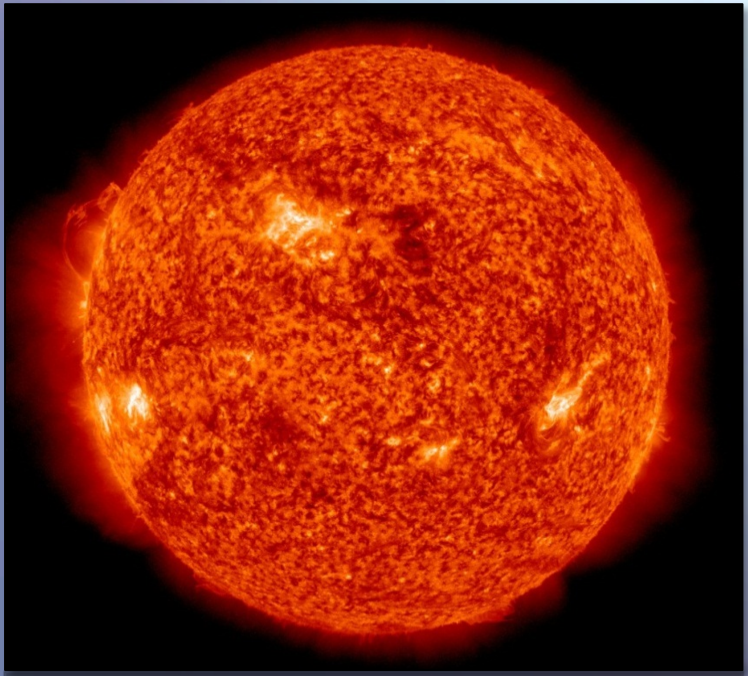
Solar Cycle Predictions



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HSS Letcure

Aug 5th 2017

Why do we care about predicting solar cycles???

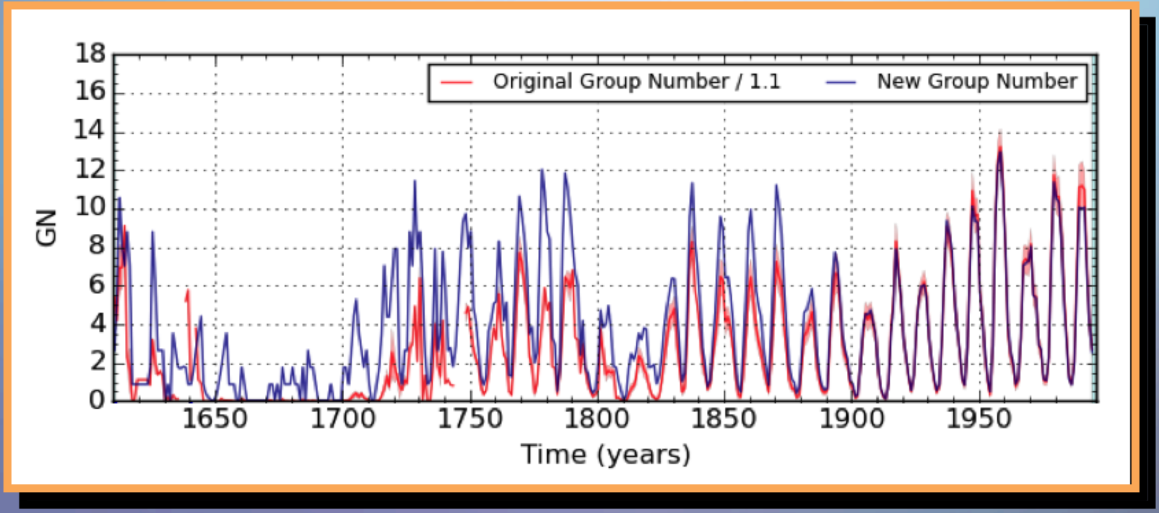
Motivation

- **Space Weather is modulated by the Solar Cycle**
  - Threat to Astronauts in Space
  - Satellites (direct hit or changing orbits)
  - Galactic Cosmic Ray Flux (Manned Mission to Mars)
  - GPS & Radio Communications
  - Disrupt Power Grids (1989 Quebec)
  - Atmosphere – Ozone and Clouds (maybe??)
  - Climate (maybe???)
- **Scientific Knowledge and Understanding**
  - Dynamo Mechanisms
  - Sun as a Star

What do we even know about solar cycles???

New Sunspot Cycle Data

- What is the "REAL" Sunspot Cycle?
  - Is the Modern Maximum Unique?
    - What did the Maunder Minimum really look like?
      - Do we even know what a "normal" cycle is?

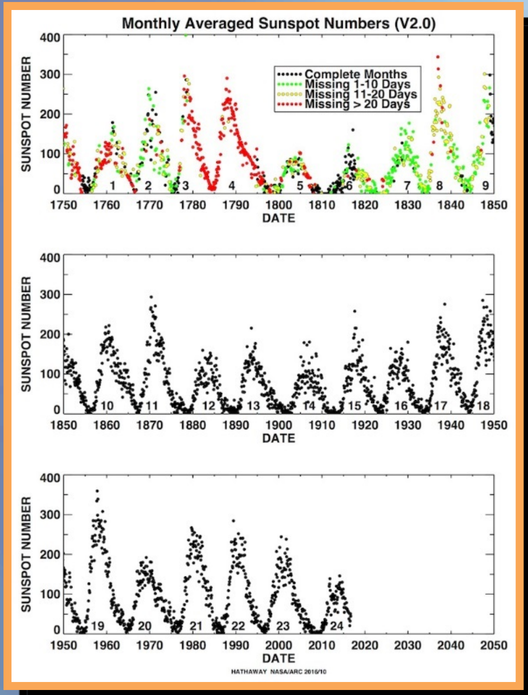


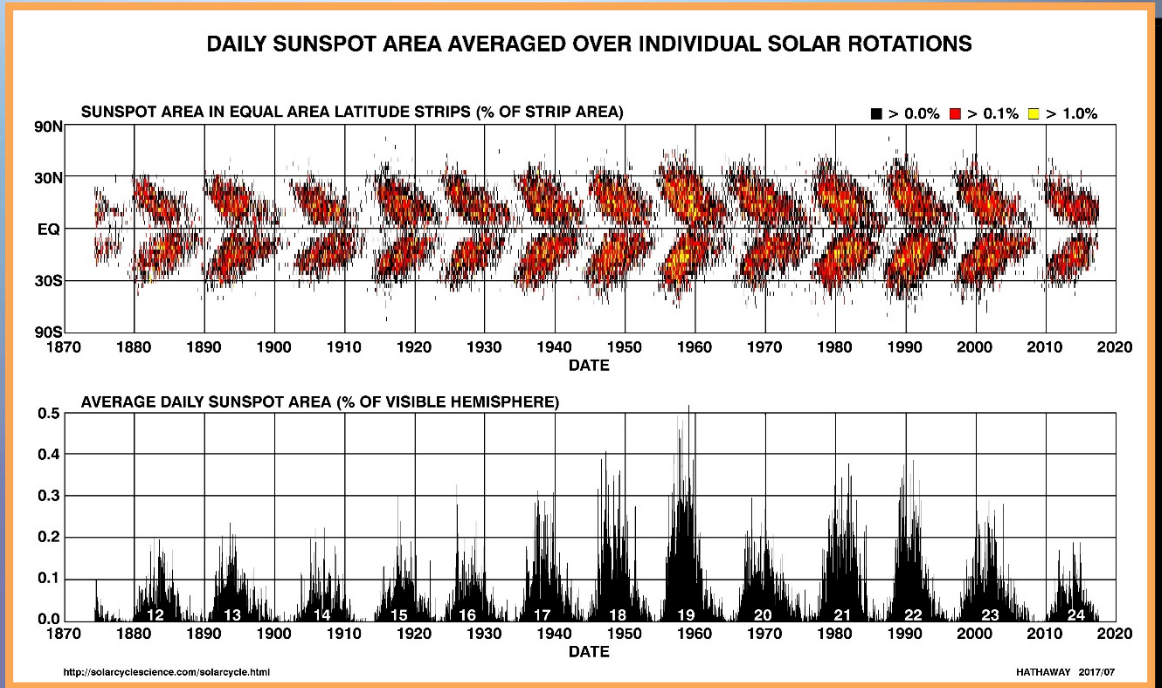
Hoyt, Schatten, Clette, Svalgaard

24 Cycles and Counting

Activity on the Sun is periodic with the average cycle lasting ~11 years and the peak Sunspot Number of ~100.

- **Sunspots appear in two bands on either side of the equator.**
- **These bands drift toward the equator as the cycle progresses.**
- **Cycles generally overlap by 2-3 years.**

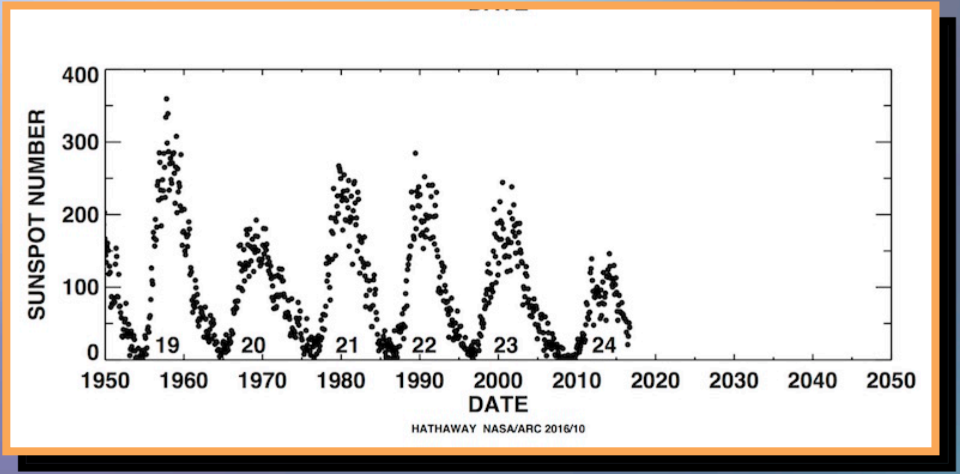




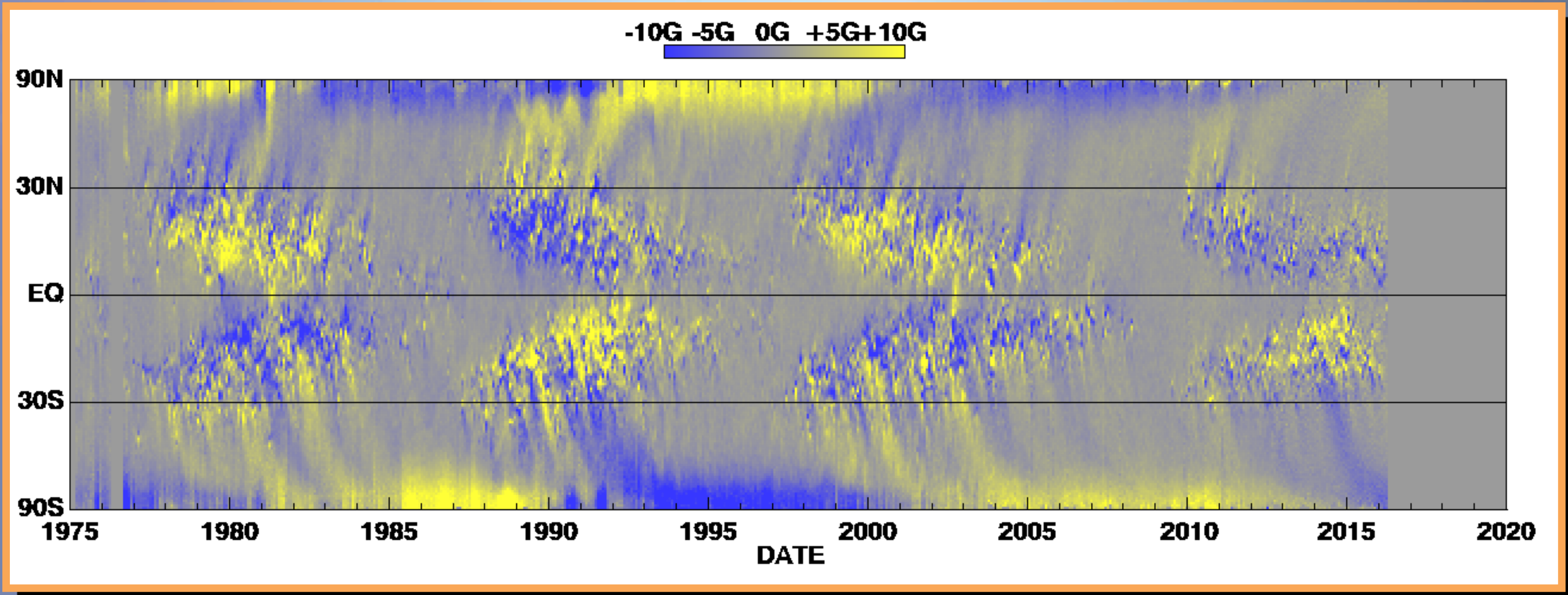
Crude Approximations

- Treat Solar Cycle as a Time Series
- Next Cycle = Average Cycle (~110)
- Next Cycle = Next Cycle (23 -> 24)
- Wave Analysis (19->20)

We Need the Physics!

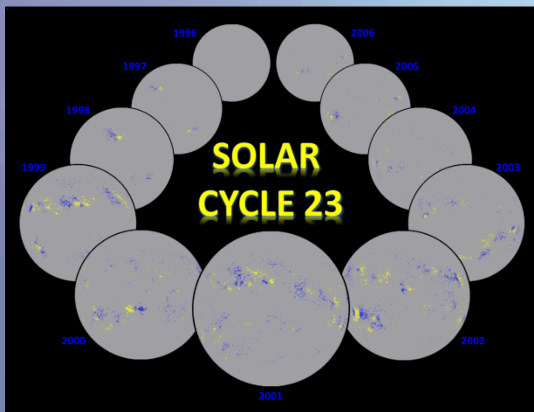


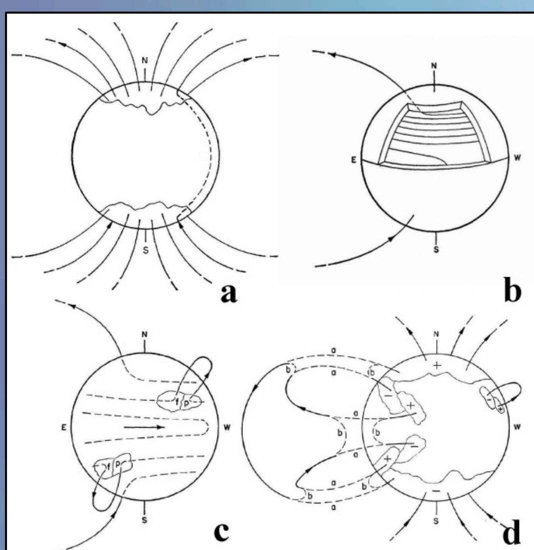
The Magnetic Field



In addition to the magnetic field in Active Regions, the Sun has polar magnetic fields that form a weak dipole. The polarity of the polar fields reverses from one cycle to the next. This reversal comes around the time of solar cycle maximum.

Babcock Dynamo Model





Babcock (1961) created a phenomenological model to help explain the sunspot cycle.

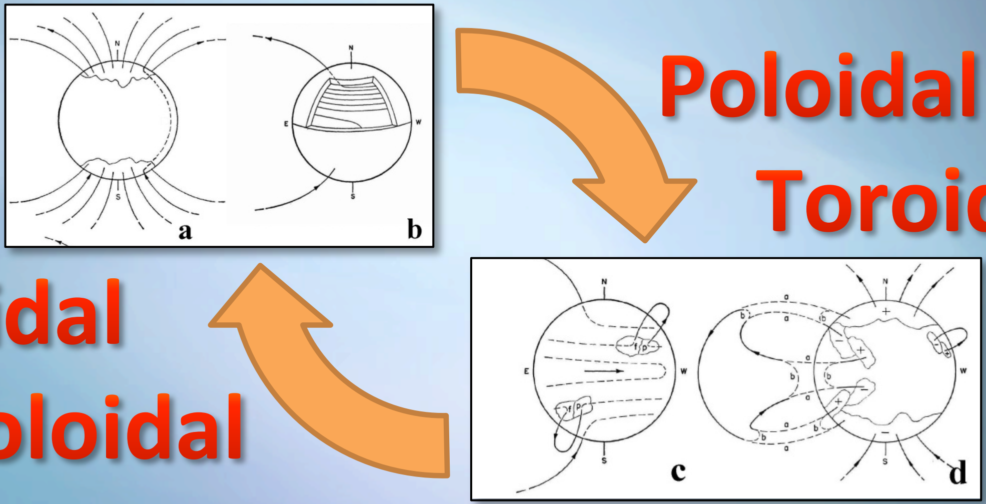
a) Solar Minima. A relatively weak axisymmetric dipole (poloidal) field exists. Field lines emerge at $\lambda \geq 55°$.

b) **Differential Rotation** shears the submerged magnetic field in toroidal direction. The field is strengthened by this shearing.

c) The toroidal field become buoyant and causes sunspots to emerge with **Joy's Tilt** and **Hale's Polarity**. (Polarity of leading spots matches the polarity of the initial polar field.)

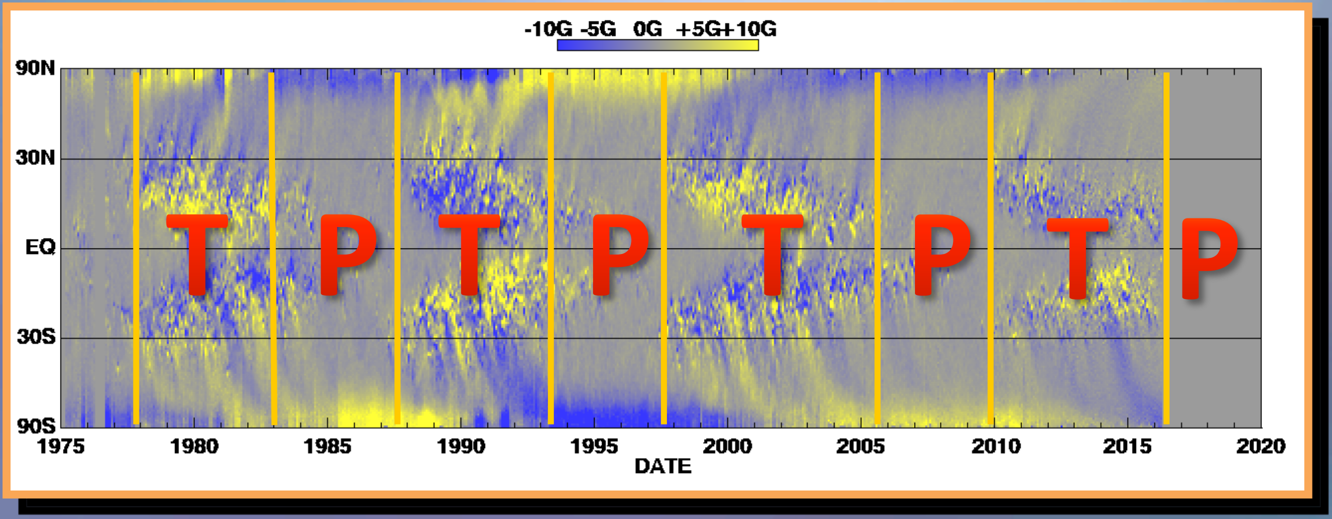
d) Magnetic flux is shredded off of the sunspots and is spread out by the **Convective Motions**. The leading polarity fields cancel across the equator. The **Meridional Flow** transports the following polarity to the poles. The following polarity cancels the old poloidal field and creates a new poloidal field with opposite polarity.

Babcock Leighton



Poloidal to Toroidal

Toroidal to Poloidal

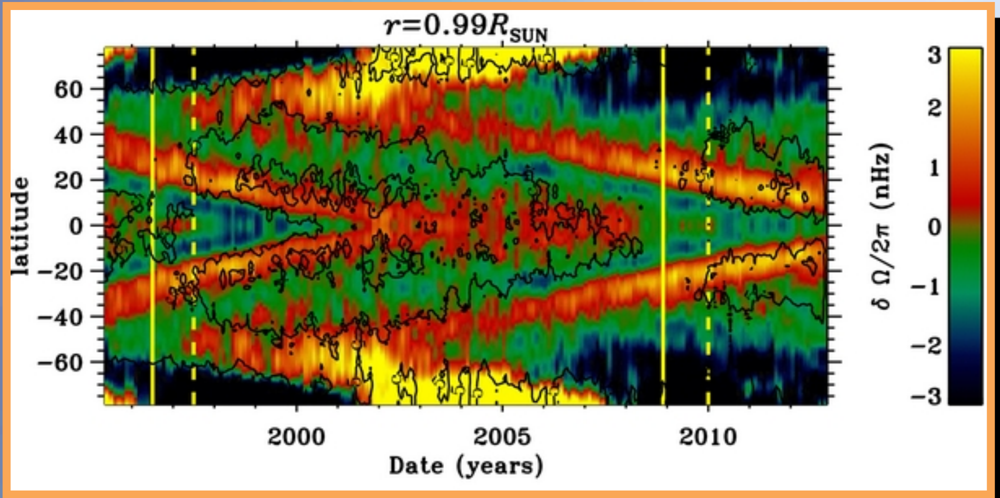


Dynamo Modeling

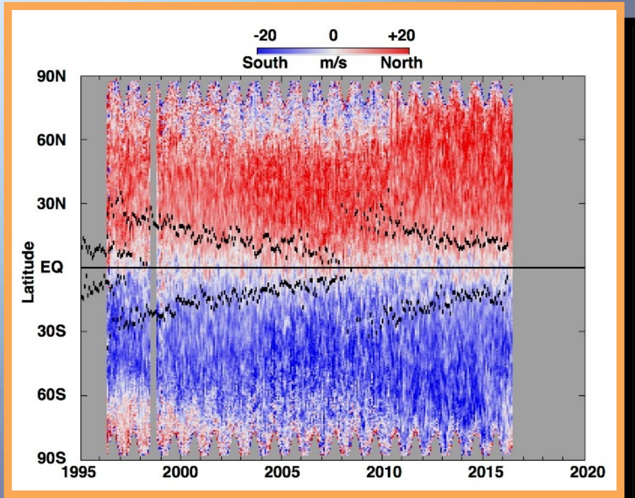
- **Can we simulate solar cycles?**
- **How are cycles modulated in Dynamo Models?**
  - **The Lorentz Force**
  - **Stochastic Processes**
- **What do we really know about the interior?**
  - **Meridional Circulation**
  - **Convection Velocities and Structure**
  - **Active Region Formation**

Lorentz Force

- **Interaction between the magnetic field and the current (jxB) produces a Lorentz Force**
  - **The Lorentz Force opposes the plasma motions.**
  - **Differential Rotation (Torsional Oscillations)**
  - **Meridional Flow (Quenched near Active Regions)**



Howe et. al. 2013



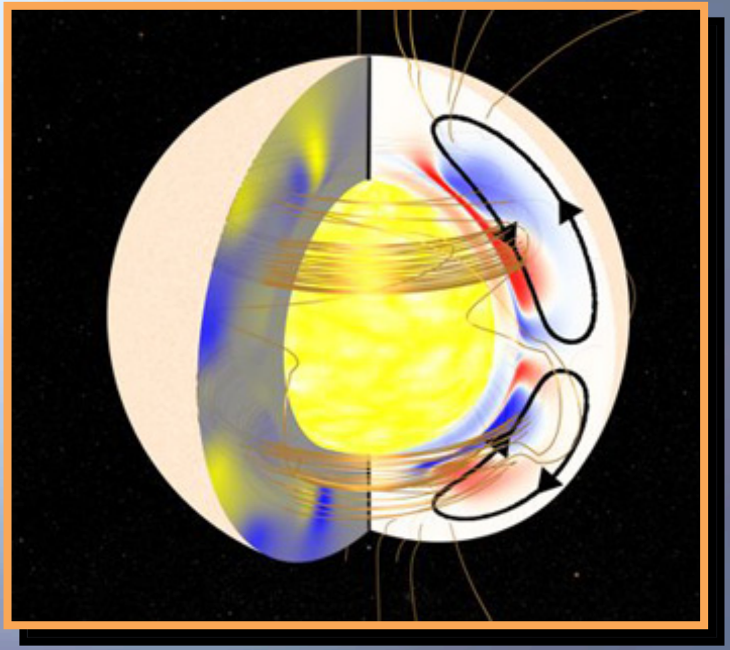
Hathaway and Rightmire

Time delays

Cycle Period is regulated by the Meridional Flow

- **A weakening of the Meridional Circulation shortens the time that it takes for the poloidal field to advected to bottom of the convection zone and propagate equatorward, where it is then converted in to toroidal field.**

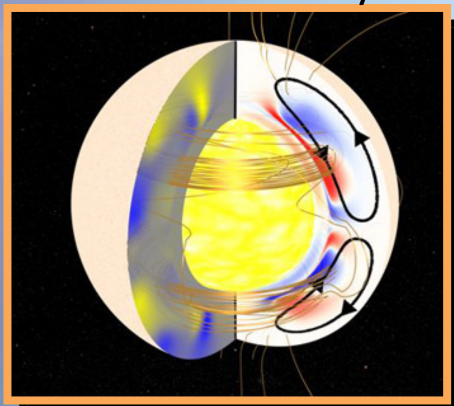
Durney 2000
Charbonneau 2001
Charbonneau et. al. 2007

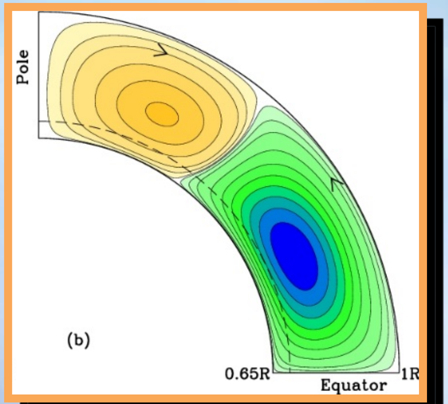


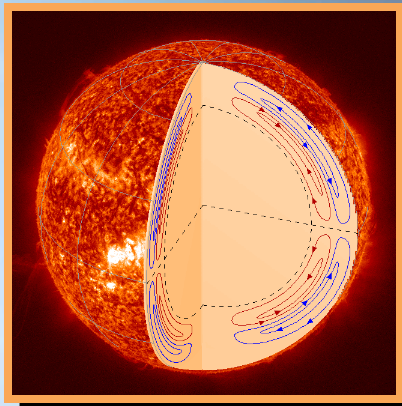
What does the Meridional Flow Really Look Like?

Dynamo Models

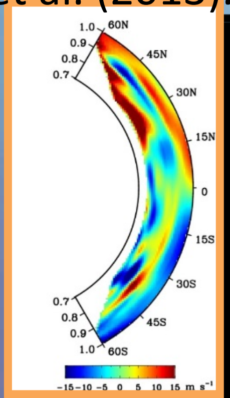
Observations



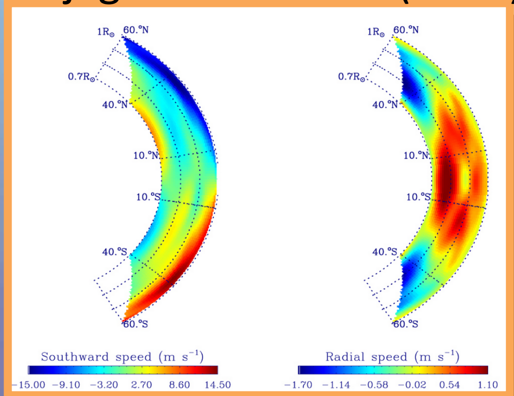




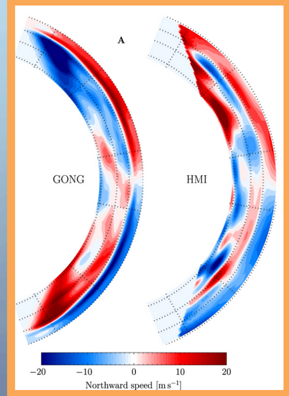
Zhao et al. (2013).



Rajaguru and Antia (2015)



J. Jackiewicz et al.(2015)

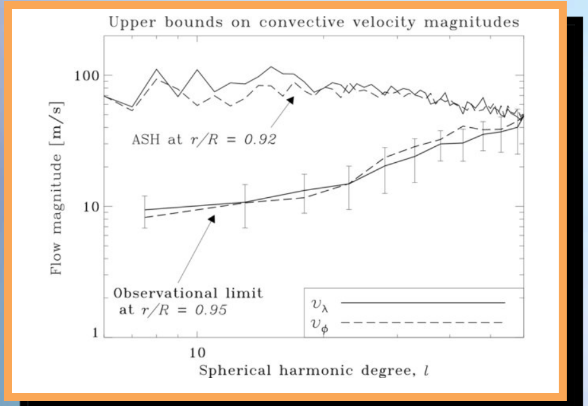


Stochastic Forcing

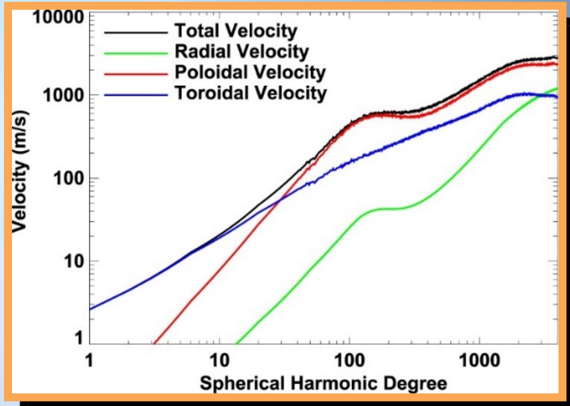
- **Arises from Turbulent Convection**
  - Creates Small-Scale Magnetic Field.
  - Causes Fluctuations in the Mean Flows.
  - Destabilizes Flux Ropes to form Active Regions.
  - Creates Large Scatter in Joy's Law Tilt.
  - Causes long-time scale Modulations in the Cycles (i.e., multiple cycle periodicities.
  - Creates Cycle Intermittency (i.e., grand minima)
- **Typically increases amplitude and duration of the cycles**

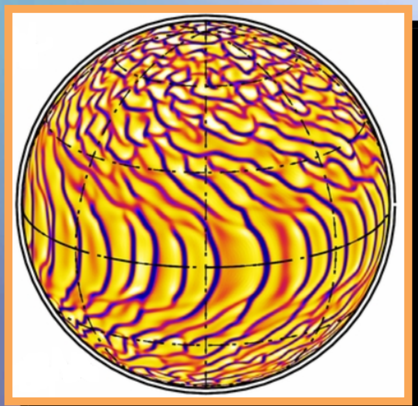
Large-Scale Convection

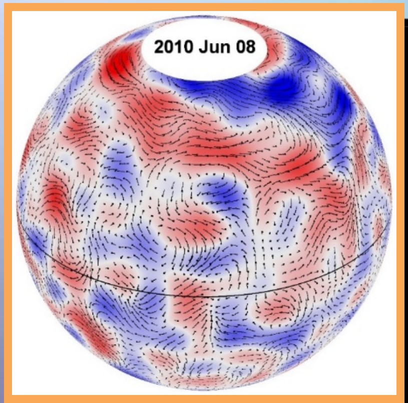
Hanasoge et al. (2010)



Hathaway et al. (2015)



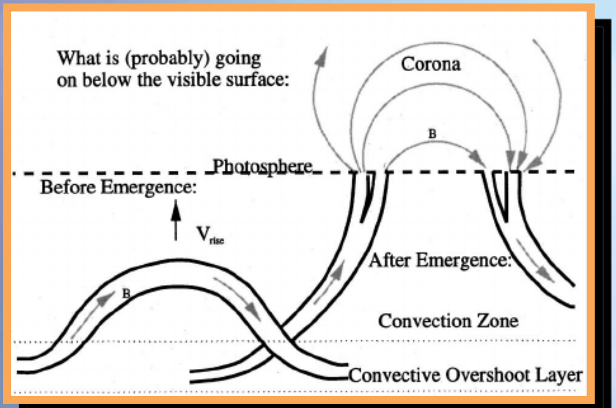




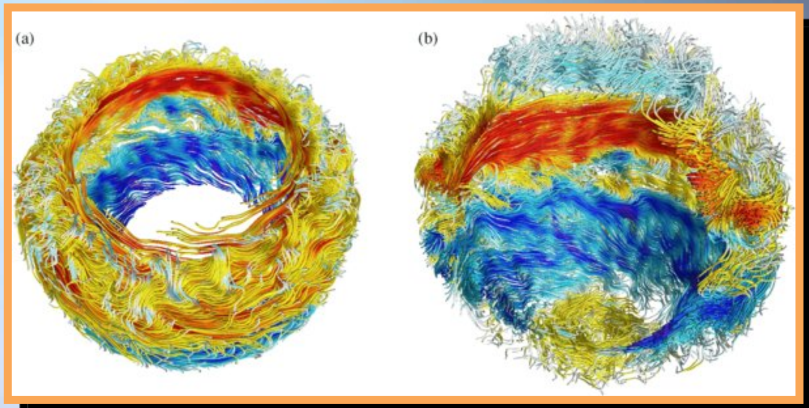
v_r -- Augustson et al. (2012)

v_Φ -- Hathaway et al. (2013)

Active Regions Formation



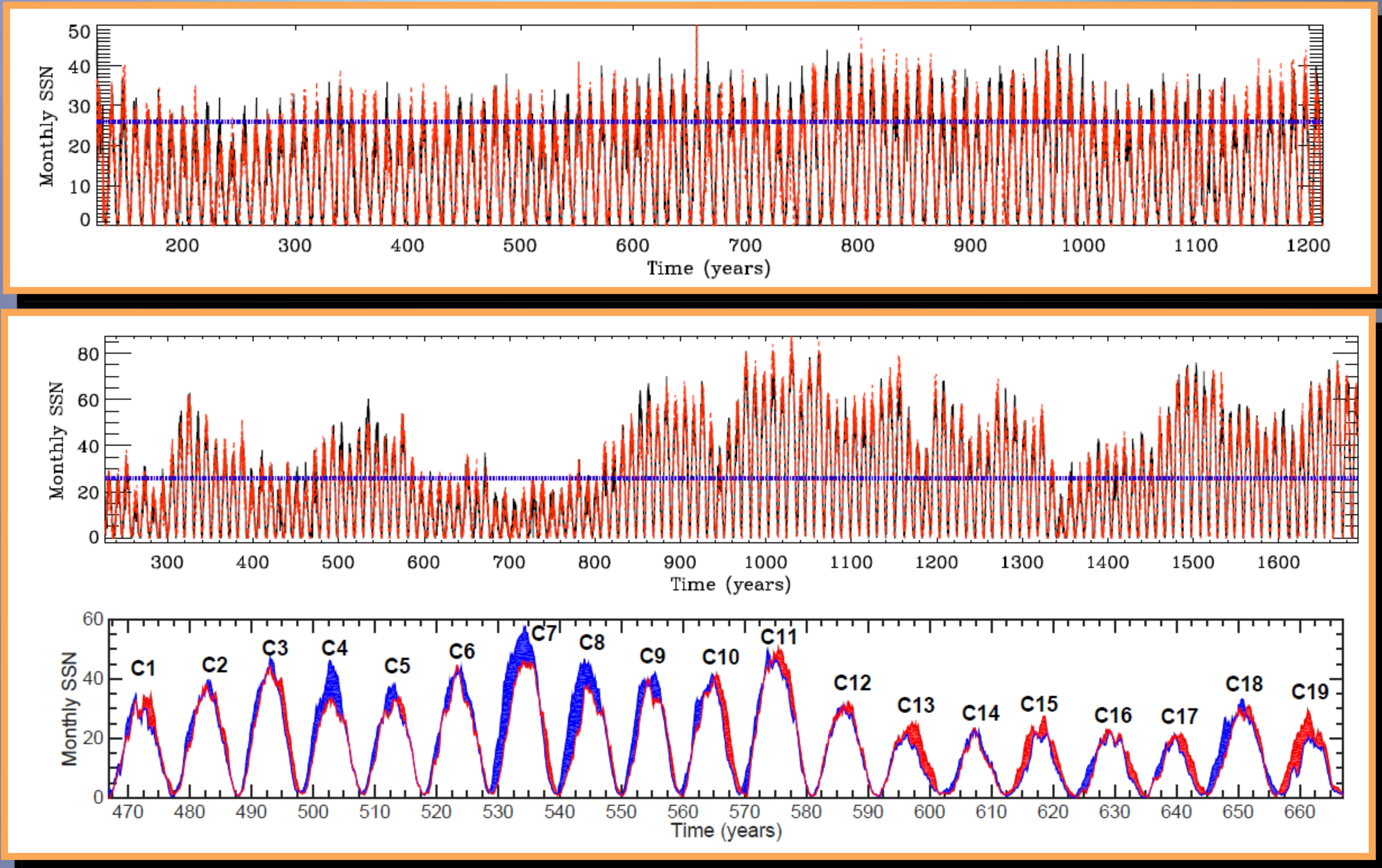
Fisher et al. (2000)



Brown et al. (2011)

- **Do they form in the tachocline in the mid Convection Zone?**
- **Are they rooted or do they break off and rise to the near surface?**

Joy's Law in a Dynamo



Karak & Miesch (2017, submitted)

So, let's just focus on predicting cycle one cycle ahead.

A Tale of Two Models

- Two Babcock-Leighton Models Predict SC24
  - Same Flow Profiles (MF, DR, diffusivity).
  - Both use (different) solar magnetic field observations.
  - Different Poloidal Source Term

- Dikpati et al. (2006)
  - SSN = 150-180

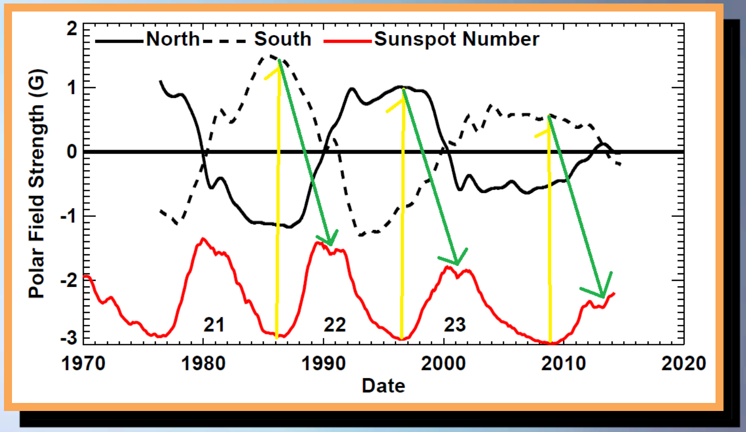
- Chouduri et al. (2006)
  - SSN = 80

All of this goes to show that despite their successes, Dynamo modeling is Hard! Details Matter and there is more work to be done.

What other options do we have?

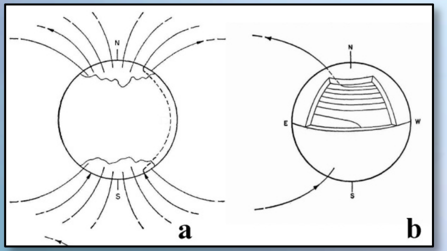
Polar Field Precursors

- Theorized by Schatten et al. (1978)



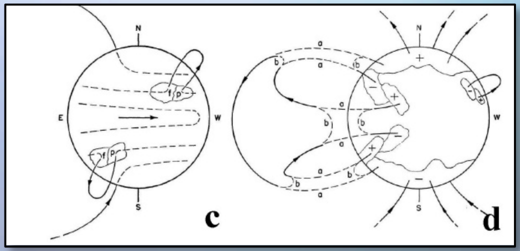
Polar Field Precursor

Linear



Poloidal to Toroidal

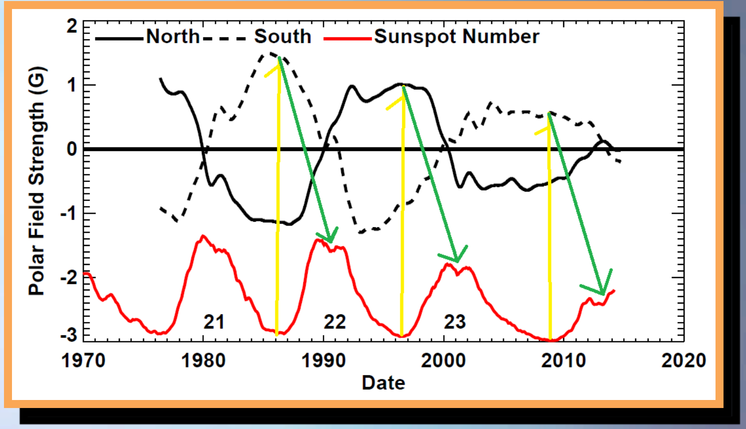
Toroidal to Poloidal



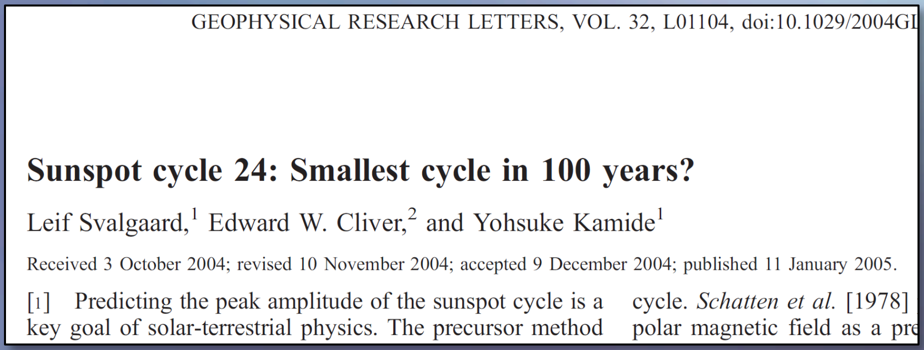
Stochastic

Polar Field Precursors

- Theorized by Schatten et al. (1978)



- Used to successfully predict SC 24 (Svalgaard et al., 1978)


GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L01104, doi:10.1029/2004GL

Sunspot cycle 24: Smallest cycle in 100 years?

Leif Svalgaard,[1] Edward W. Cliver,[2] and Yohsuke Kamide[1]

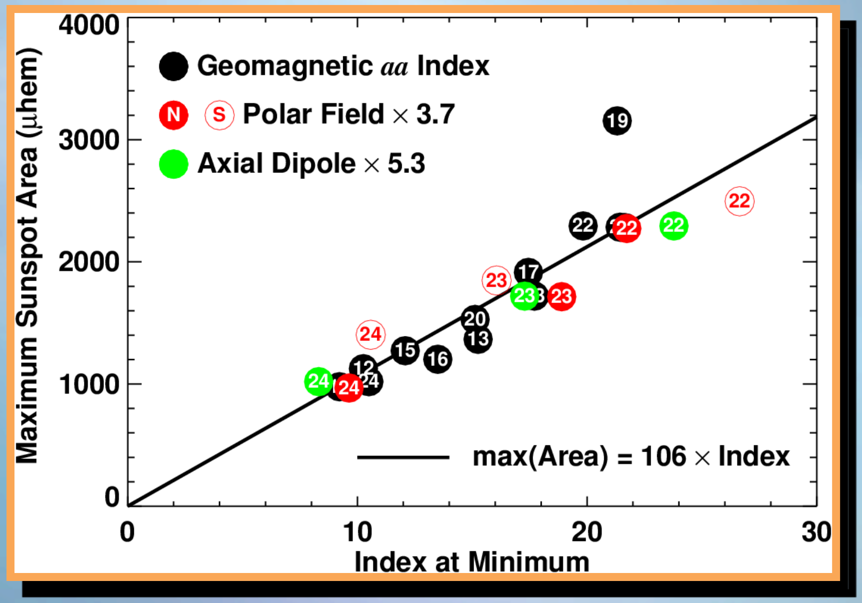
Received 3 October 2004; revised 10 November 2004; accepted 9 December 2004; published 11 January 2005.

[1] Predicting the peak amplitude of the sunspot cycle is a key goal of solar-terrestrial physics. The precursor method

cycle. *Schatten et al.* [1978] polar magnetic field as a pre

Cycle 24 has indeed proven to be the weakest solar cycle in at least a hundred years!!!

The Varying Solar Cycle



- The strength of the Sun's polar magnetic fields at solar minimum have been well established as a predictor of the amplitude of the following cycle. (Munoz-Jaramillo et al. 2012; Svalgaard and Kamide 2013).

Can we determine the polar field strength for Cycle 24 minimum and predict Cycle 25 sooner?

How long does it take residual flux from Active Regions to reach the polar fields???

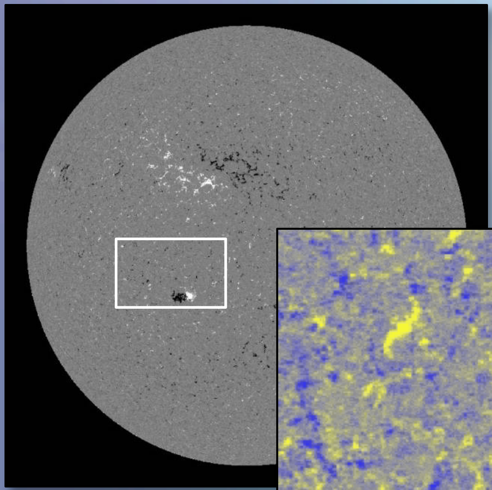
```
IDL> Rsun = 695500000.
IDL> dia = 2*!pi*rsun
IDL> stime = (dia/4.)/15.
IDL> print, stime/(60.*60.*24.)
      842.970
IDL>
```

Surface Flux Transport

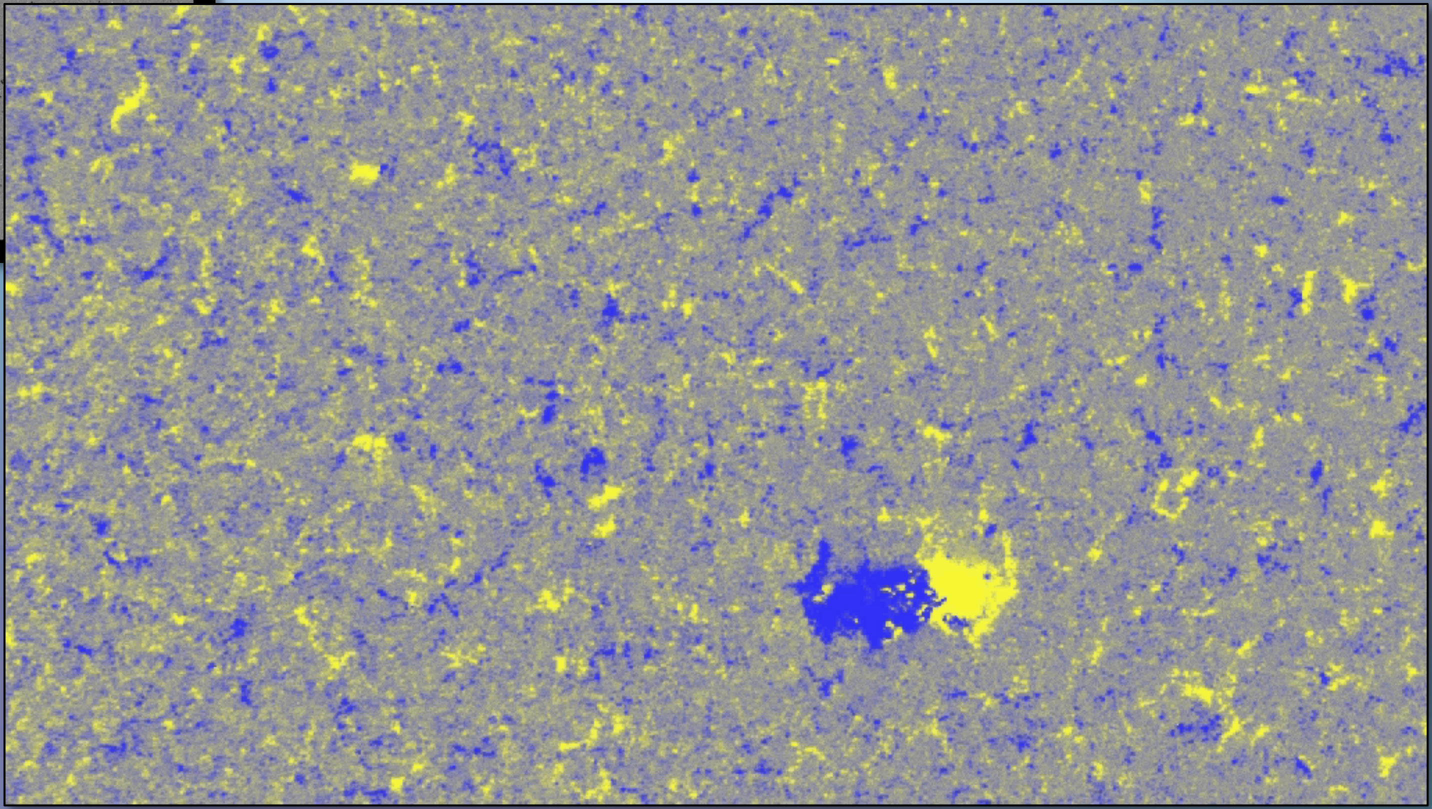
- **Take B_r today and evolve it forward in time.**
- $\partial B \downarrow r \,/\partial t + \nabla\cdot(uBr)=S(\theta,\varphi,t)+\eta\nabla 2 Br$

  - **B_r is the radial magnetic flux**
  - **u is the horizontal velocity vector** (which includes the observed axisymmetric flows and the non-axisymmetric convective flows)
  - **S is a magnetic source term**
  - **η is the diffusivity**

Flux Transport in Action



Looping video showing 4 days of HMI observations



Advective Flux Transport

Take B_r today and evolve it forward in time.

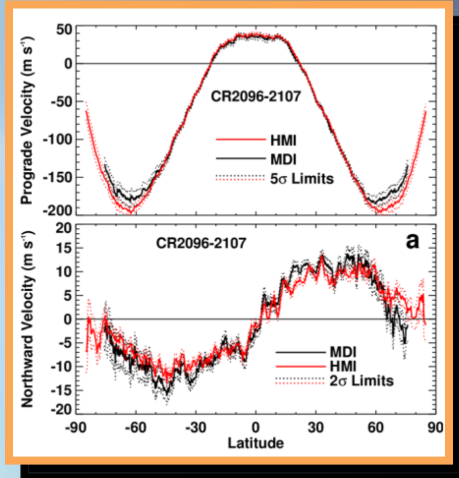
- Observed Surface Flows
- Observed Magnetic Field

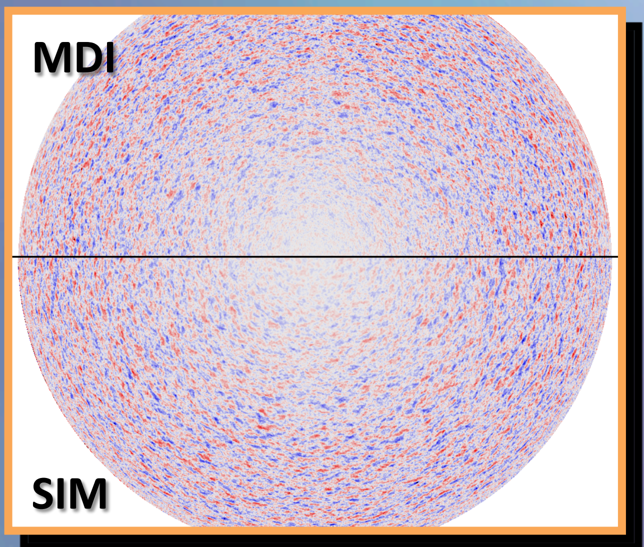
- Flux Maps of entire Sun
- Butterfly diagrams
- Polar Field Plots
- AR evolution

Upton, L., & Hathaway, D. H. 2014a, ApJ, 792, 142
Upton, L., & Hathaway, D. H. 2014b, ApJ, 780, 5

Observed Flows

- Differential Rotation
- Meridional Flow
  - Measured with Feature Tracking.
  - Averaged over each 27-day rotation.
  - Smoothed in time and integrated in the model.





- Convective Flow
  - Explicit convective simulation rather than a diffusivity coefficient alone.
  - The convective simulation uses an evolving spectrum of spherical harmonics.
  - Reproduces the observed velocity spectrum, the cell lifetimes, and the cell motions in longitude and latitude.

Observed Magnetic Field

Incorporate magnetice field in two ways: by assimilating magnetograms and by simulating active region emergence.

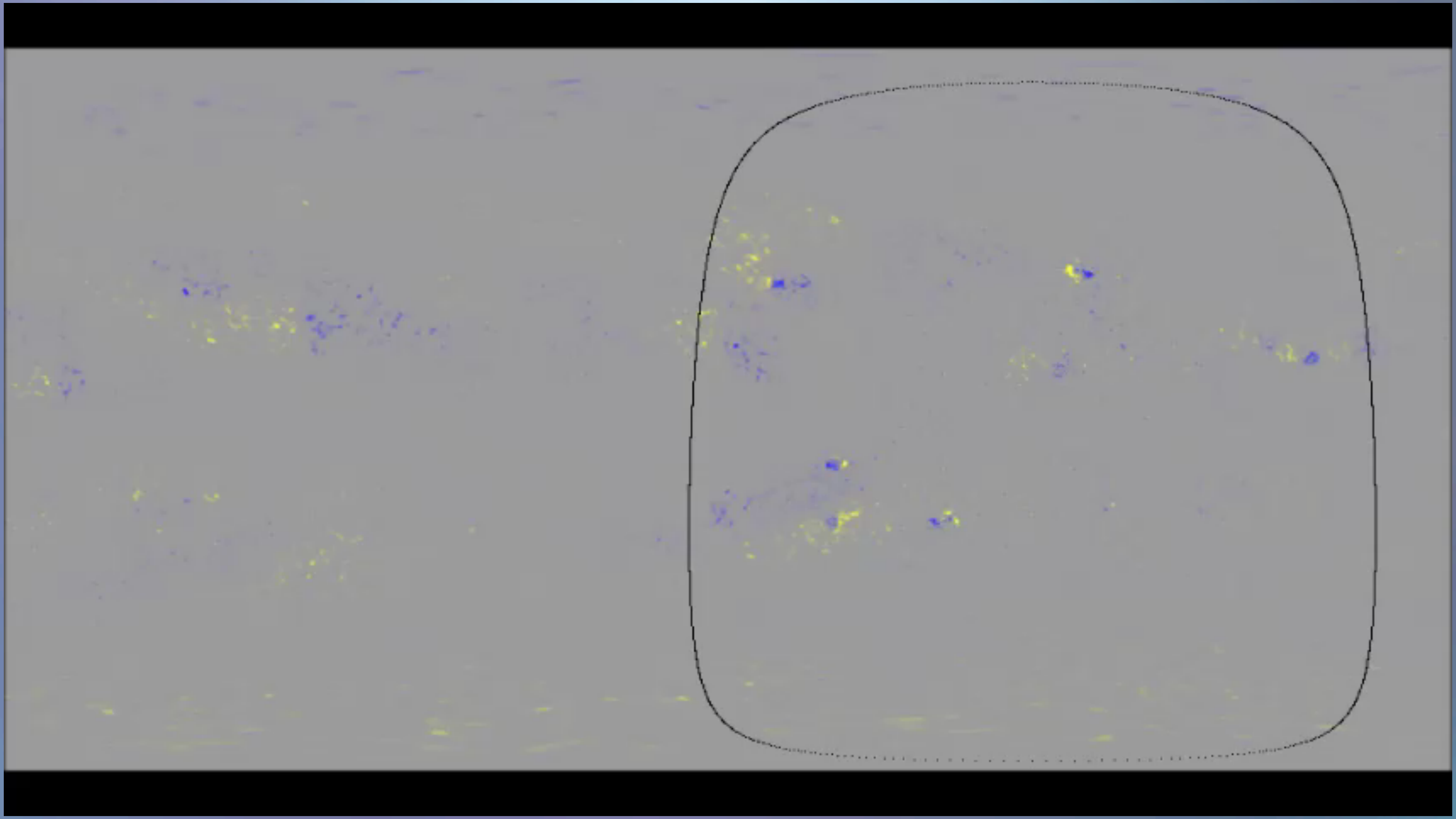
Data Assimilation

- Provides the magnetic history
- Corrects for any differences between data and model
- Provides the closest contact with observations

Simulate Active Regions

- Incorporates active region observations & statistics
- Provide estimate of future AR emergence

Flux Transport Movie



What are some possible sources of stochastic effects in SFT???

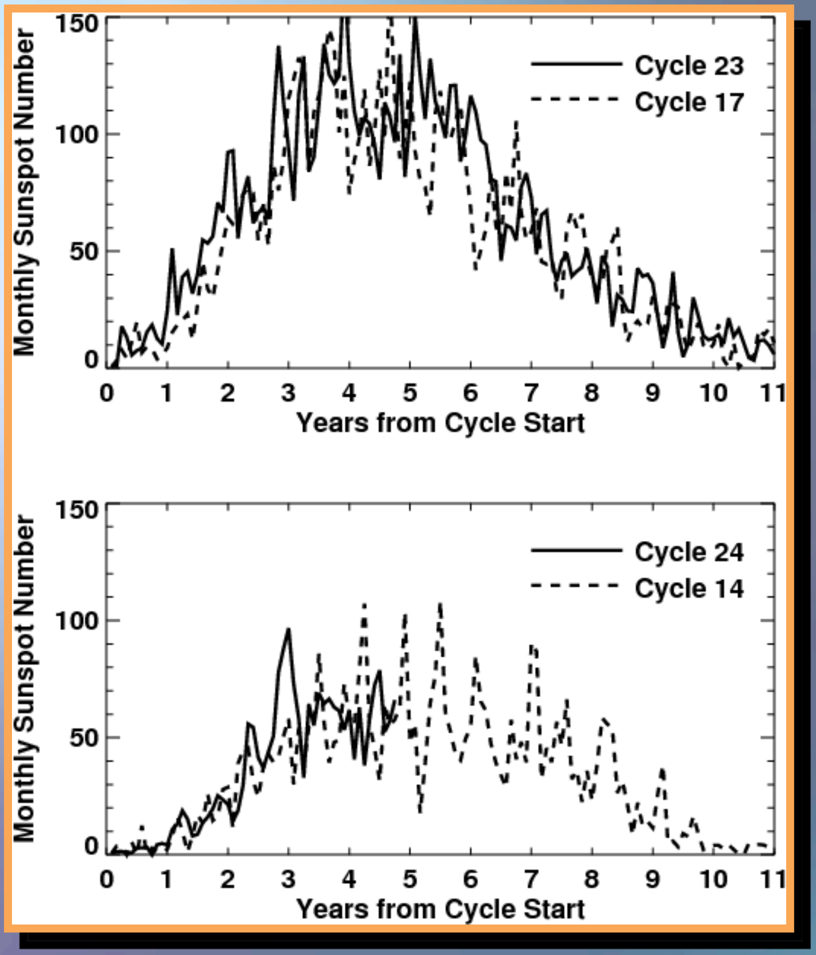
Stochastic Effects

- Joy’s Law Tilt
- Active Region Placement
- Convection Pattern
- Meridional Flow

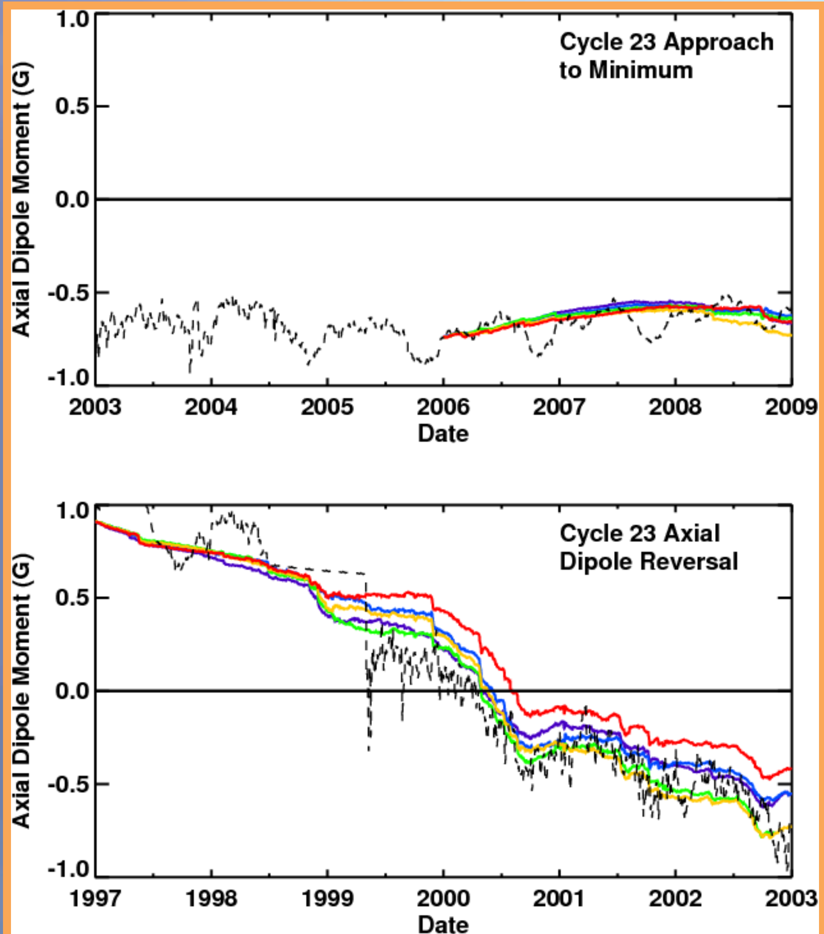
Active Region Sources

Solar Cycle Proxies

- Active region sources are simulated by using prior solar cycles as proxies for the modeled cycles.
- Solar Cycle 17 is chosen as a proxy for Solar Cycle 23 (top).
- Solar Cycle 14 is chosen as a proxy for Solar Cycle 24 (bottom).



Predicting Cycle 23



Solar Cycle 23

- Predictions of Cycle 23 with Cycle 17 active regions.
- Axial dipole moment predictions with a start time of ~three years ahead.
- Cycle 23/24 minimum (top).
- Cycle 23 polar fields reversal (bottom).
- Five supergranule realizations (color) - the stochastic nature of supergranular motions had a larger effect during reversal.

Why do Convection Cells have a bigger stochastic effect at solar maximum than solar minimum???

There is less flux to interact with.

Break Time!

When we return: Predicting cycle 25 with AFT.

And we'll look at the stochastic effects of Meridional Flow and Joy's Law Tilt.

Predicting Cycle 25

Predict Amplitude of Cycle 25

- Simulate the Evolution from 2016-2020 Using Cycle 14 Active Regions
- Use Polar Field Strength Predictions to Estimate Strength of Cycle 25

Investigate Stochastic Effects

- Meridional Flow – 2 Sets
- Joy's Law Tilt – 8 Sets
- Convective Pattern – 8 Sets

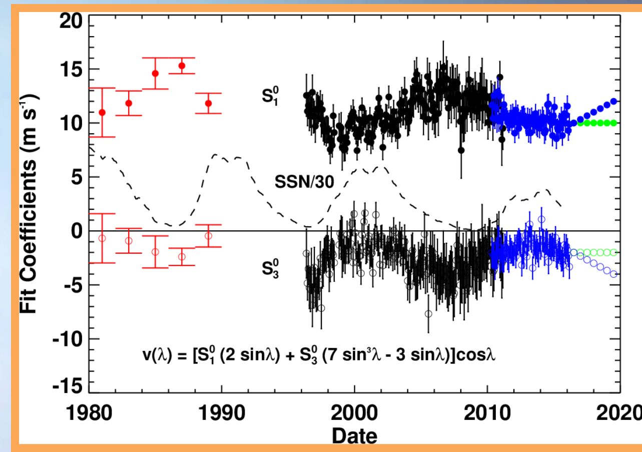
MF1		MF2	
JL1	CP1	JL1	CP1
JL2	CP2	JL2	CP2
JL3	CP3	JL3	CP3
JL4	CP4	JL4	CP4
JL5	CP5	JL5	CP5
JL6	CP6	JL6	CP6
JL7	CP7	JL7	CP7
JL8	CP8	JL8	CP8

32 Total Simulations

Stochastic Effects

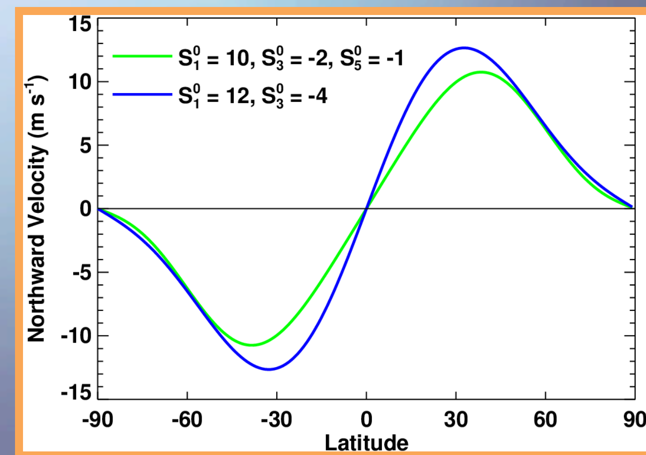
Meridional Flow

- MF seen at the end of January 2016 continues without changing
- MF evolves to more closely match the profile found at the last cycle minimum.



Joy's Law

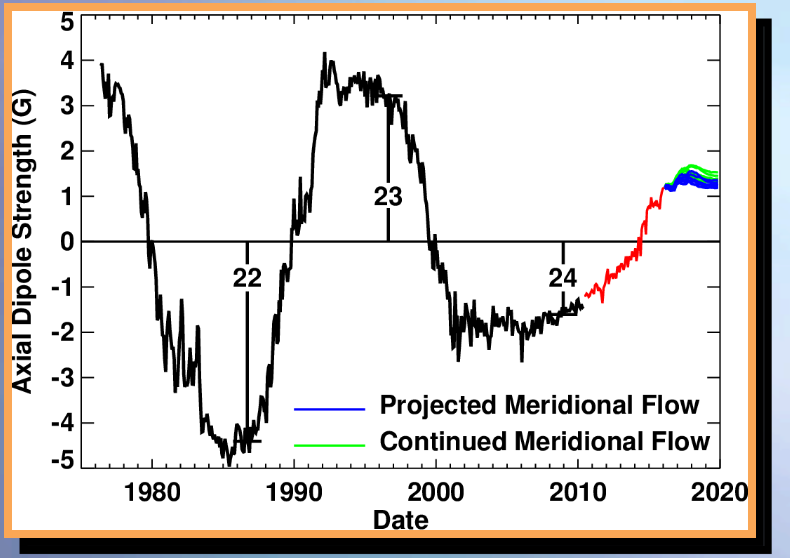
- Based on Stenflo and Kosovichev (2012)
- $\Delta\lambda(A, \lambda, \Phi) =$
$\Delta\varphi(A) \tan(32.1^\circ \sin\lambda + \delta\lambda(\Phi))$
- $\delta\lambda(\Phi) = 25.3^\circ + 154.7^\circ 1.59/(1.59 + \Phi \uparrow 0.84)$



Convection Pattern

- One realization
- Shifted by 8 multiples of 45° in longitude.

Meridional Flow Variability



- While there is some variability in the axial dipole due to the variations in the convection pattern, the systematic variation with the meridional flow profile is more apparent (i.e., the offset between the green and blue lines).

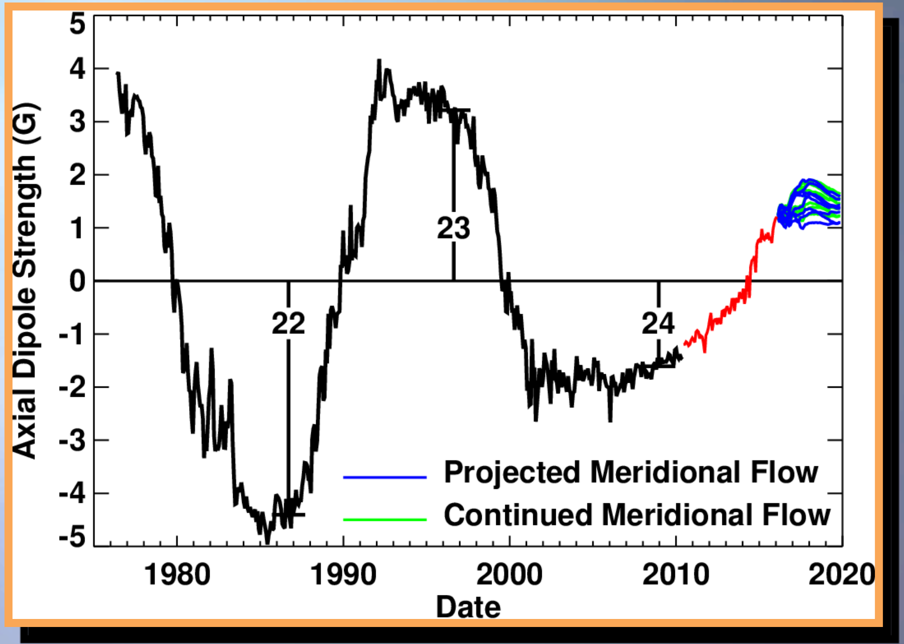
- As expected, the slower continued meridional flow profile produces a stronger axial dipole.

Why does a slower meridional flow produce a stronger dipole???

Due to increased cancellation at low latitudes.

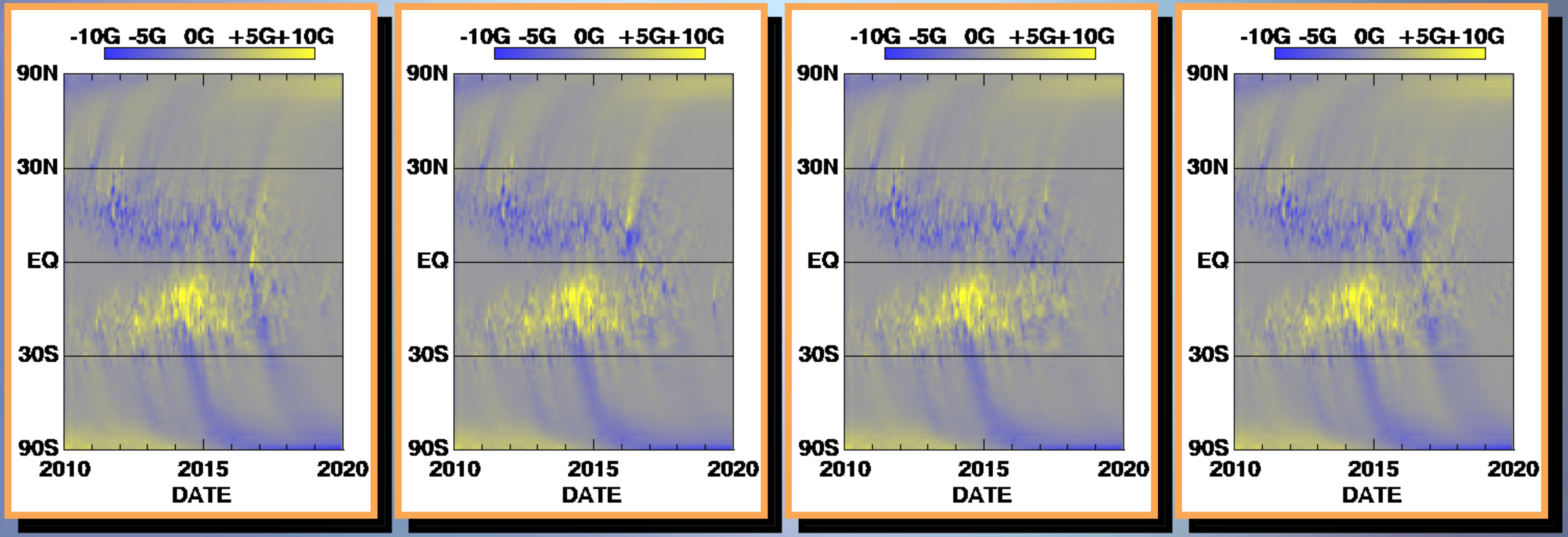
Joy’s Law Variability

- The axial dipole strength at the start of Cycle 25 is similar to that at the start of Cycle 24 in late 2008 but substantially smaller than that at the start of Cycle 23 or Cycle 22.

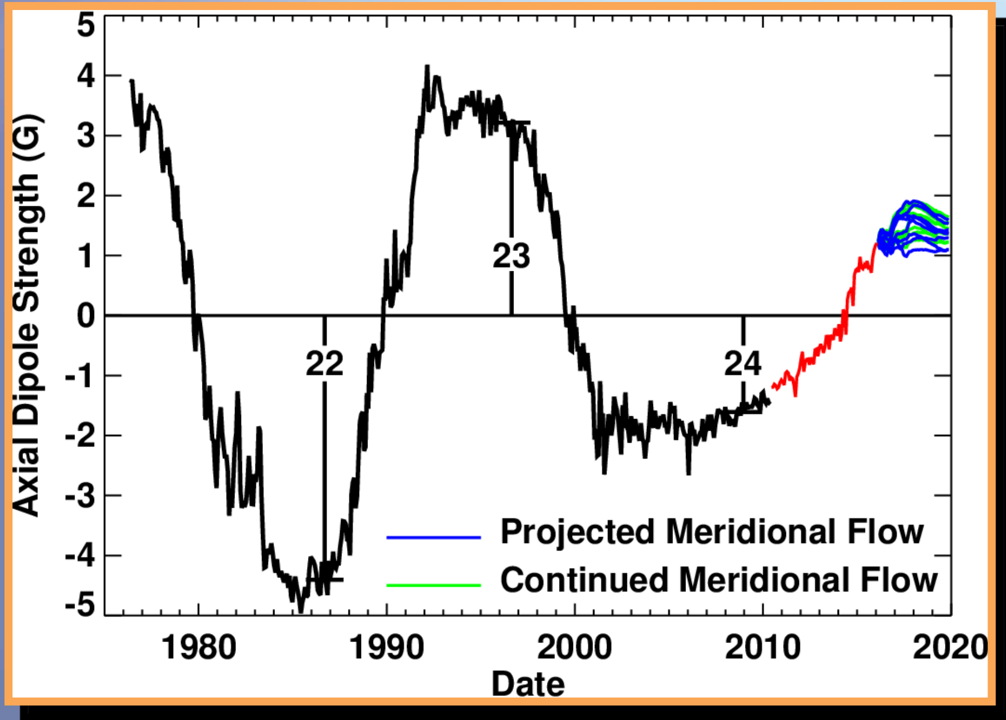


- The variations in the Joy’s Law tilt of active regions clearly has a more substantial impact on the axial dipole strength -- large enough to over-power the variations due to changes in the meridional flow.
- After 4 years of simulation, this results in an uncertainty of ~ 15%.

Joy's Tilt Variation



How big will Cycle 25 be?

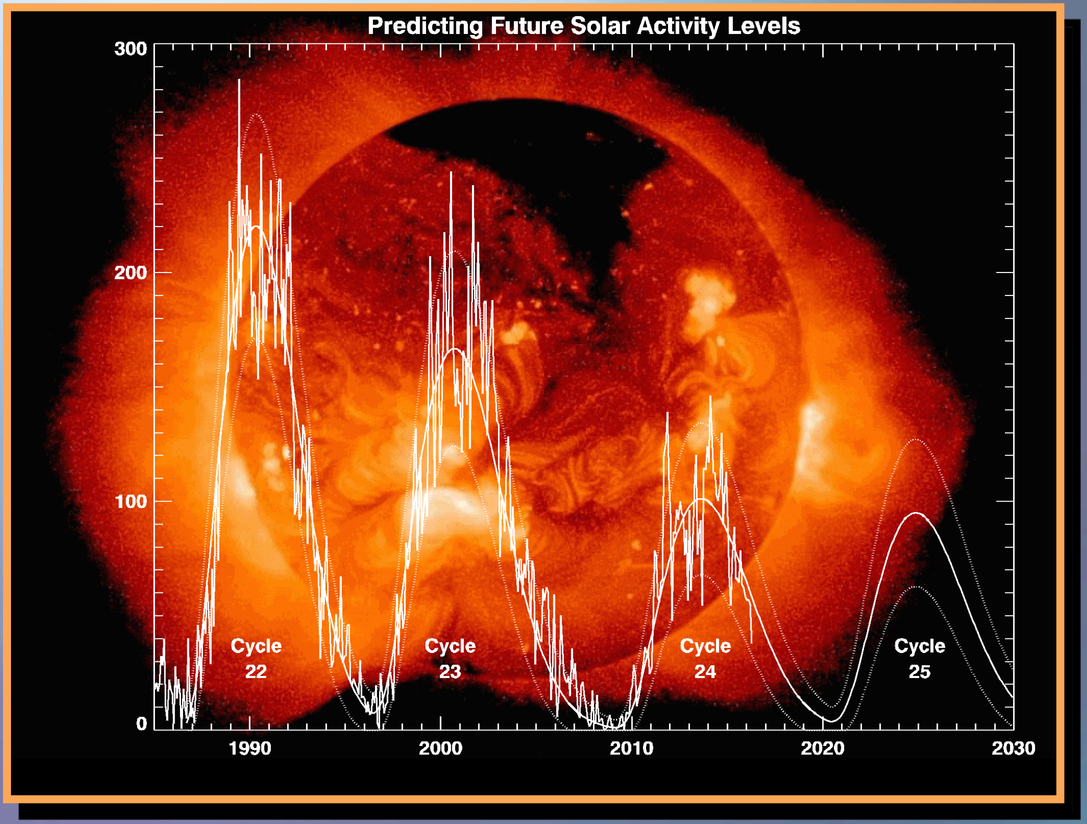


- The average of all 32 realizations gives the axial dipole strength at the start of 2020 (start of Cycle 25) as **+1.36 ± 0.20**

- The axial dipole strength was -1.61 G at the start of Cycle 24, +3.21 G at the start of Cycle 23, and -4.40 G at the start of Cycle 22.

Cycle 25 Prediction

- Cycle 25 will be a small cycle like Cycle 24, perhaps slightly smaller.
- Small cycles, like Cycle 24, start late and leave behind long cycles with deep extended minima [Hathaway, 2015].
- We expect a similar deep, extended minimum for the Cycle 24/25 minimum in 2020.



Why do long, extended minima precede small cycles ???

A weak poloidal field takes longer to build up a toroidal to produce active regions.

Can we extend our predictions out further?

Is there a limit?

As the next generation of solar physicists, I challenge you to find out!!

QUESTIONS

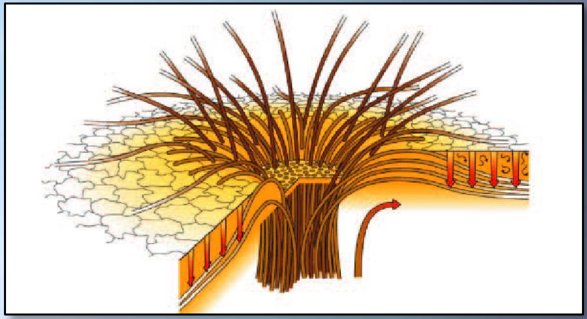
and

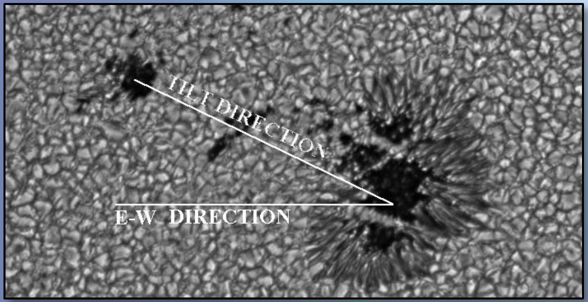
COMMENTS

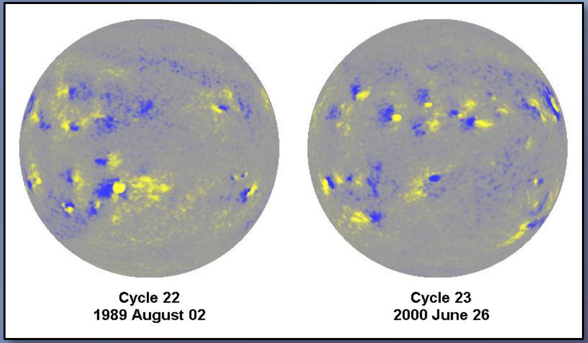
Supplementary Slides to follow…

Sunspots

Sunspots are the first magnetic structures observed on the Sun. These cool dark regions are formed where the magnetic field lines pass through the photosphere.

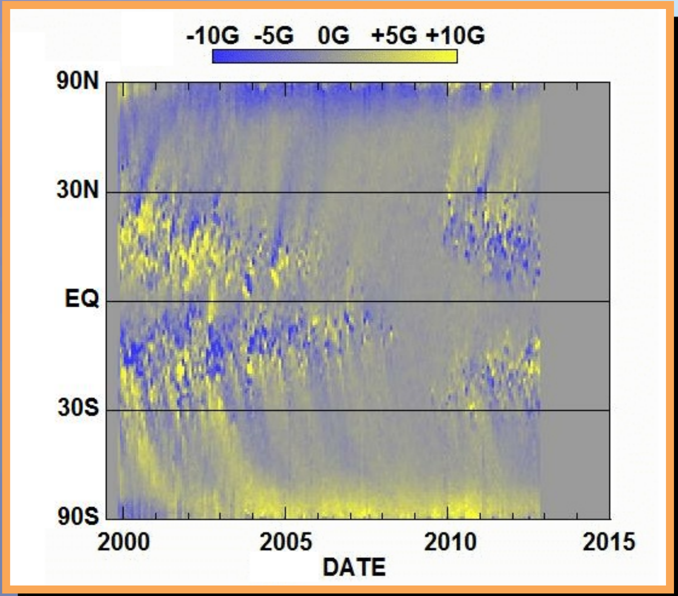




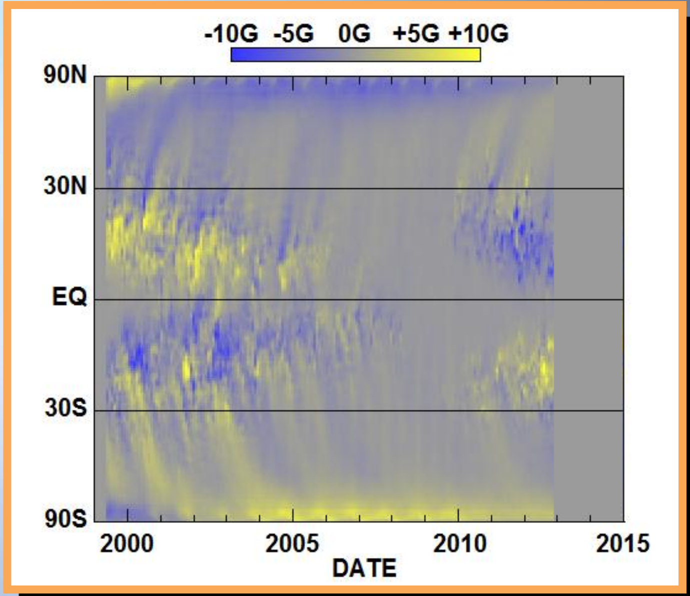


- Usually form in groups that last anywhere from a few days to a few weeks.
- Were used to determine that the sun rotates in about 27 days (or 1 Carrington Rotation).
- **Joy's Law Tilt**: sunspot groups are tilted with the leading spots closer to the equator.
- **Hale's Polarity Law**: sunspot groups have opposite polarity from north to south and polarity changes from cycle to cycle.

Compared to Observations



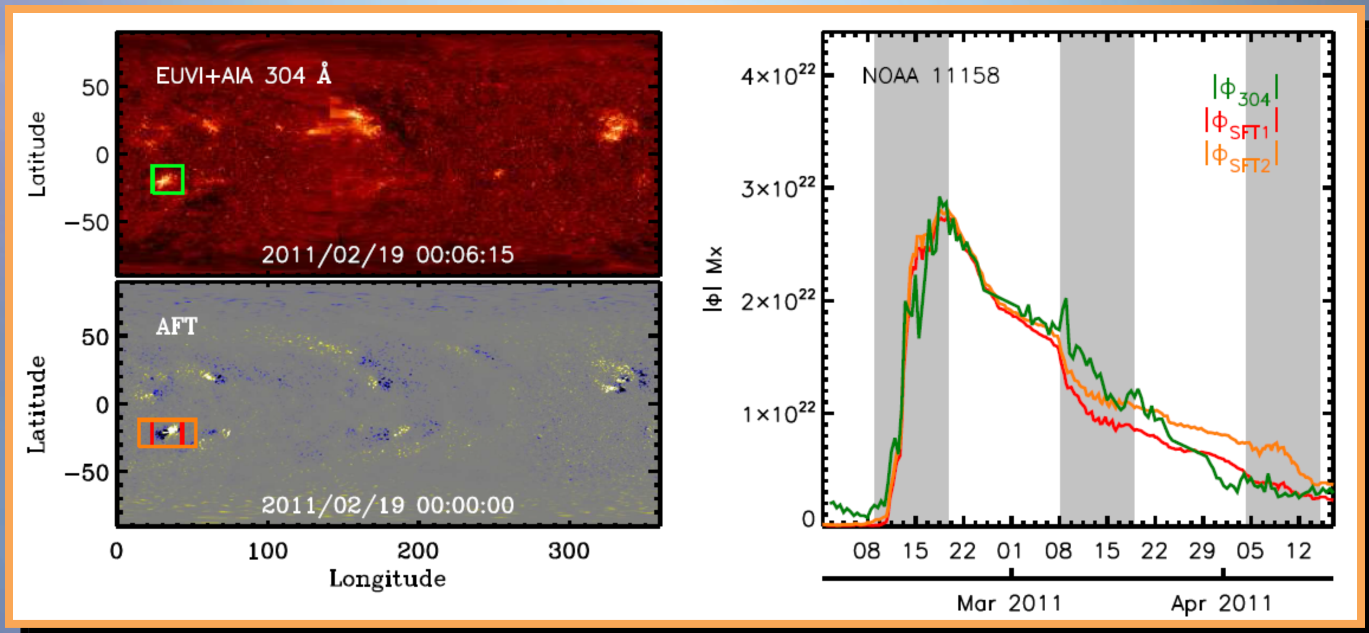
NSO Observed



Baseline

The magnetic butterfly diagram created with NSO observations is nearly identical to the Baseline magnetic butterfly diagram.

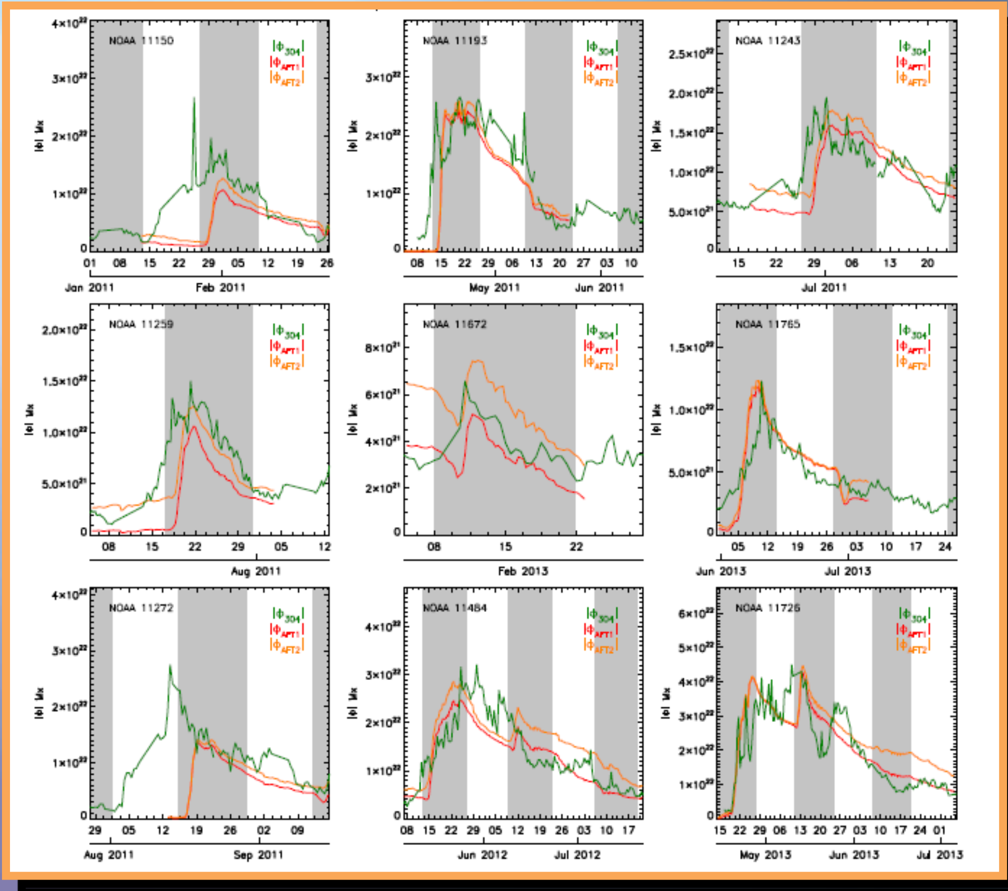
Long Term AR Evolution



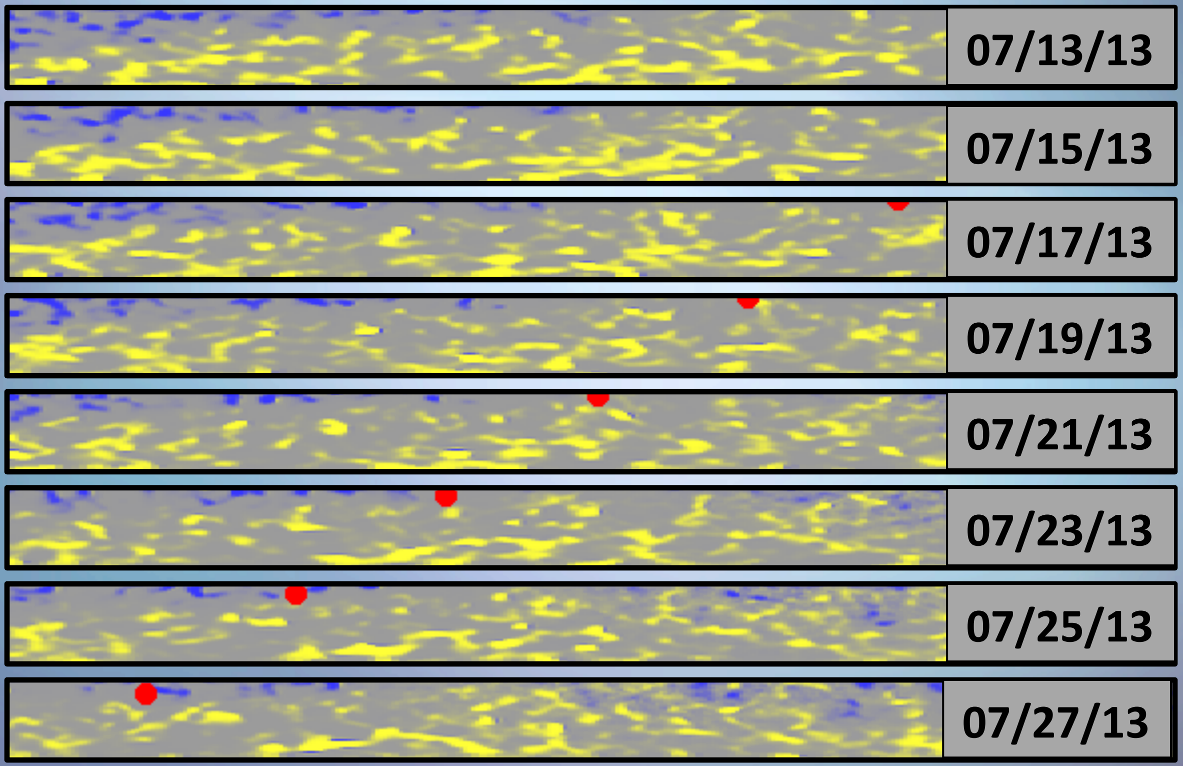
- We compared composite EUVI+AIA 304°A and AFT model maps for NOAA 11158.
- The plot shows the total unsigned magnetic flux as function of time for the 304°A proxy (green) and for two area integrations of the AFT model (red and orange).
- Grey areas mark the times when the active region is on the Earth side, when data from HMI magnetograms is being assimilated.
- The two are in good agreement for several rotations of the AR.

More Examples

- This was repeated for several simple Active Regions with similar results.
- The close match of the curves during times of assimilation serves as an assurance that our 304°A proxy approach works
- The close match elsewhere shows that the AFT model can accurately reproduce the active region evolution when the active region is not being observed by HMI.

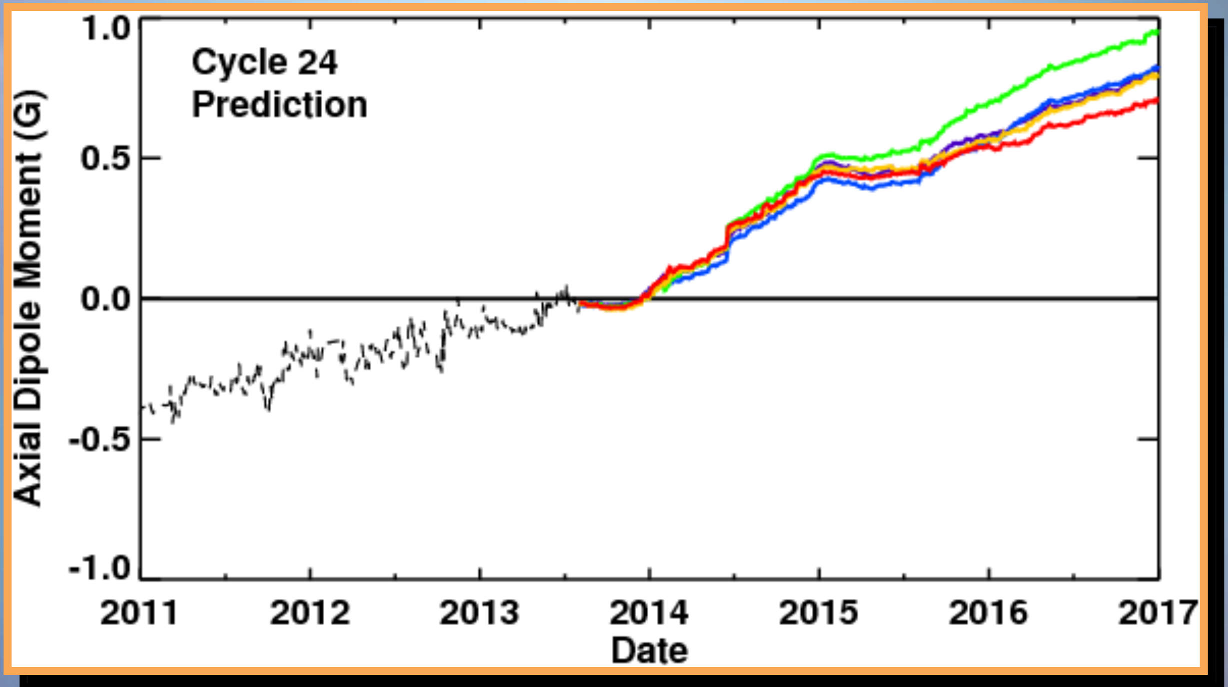


Coronal Cavities



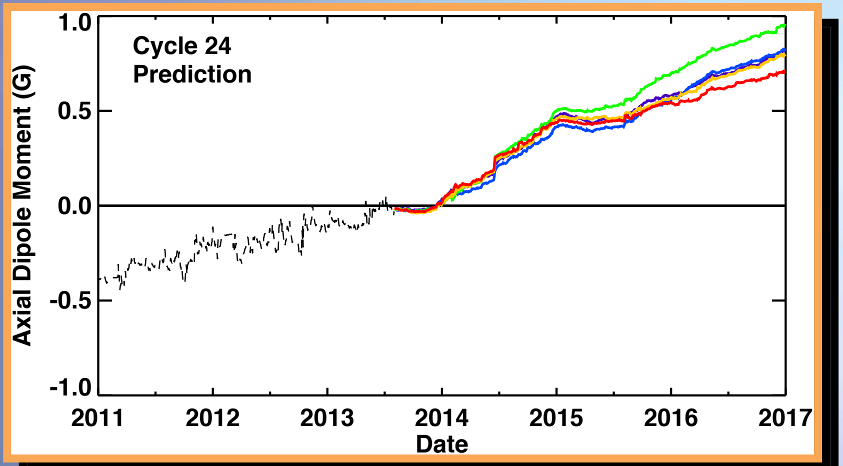
- Nishu Karna tracked the position of a coronal cavity over time.
- This location (red dot) was superimposed onto saturated AFT maps.
- The location of this cavity tracks nicely with the polar PIL line.

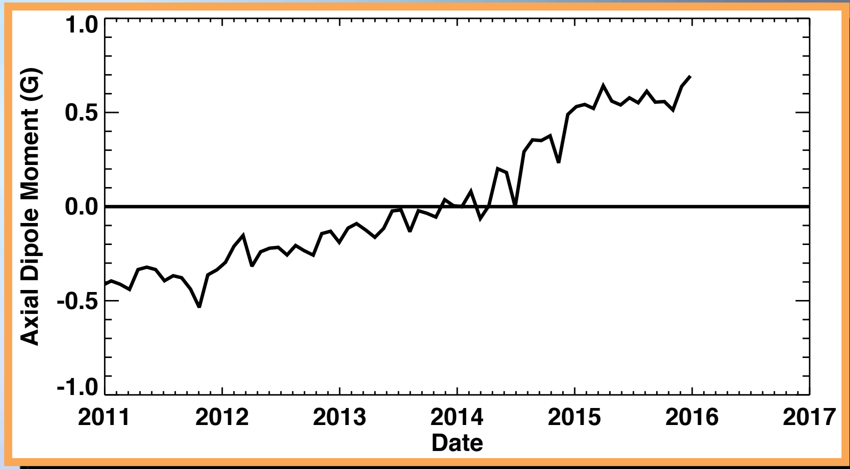
Predicting Cycle 24



- Predictions of Cycle 24 with Cycle 14 active regions.
- Axial dipole moment predictions with a start time of ~three years ahead.
- Five supergranule realizations are shown in color.
- Predictions made 2-3 years prior to minimum (2017-2019) will provide a accurate estimate of the amplitude of Cycle 25.

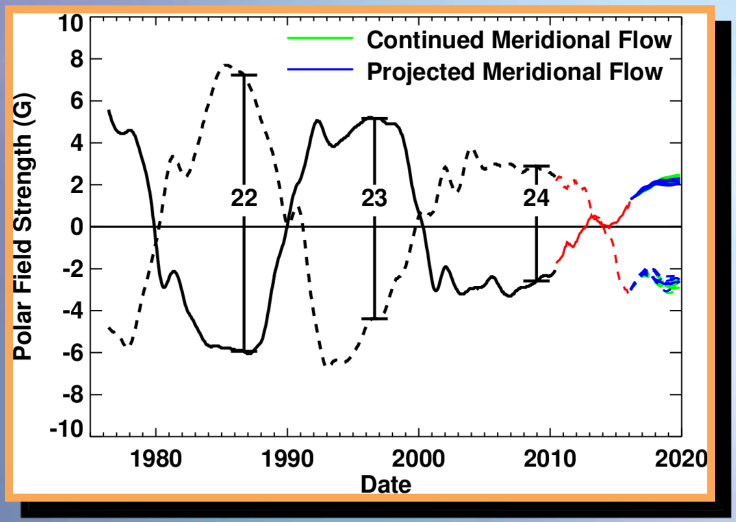
Validating Predictions

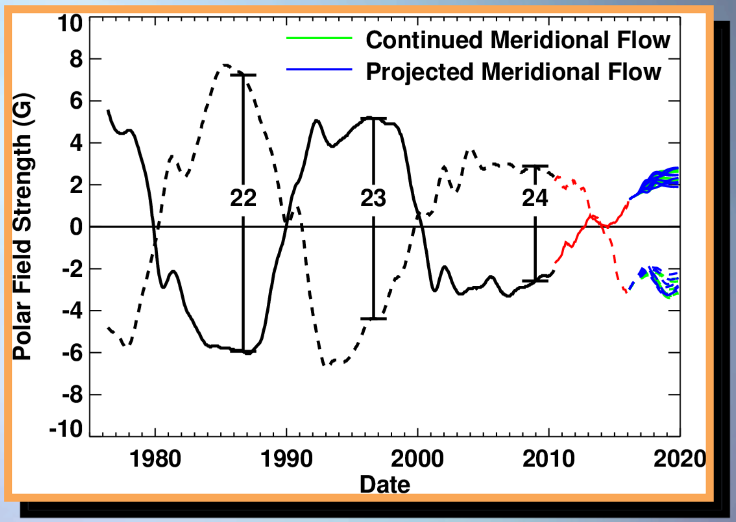




- Nearly three years later, the observations agree well with the predictions.
- A relapse was observed during the later half of 2013.
- A steady increase was observed through 2014.
- A plateau occurred through 2015.
- Both the predictions and the observation give an axial dipole moment of ~0.6 G for the start of 2016.

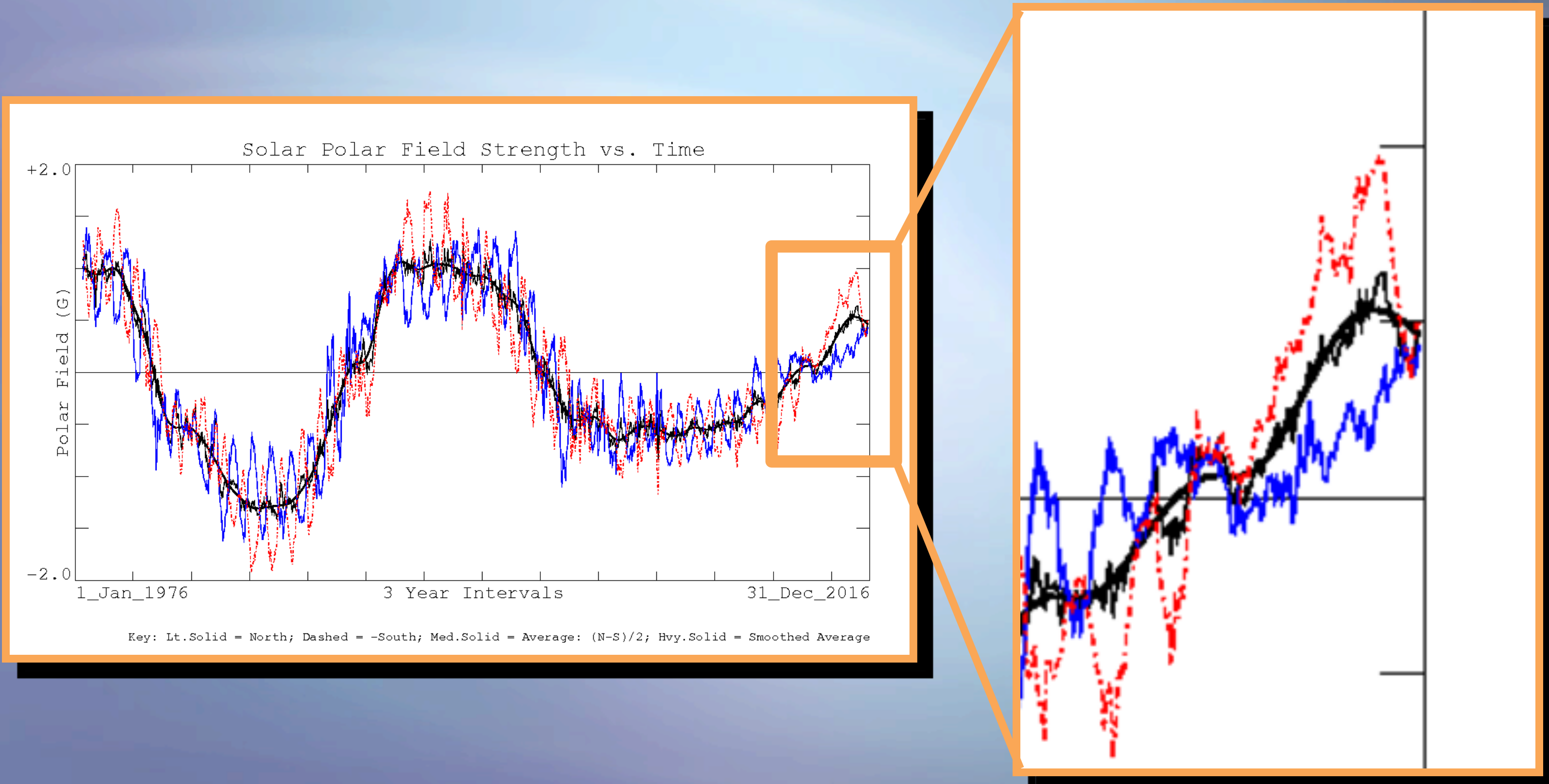
Hemispheric Assymetry





- **The predicted asymmetry of Cycle 25 is -0.16 – the southern hemisphere should dominate the north.** (Cycles 22, 23, and 24 were -0.20, +0.16, and -0.11)
- **We predict that the polar fields in the south will weaken in late 2016 and into 2017 before recovering.**
- **This weakening is seen in all of our realizations and is attributed to magnetic field patterns that are already on the Sun in our initial magnetic map**

Latest WSO



- WSO now shows that this weakening is now occurring.