
Neil Sheeley has counted a century's worth of polar faculae in four data reduction campaigns (1966, 1976, 1991, 2008)



- The problem was that there was an increasing inconsistency across campaigns.

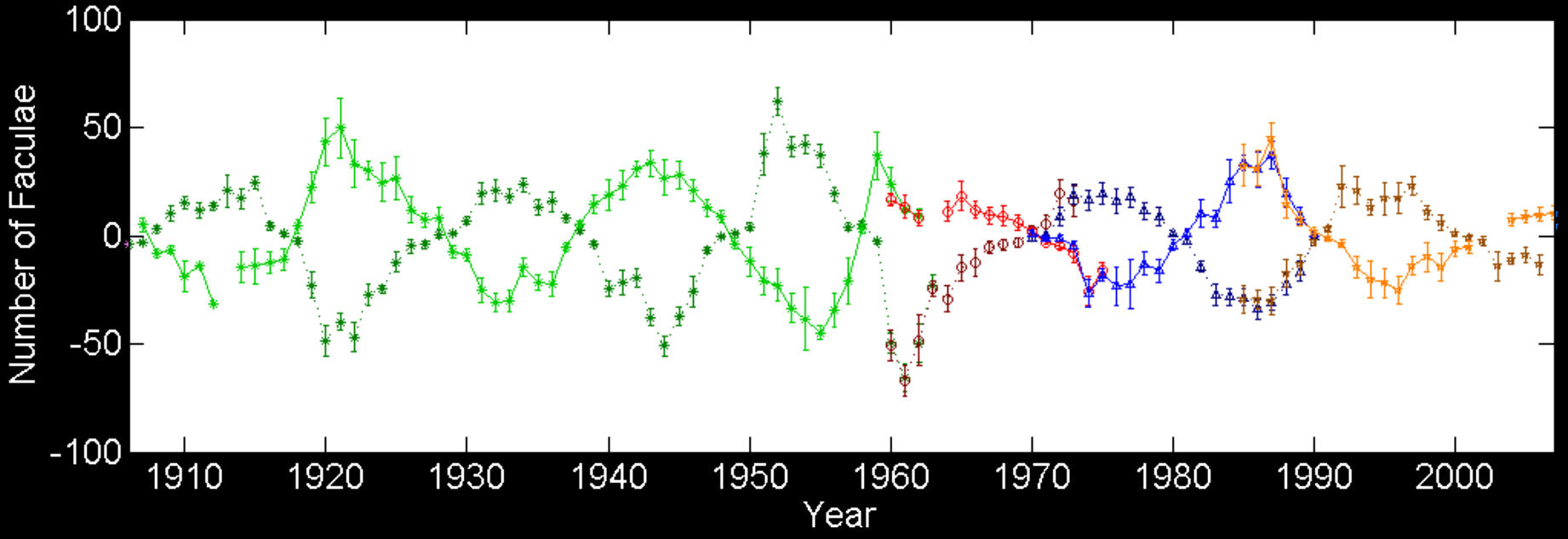
We validated the MWO methodology by counting faculae automatically on SOHO/MDI intensitygrams





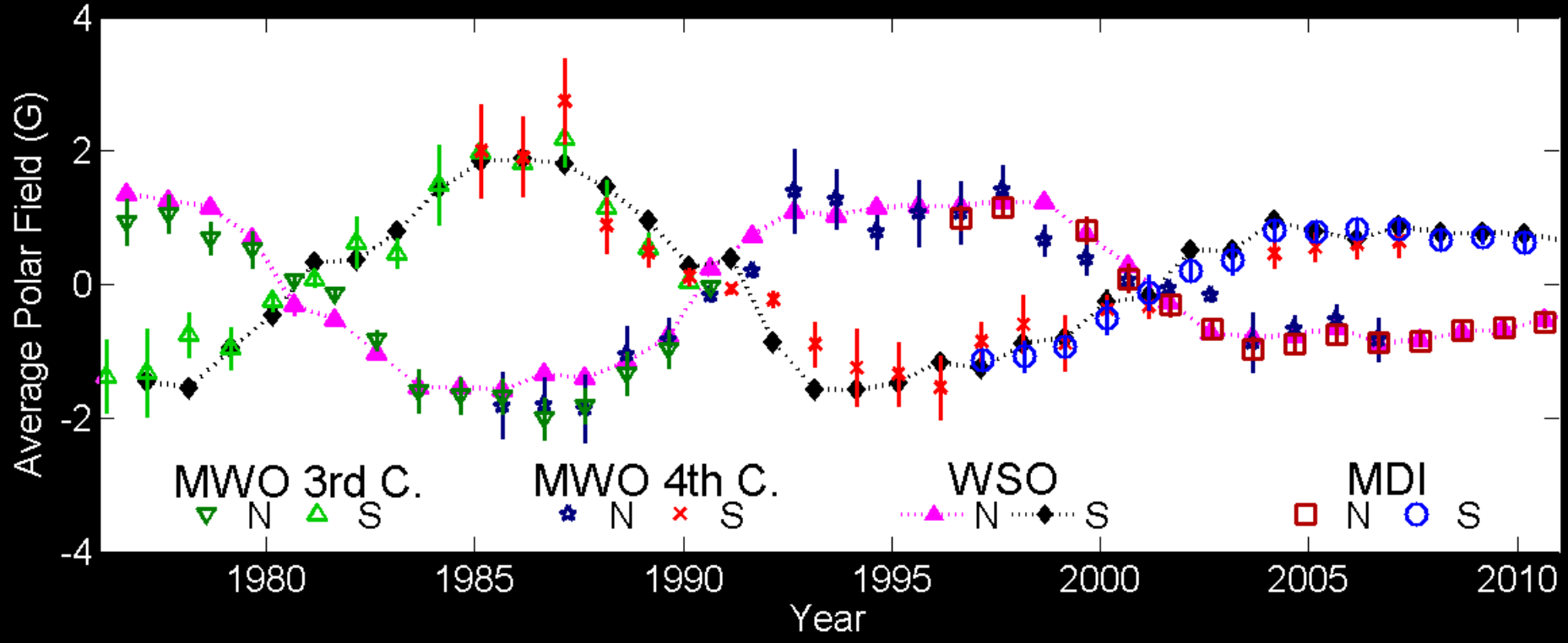
The facular counts obtained by the two methods are consistent.

We used campaign overlaps to standardize Neil's data



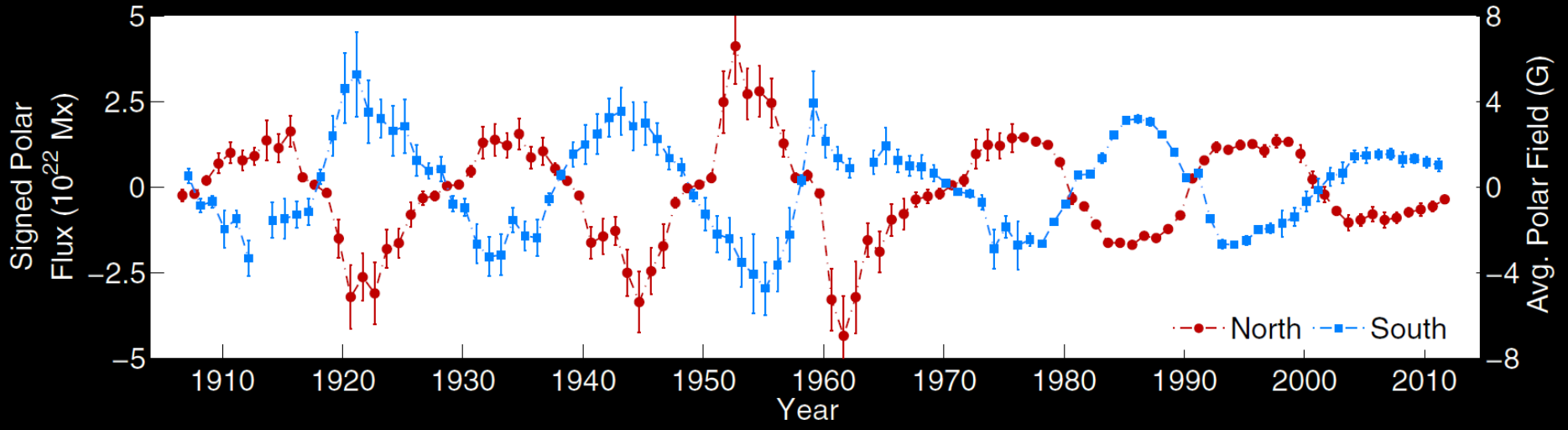
- Finding good agreement across campaigns once the calibration is applied.

We calibrate facular count using magnetic data from WSO and MDI



- This shows the validity of the cross-campaign validation and of faculae as a magnetic proxy.

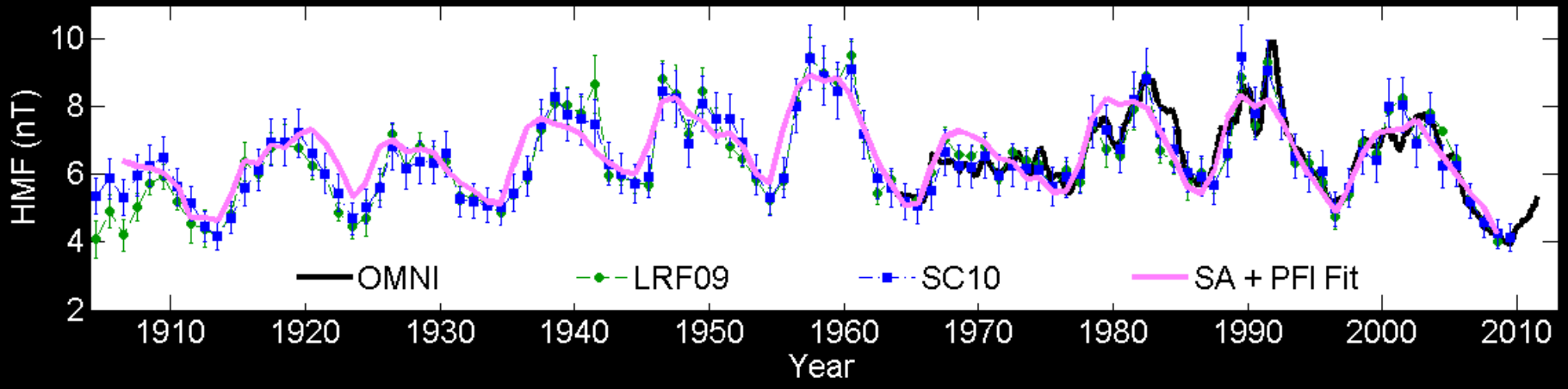
We calibrate facular count using magnetic data from WSO and MDI



- This shows the validity of the cross-campaign validation and of faculae as a magnetic proxy.
- It also can be used to study the evolution of the polar fields.

We use it to study the evolution of the heliospheric magnetic field

- The heliospheric magnetic field is believed to be determined by the dipolar moments of the solar magnetic field. Wang & Sheeley (2003) and Wang et al. (2005).
- We look at this from an observational perspective, using the HMF reconstructions of Svalgaard & Cliver (2010) and Lockwood et al. (2009)



Sunspot area (equatorial dipole) and polar flux (axial dipole) can explain most of the HMF variability during the last century.

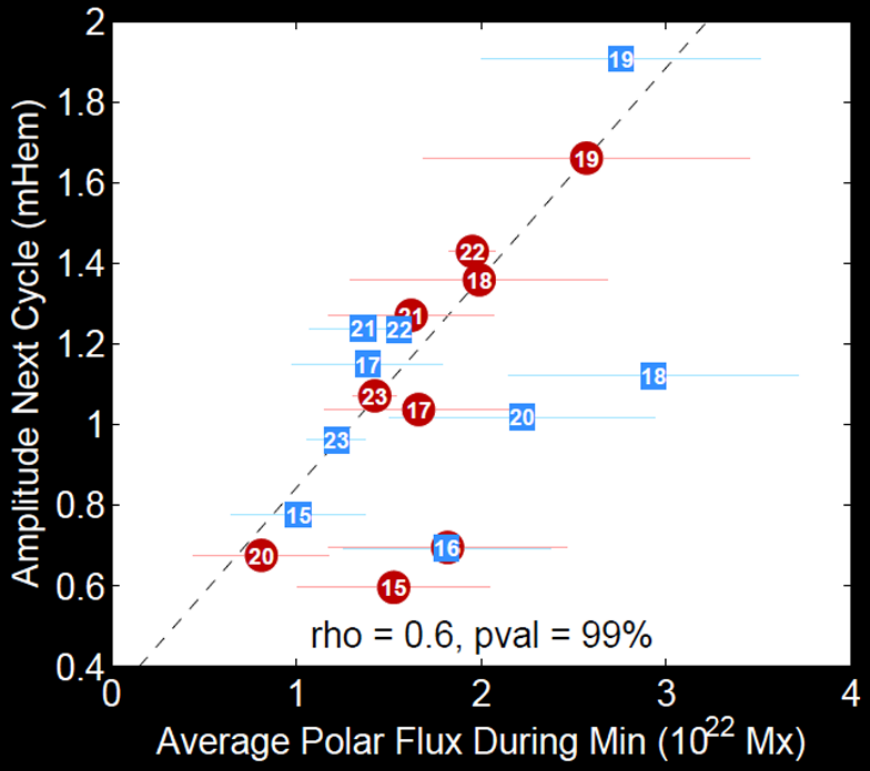
GOING BACK TO OUR QUESTIONS…

Muñoz-Jaramillo, Dasi-Espuig, Balmaceda & DeLuca, *Submitted*

Cycle Propagation and Prediction

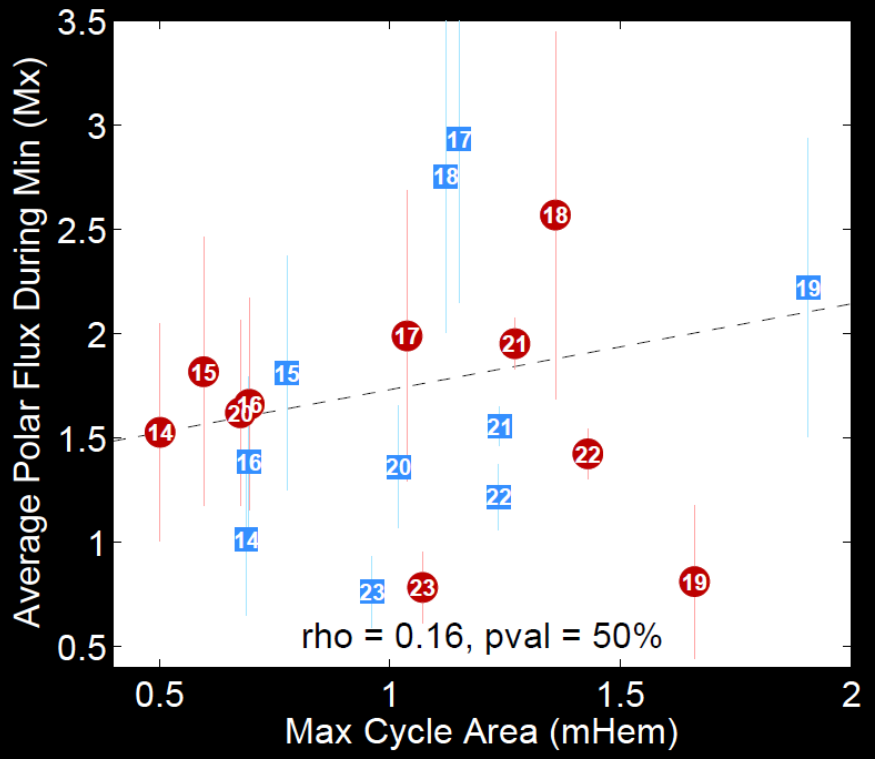
Polar Fields as the Seed of the Next Cycle

Choudhuri et al. (2007)



Sunspot Area as the Source Of Polar Fields

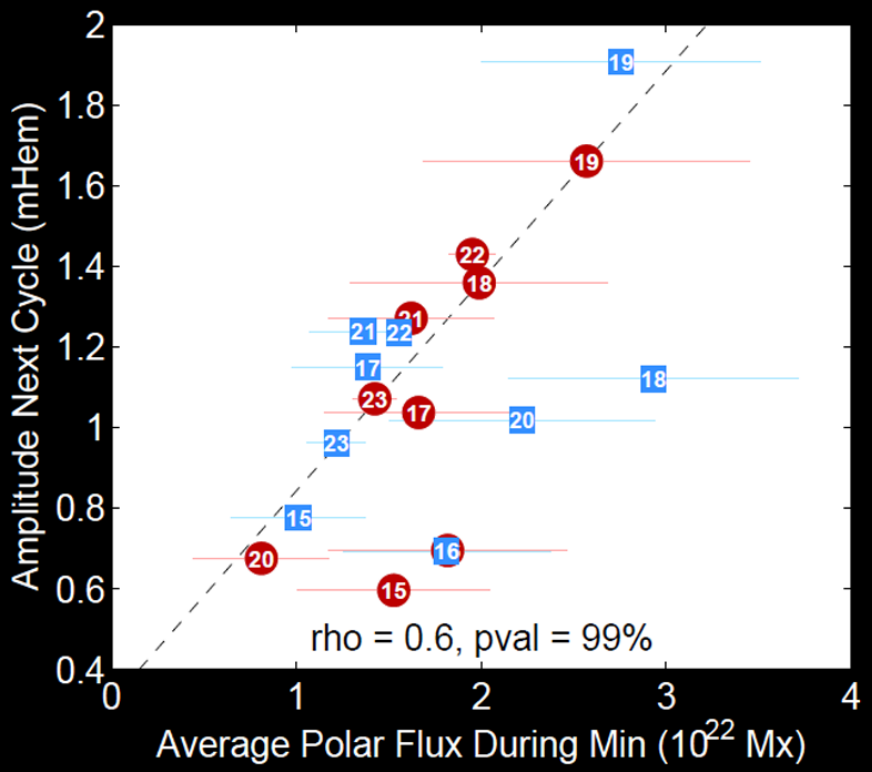
Dikpati et al. (2006)



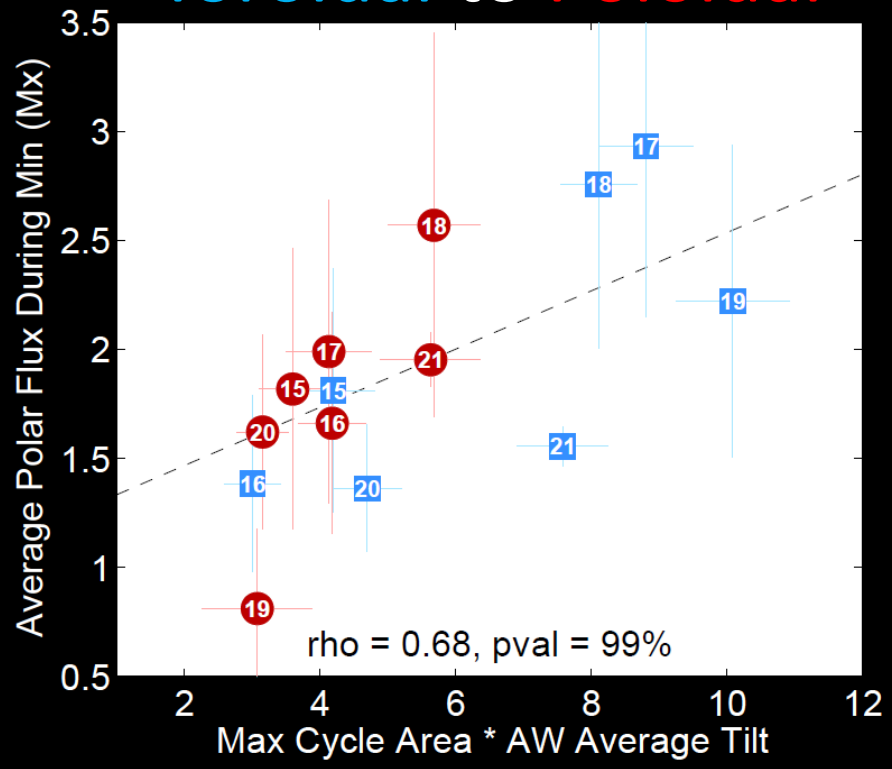
What about the Babcock-Leighton mechanism?

In the BL mechanism the polar fields are generated by the emergence and decay of tilted active regions

Poloidal to Toroidal



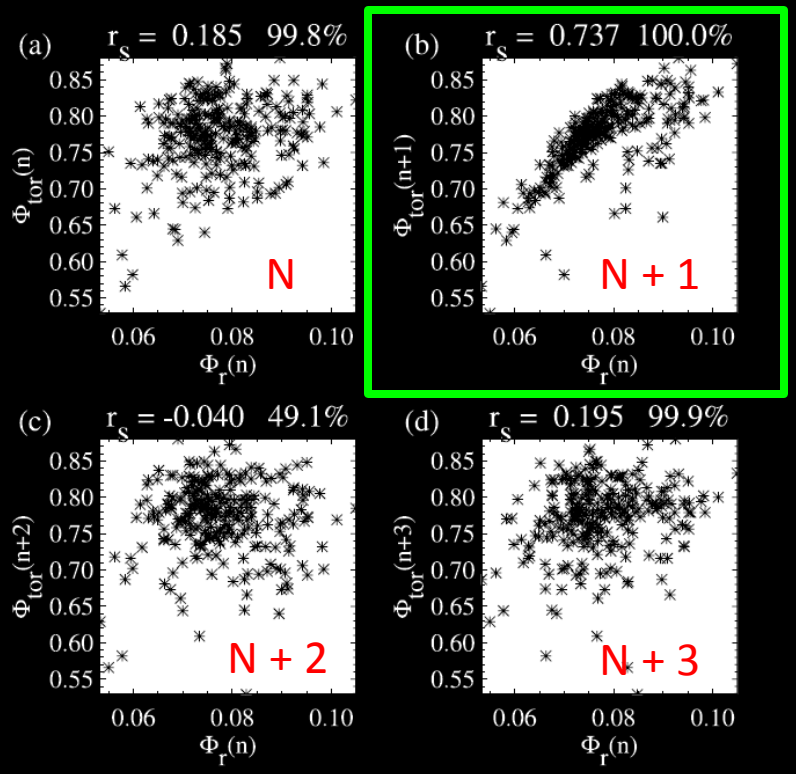
Toroidal to Poloidal



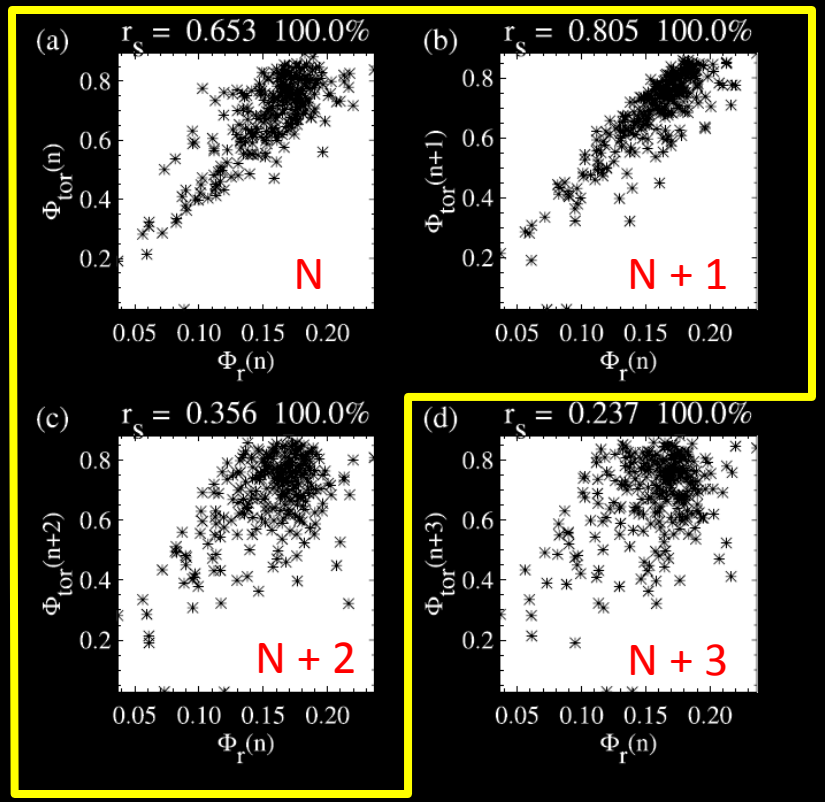
The BL mechanism is there, but tilt needs to be taken into account

Cycle Memory

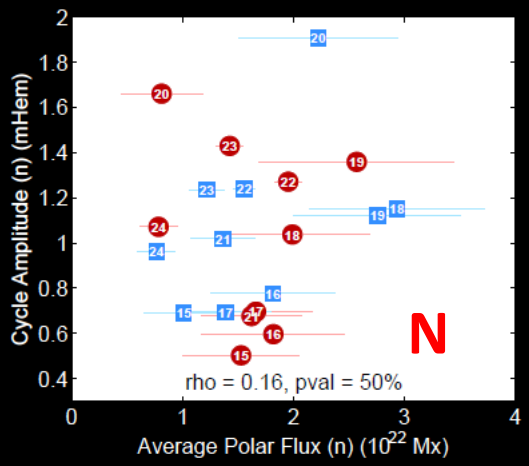
Dominated by
Turbulent Diffusion
Choudhuri et al. (2007)

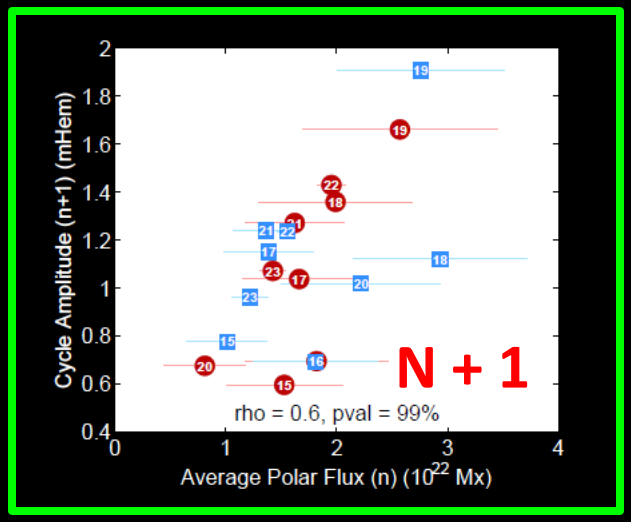


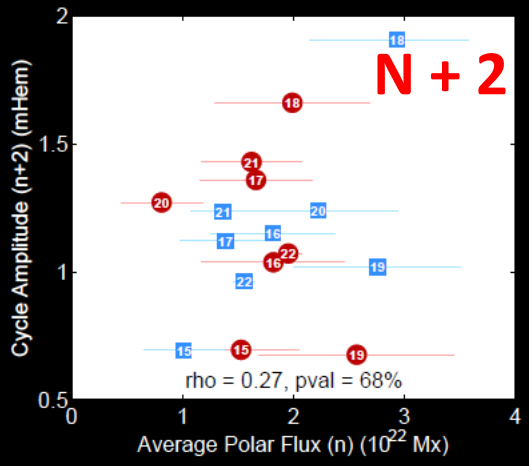
Dominated by
Meridional flow
Dikpati et al. (2006)

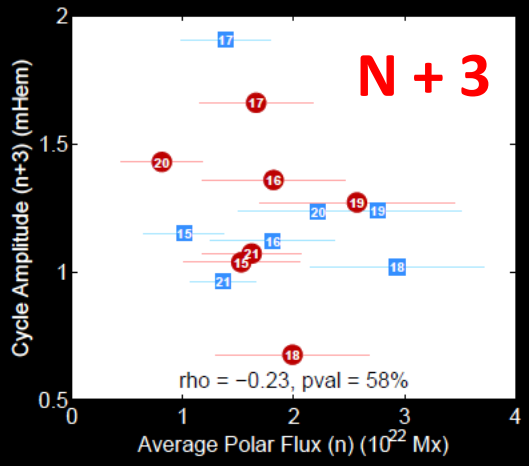


Cycle Memory









Observations are consistent with a short term memory regime

IMPLICATIONS AND CONCLUDING REMARKS

From the point of view of the dynamo

- We standardized, validated and calibrated a long-term facular dataset spanning a hundred years.
- This dataset is very useful, as a complement to sunspot data, for studying cycle propagation.
- The relationship between the poloidal and toroidal magnetic proxies is consistent with our current understanding of the cycle.
- Active region tilt plays a crucial role in the generation of the poloidal field (BL mechanism).

From the point of view of cycle prediction

- We find observations to be consistent only with a dynamo operating in a short term memory regime. This suggests that turbulent flux transport is as important as advective transport (meridional flow).
- In terms of data assimilation we find AR tilt to be as important as AR flux for determining the strength of the polar fields. (Cameron et al. 2010, Jiang et al. 2011)
- When it comes down to results, the prediction of Choudhuri et al. will likely be the most accurate. However, by using AR data to drive their model Dikpati et al. have the best approach.

Acknowledgements

- Organizers for giving me the opportunity to come and talk about my work.

- The NASA-LWS Jack Eddy Postdoctoral Fellowship Program, administered by the UCAR Visiting Scientist Programs.