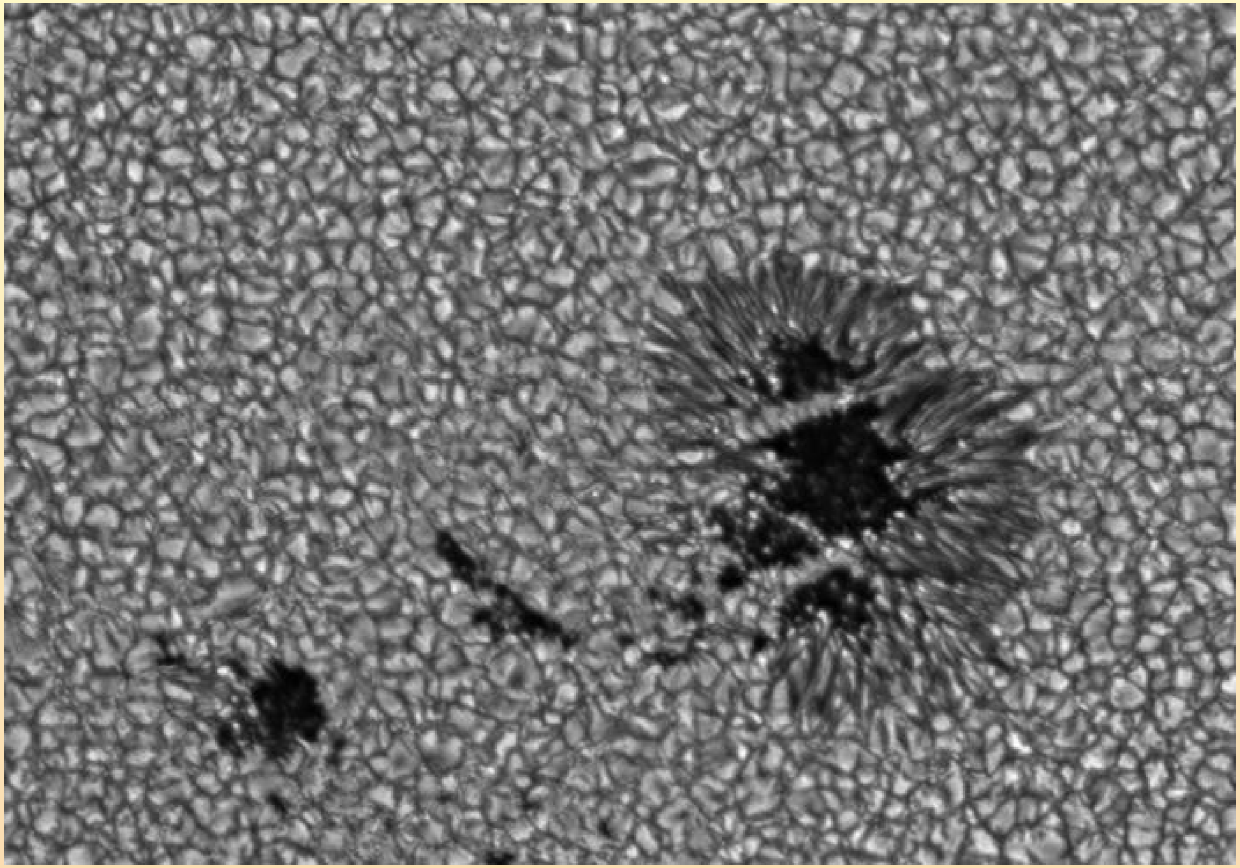
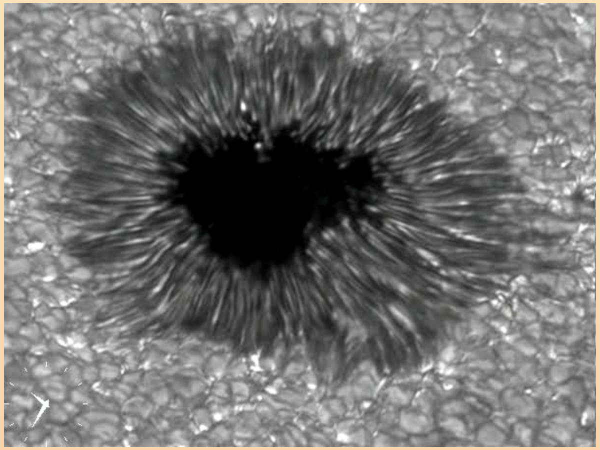
The Origin of the Solar Cycle & Helioseismology

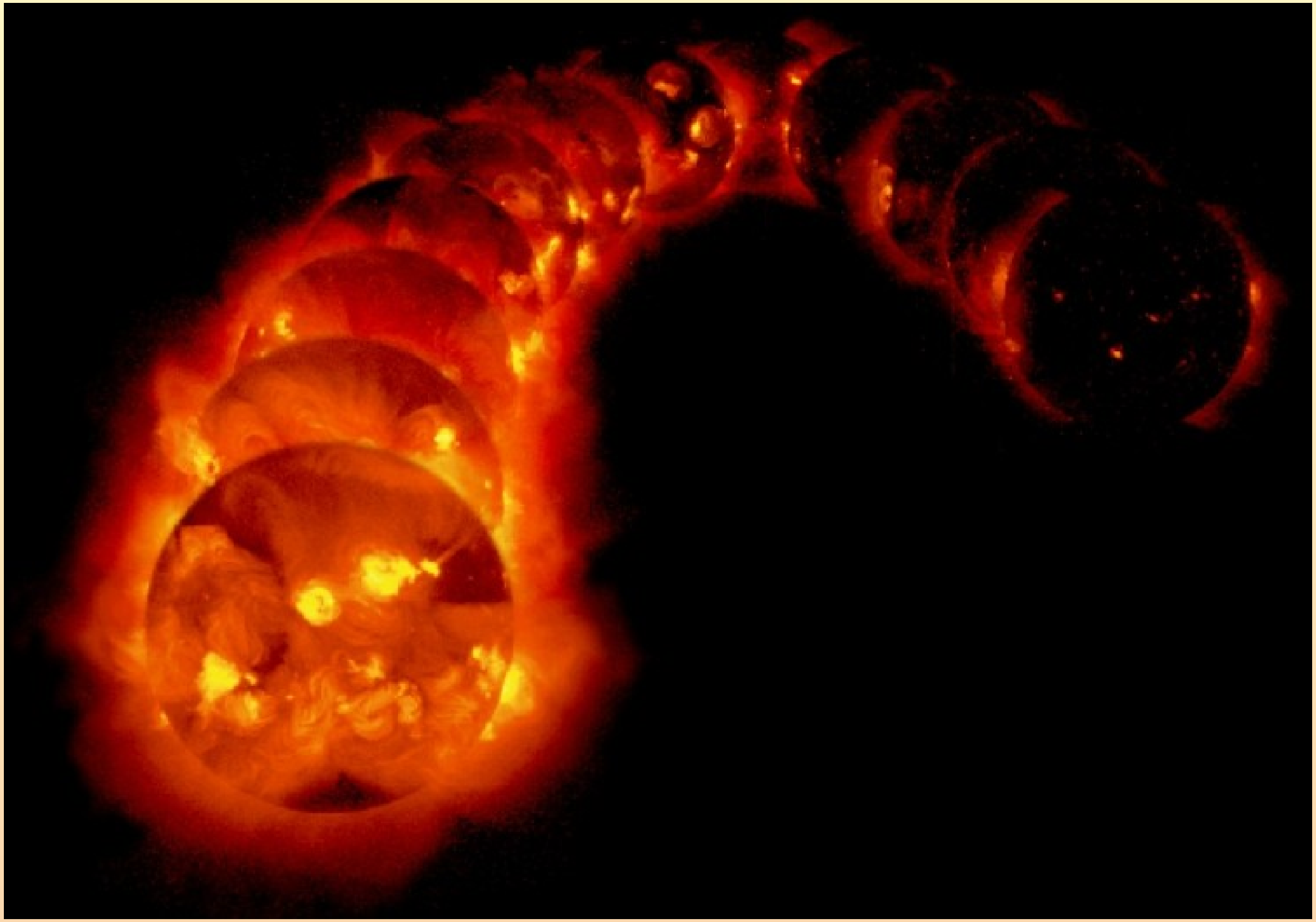
- What is the solar cycle?
- Simple concept of cycle mechanism, dynamo
- What is helioseismology?
- Global properties of the solar interior
- Local properties of the solar interior
- Far side imaging
- What are the big questions?

What is the Solar Cycle?



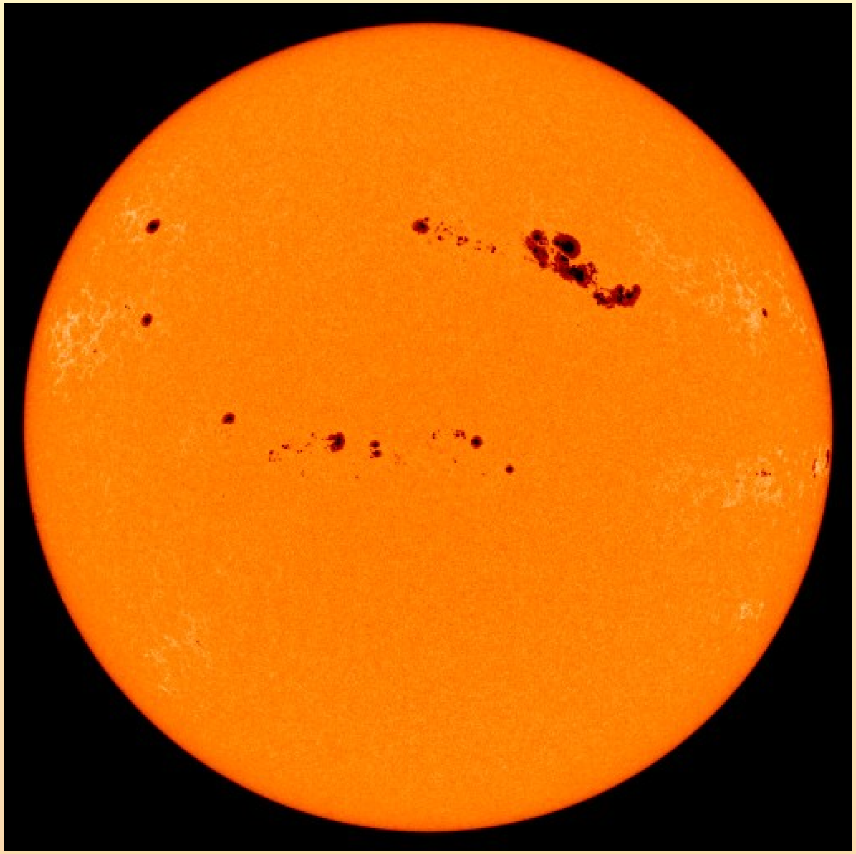


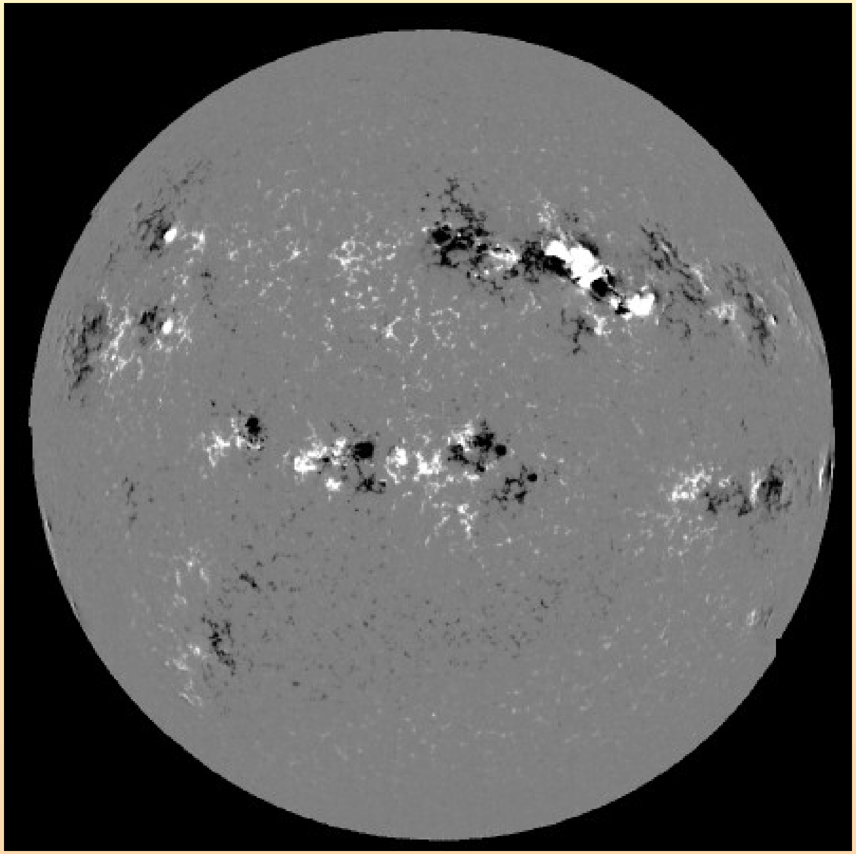
Cycle Variation of X-Rays



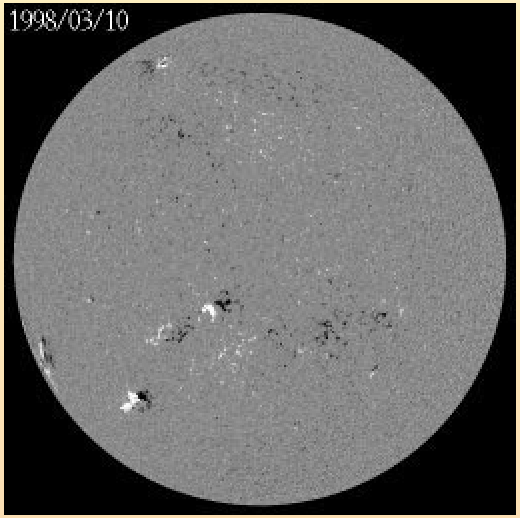
Yohkoh

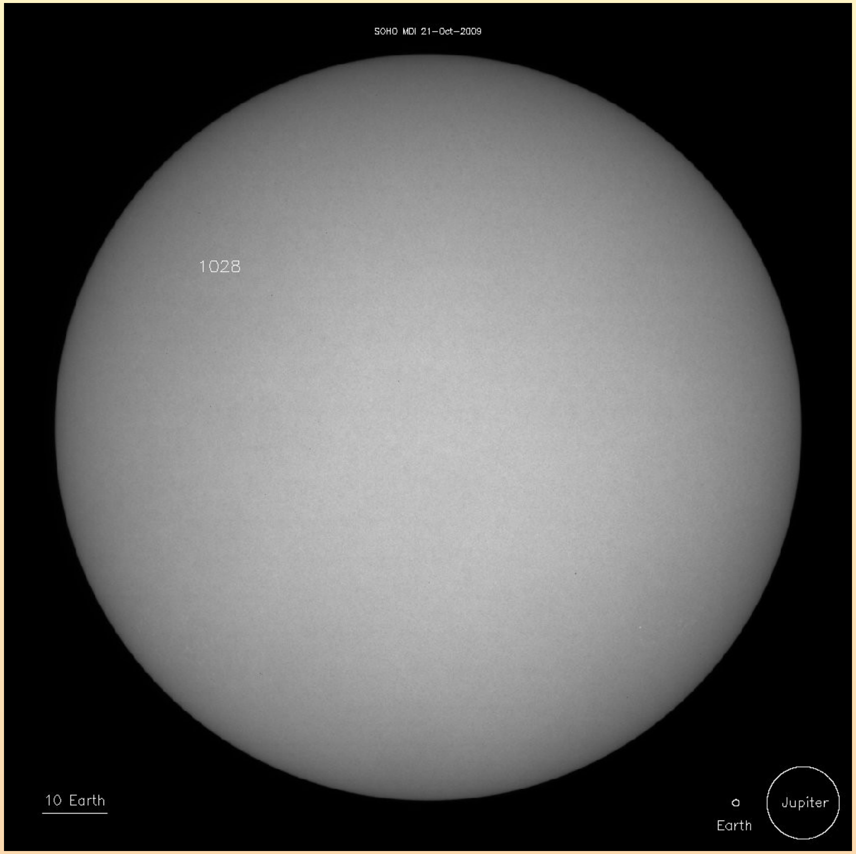
Visible and Magnetic Sunspots



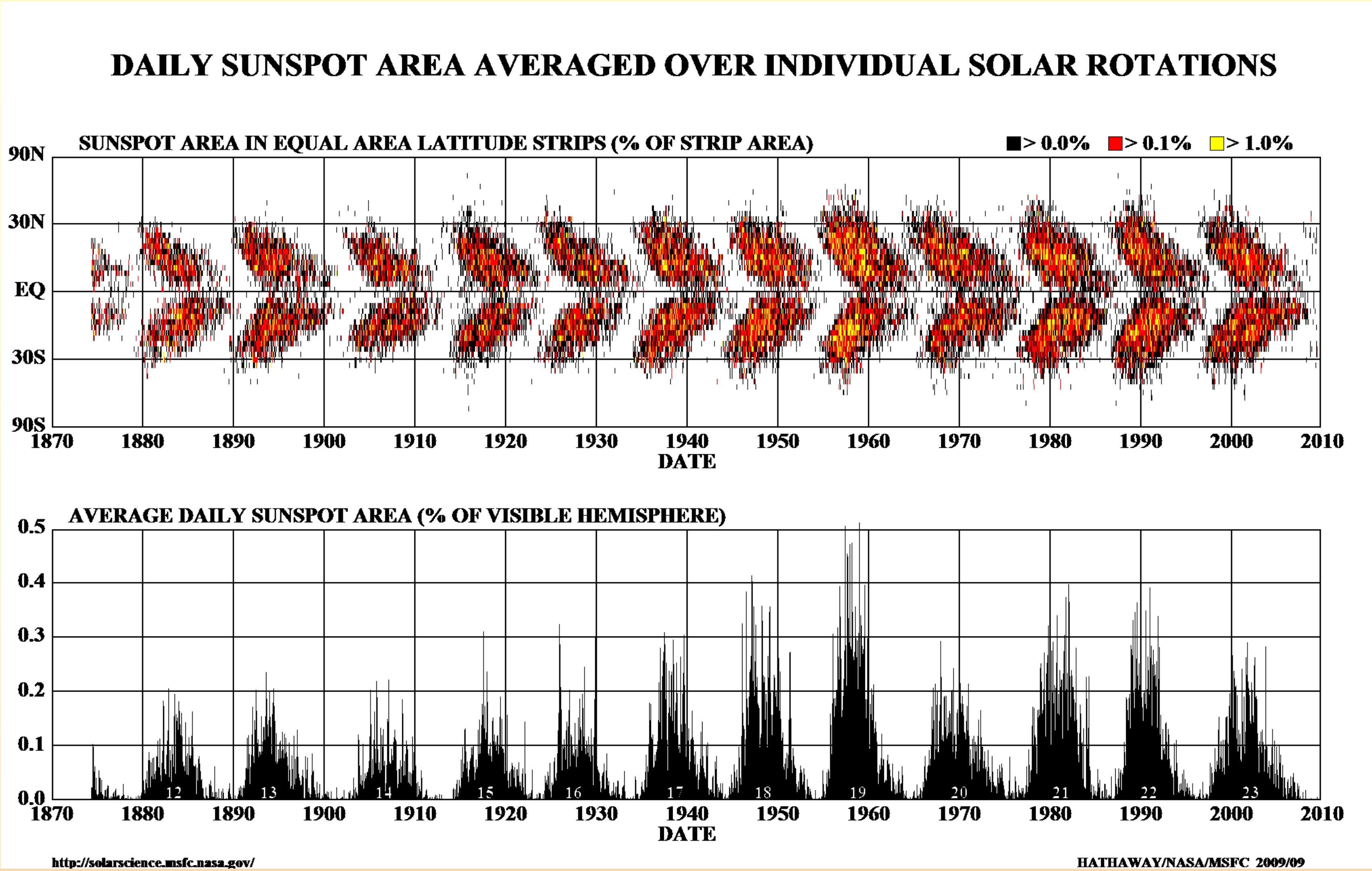


Rotation of Magnetic Field Movie

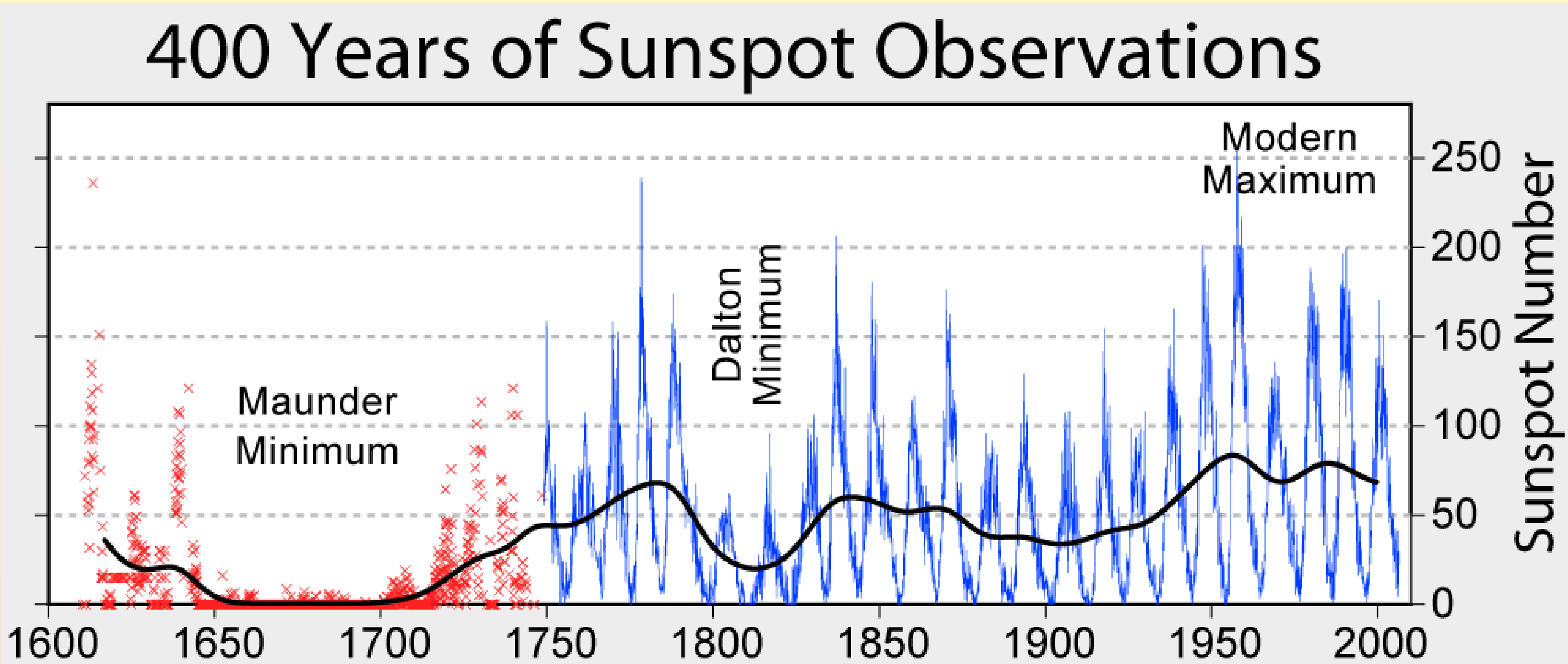


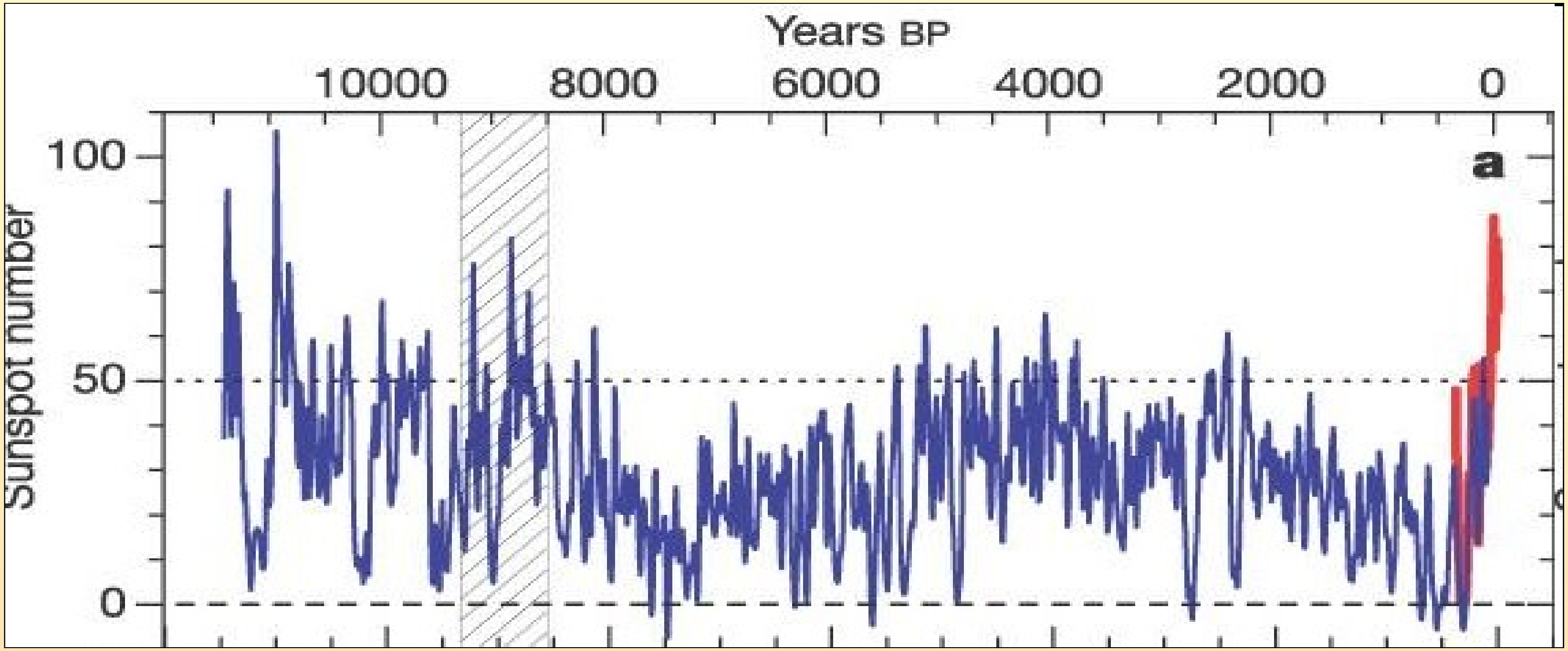


Pattern of Solar Activity



Sunspot Index of Solar Activity

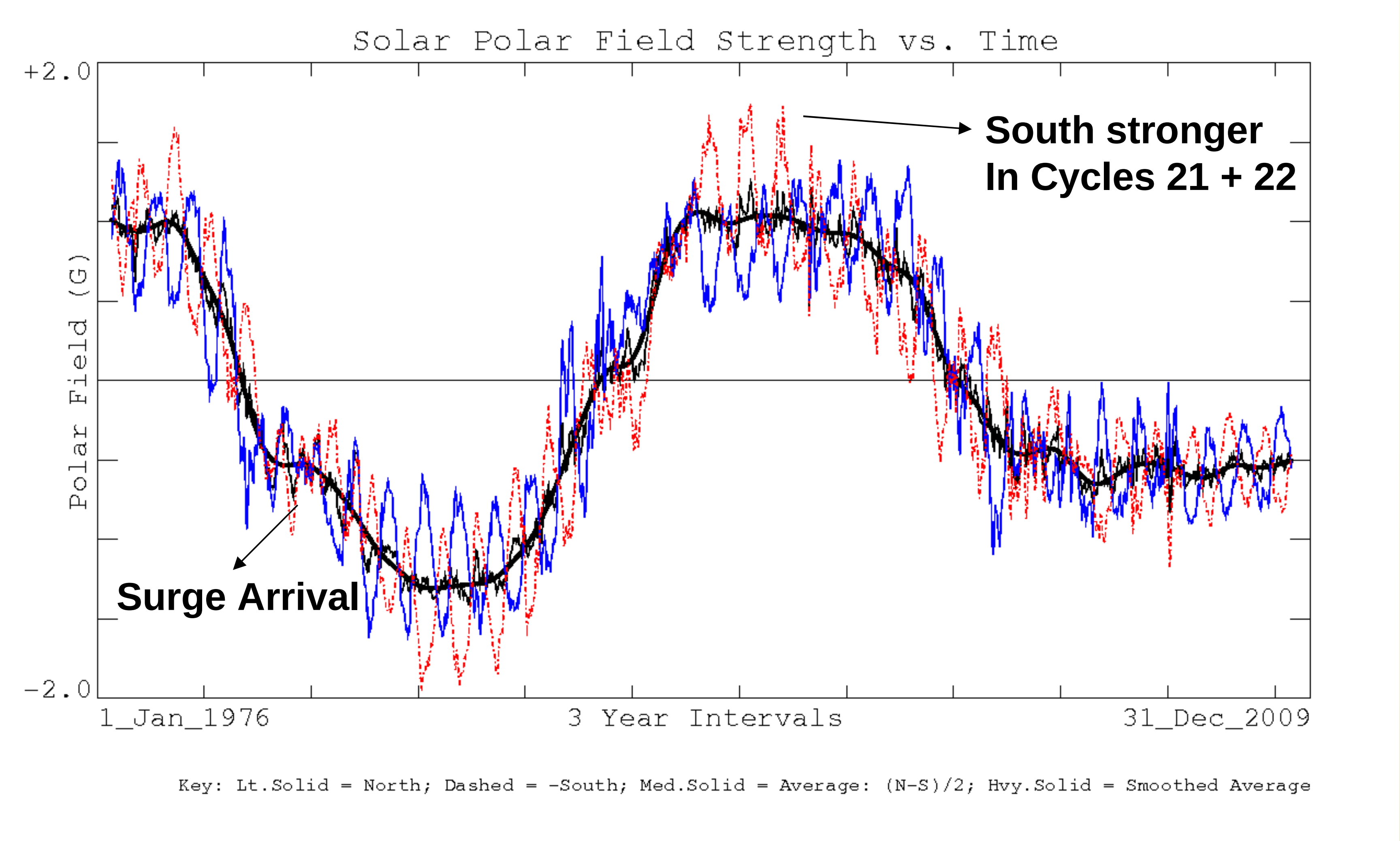




Long Term Solar Activity Variation Determined from C^{14} in Trees

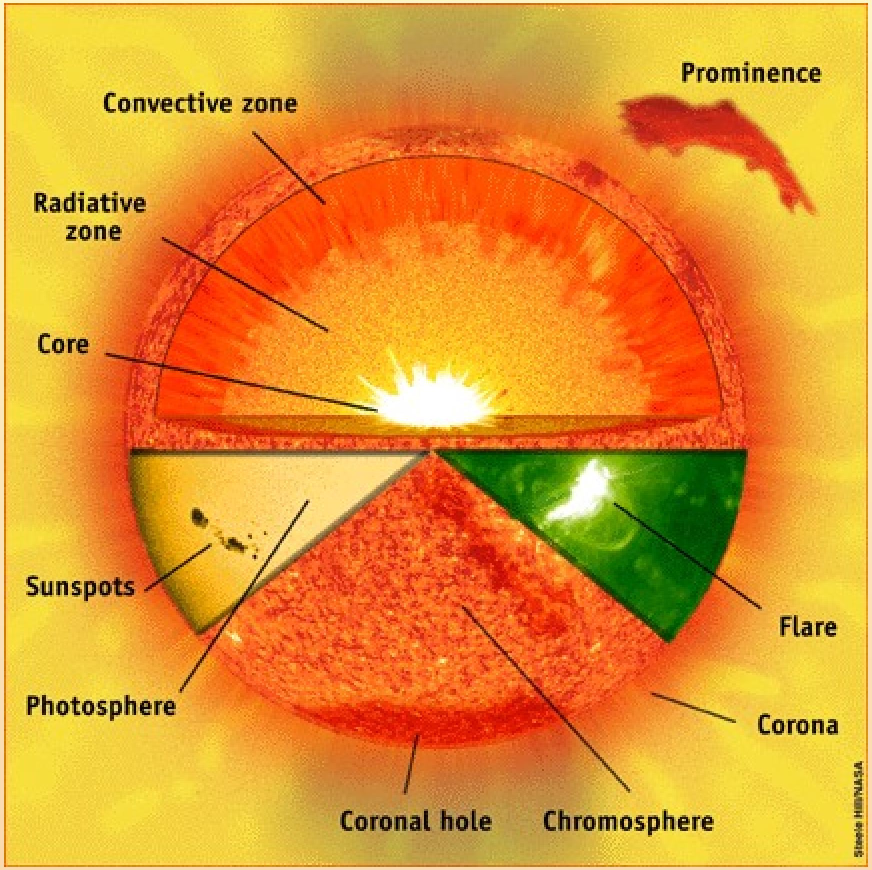
Solanki et al., Nature 2004.

4 Solar Minima, 3 Polar Reversals
1976 - 2009

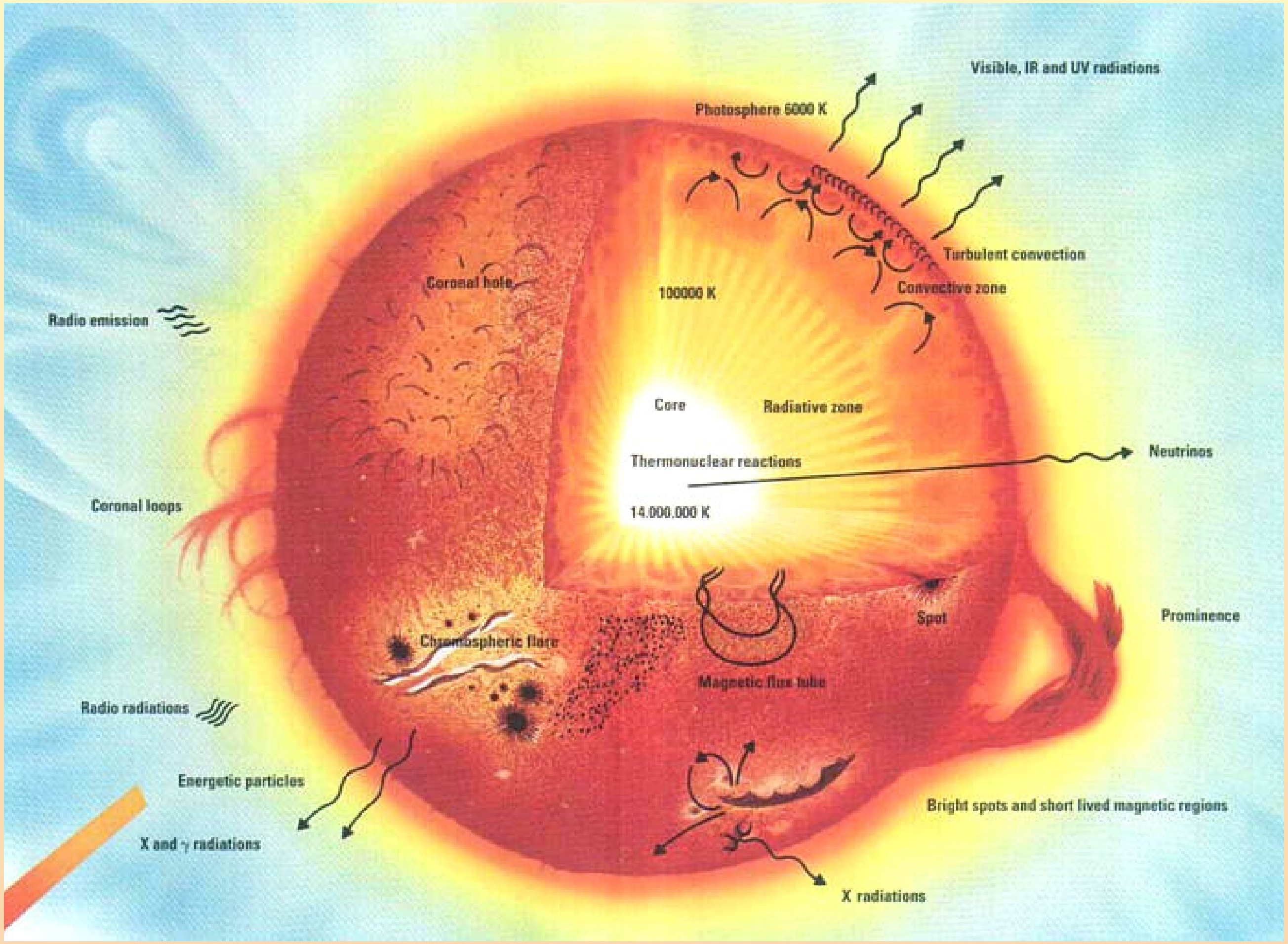


Wilcox Solar Observatory Large-scale Polar Aperture 55 to Pole

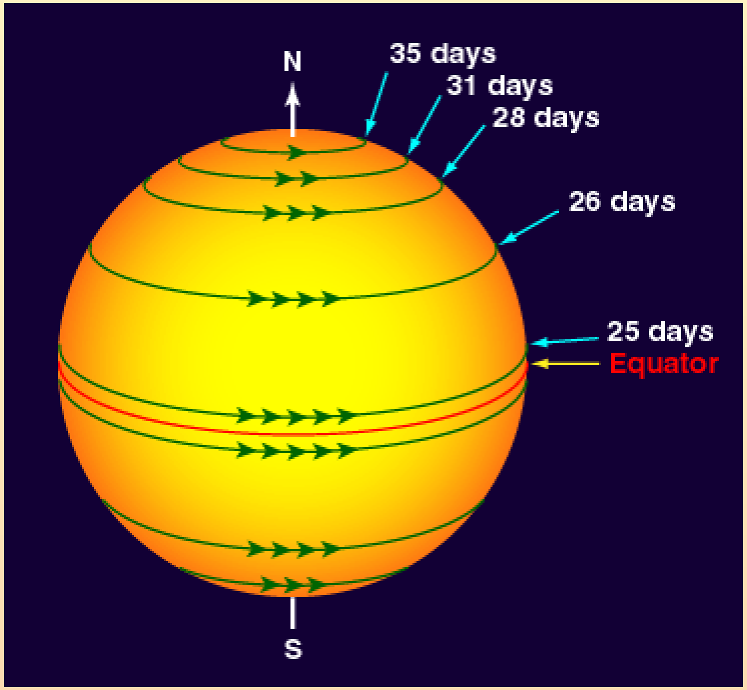
Inside the Sun – Nuclear Core, Radiative Zone, Convection Zone



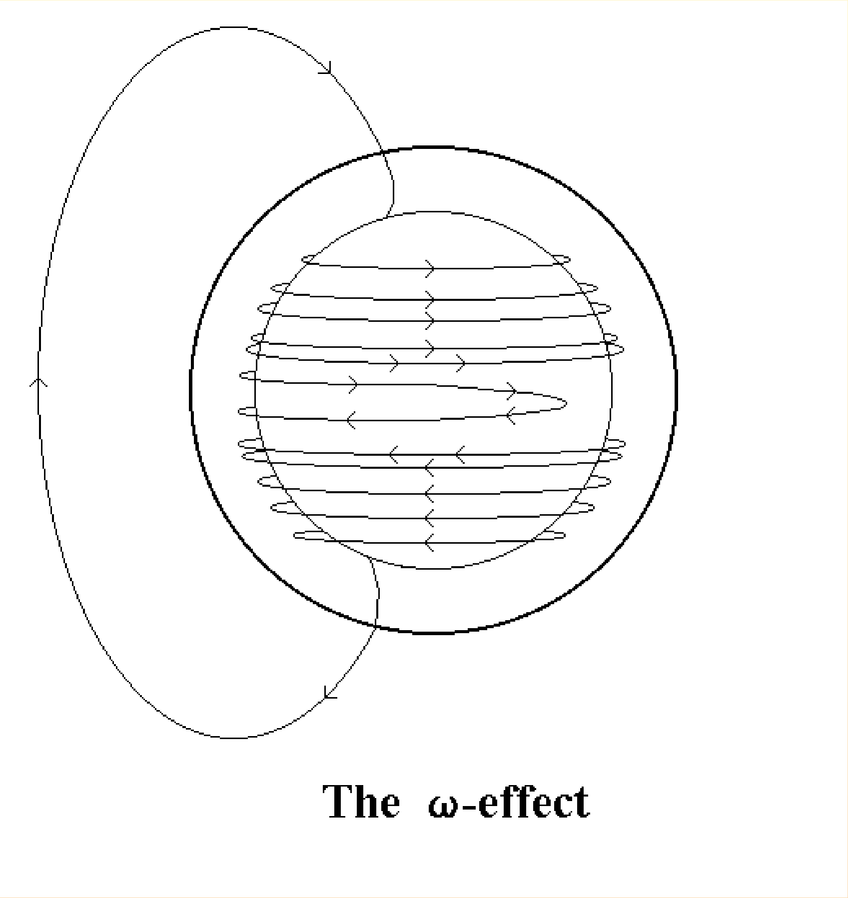
Inside the Sun – The Surface is More Complex (Because We Can See It)

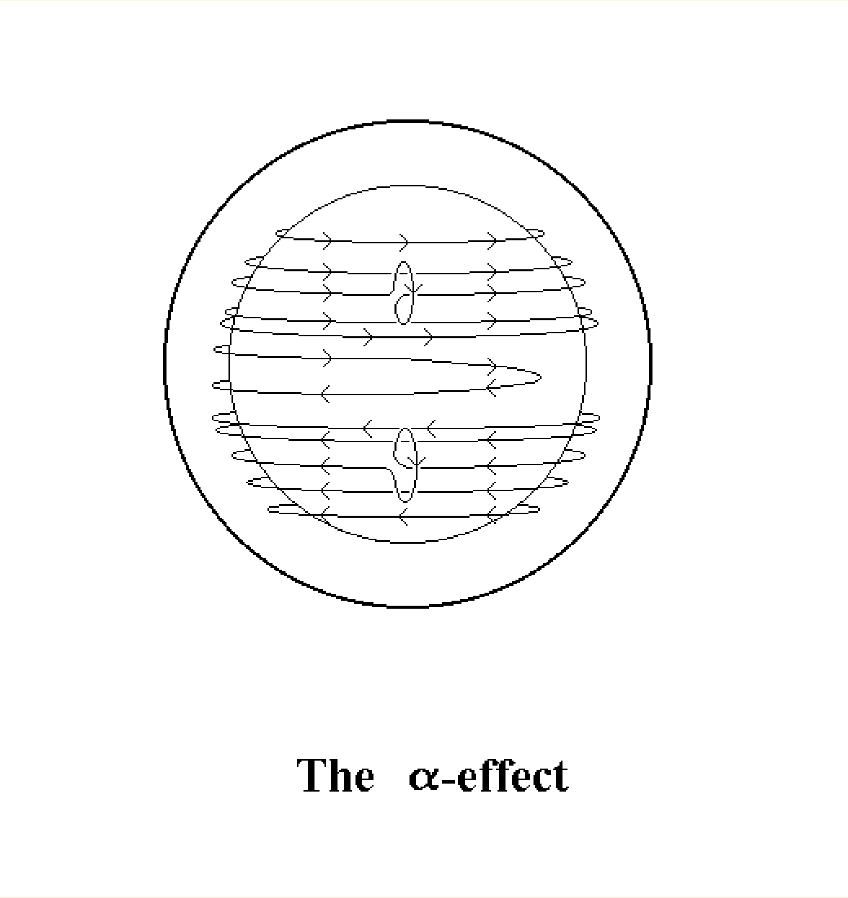


Solar Differential Rotation

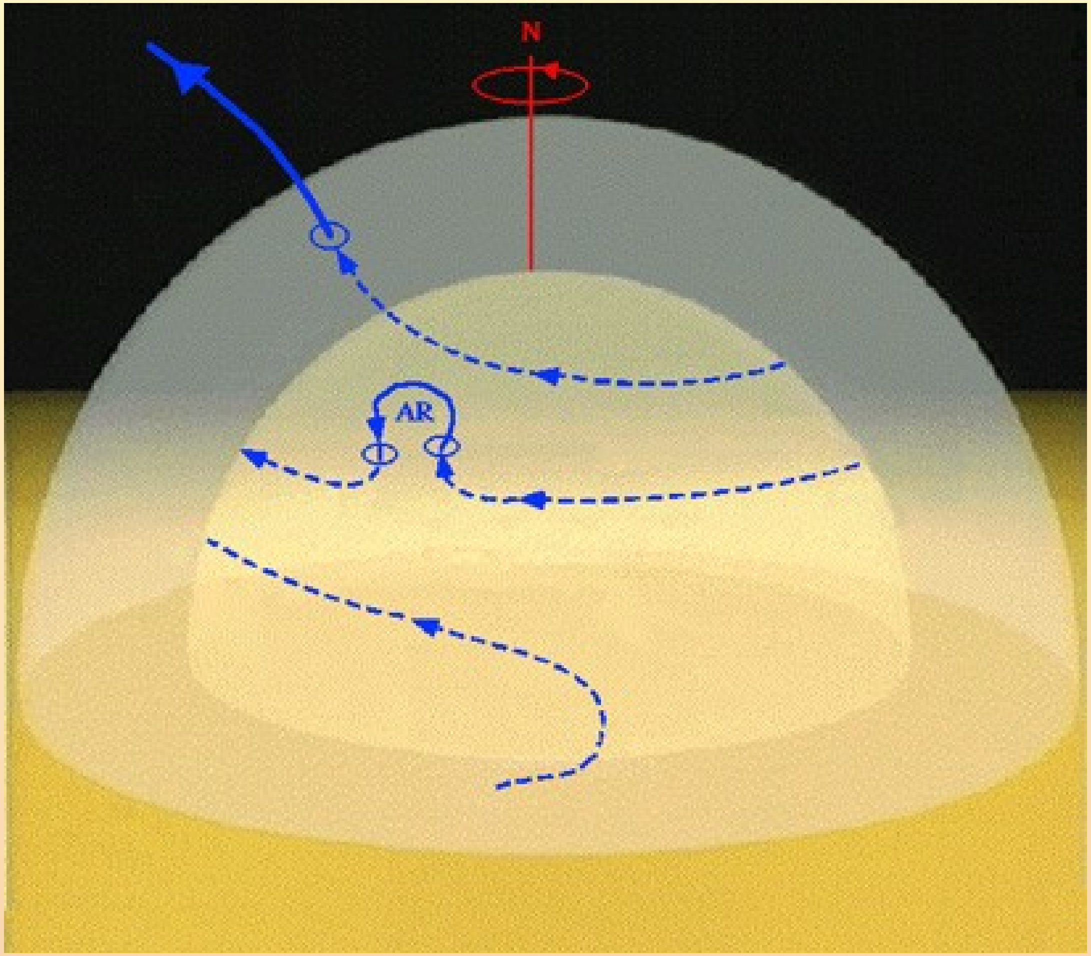


Components of the Classic ά-ώ Dynamo

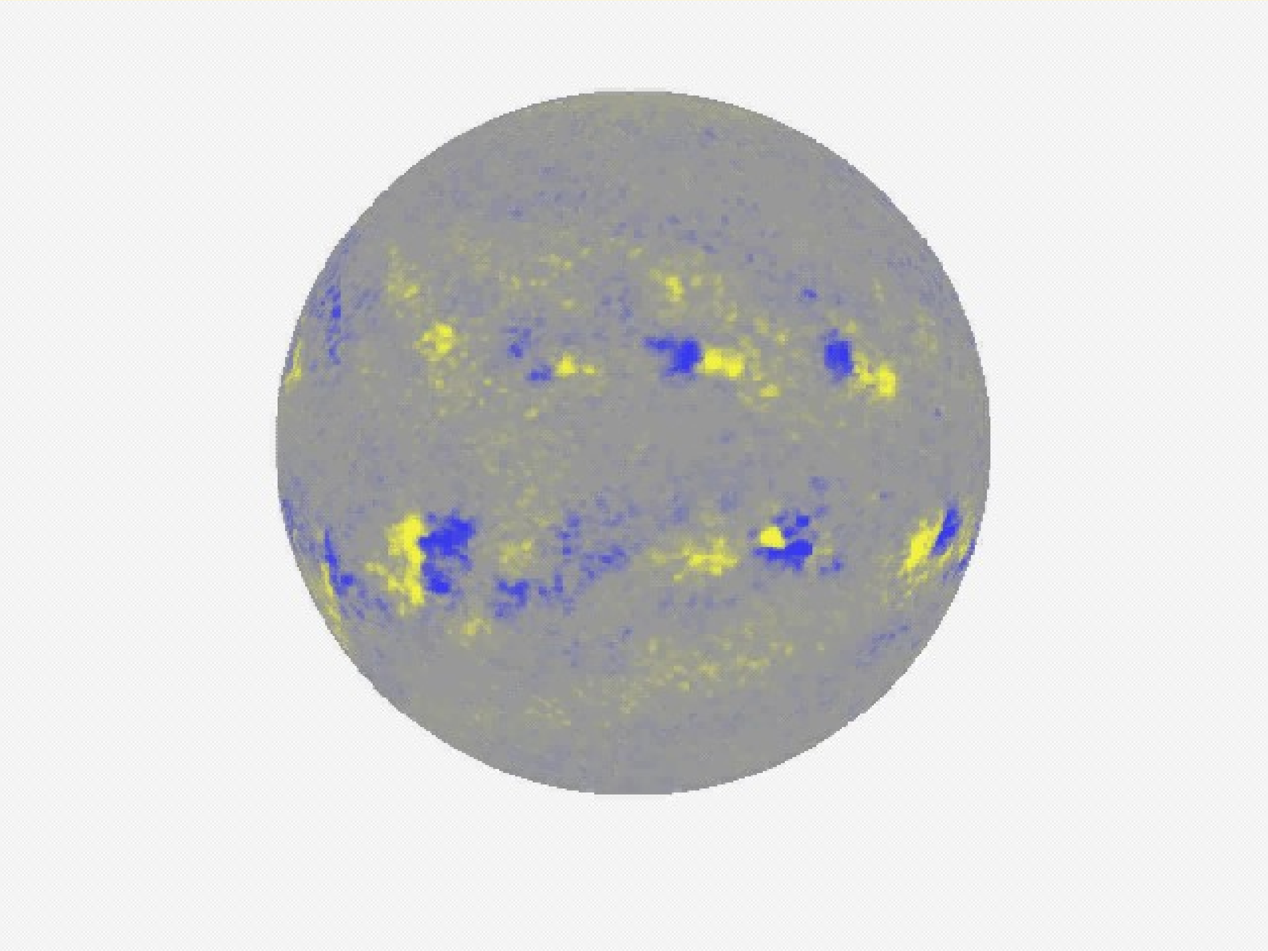




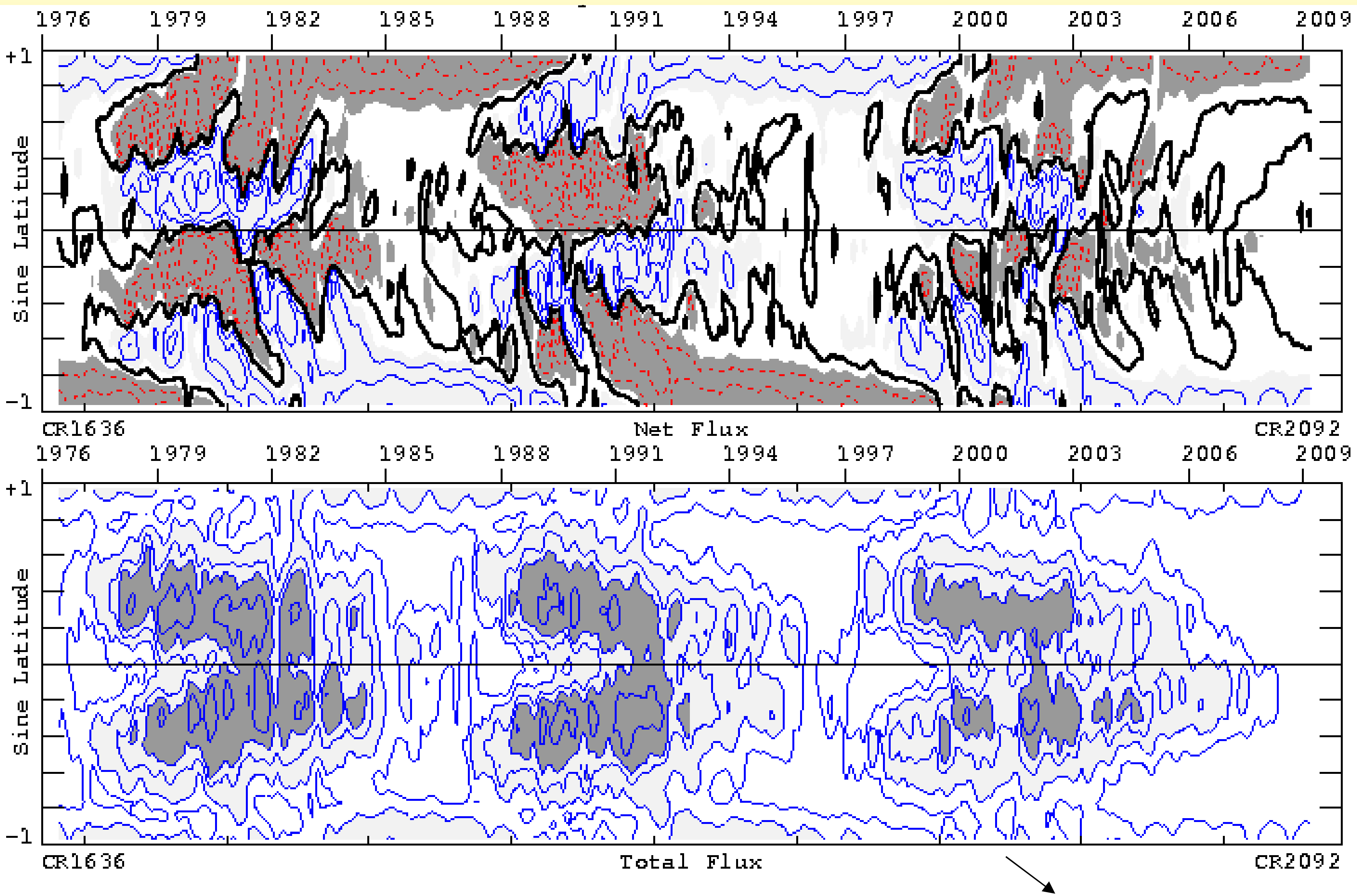
Active Regions Emerge from the Base of the Convection Zone



Magnetic Cycle Movie

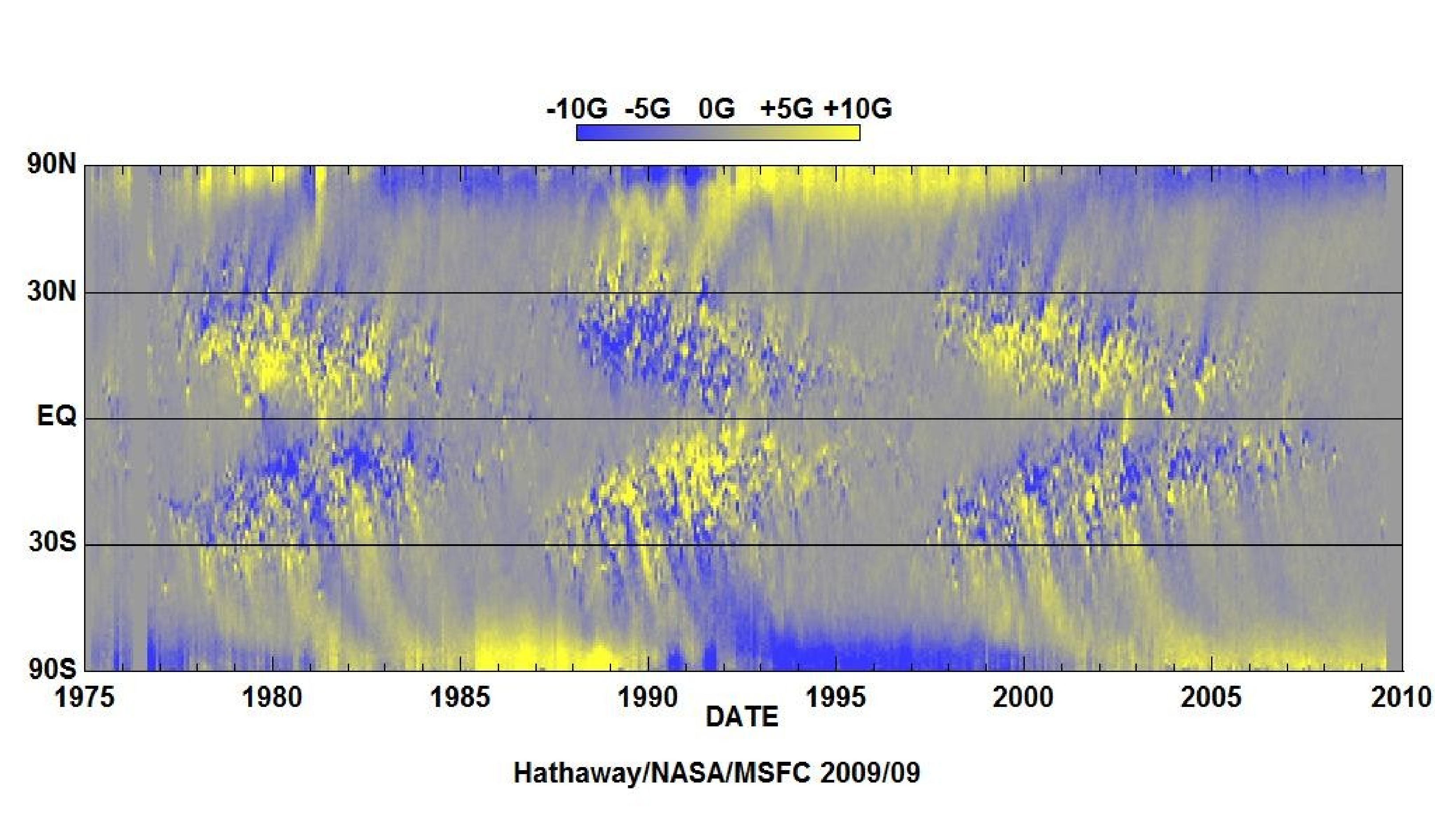


Zonal Average of Total Flux and Net Flux – 3 Cycles 1976-2009 from WSO

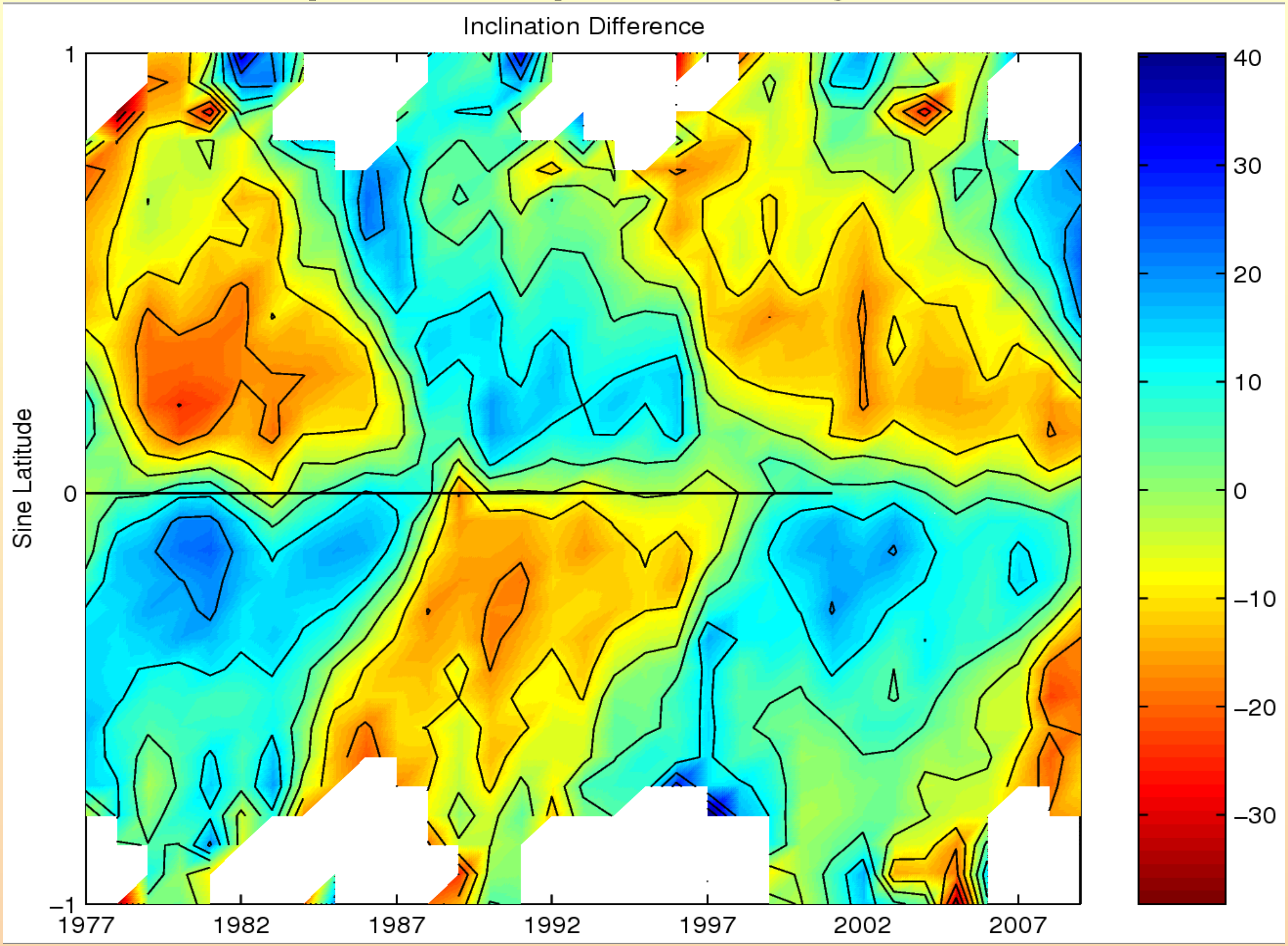


~2001 WSO Sensitivity

Zonal Average Flux from Mt Wilson



Toroidal (East-West) Field – 3 Cycles from WSO

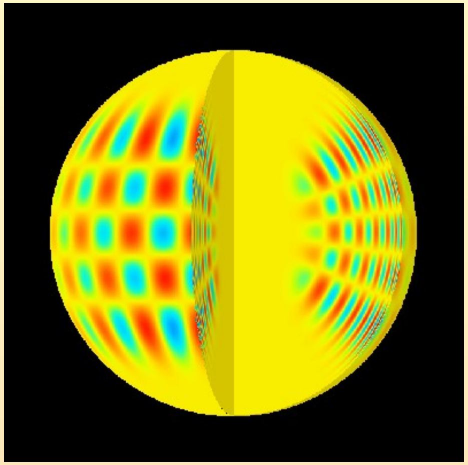


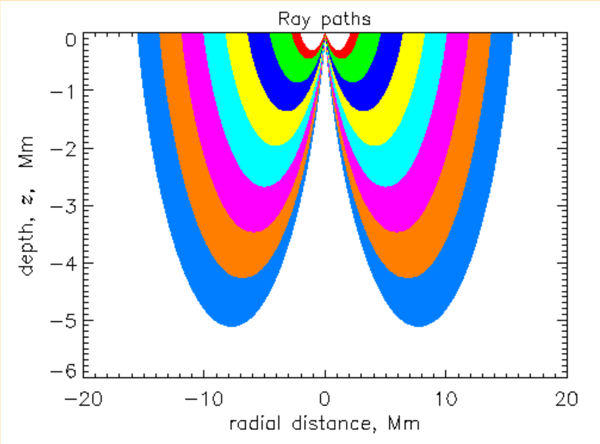
Cycles overlap several years and are extended

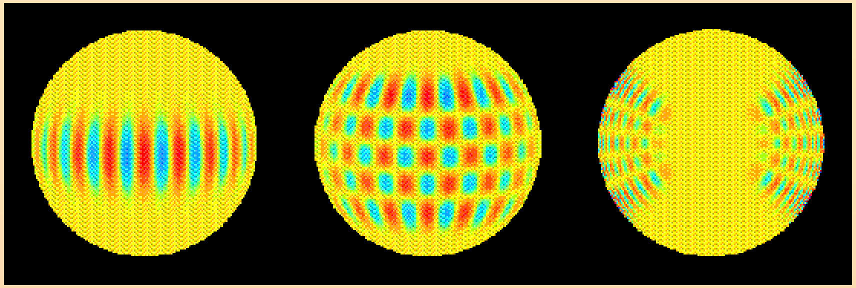
Lo et al., 2009

What is Helioseismology?

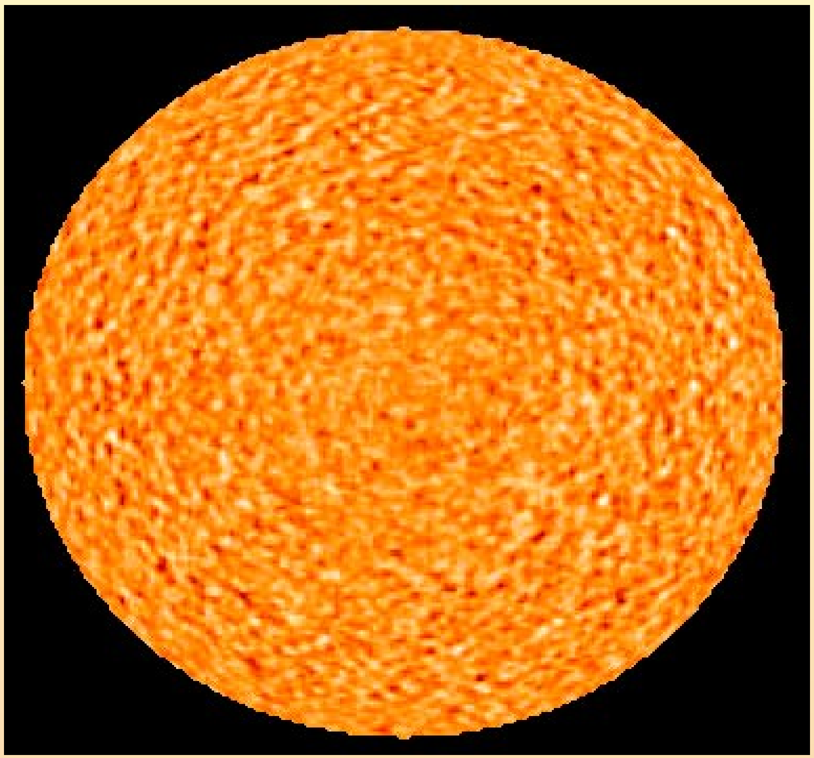
- Global Seismology
- Local Seismology







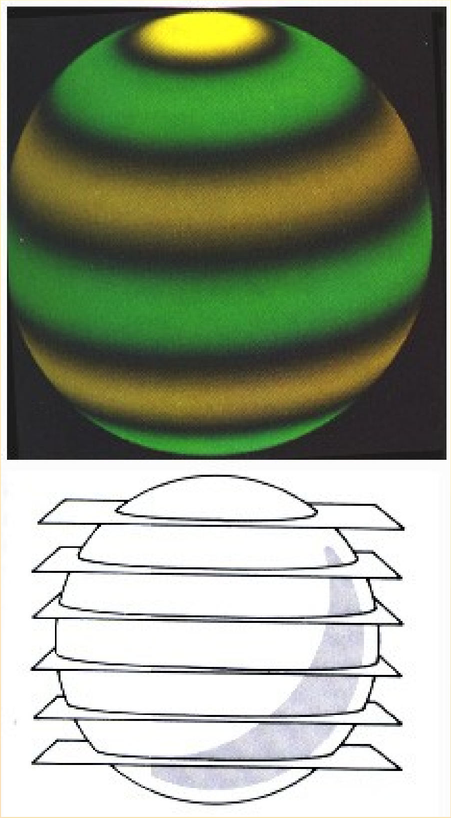
Solar oscillations

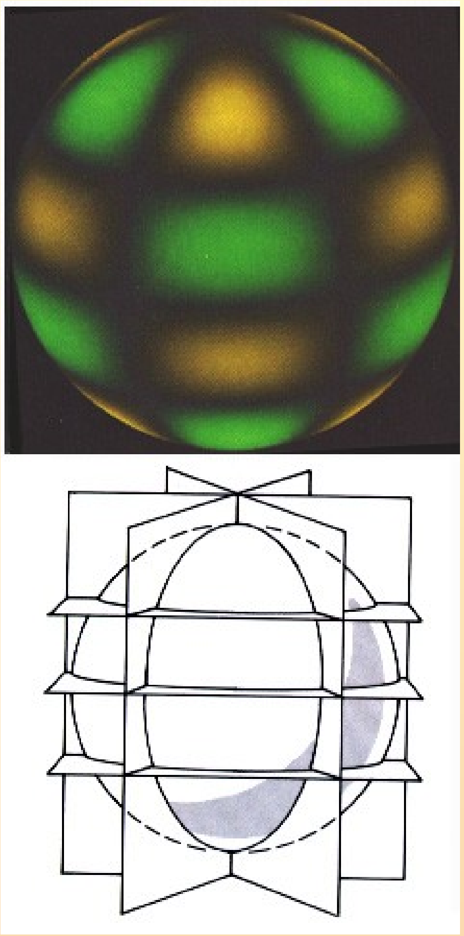


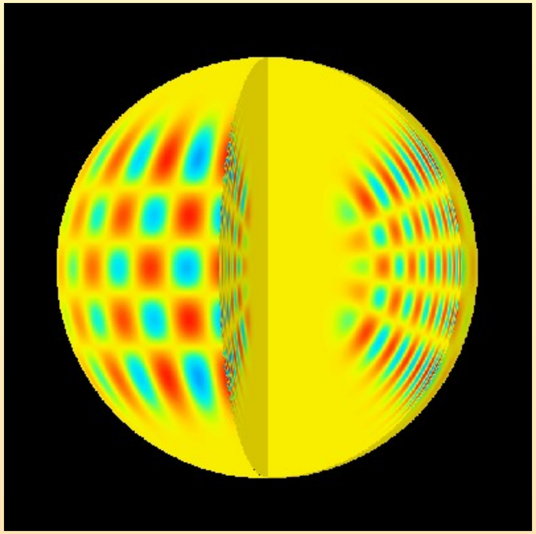
Velocity images (1 min cadence, mean image subtracted) measured with MDI on the SOHO spacecraft

- The Sun is filled with internal acoustic waves with periods near 5 min (freq. near 3 mHz).
- Waves are excited by near-surface turbulent convection.
- Surface motions (Doppler shifts) are a few 100 m/s, superimposed on the 2 km/s solar rotation.

Global Seismology Analyzes Normal Modes of Oscillation







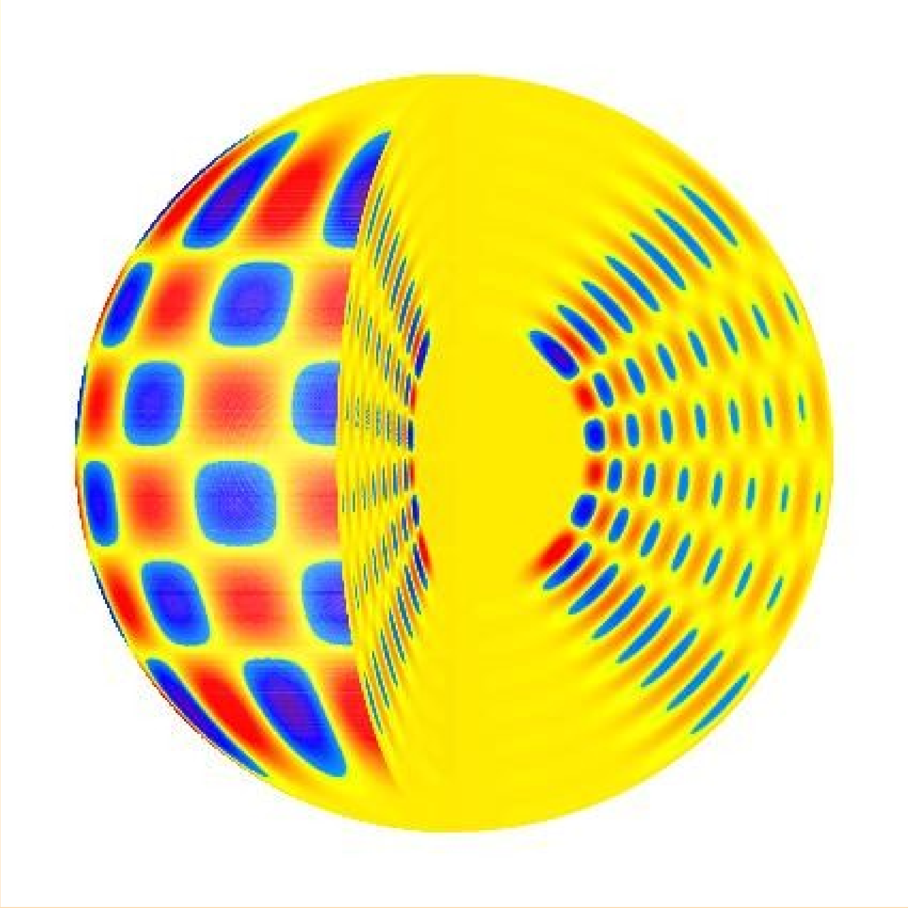
Noyes, Robert, "The Sun", in _The New Solar System_, J. Kelly Beatty and A. Chaikin ed., Sky Publishing Corporation, 1990, pg. 23.

Global helioseismology

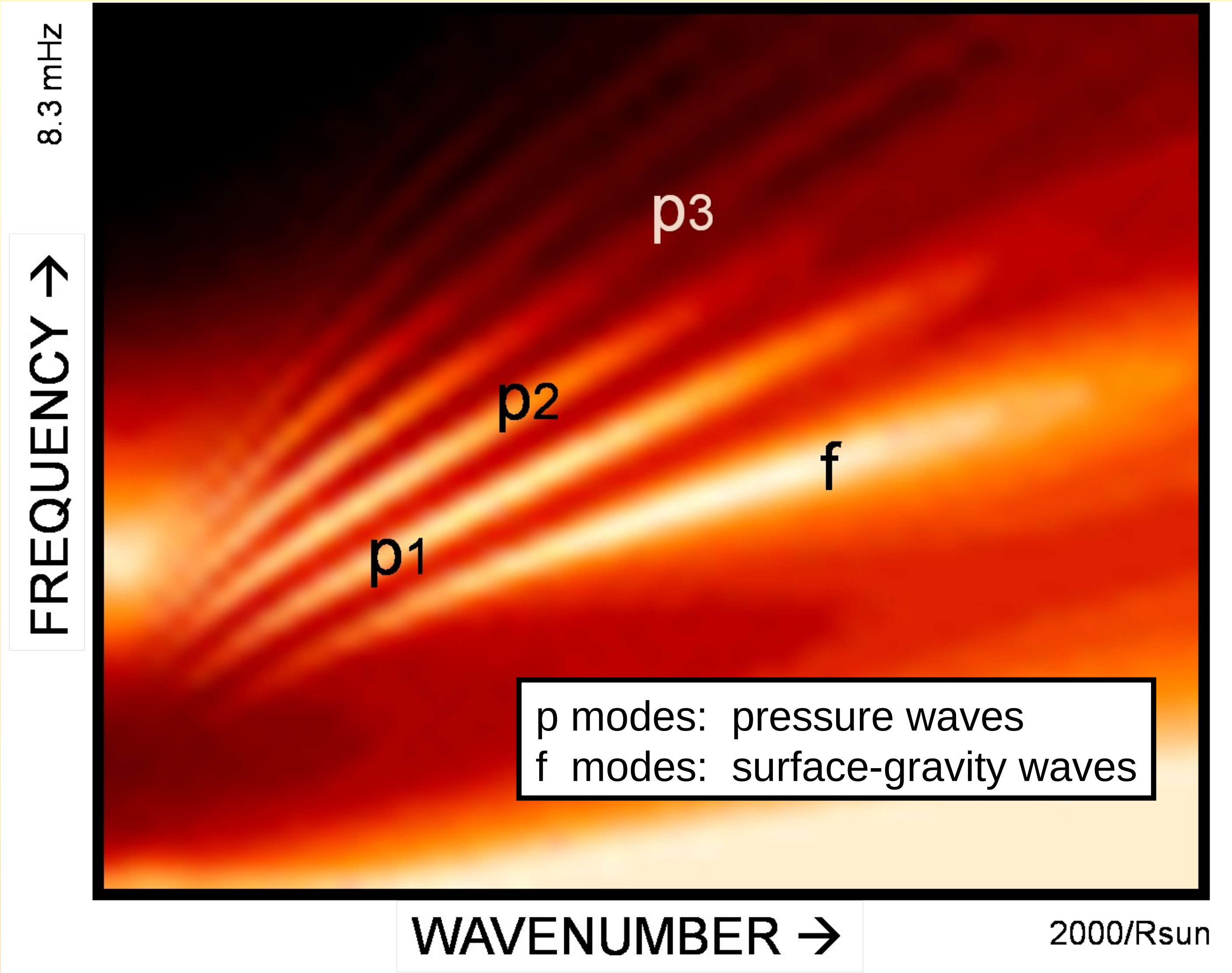
- **Measurement and inversion of the frequencies of the global modes of resonance (many thousands of individual modes are resolved in freq space)**

- **Among the most precise measurements in astrophysics.**

- **→ internal structure and rotation as a function of radius and latitude (2D)**

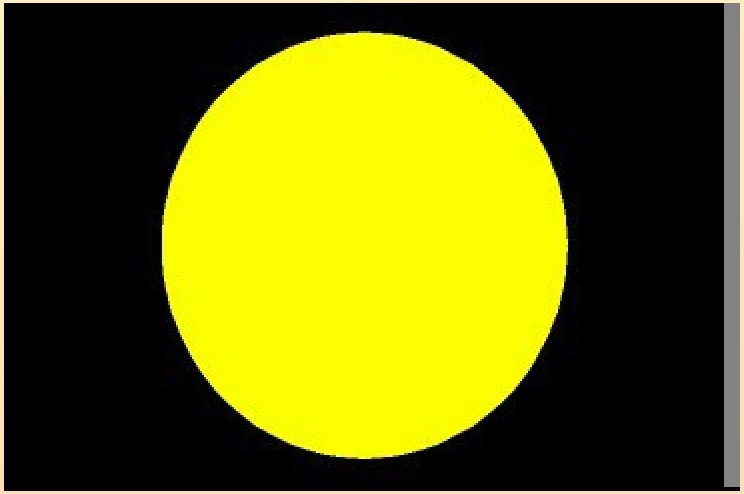


Power Spectrum of Solar Oscillations

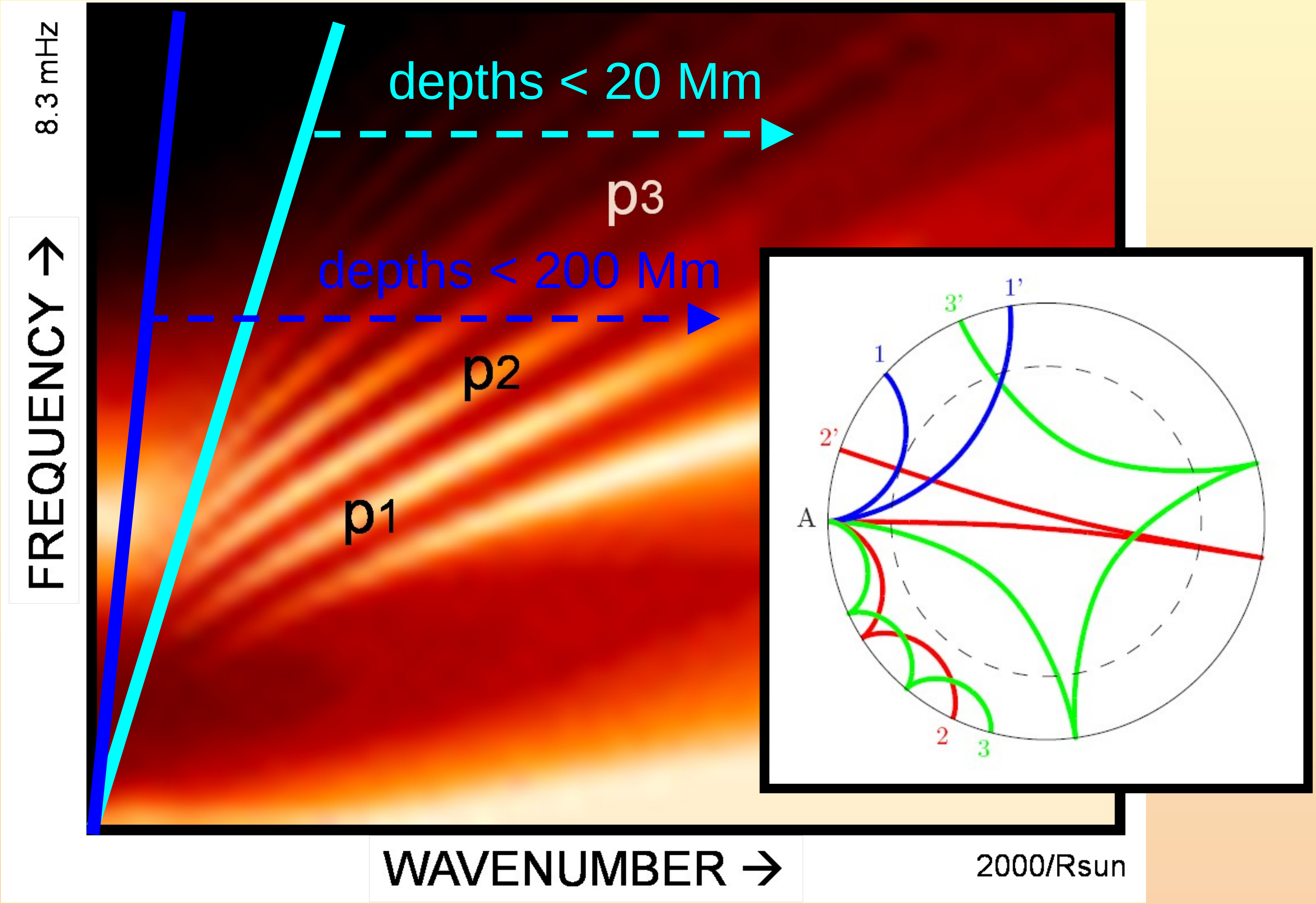


Gizon, 2009

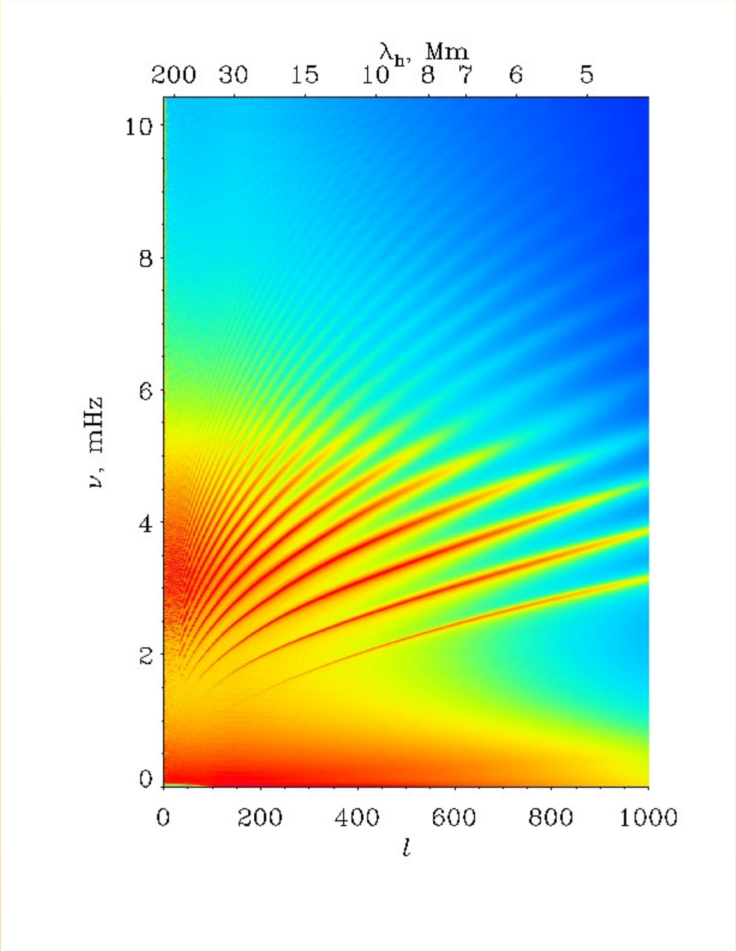
Individual Ray Paths

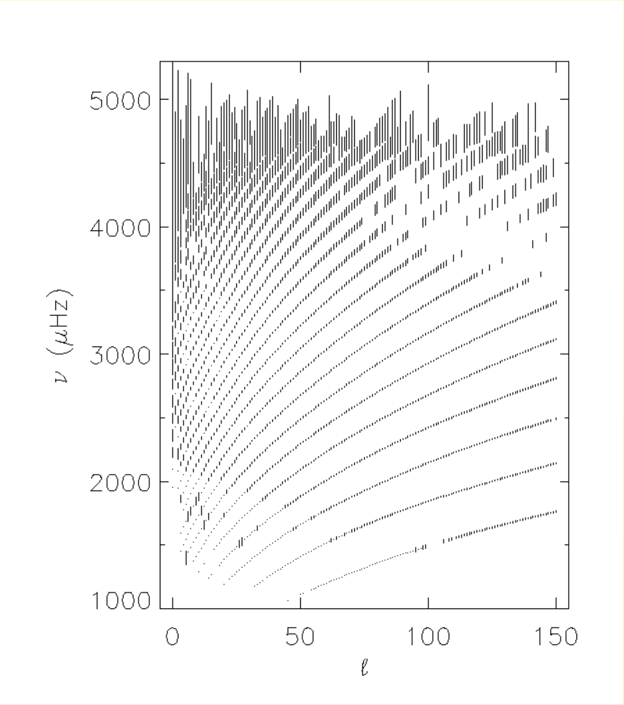


Power spectrum of solar oscillations



Exquisite Detail in Identifying Frequencies of Normal Modes



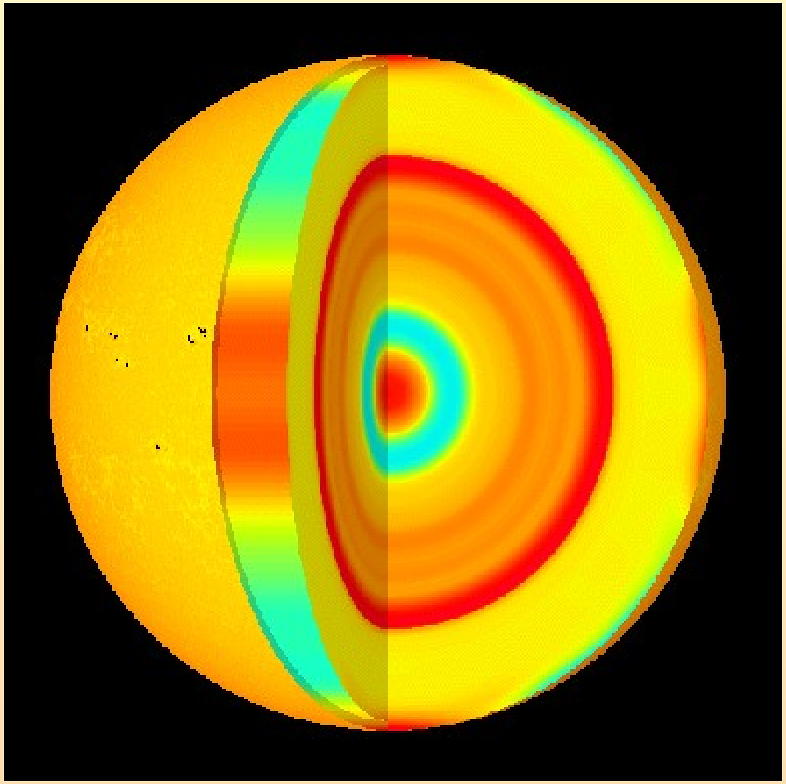


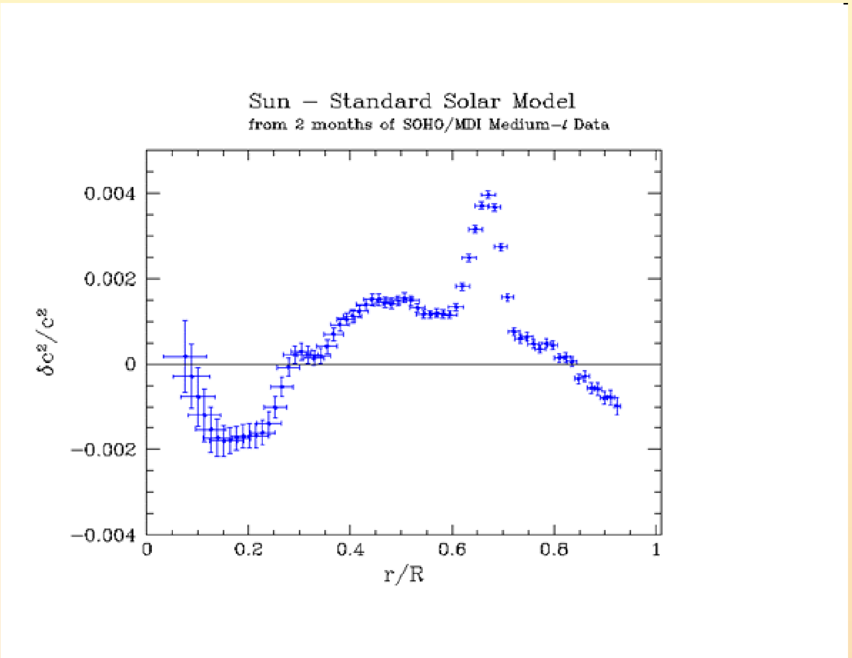
1000 sigma error bars!
Rhodes et al., Solar Physics, 1997

Global properties of the solar interior

- Internal Rotation Profile
- Rotation of Core
- Tachocline

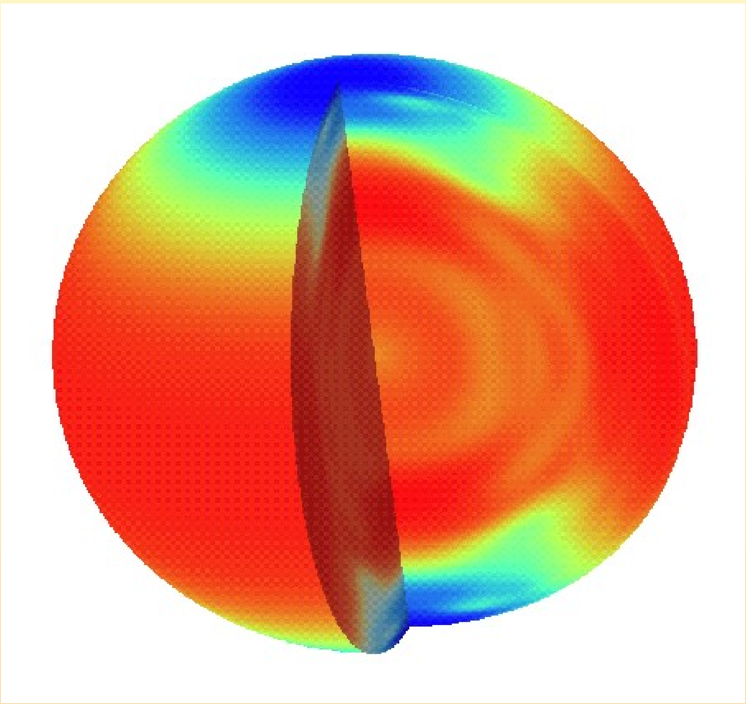
Temperature/Sound Speed





This graphic from A.G. Kosovichev shows the radial and latitudinal variations of the sound speed in the Sun, relative to a standard solar model. Red color corresponds to the positive variations (`hotter' regions), and blue color corresponds to negative variations (`cooler' regions).

Global helioseismology



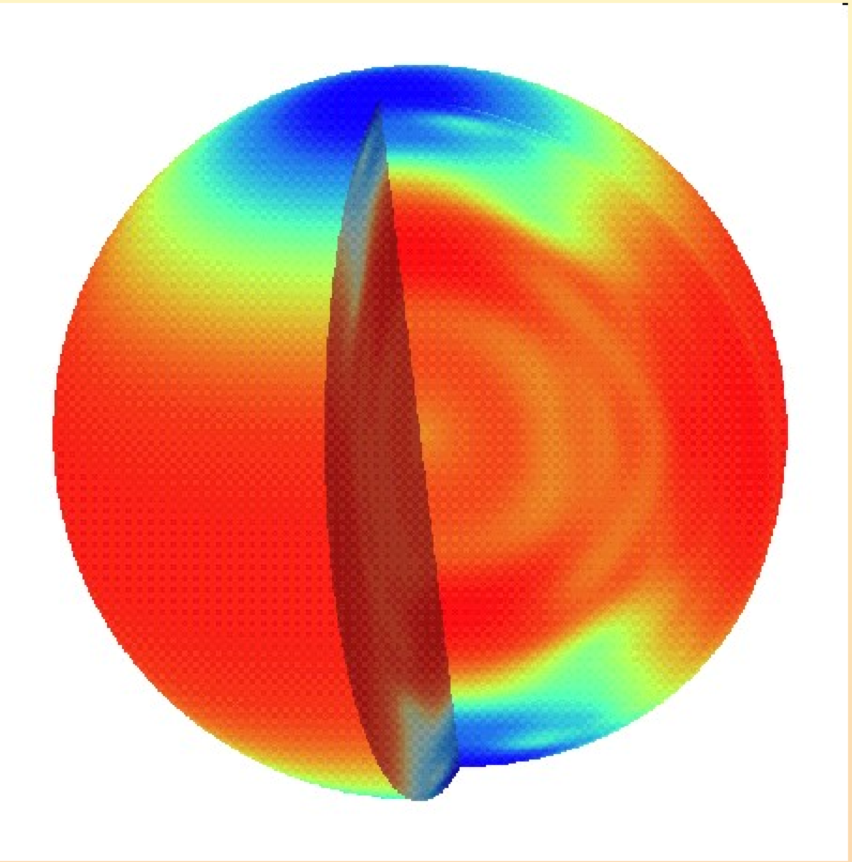
red is faster (P=26 days)
blue is slower (P=35 days)

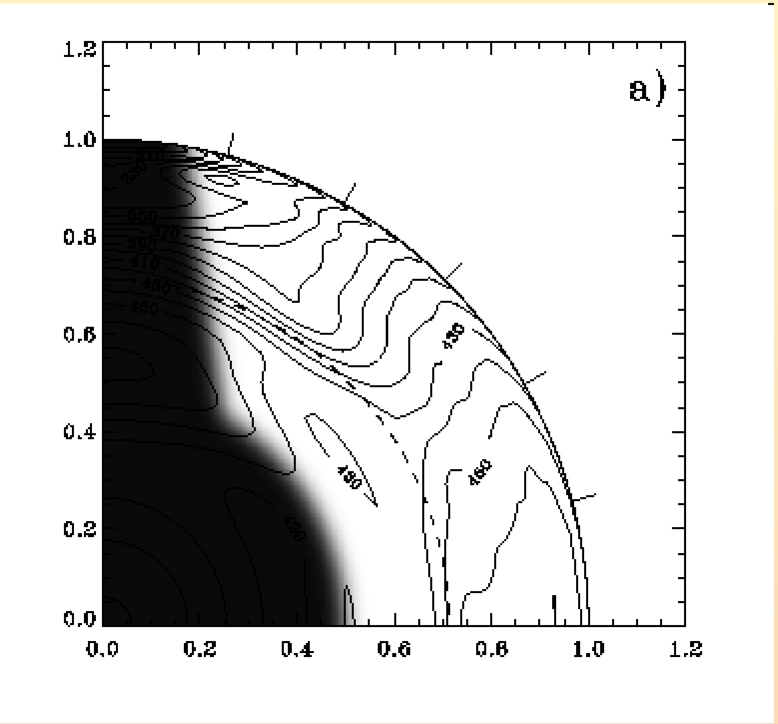
Example: Internal rotation

- Frequencies of the normal modes of oscillations are Doppler shifted by rotation

- Differential rotation in the convective envelope.
- Uniform rotation in the radiative interior.
- very small temporal

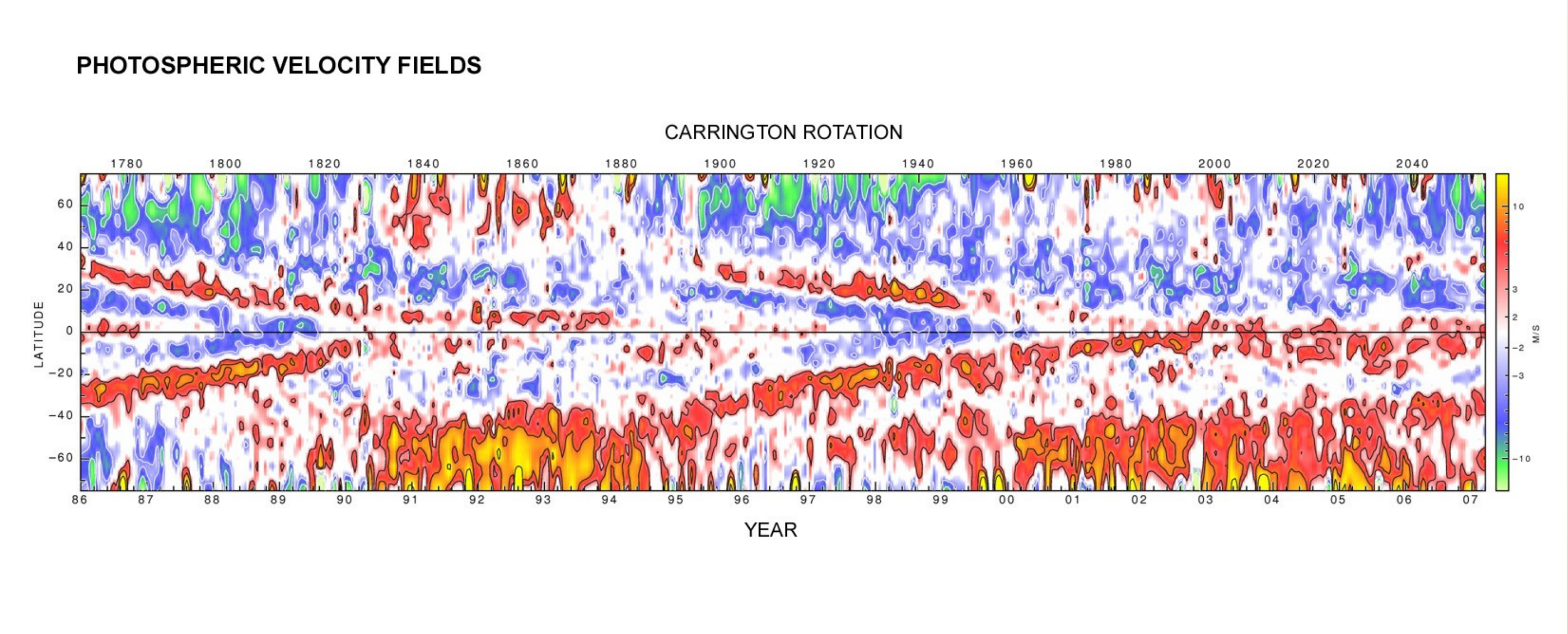
Internal Rotation Constrains Dyanamo





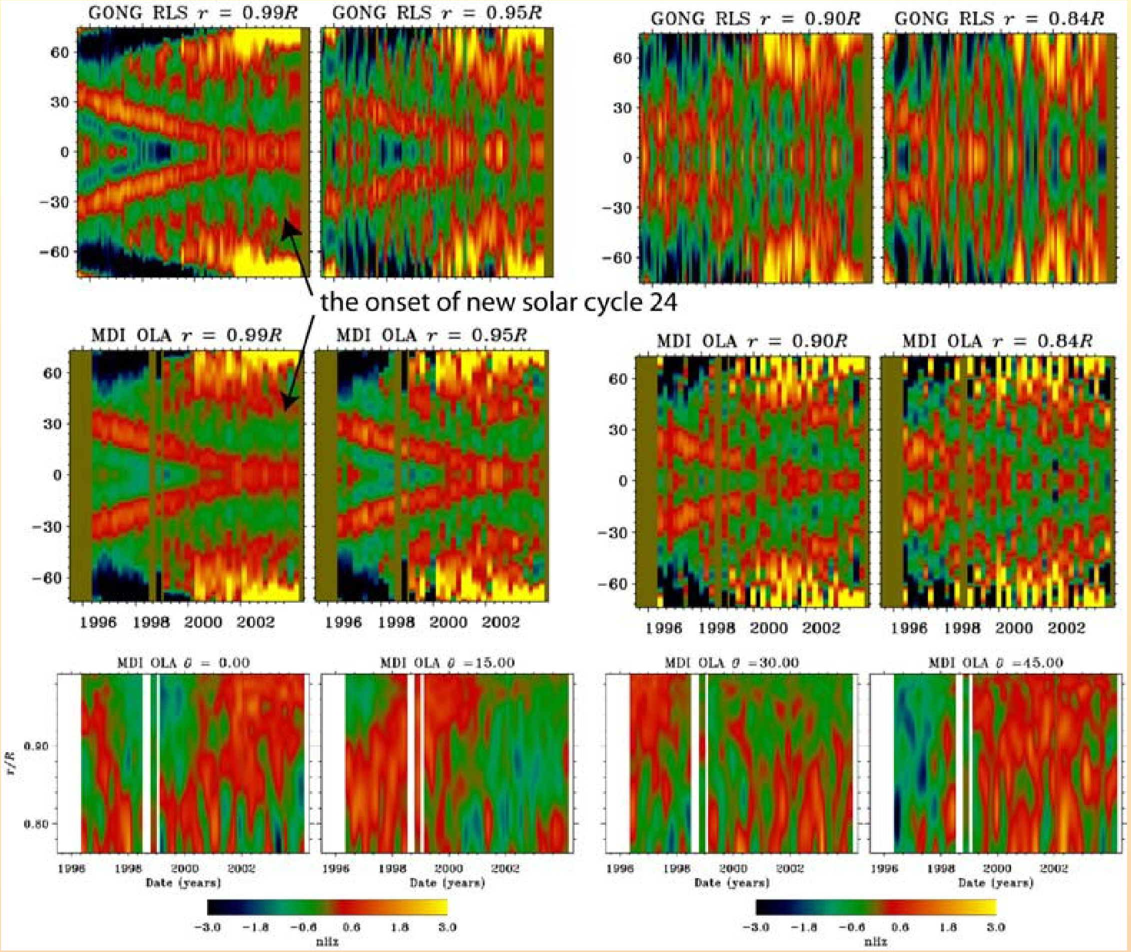
Kosovichev et al, 1997

Extended Solar Cycle In Torsional Oscillation At Solar Surface



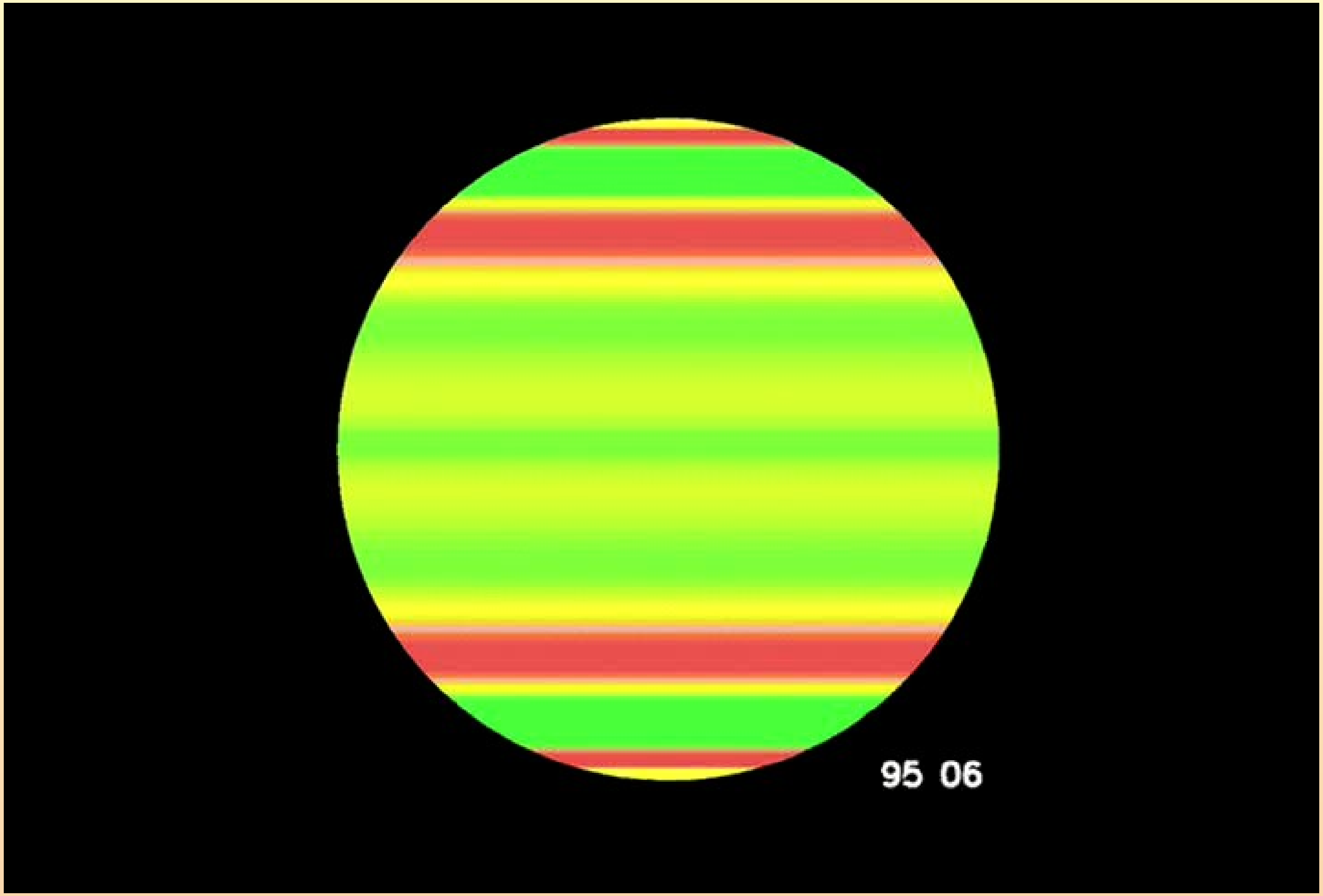
Mt. Wilson Solar Observatory

Time-latitude (top and middle panels) and time-radius maps of the zonal flows ("torsional oscillations") obtained by helioseismic inversions from GONG & MDI.



Howe, et al., 2004

Torsional Oscillation Movie

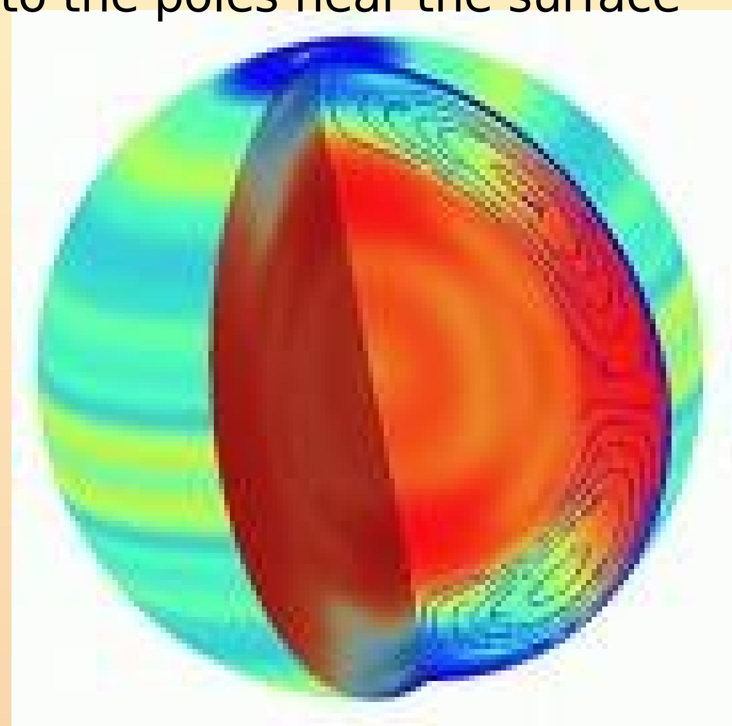


Meridional Flow

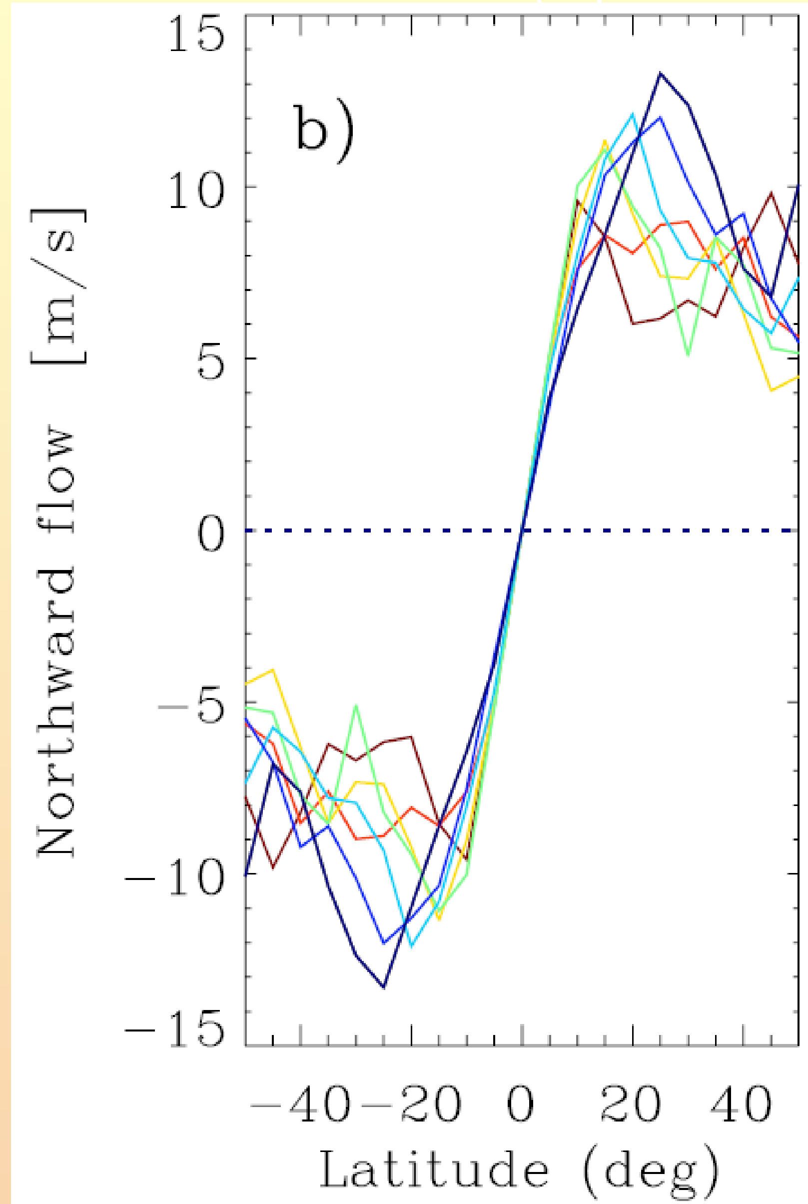
Near surface (top ~10 Mm)

North-south travel-time differences
averaged over longitude

~10 m/s flow from the equator to the poles near the surface



Giles (1999)

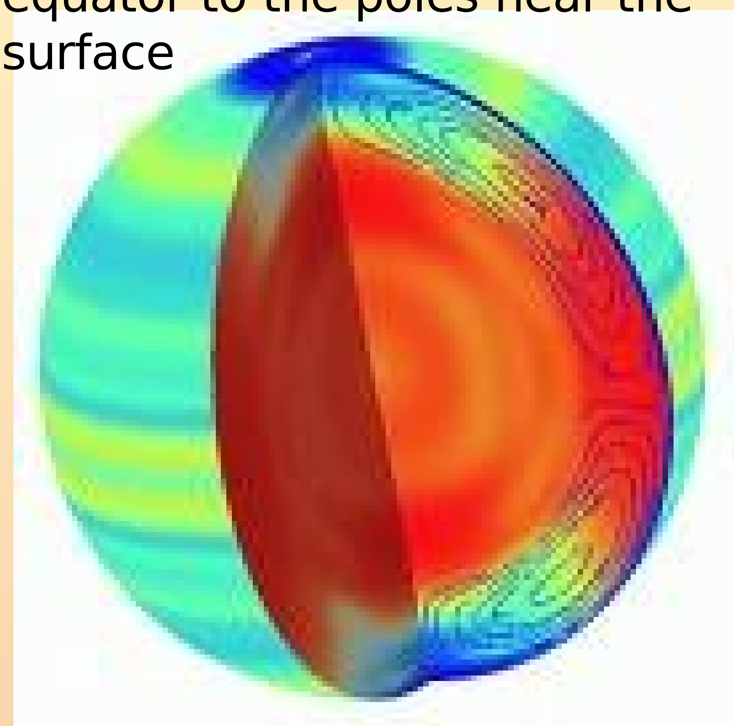


Gizon & Rempel (2008)

Meridional Flow

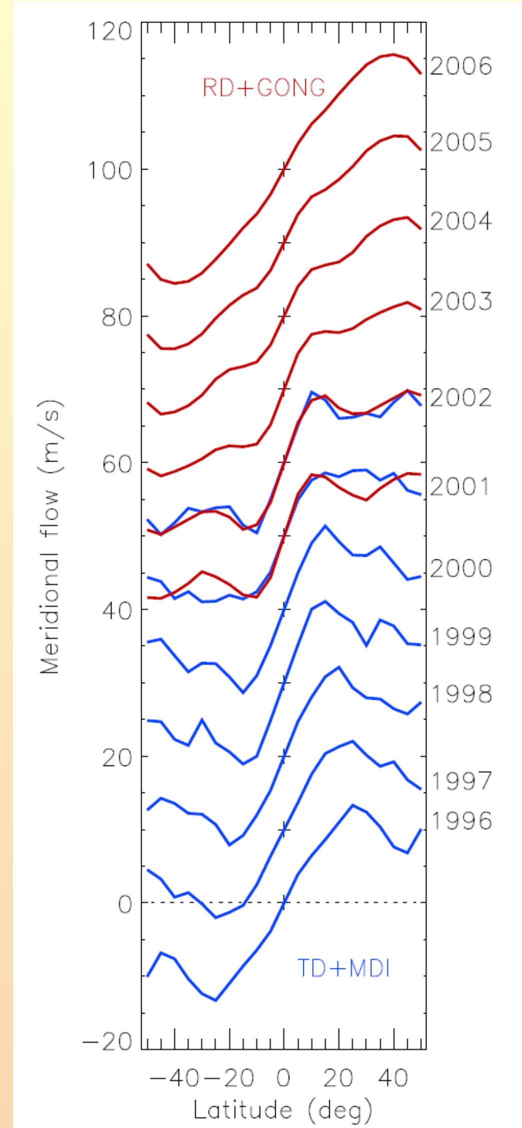
North-south travel-time differences
averaged over longitude

10-15 m/s flow from the equator to the poles near the surface



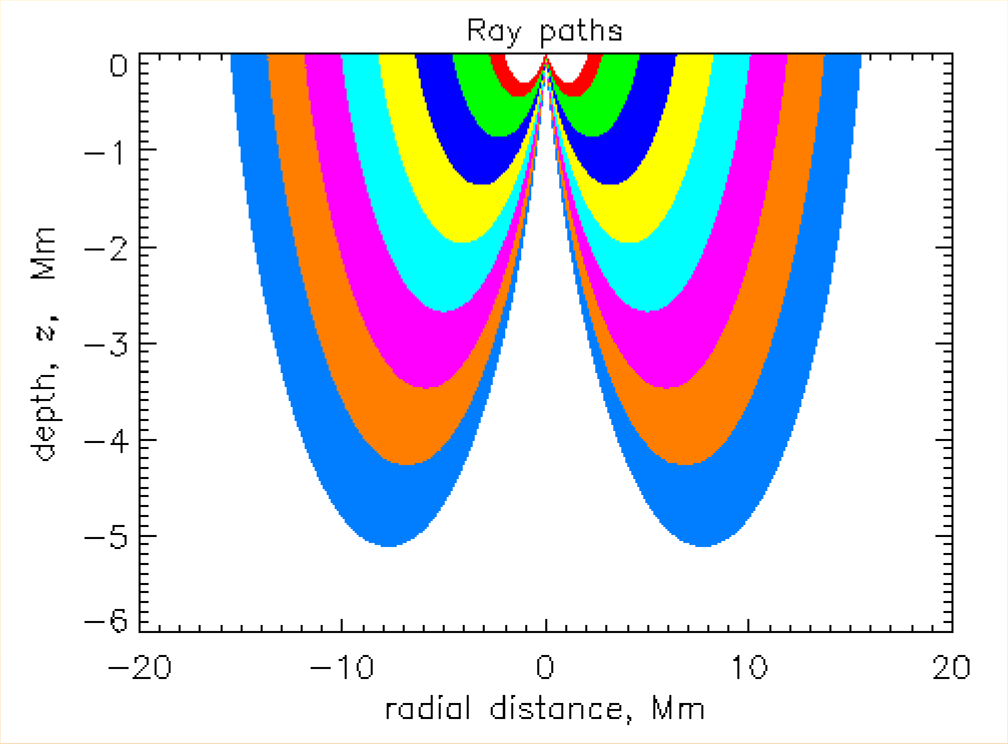
Giles (1999); Kosovichev et al., 1997

Solar cycle dependence

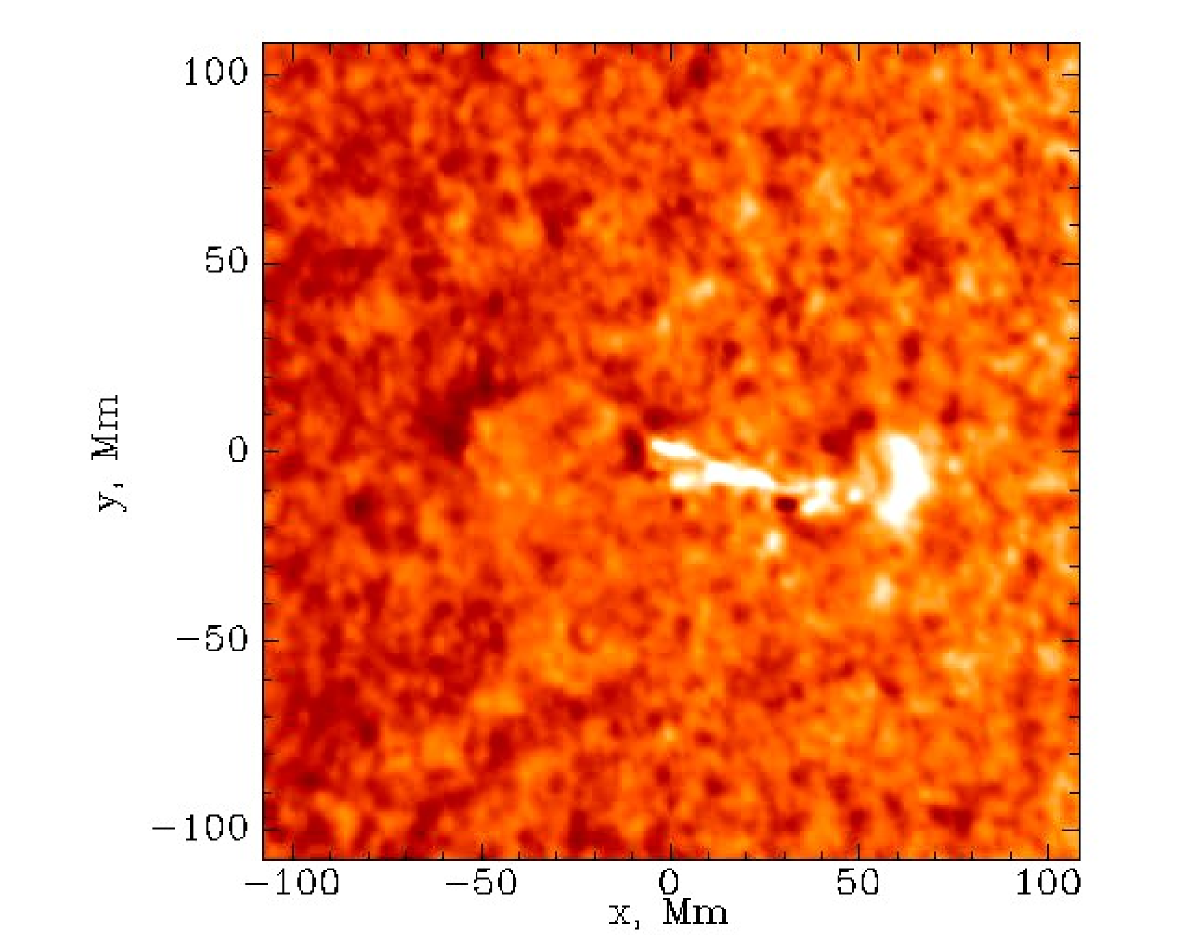


Gizon & Rempel (2008)
Gonzalez Hernandez et al. (200

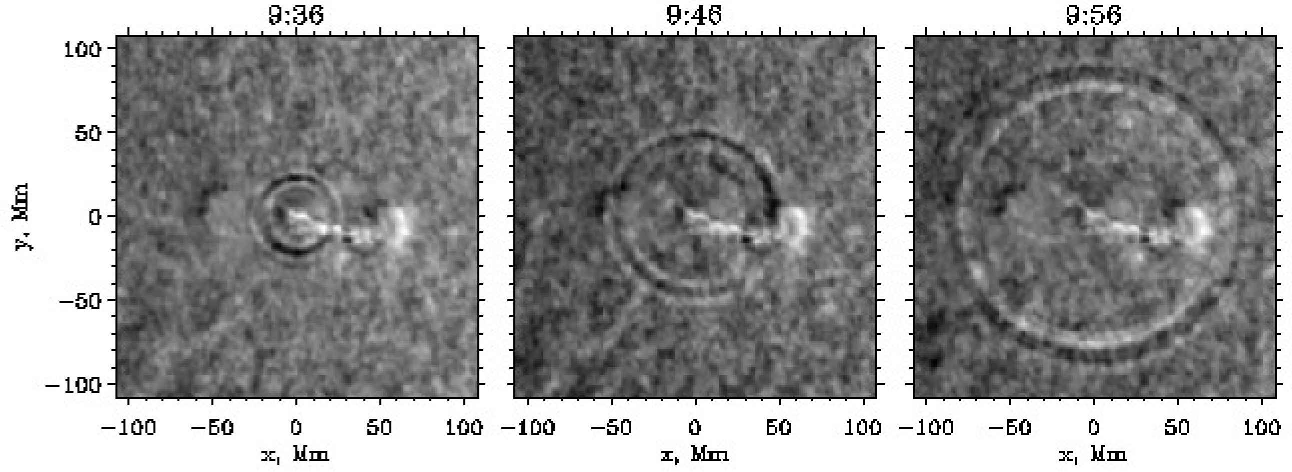
Paths that Acoustic Waves Follow Beneath the Solar Surface



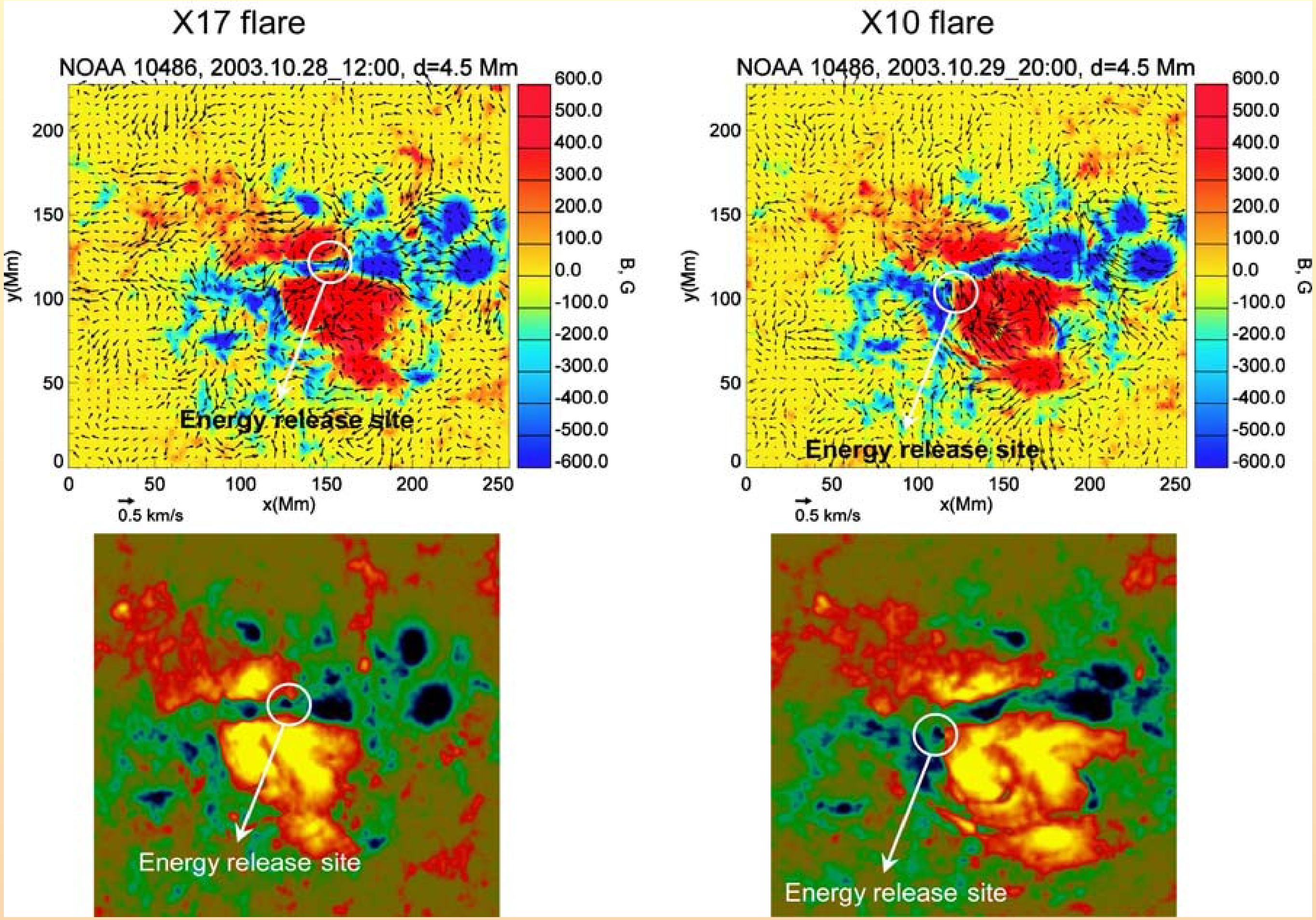
Flare Oscillations Movie



Subsurface Flare Signals

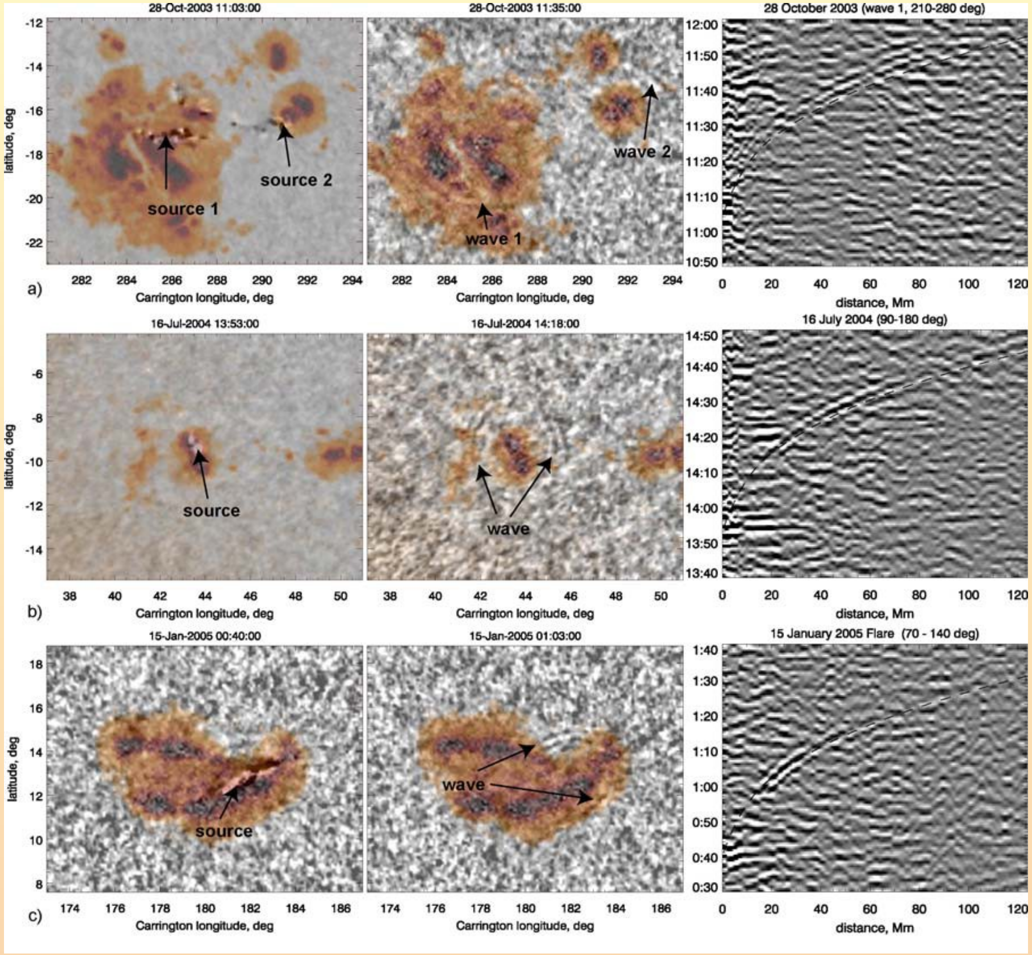


High-resolution maps of subsurface plasma flows obtained by time-distance helioseismology (top panels) and MDI magnetograms (background top and bottom images) during two solar flares: left, X17 (Oct. 28, 2003, 11:10 UT) and X10 flare (Oct. 29, 2003, 20:37 UT) During the flare strong plasma flows are observed at depth 4-6 Mm, shearing and converging in the magnetic neutral line region where the magnetic energy was released.



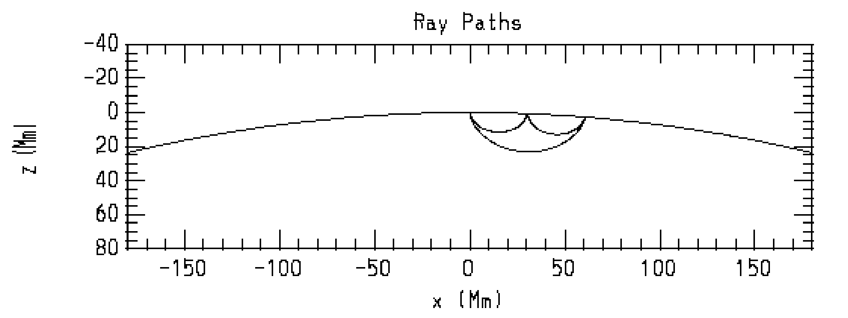
Dzifcakova et al, 2003; Kulinova et al., 2003

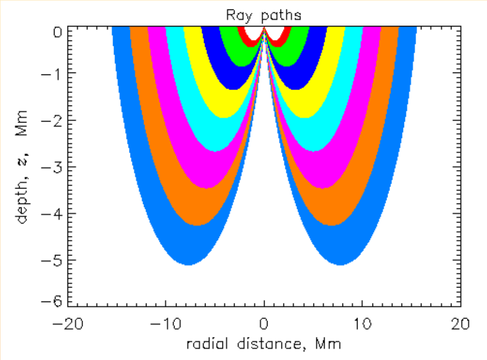
Observations of the seismic response of the Sun (‘sunquakes”) to three solar flares: X17 of October 28, 2003 (top panels), X3 of July 16, 2004 (middle panels) and X1 flare of January 15, 2005. The left panels show a superposition of MDI white-light images of the active regions and locations of the sources of the seismic waves determined from MDI Dopplergrams, the middle column shows the seismic waves, and the right panels show the time-distance diagrams of these events. The dashed curve is a theoretical time-distance relation for helioseismic waves.

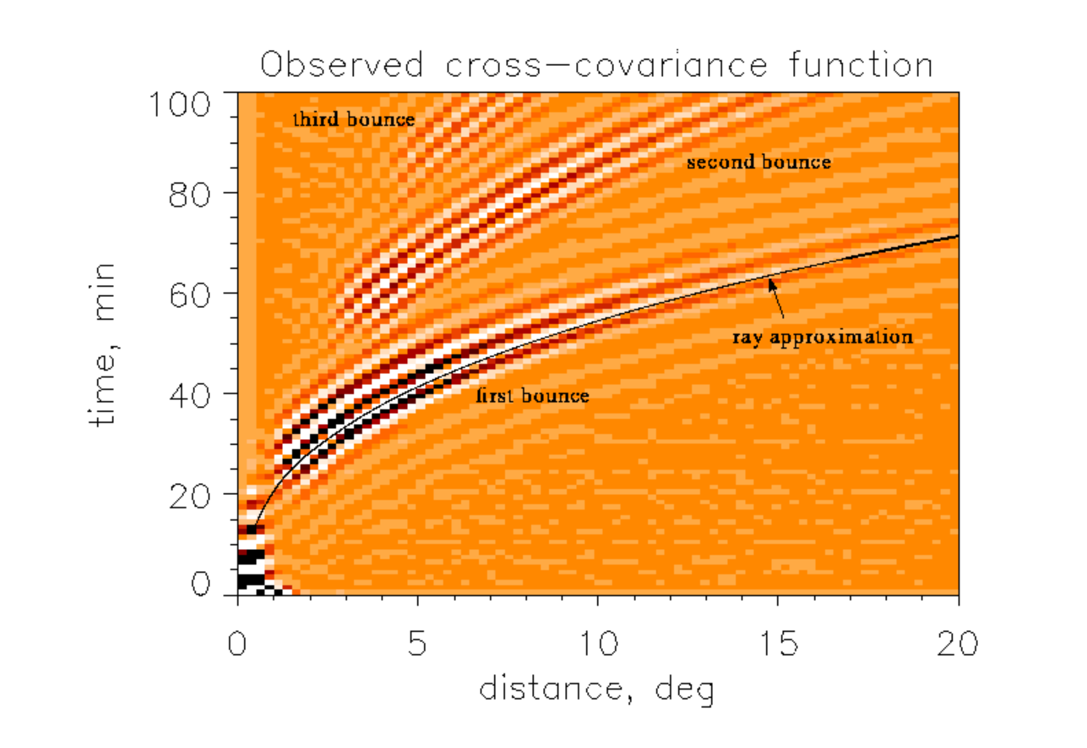


Kosovichev, 2007

Waves Refracted Inside the Sun are Detected When They Reflect Off the Surface

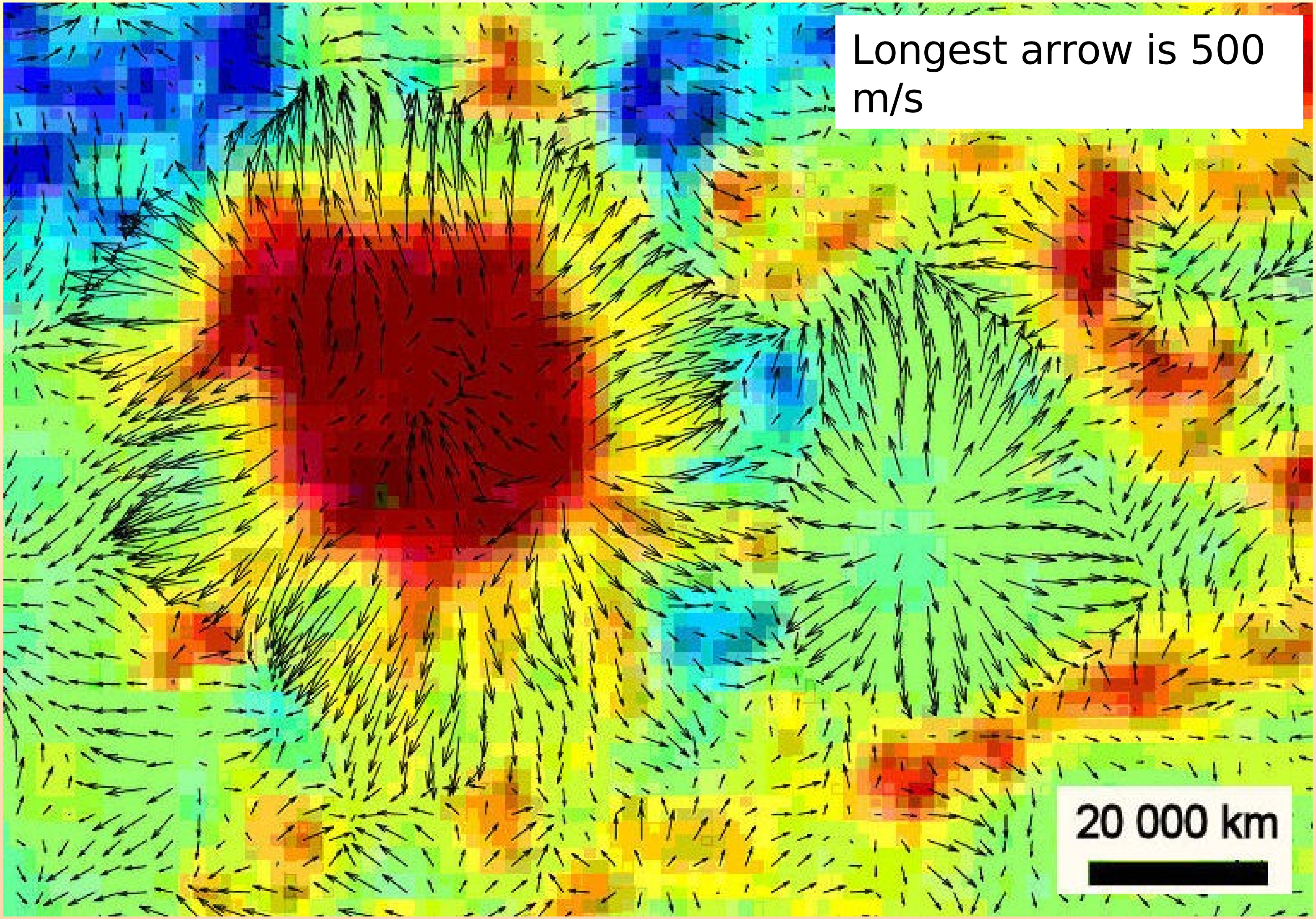






Duvall et al., 1997

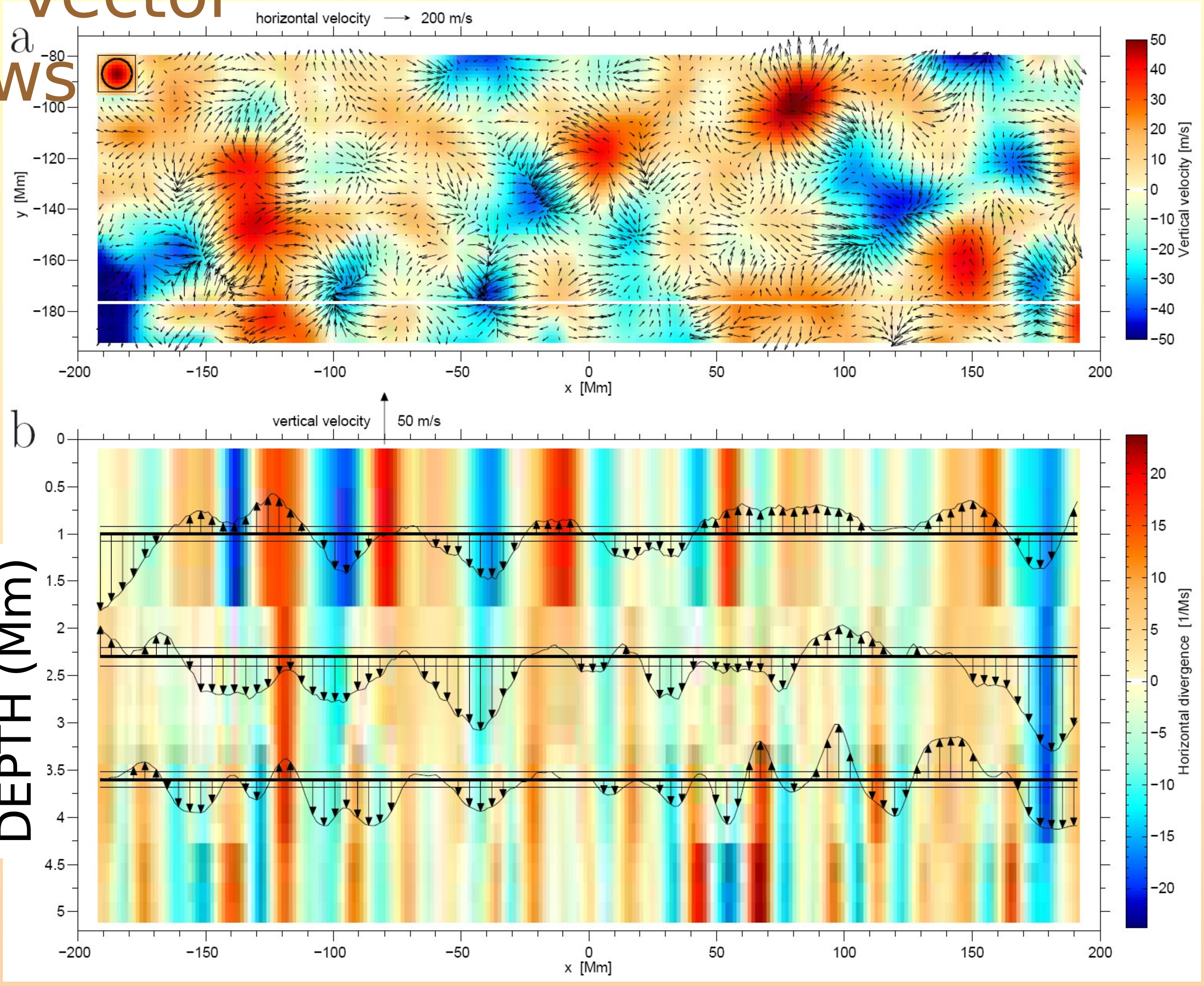
Horizontal Hlows



Arrows: u_x and u_y at depth 1 Mm

Gizon, 2009

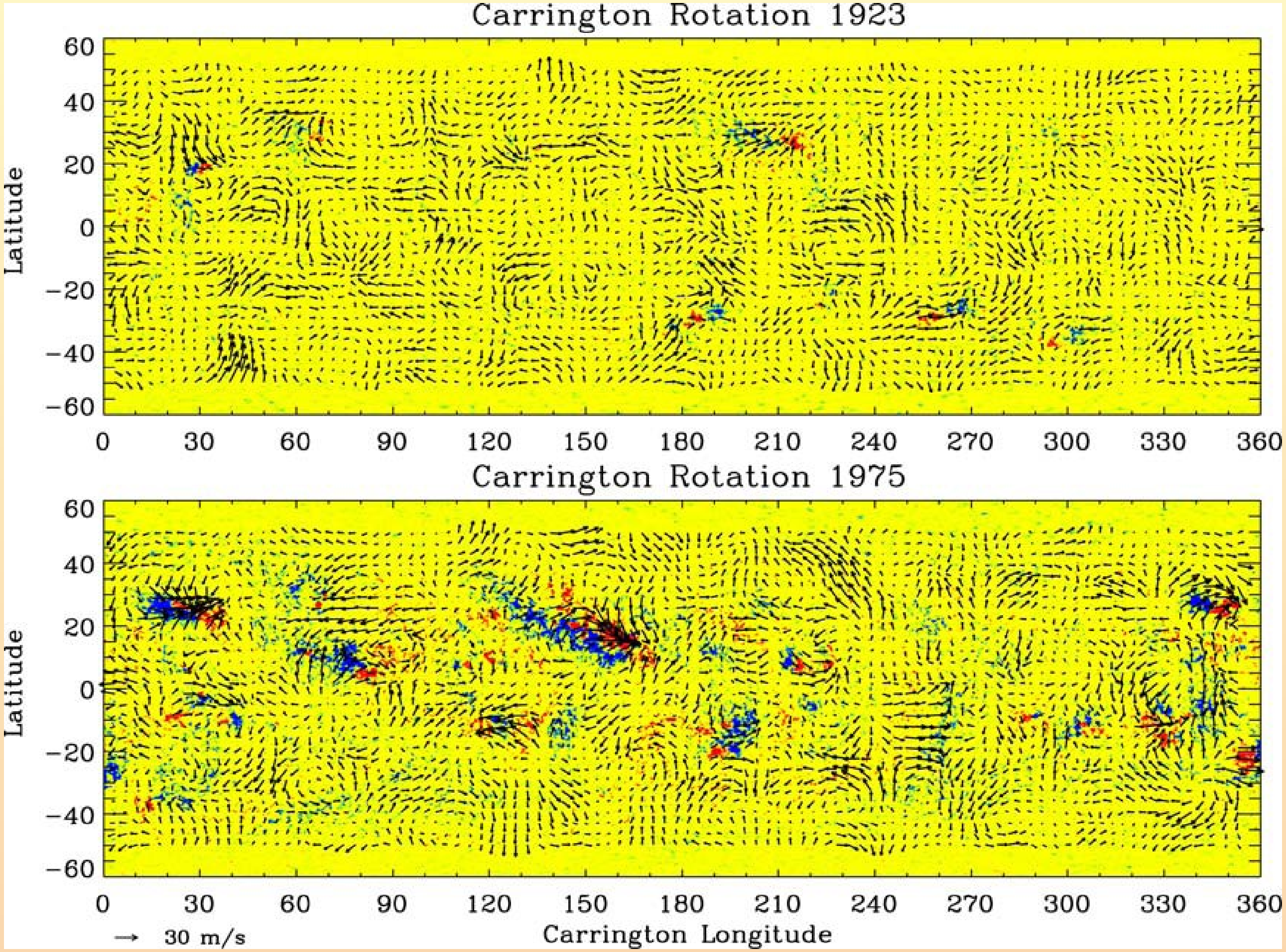
3D vector flows



DEPTH (Mm)

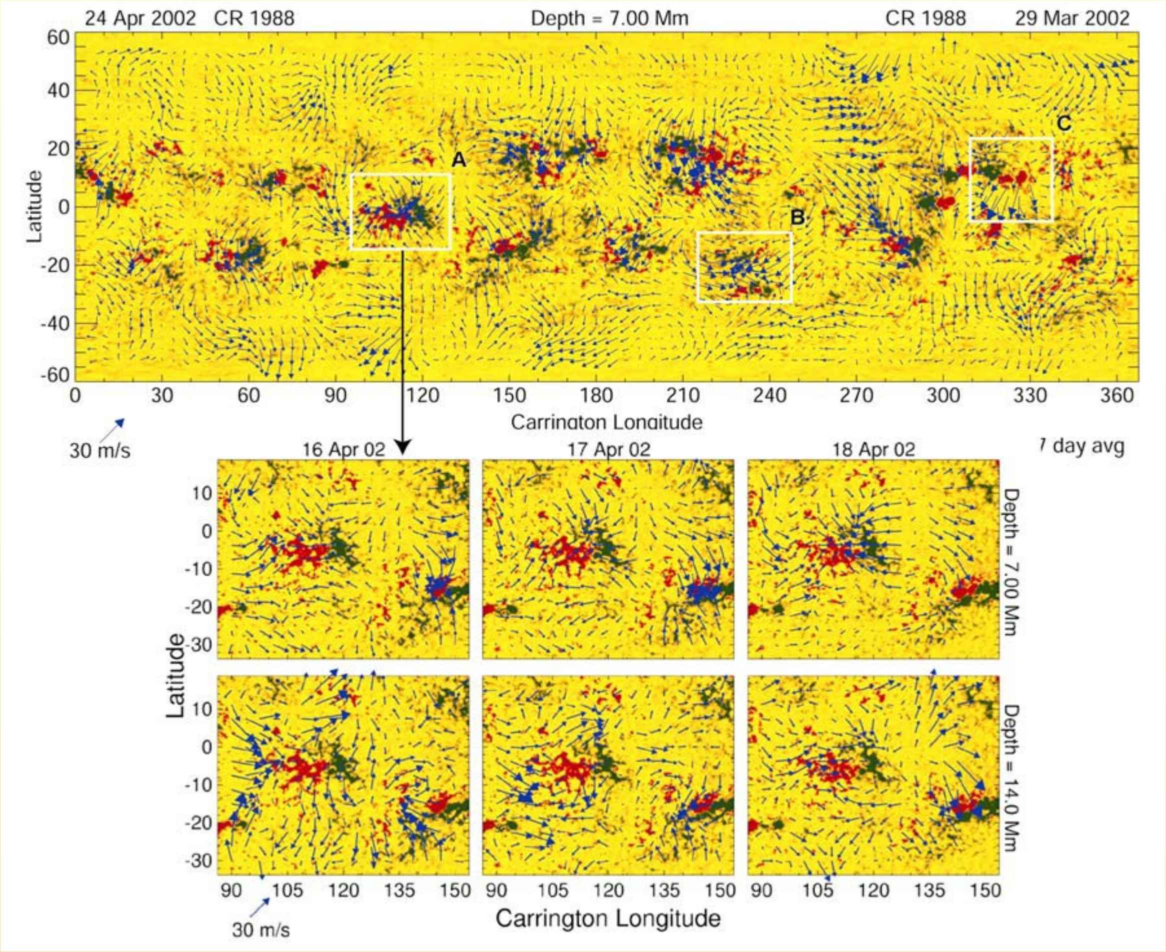
Jackiewicz, Gizon, Birch (2008)

Synoptic maps of large-scale subphotospheric flows obtained from SOHO/MDI during the activity minimum (upper panel) and activity maximum (lower panel). The color background shows the corresponding synoptic maps of the photospheric magnetic field positive (red) and negative (blue) polarities. Evidently, magnetic activity of the Sun is associated with substantial changes of the subsurface flow patterns (‘subsurface solar weather’).



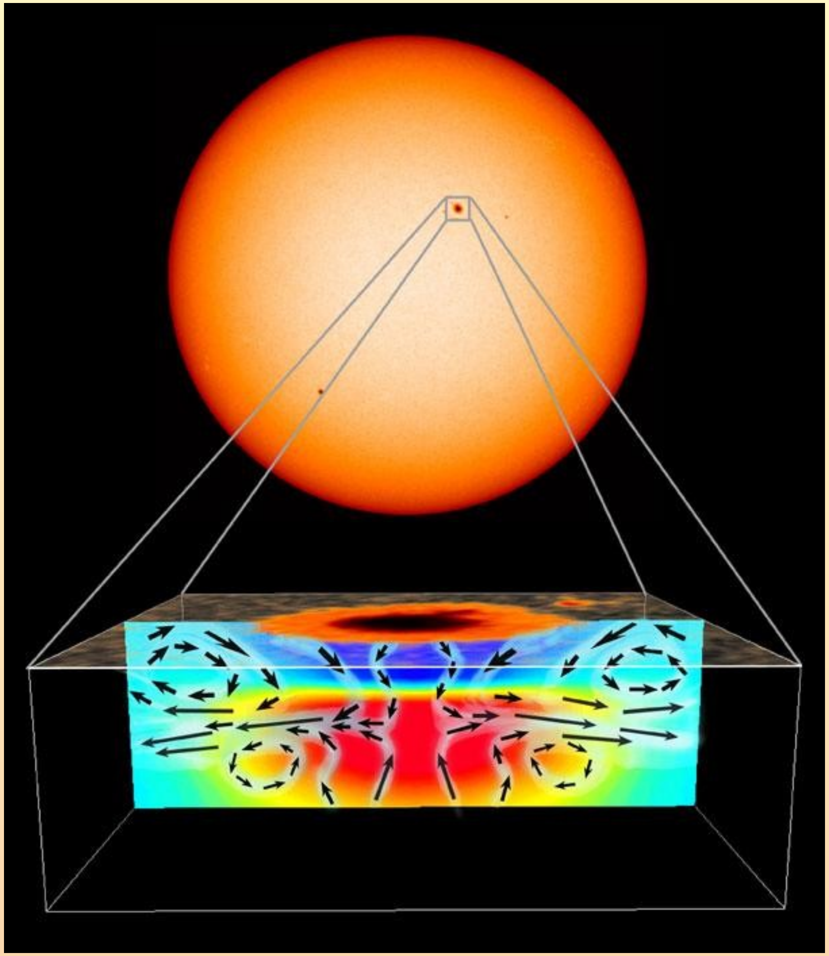
D. Haber, 2004; J. Zhao and A. Kosovichev, 2004

Figure 8. Synoptic maps of subsurface velocity fields at depth 7 Mm (upper panel) obtained from the SOHO/MDI full-disk dynamics data. Large scale flows in the vicinity of active regions display a variety of flow phenomena. Three flow types are shown here: Region A (NOAA 9907) shows converging flow at shallow depths and diverging flow at deeper layers (the lower panels). Region B (9904) is marked by converging flows at all depths. Region C (9885) displays diverging flows at all depths.

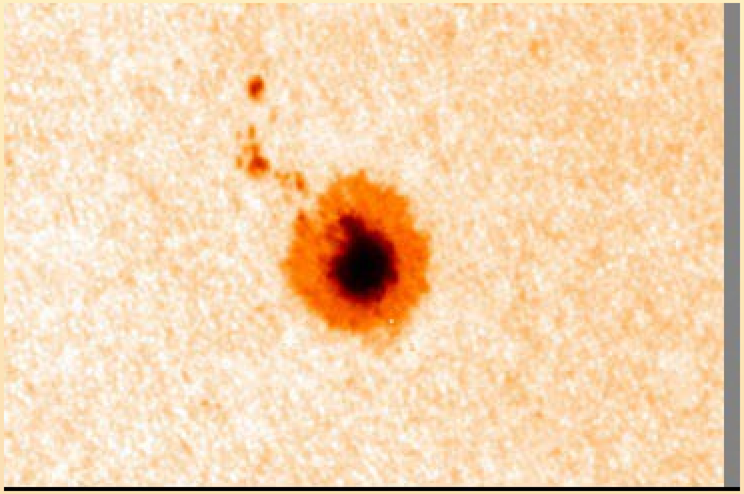


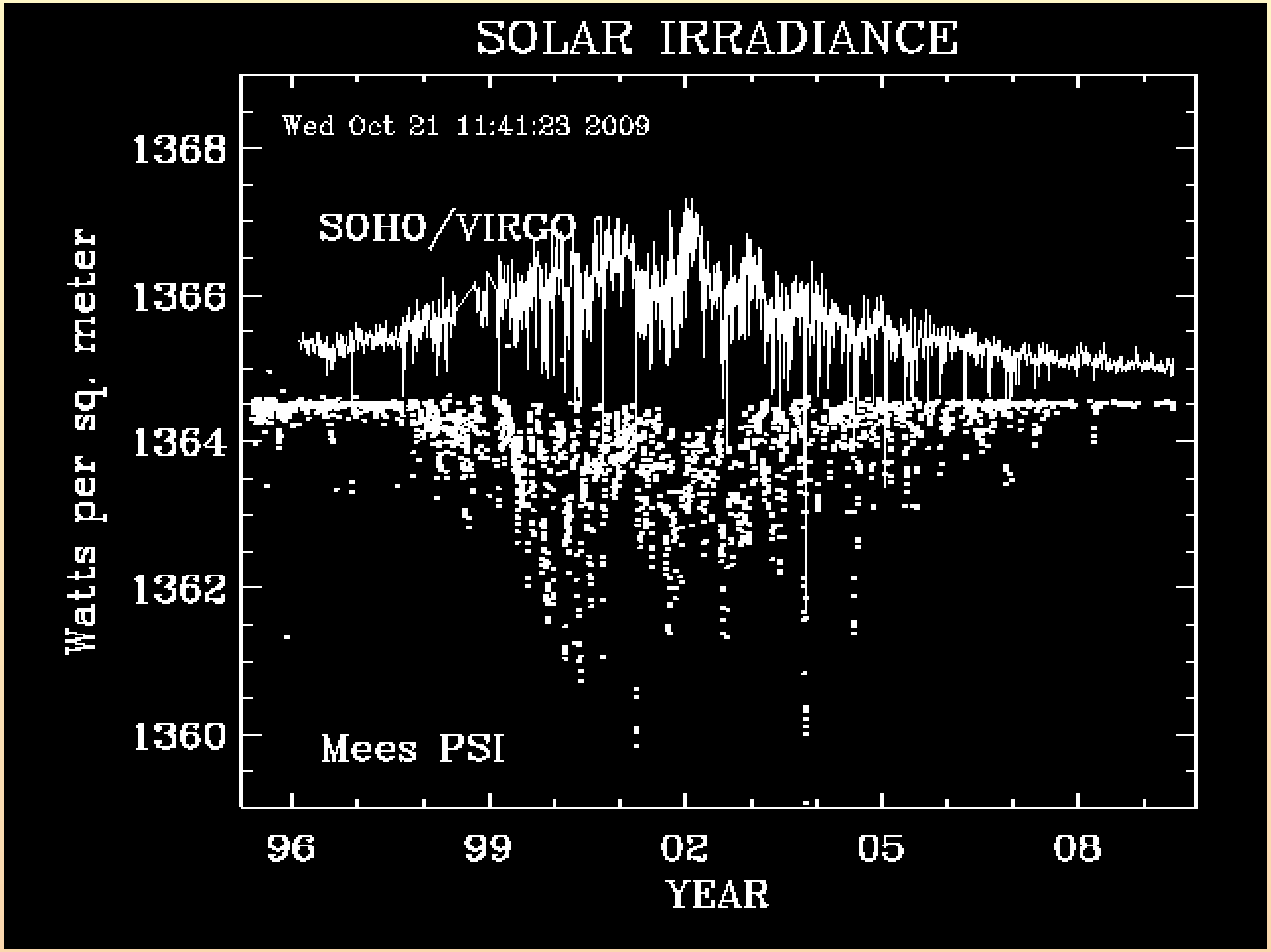
Brown et al., 2004

Below a Sunspot

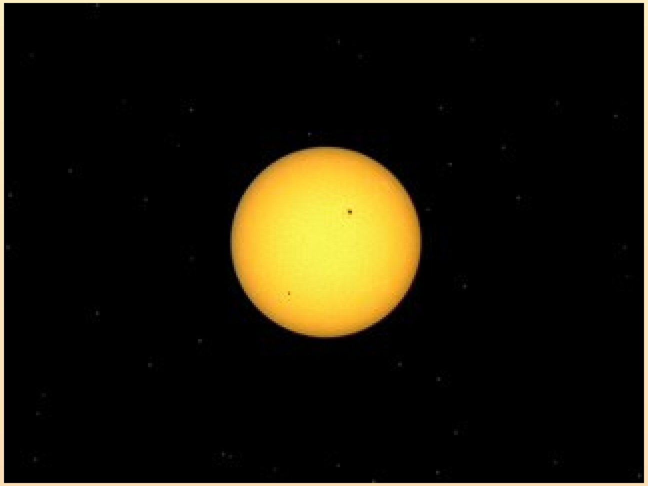


Below a Sunspot Movie
Anatomy of Temperature & Flow



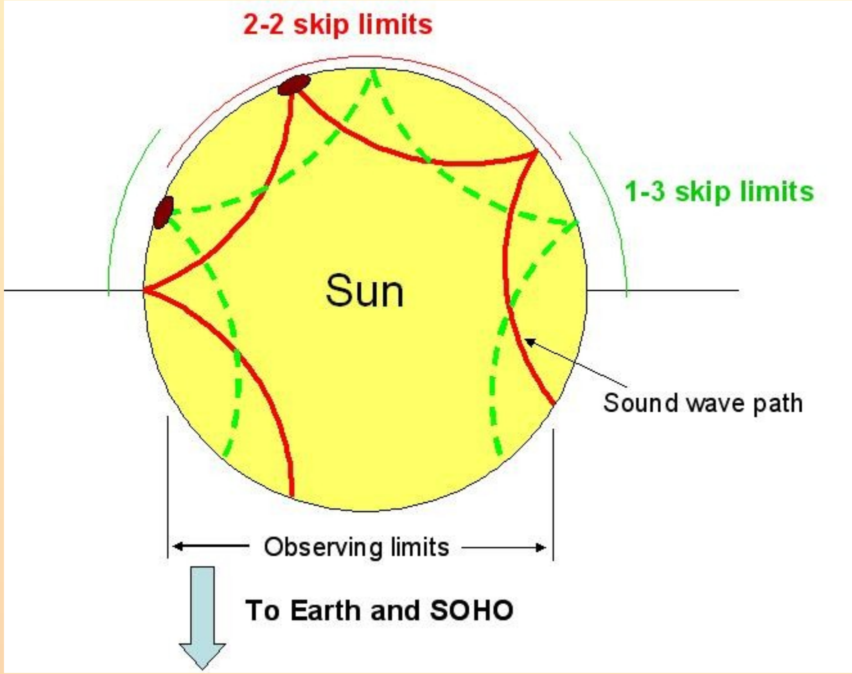

SOLAR IRRADIANCE
Wed Oct 21 11:41:23 2009
SOHO/VIRGO
Mees PSI
Watts per sq. meter
1368
1366
1364
1362
1360
96
99
02
05
08
YEAR

Rendering of Physical Conditions Beneath a Sunspot - Movie

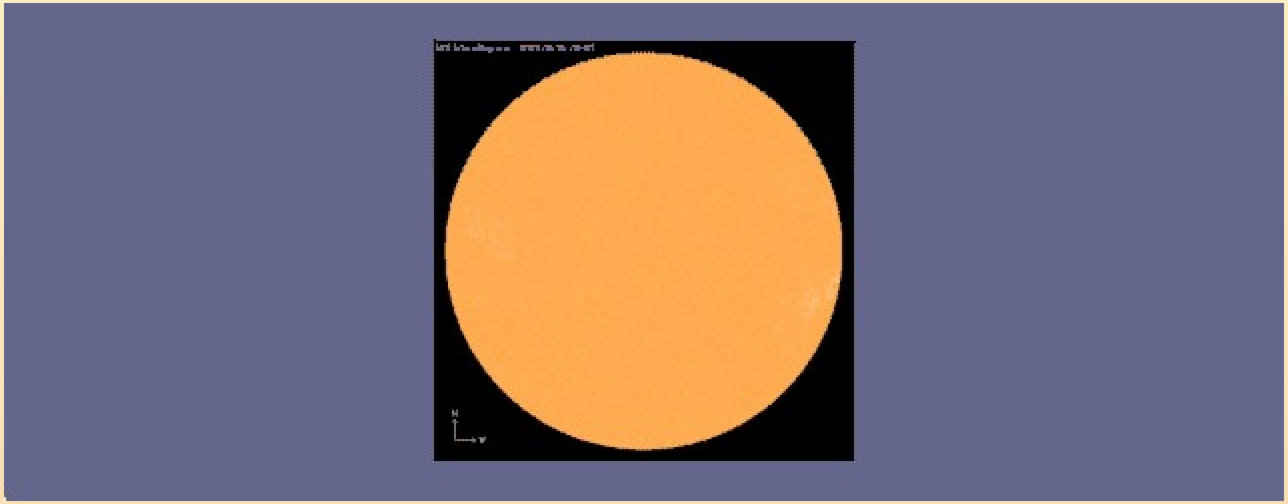


Far Side Imaging

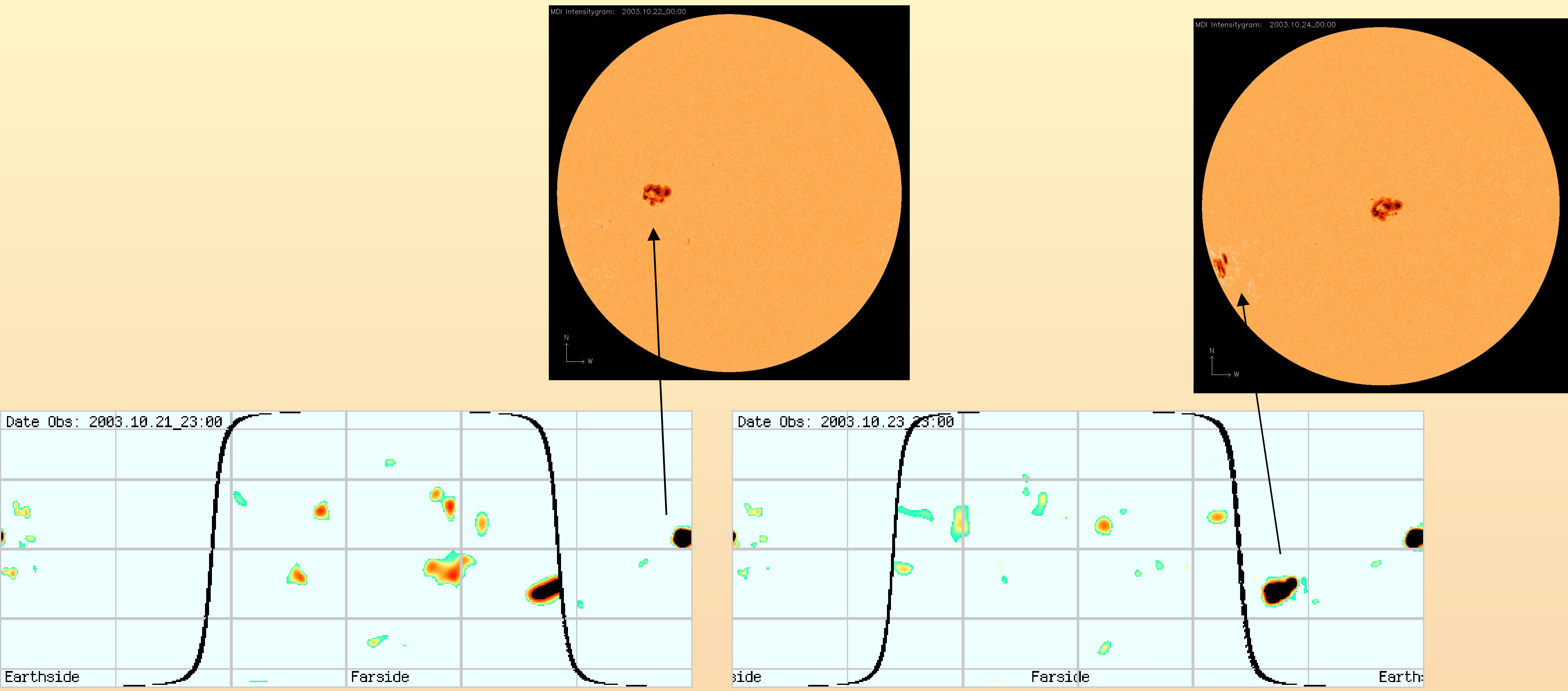
- http://soi.stanford.edu/data/full_farside/



Far Side Movie



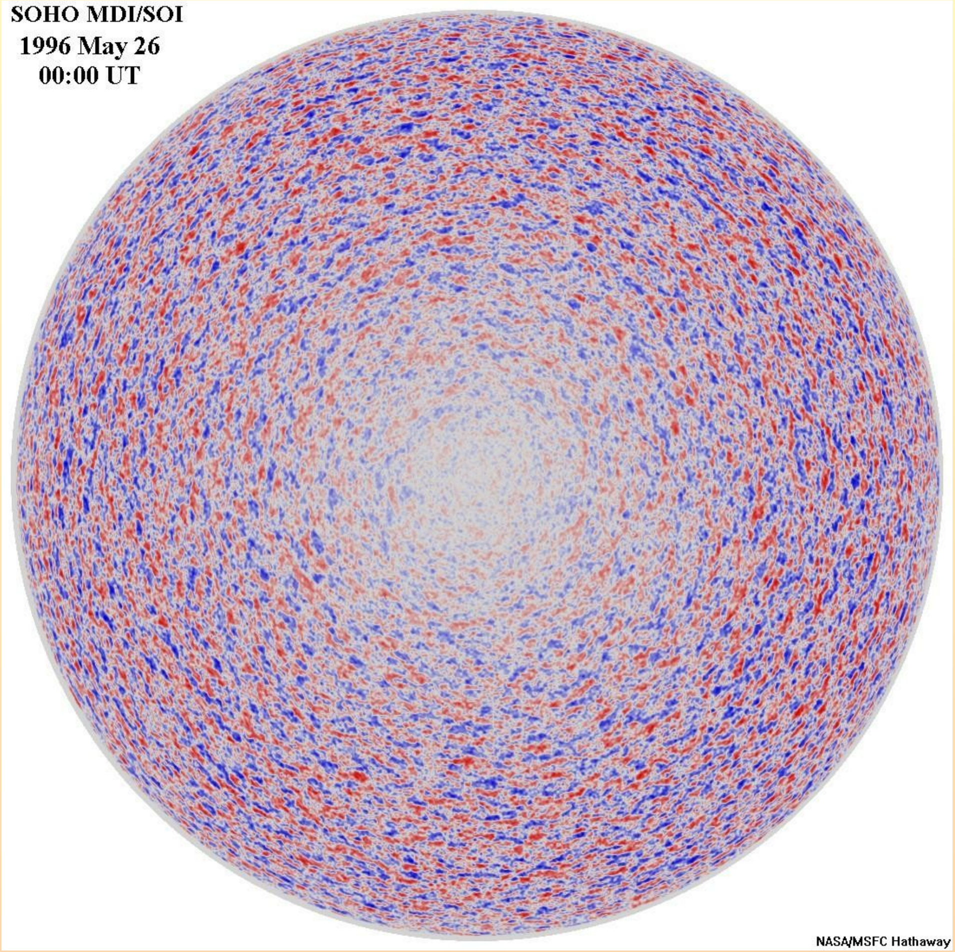
A Large Active Region Rotates onto the Disk



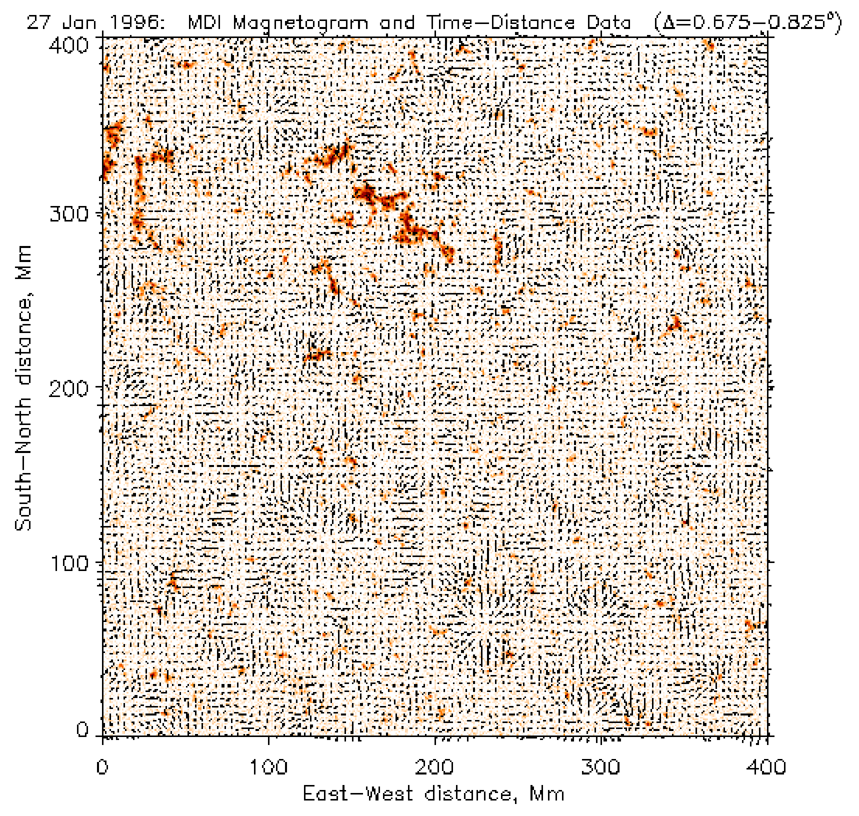
The Next Big Questions?

- Prediction of the next cycle
- Forecasting active regions & events
  - Emergence, complexity, evolution, and decay
- The base of the convection zone
- Deeper below sunspots – subsurface weather
- The poles
- Small-scale dynamo action
- The solar – stellar connection
- Better data and better models

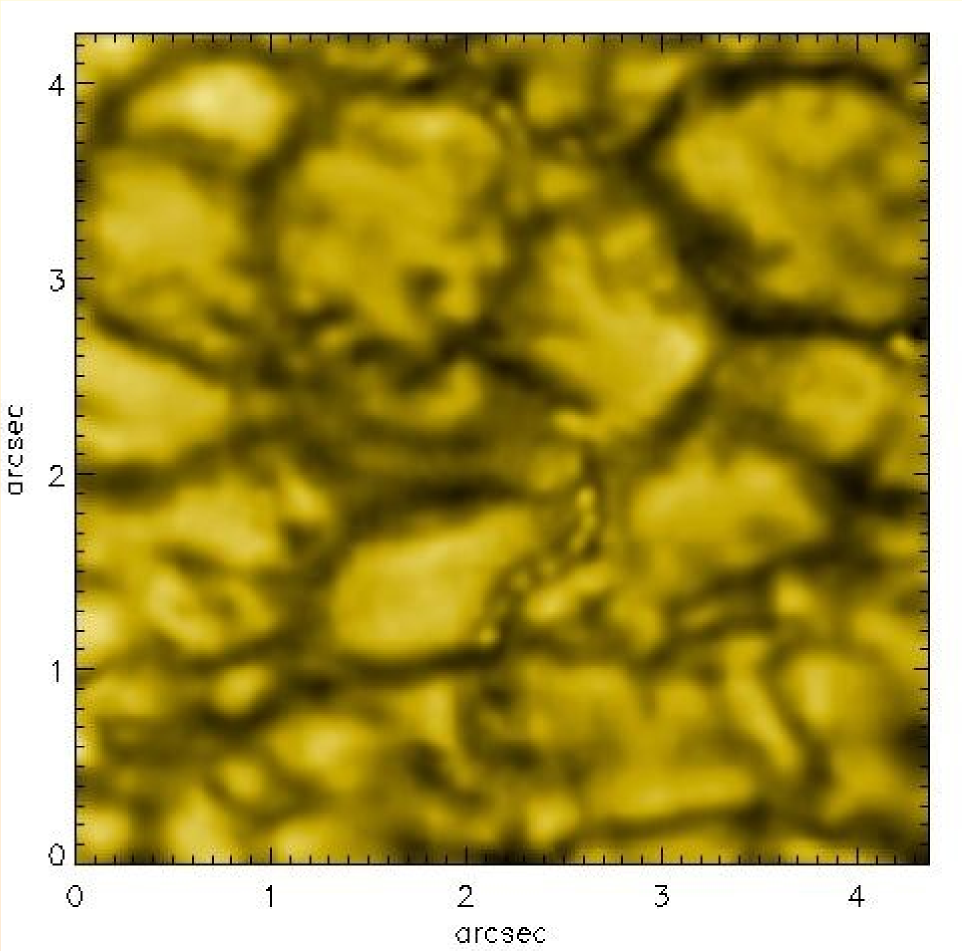
Supergranules on Solar Surface



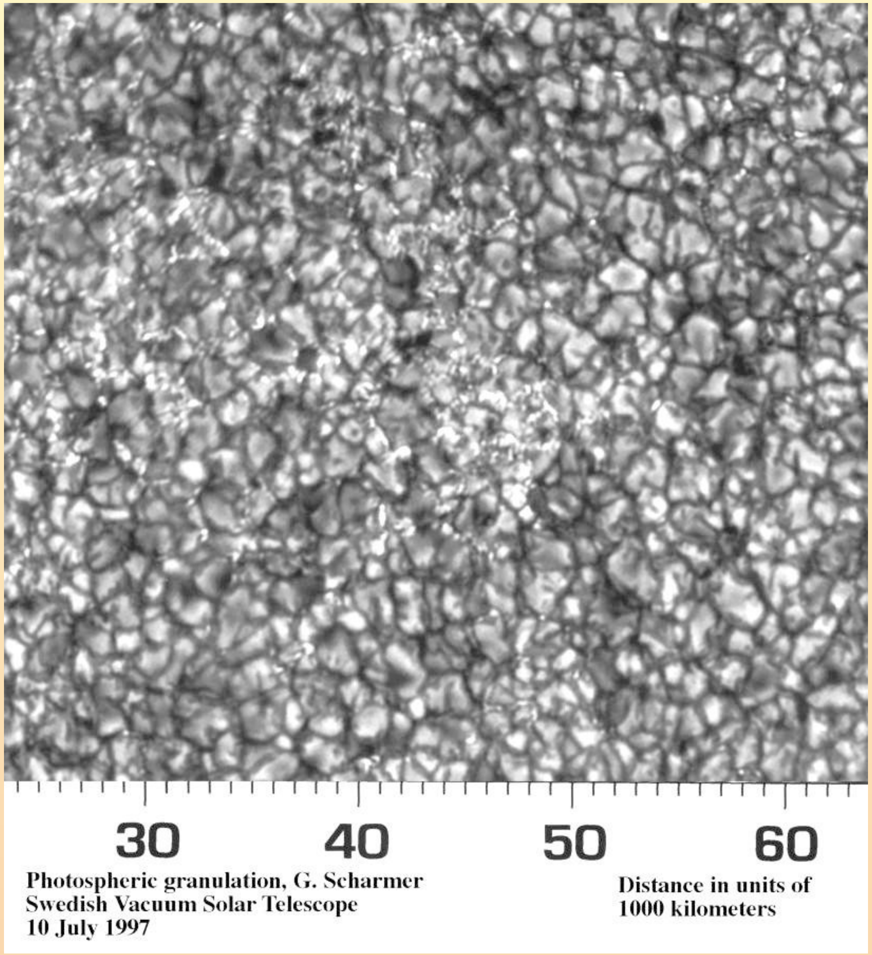
Derived Near-Surface Flows Show Supergranular Patterns



First Light Image from NST - the New Solar Telescope at Big Bear

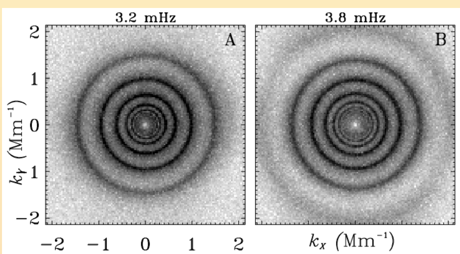


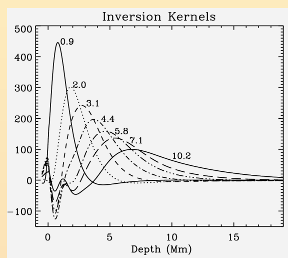
Solar Granulation and Small Magnetic Elements



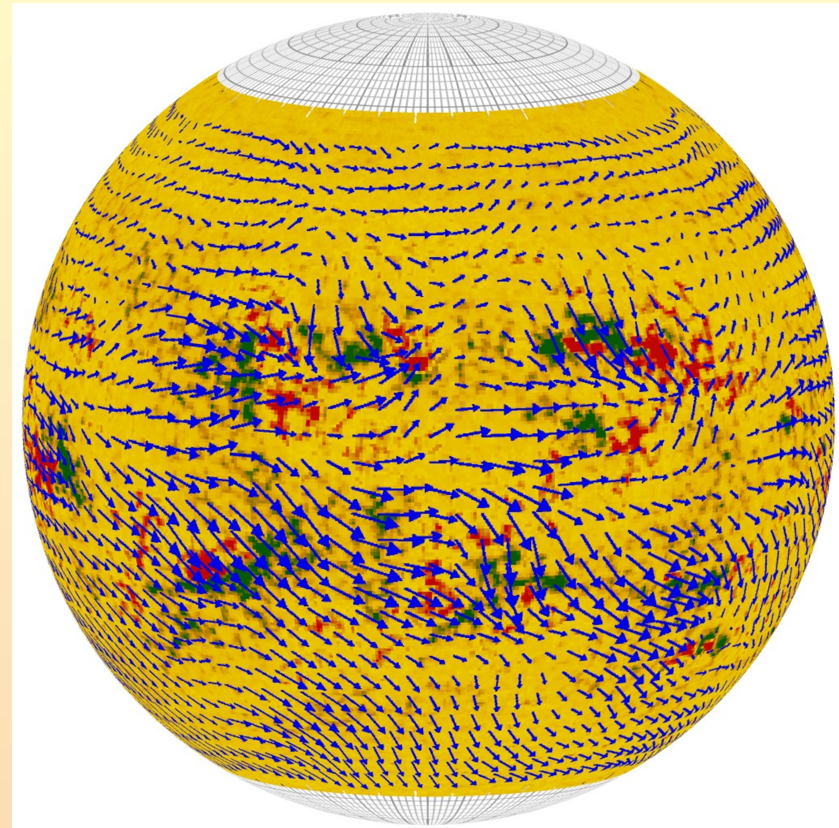
Solar Subsurface Weather

- First ``Solar Weather Maps'' showing changing "wind" patterns on a star
- From time-distance and ring-diagram analysis
  - Analyze acoustic wave fields of mosaics of tracked localized regions (each 15º square)
  - Measure anisotropic frequency splittings of local *f* and *p* modes in power spectra
  - Invert splittings to deduce flows with depth





- Large transient wind streams visible
- Major active regions exhibit prominent inflows in upper 7 Mm, outflows below 11 Mm
- Clear interplay between SSW flows and magnetic fields. (Who pushes whom around?)
- Flow evolution: streaming features strengthen and converge toward active regions

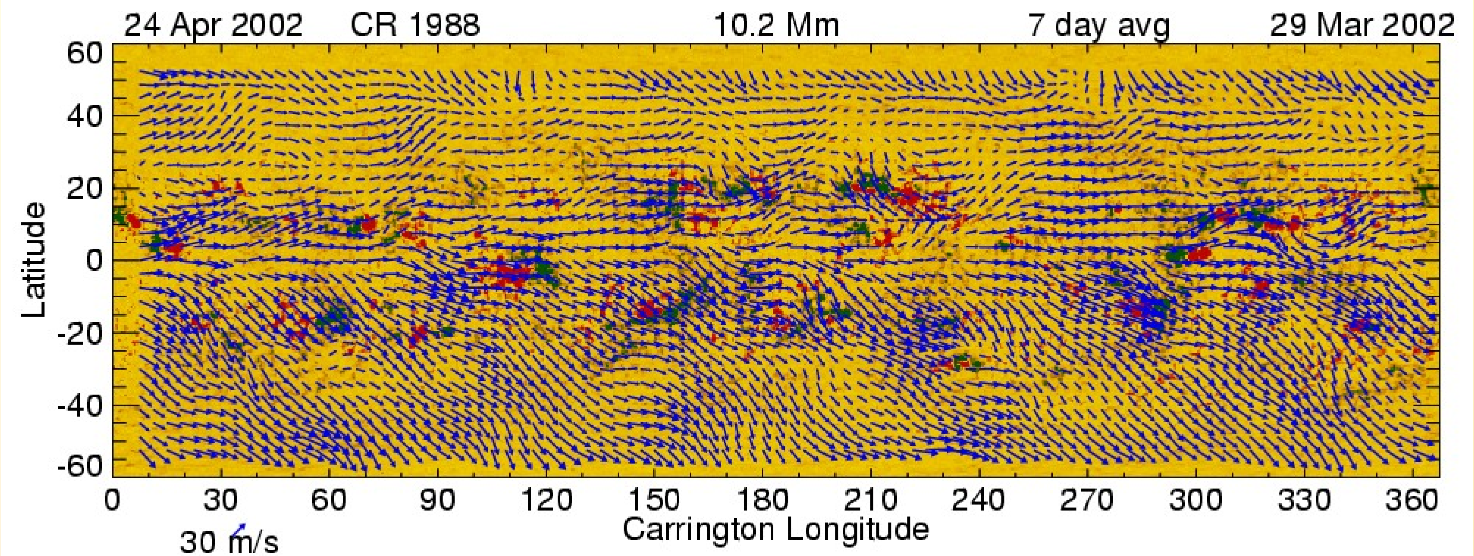


SSW in April 2002

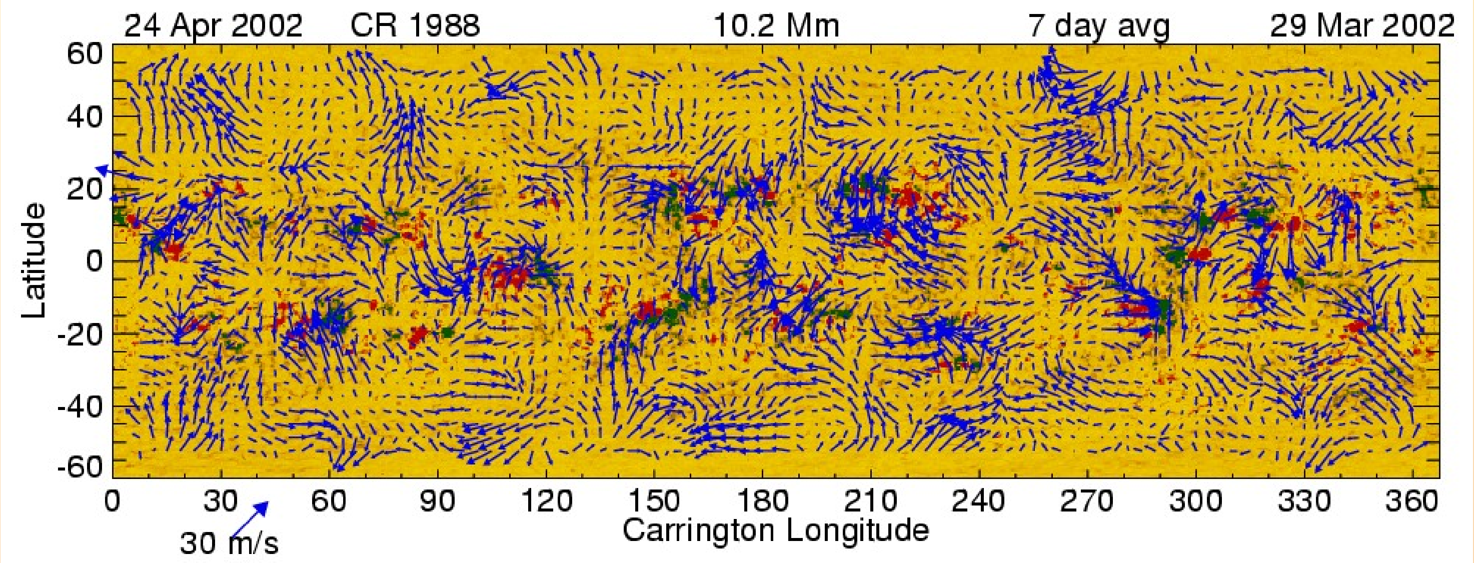
- Magnetic fields: black/red

- Flows: blue arrows

Solar Subsurface Weather Maps
April 2002 – CR 1988 – Depth: 10.2 Mm

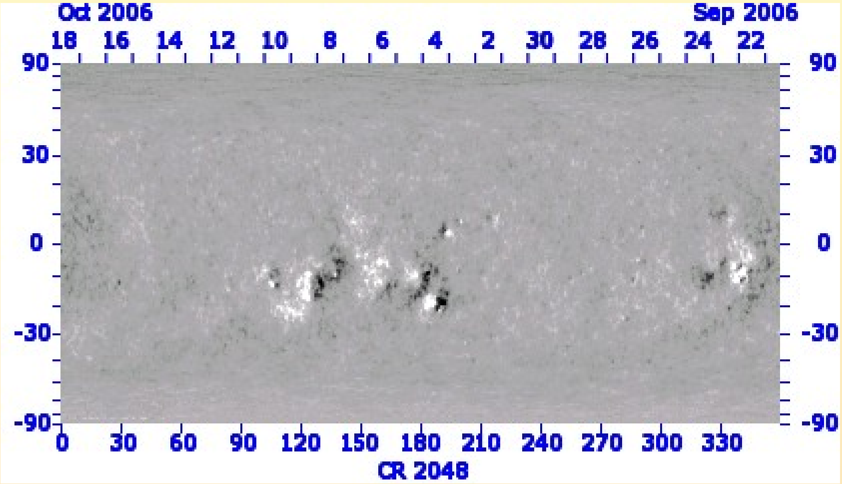


Total



Fluctuations

The long decline of Solar Cycle 23 has been marked by very few, well separated Active Regions



(GONG website movie, MSFC sunspot illustrations)