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

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THE SOLAR CYCLE
A historical introduction
Sunspots were first studied with the advent of the telescope (1610)

Drawing by Galileo (circa 1610)

SOHO/MDI
Alternating peaks in solar activity (maxima), followed by quiet periods (minima).

Time variation is predominantly cyclic, mean period is 11 years.

Discovered in 1843 by Samuel Schwabe.
Sunspots are associated with regions of strong magnetic field (Hale 1908)
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- A sunspot group is commonly known as an **Active region**.
- Active regions have systematic tilt, which increases with latitude.
Sunspots are associated with regions of strong magnetic field (Hale 1908)

- A sunspot pair is commonly known as an Active region.
- Active regions have systematic tilt, which increases with latitude.
- The polarity orientation is opposite in the two hemispheres.
The most visible features of the cycle are associated with active regions.
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- Equatorward migration of Active Regions.
- Poleward migration of their decayed diffuse field
- Polar field reversal at the maximum of the cycle.

Image by David Hathaway
Active Regions have a complex magnetic field frozen in the plasma with a lot of free energy
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Active Regions have a complex magnetic field frozen in the plasma with a lot of free energy
Violent reconfigurations of the solar magnetic field release this energy in the form of:

- **Flares**
- **Coronal Mass Ejections**
SOLAR CYCLE PREDICTION

One of the main practical goals of solar physics
Why do we want to predict the solar cycle?

The solar cycle is the main driver behind solar and heliospheric variability.
Highly energetic events are modulated by the solar cycle

Both Flares...

Aschwanden & Freeland 2012
Highly energetic events are modulated by the solar cycle

... and CMEs

Owens & Lockwood 2012
The radiative output of the Sun is modulated by the cycle

- Particularly evident in UV and X-rays
The radiative output of the Sun is modulated by the cycle

• Can also be observed in total solar irradiance
Solar wind properties also change with the cycle

- Hot plasma that expands in all directions from the solar corona.
- Fast solar wind emanates from coronal holes at a speed up to 800 km/s.
- Slow solar wind emanates from other regions in the corona at speeds up to 400 km/s.
- Solar wind carries the Sun’s magnetic field out into the solar system.
Solar wind properties also change with the cycle at solar minimum.
Solar wind properties also change with the cycle at solar maximum.
Solar wind properties also change with the cycle.
Low-energy cosmic ray flux is modulated by the cycle
Predictions exist, but we their results vary widely...

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
Choudhuri et al. predicts a weaker solar cycle 24.
Dikpati et al. predicts a stronger solar cycle 24.

Why the difference?
SOLAR CYCLE UNDERSTANDING AND DYNAMO-BASED PREDICTIONS
Current understanding of the solar cycle

Poloidal $r - \theta$

Toroidal $\phi$
Current understanding of the solar cycle

Poloidal \( r - \theta \)

Toroidal \( \phi \)

Credit: J. J. Love
Current understanding of the solar cycle

Poloidal
$r - \theta$

Differential Rotation

Emergence and Decay of Tilted Active Regions (Sunspots)

Toroidal
$\phi$
Current understanding of the solar cycle

Poloidal $r - \theta$

Differential Rotation

Emergence and Decay of Active Regions (Sunspots)

Toroidal $\phi$

Meridional Flow

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

**Poloidal** $r - \theta$

- Dipole Moment
  - Choudhuri et al. (2007)

**Toroidal** $\phi$

- Sunspot Number
  - Predictive target

**Differential Rotation**

Emergence and Decay of Tilted Active Regions (Sunspots)

- Sunspot area
  - Dikpati et al. (2006)
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:

Poloidal \( r - \theta \)  

Differential Rotation  

Toroidal \( \phi \)

- 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 \( (Dikpati et al. 2006; Pf_n \rightarrow Tf_{n+1}, Tf_{n+2}, Tf_{n+3}) \)
The second important difference is the nature of flux transport:

**Dominated by Turbulent Diffusion**
Choudhuri et al. (2007)

- (a) $r_s = 0.185$ 99.8%
- (b) $r_s = 0.737$ 100.0%
- (c) $r_s = -0.040$ 49.1%
- (d) $r_s = 0.195$ 99.9%

**Dominated by Meridional flow**
Dikpati et al. (2006)

- (a) $r_s = 0.653$ 100.0%
- (b) $r_s = 0.805$ 100.0%
- (c) $r_s = 0.356$ 100.0%
- (d) $r_s = 0.237$ 100.0%
• 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

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

We use the sunspot area database of Balmaceda et al. (2009) as our toroidal field proxy.
Magnetic data only spans four cycles so we need to use proxies

- 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.

**Poloidal** $r - \theta$  
**Toroidal** $\phi$
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.

- 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.
We validated the MWO methodology by counting faculae automatically on SOHO/MDI intensitygrams.
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 facular 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.
GOING BACK TO OUR QUESTIONS...

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 AR emergence and decay (BL mechanism) to close the cycle?
In the BL mechanism the polar fields are generated by the emergence and decay of tilted active regions.

This supports the current understanding of the cycle.
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 supporting a dynamo that operates in a turbulent 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.
• The NASA-LWS Jack Eddy Postdoctoral Fellowship Program, administered by the UCAR Visiting Scientist Programs.

- The problem was that there was an increasing inconsistency across campaigns.
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.
Modulation by sunspot area (equatorial dipole) is evident, but what about the polar fields?

Focusing on solar minima we find:
- The HMF drops to values determined by the strength of the polar fields (axial dipole).