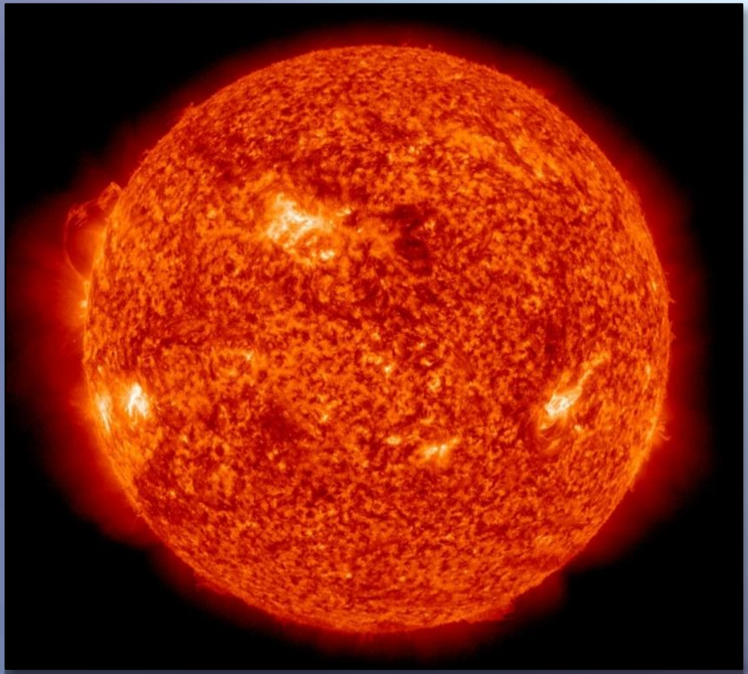
Introduction to the Solar Dynamo



L. A. Upton

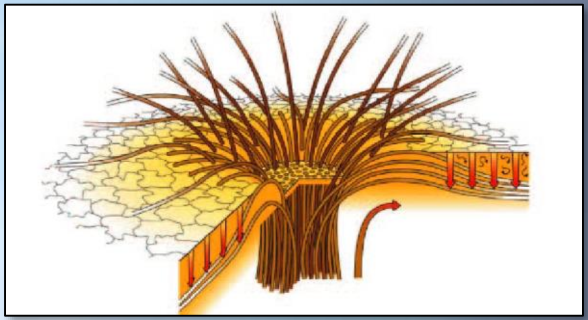
Heliophysics

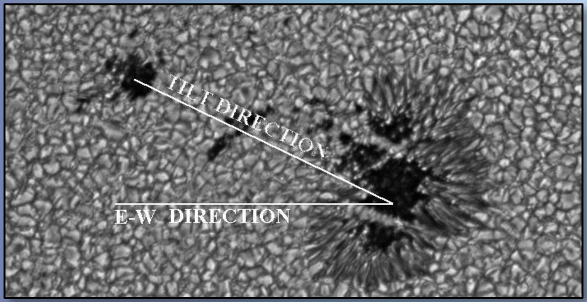
Summer School

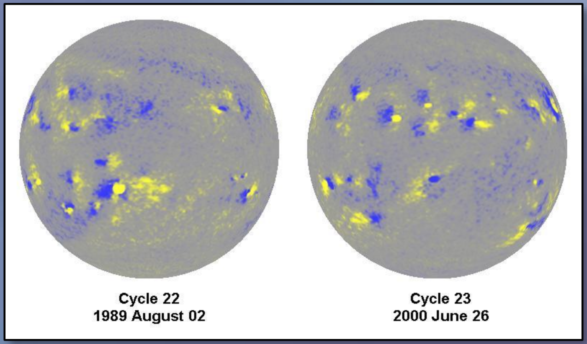
July 27th 2016

Sunspots

Sunspots, cool dark regions appearing on the surface of the Sun, are formed when the magnetic field lines pass through the photosphere. (6000 times stronger than Earth's Magnetic Field)





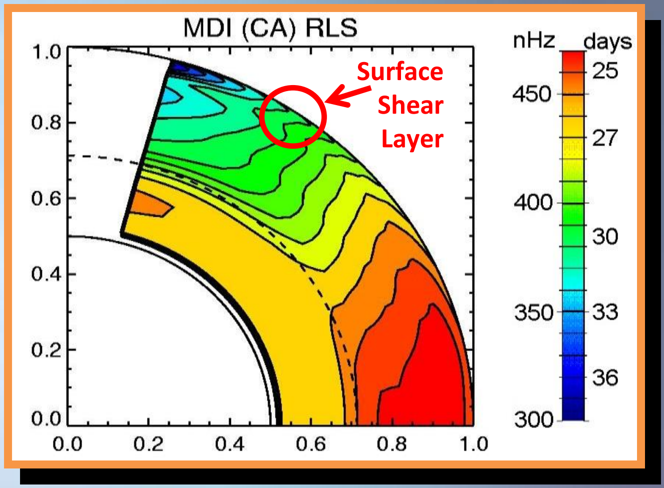


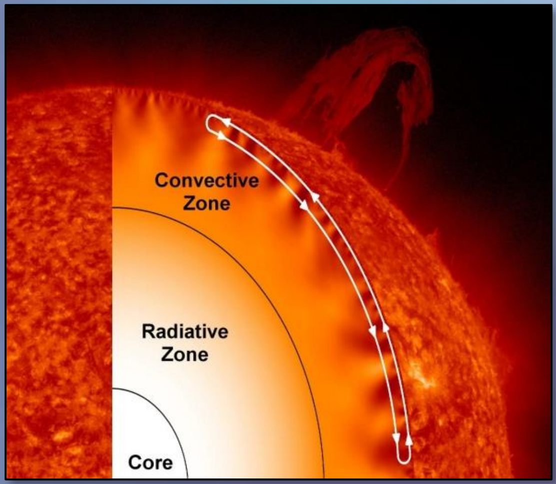
- Usually form in groups that last anywhere from a few days to a few weeks.
- Were used to determine that the sun rotates in about 27 days (or 1 Carrington Rotation).
- **Joy's Law Tilt**: sunspot groups are tilted with the leading spots closer to the equator.
- **Hale's Polarity Law**: sunspot groups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

Axisymmetric Flows

Differential Rotation

- Sun is not a solid body
- Rotation rate changes with depth and latitude
- Relative velocity ~200-250 m/s





Meridional Flow

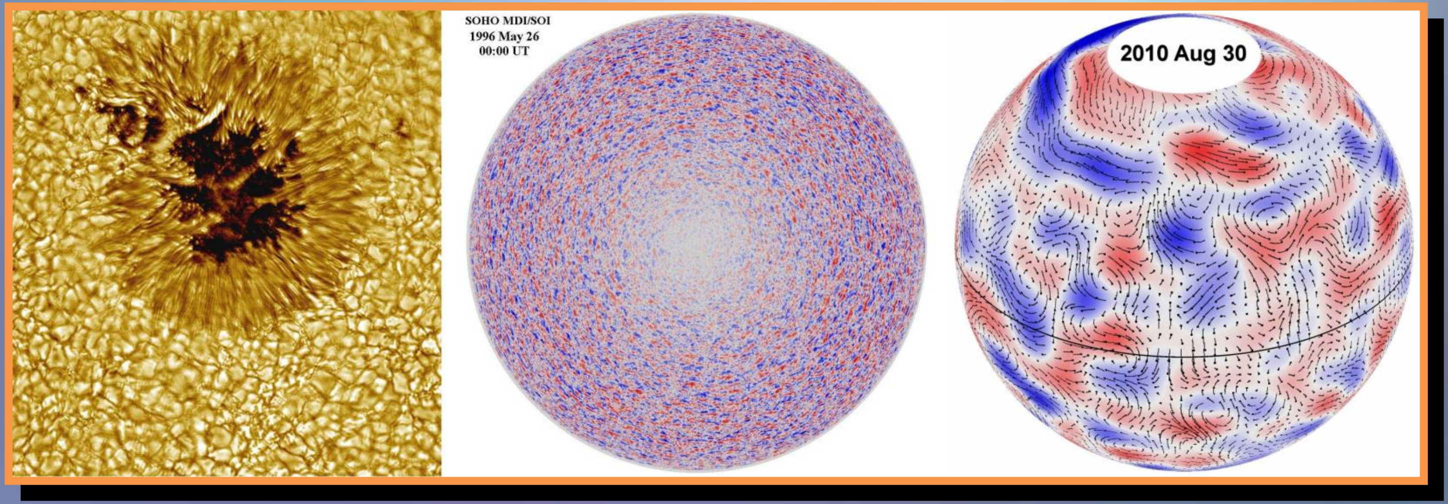
- Poleward flow at the surface
- Velocities ~10-20 m/s
- Equatorward flow at some depth
- Countercells (polar or radial) may exist

Convective Flows

- Turbulent Convection
  - Large T gradient in the Convection Zone
  - Plasma Rises and Falls (like boiling water)
  - Magnetic Elements (B) are transported to the boundaries of the convective structures
  - B becomes concentrated in the downdrafts as small B_r field.
  - B_r is then transported like passive scalars (corks) by the flows.
  - Horizontal Velocities at the surface ~300-500 m/s

Convective Structures

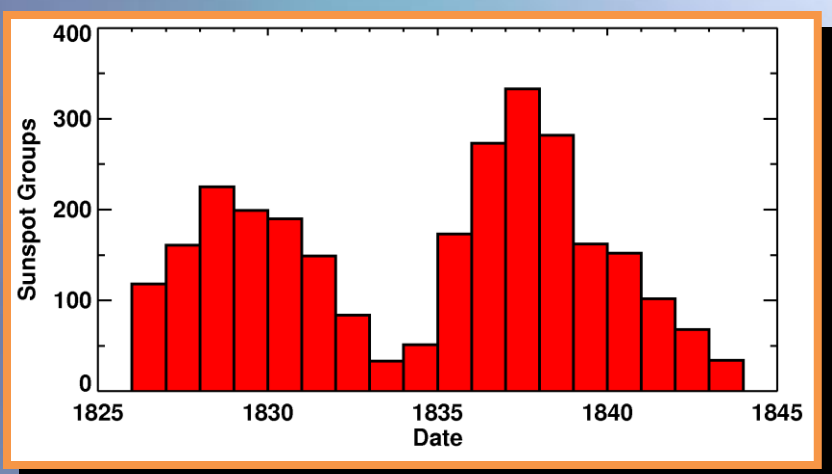
- **Granules**
  - d ~ 1,000 km
  - v ~ 3,000 m/s
  - τ ~ 10 mins
- **Supergranules**
  - d ~ 30,000 km
  - v ~ 500 m/s
  - τ ~ 1 day
- **Giant Cells**
  - d ~ 200,000 km
  - v ~ 10 m/s
  - τ ~ months



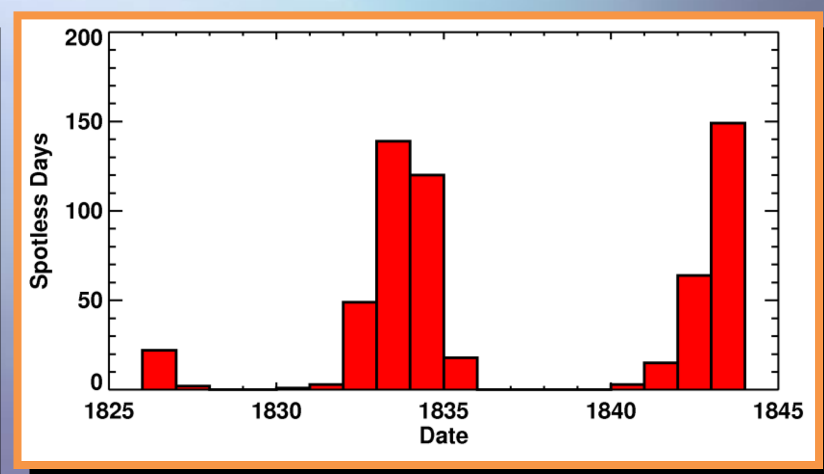
The Solar Cycle

By observing the number of sunspots in the early 1800s, Samuel Heinrich Schwabe was the first astronomer to observe that appearance of sunspots was cyclic. As new features of the Sun were discovered, it was found that they also varied along with sunspot activity. For this reason, sunspots are now commonly accepted as a measure of the solar activity cycle.

Schwabe's data for 1826 to 1843



Number of Sunspot Groups per Year

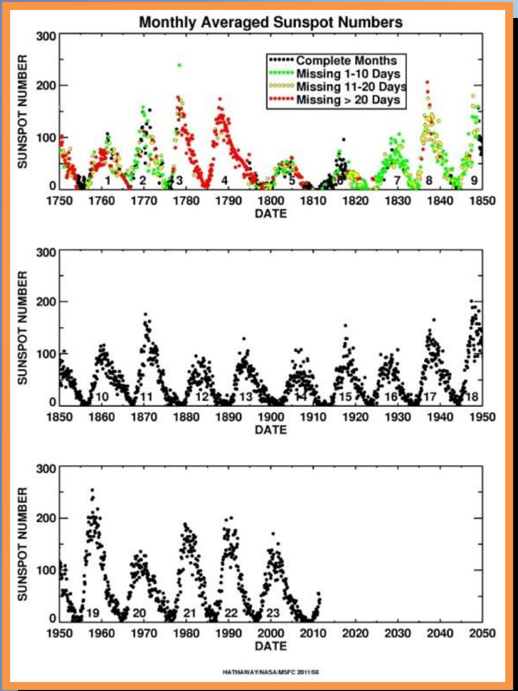


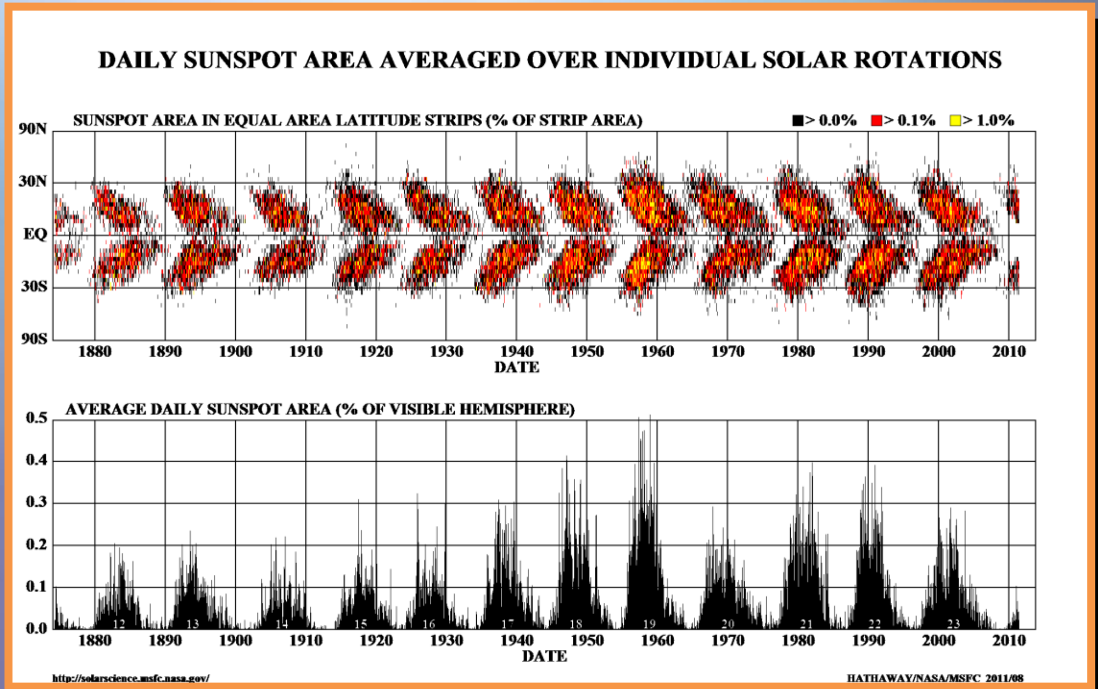
Number of Spotless Days

23 Cycles and Counting

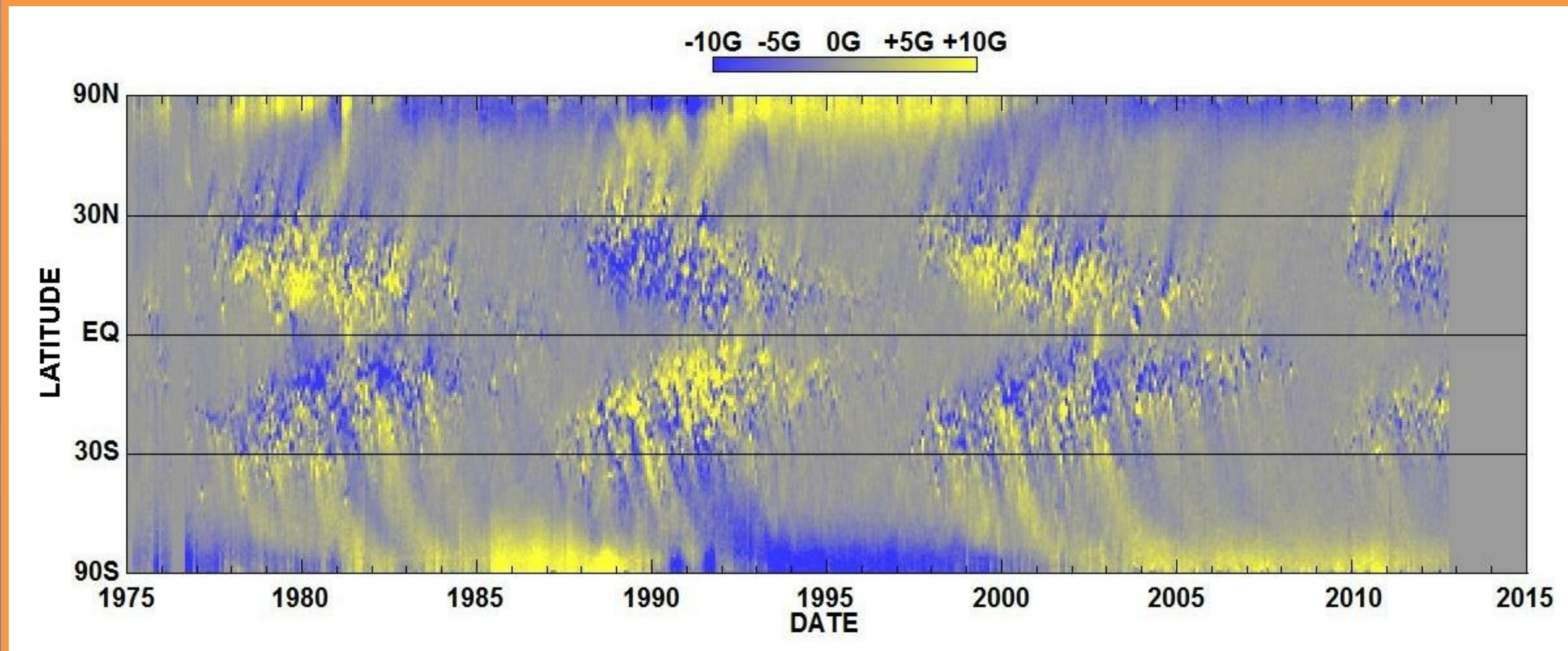
Activity on the Sun is periodic with the average cycle lasting ~11 years and the peak Sunspot Number of ~100.

- **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.**



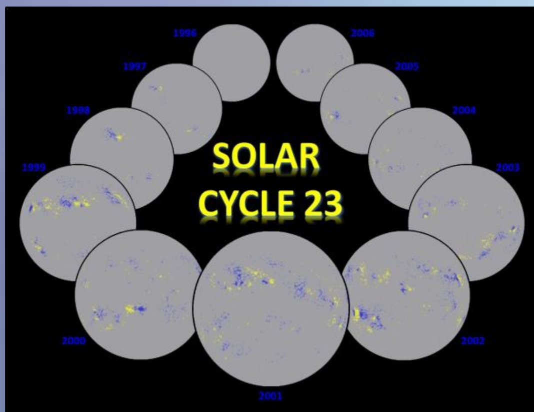


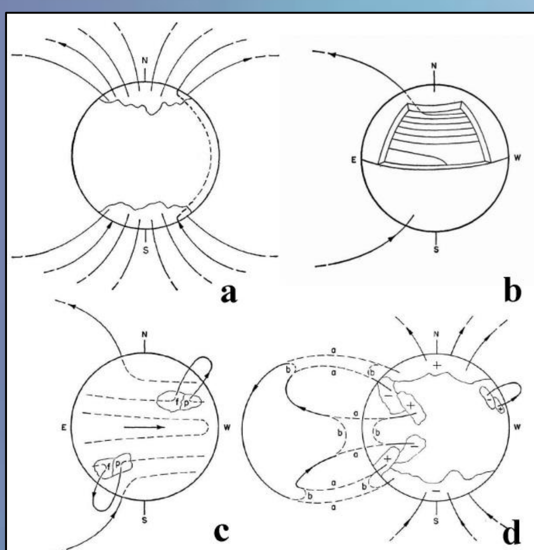
Polar Fields



The Sun has polar 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 $\lambda \geq 55°$.

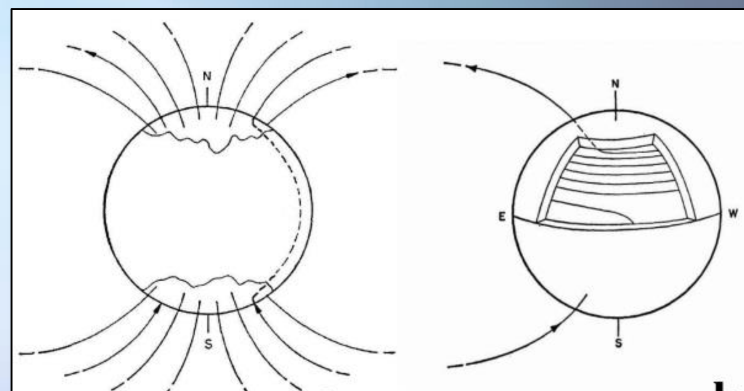
b) **Differential Rotation** shears the submerged magnetic field in toroidal direction. The field is strengthened by this shearing.

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.)

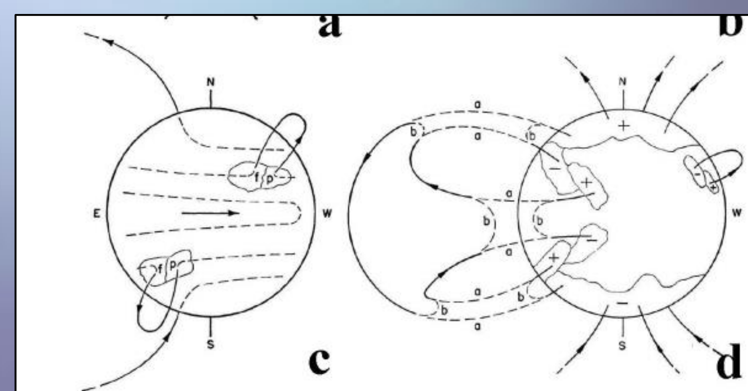
d) Magnetic flux is shredded off of the sunspots and is spread out by the **convective motions**. The leading polarity fields cancel across the equator. The **Meridional Flow** transports the following polarity to the poles. The following polarity cancels the old poloidal field and creates a new poloidal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

Babcock Dynamo Model

- Conversion of poloidal field to toroidal field



- Conversion of toroidal field to poloidal field



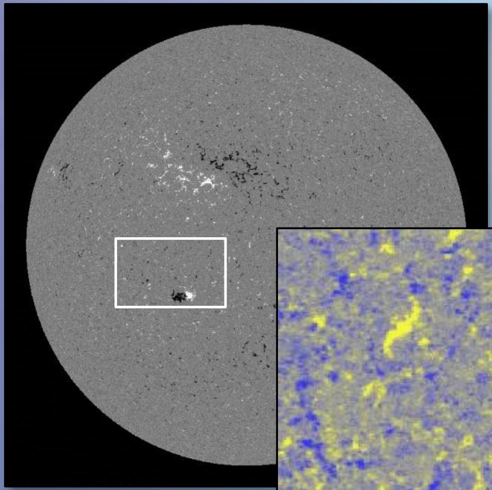
SurfaceFlux Transport

Surface Flux Transport describes the later half of this model – i.e. the conversion of the toroidal field into poloidal field . This part of the dynamo is well understood.

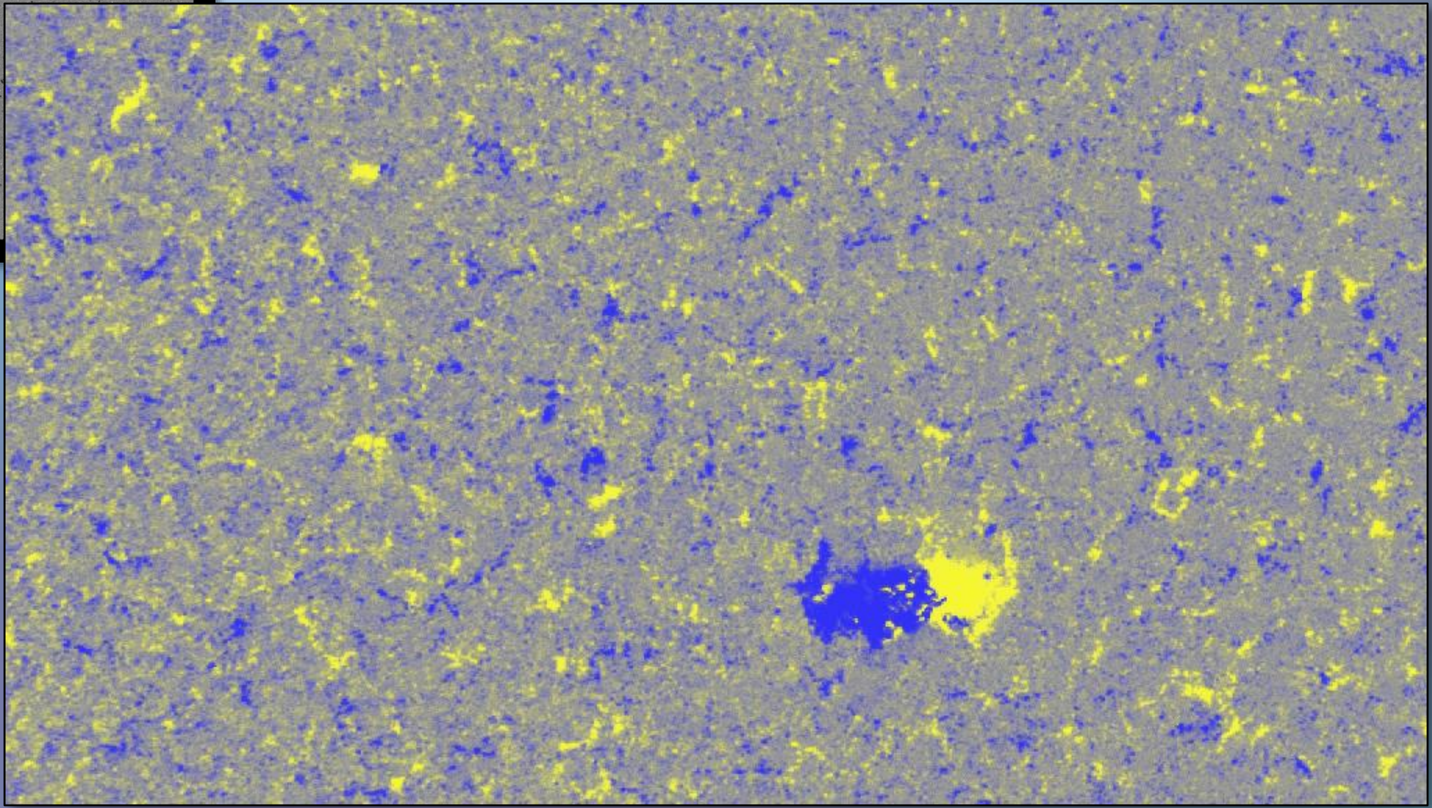
- Observed Surface Flows
- Observed Magnetic Field

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

Flux Transport in Action

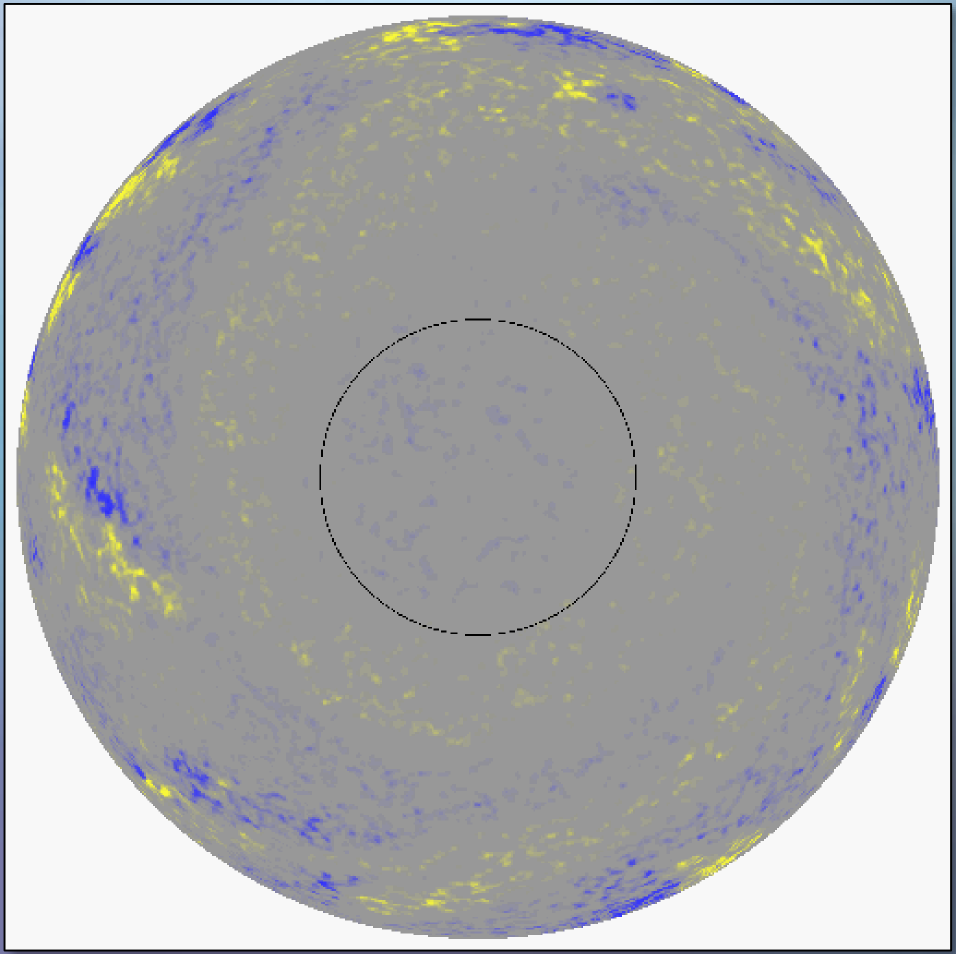


Looping video showing 4 days of HMI observations



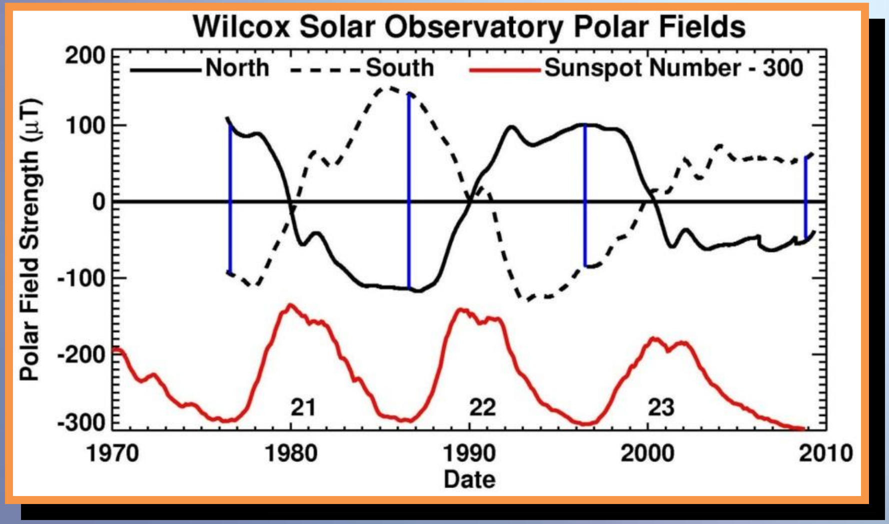
Polar Field Movie

Looping video showing polar field reversal over 6-months in 2001



Polar Fields

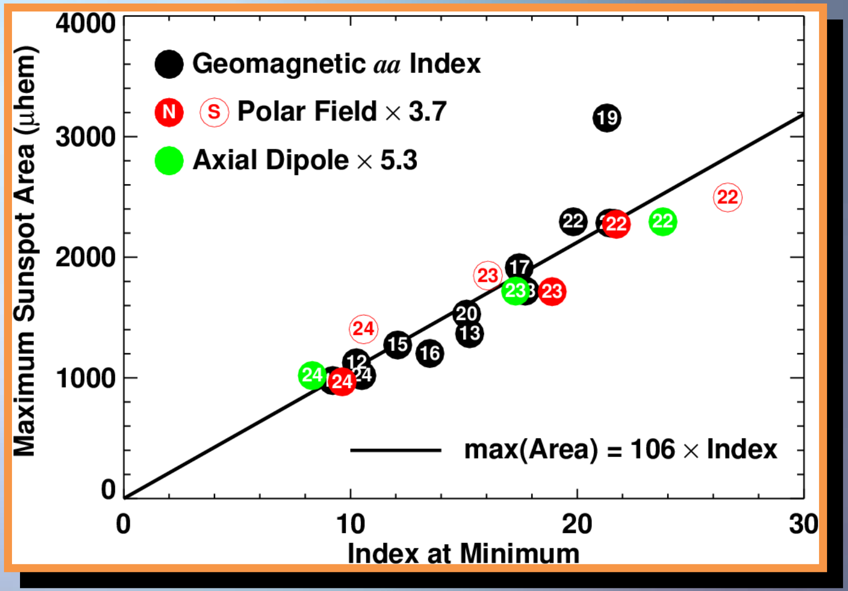
- The polar fields observed after the Cycle 23 were about half as strong as observed for the previous two cycles.



This was followed by an extended Cycle 23/24 minimum and what is proving 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. (Svalgaard et al. 2005; Munoz-Jaramillo et al. 2012; Svalgaard and Kamide 2013).



How do the poloidal fields generate the toroidal fields?

Dynamo Models

- What happens INSIDE the Sun??
  - What is the rotation rate?
  - What is the meridional flow?
  - What does convection look like?
  - Are Active Regions rooted at the tachocline or do they break off?
  - Can turbulent pumping keep the field from rising too fast?
  - How do all of the effects work together?
  - Are we missing something?