Meridional Flow, Torsional Oscillations, and the Solar Magnetic Cycle

David H. Hathaway
NASA/MSFC
National Space Science and Technology Center

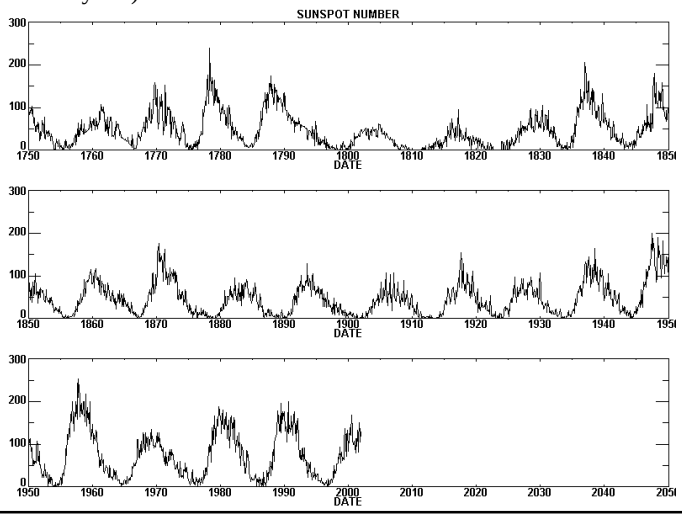
Outline

1. Key observational components of the solar magnetic cycle
2. Key theoretical components of the solar dynamo
3. Meridional flow
4. Torsional oscillations
5. Conclusions concerning the role of meridional flow and torsional oscillationals in the solar magnetic cycle

The "11-year" Sunspot or Wolf Cycle

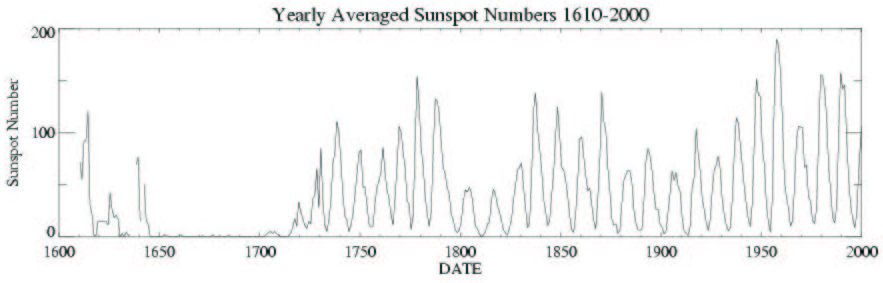
[Schwabe, 1844]

Dynamo models must explain the cycle period and cycle shape (asymmetric with a rapid rise and a slow decline with large cycles rising to maximum in less time than small cycles).



The Maunder Minimum

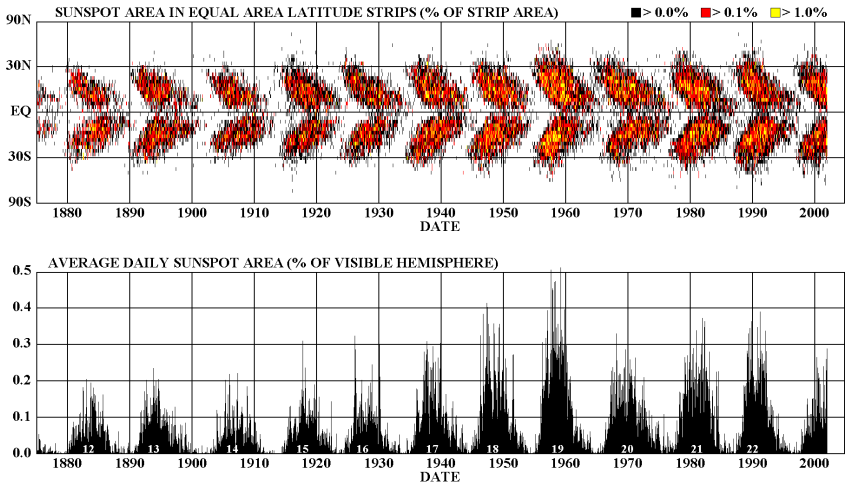
Dynamo models should explain the variability in cycle amplitude and the occurrence of periods of inactivity like the Maunder Minimum (1645-1715).



Sunspot Latitude Migration: Spoerer's Law

[Carrington, 1858]

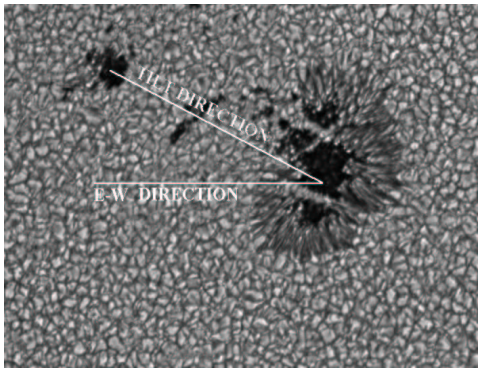
Sunspots appear in two bands on either side of the equator. These bands spread in latitude and then migrate toward the equator as the cycle progresses. Cycles can overlap at the time of minimum.

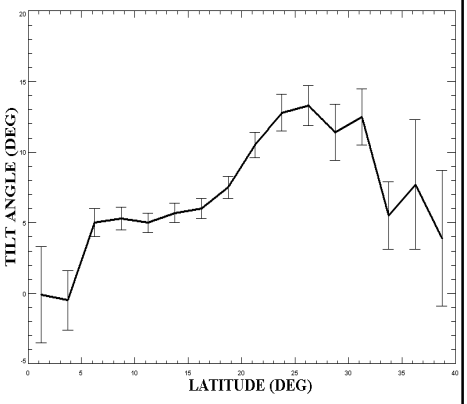


Active Region Tilt: Joy's Law

[Hale *et al.*, 1919]

Active regions are tilted so that the following polarity spots are slightly poleward of the preceding polarity spots. This tilt increases with latitude.

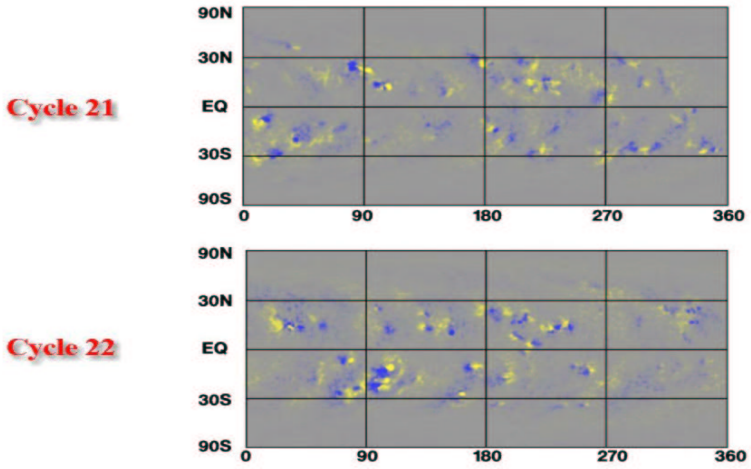




Hale's Polarity Law

[Hale, 1924]

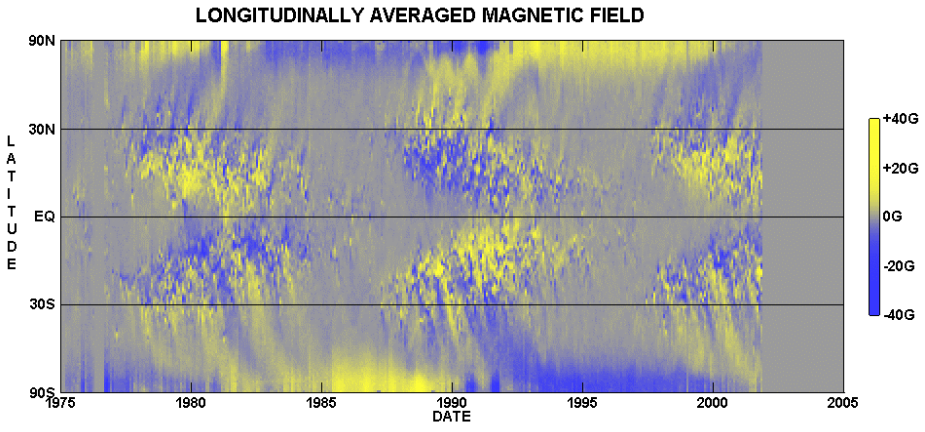
The polarity of the preceding spots in the northern hemisphere is opposite to the polarity of the preceding spots in the southern hemisphere. The polarities reverse from one cycle to the next.



Polar Field Reversal at Cycle Maximum

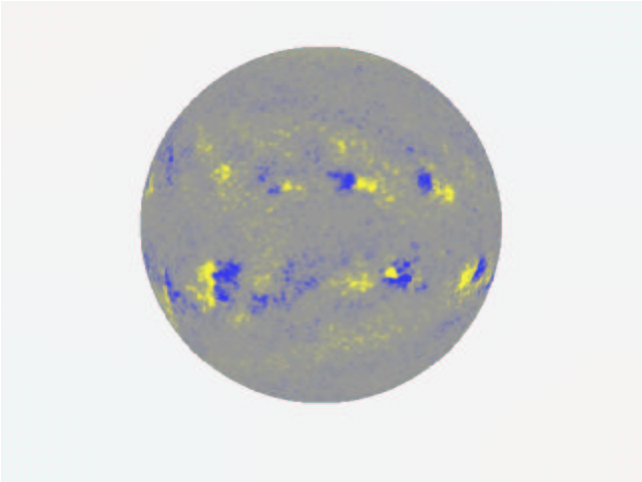
[Babcock, 1959]

The polarity of the polar magnetic fields reverses at about the time of the solar activity maximum. (Result of Joy's Law + Hale's Law + Meridional Flow + Flux Cancellation across the equator?)



Solar Cycle Magnetic Field Evolution

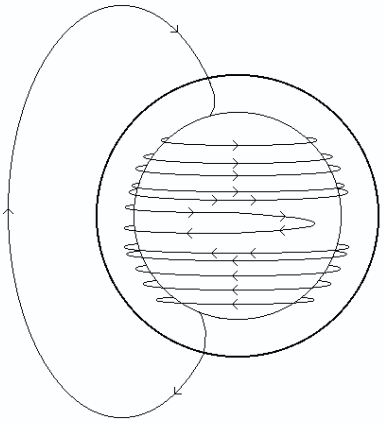
22 years of magnetic maps illustrate the 11-year cycle, active region migration, Joy's Law, Hale's Law, polar field reversal, and the effects of differential rotation and meridional flow.



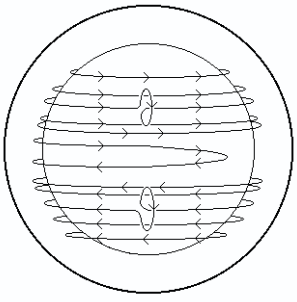
Basic Magnetic Dynamo Processes

Differential rotation in radius and latitude amplifies the poloidal field by wrapping it around the Sun to produce a strong toroidal field.

Lifting and twisting the toroidal field can produce a poloidal field with the opposite orientation.



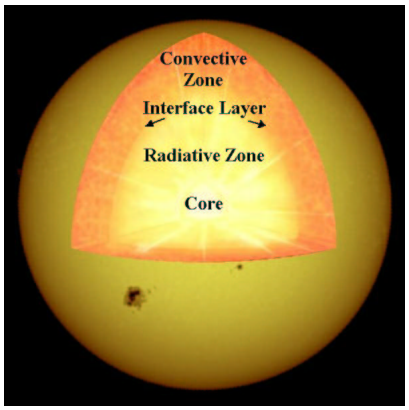
The ω-effect

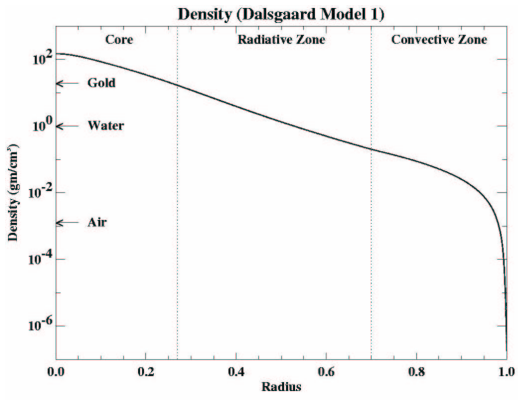


The α-effect

The Solar Interior

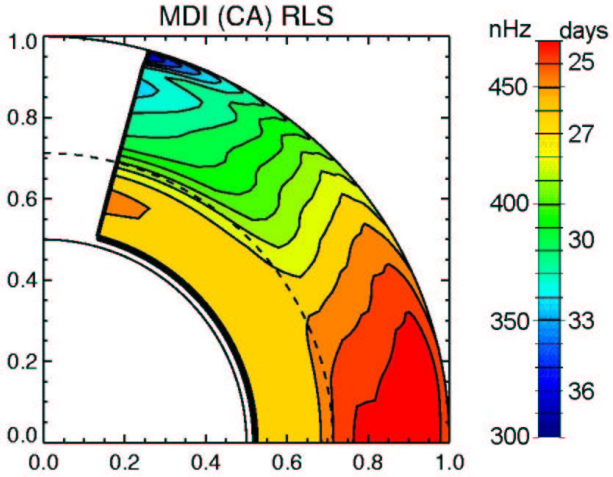
Flows within the convection zone were previously thought to be the source of the solar cycle (for both α- and Ω-effects). Now, several aspects of convection zone and flux tube dynamics indicate that the interface layer or "tachocline" is the seat of the solar cycle.



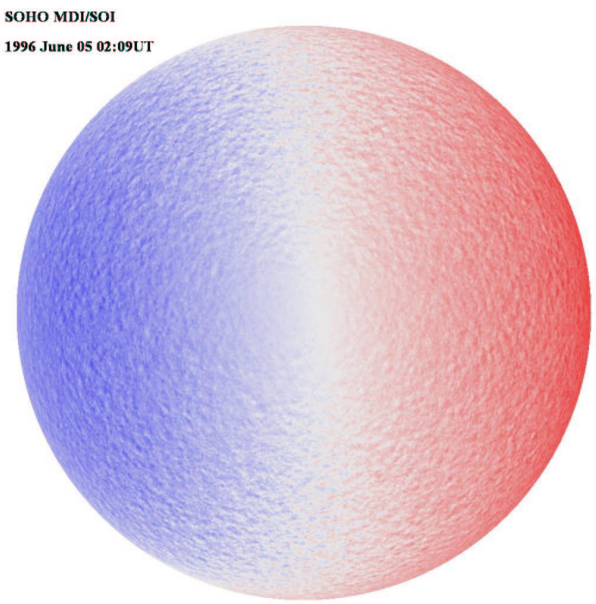


Internal Rotation Rate

Helioseismic determinations of the internal rotation rate show that the latitudinal differential rotation seen at the surface extends through the convection zone. Layers of strong radial shear are found near the surface and at the base of the convection zone (the tachocline).



Surface Flows



The surface flows are dominated by the basic rotation of the Sun and cellular flows but they also include differential rotation and the axisymmetric meridional flow.

These flows can be measured by direct Doppler imaging, feature tracking, and helioseismic inversions.

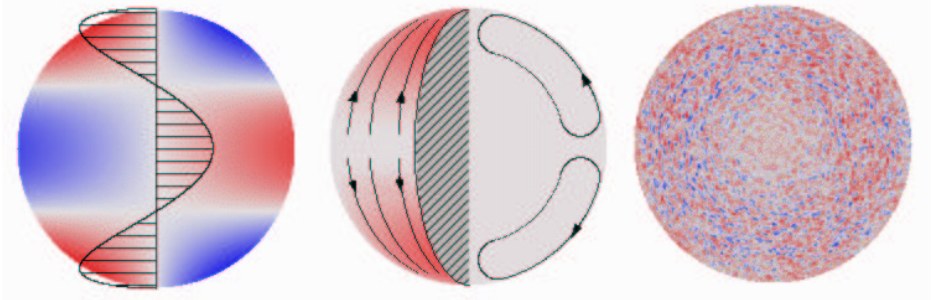
These surface flows, and their extensions into the interior, play significant roles in the solar cycle.

Flow Components

Differential Rotation ±100 m/s

Meridional Circulation ±20 m/s

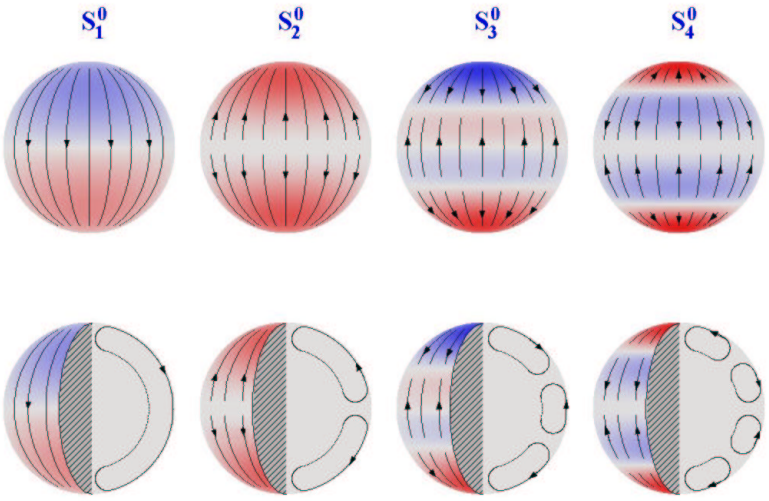
Cellular Convection ±500 m/s



The Meridional Circulation has been particularly difficult to characterize because of its weakness and masking by other velocity signals. Apparently conflicting results have been reported. Beckers (1978) – 40 m/s poleward; Duvall (1979) 20 /s poleward; Perez-Garde (1981) 20 m/s equatorward; Andersen (1984) 50 m/s poleward at low latitudes and 80 m/s equatorward at high latitudes; Snodgrass (1984) 10 m/s poleward.

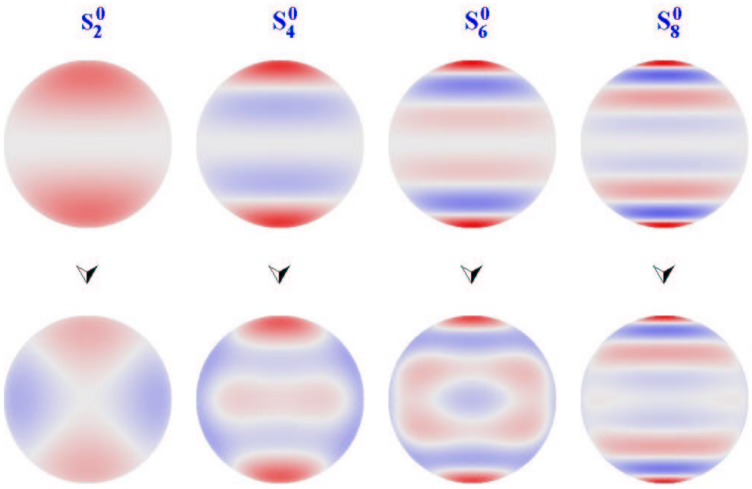
Meridional Circulation Components

The axisymmetric meridional flow can be fully represented by a series of components based on the spherical harmonic functions.



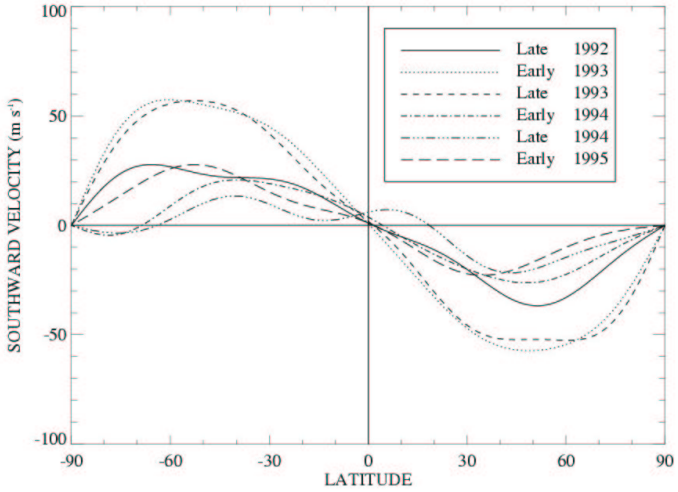
Meridional Circulation Doppler Signal

The Doppler signal produced by the Meridional Circulation components are altered when the Convective Blue Shift signal is removed (removing the average signal in annular rings about disk center). It is these altered patterns that are extracted from the Doppler data.



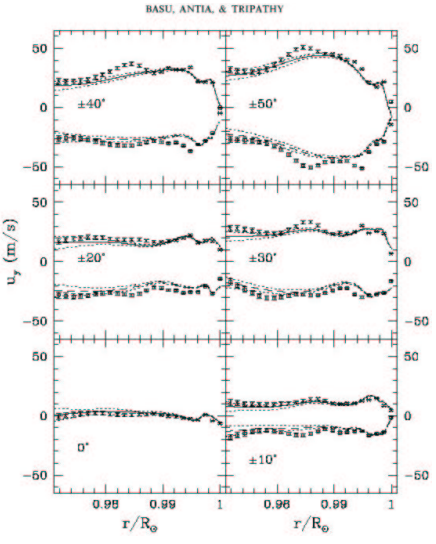
The Photospheric Meridional Circulation

At and near the surface the flow is largely poleward with a peak velocity of about 20 m/s. There is continuing evidence that the strength and structure of the flow is time-dependent.

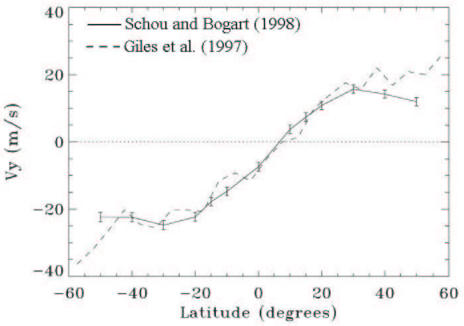


The Interior Meridional Circulation

Local Helioseismology has recently revealed aspects of the internal structure of the Meridional Circulation. (Giles et al., 1997; Braun and Fan, 1998; Schou and Bogart, 1998; Basu, Antia, and Tripathy 1999)

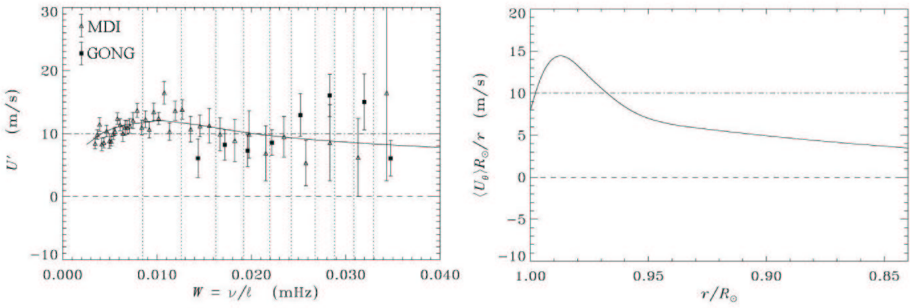


All of these investigations indicate a poleward meridional flow of about 20 m/s that persists with depth.

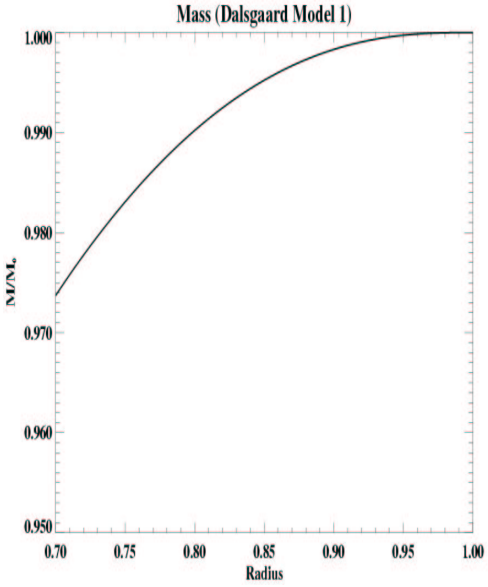


"Deep" Interior Meridional Circulation

Braun and Fan (1998) found that the poleward flow extends at least 10 to 15% into the solar interior (30 to 50% through the convection zone). By mass conservation there must be a return flow deeper in, but probably still within the convection zone.



The Meridional Circulation Return Flow



The outer 15% of the Sun contains 0.5% of its mass. The rest of the convection zone contains over 2.5% or 5 times as much mass.

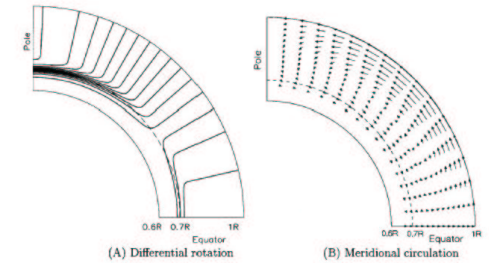
A poleward flow of 10 m/s in the outer half of the convection zone requires an average equatorward flow of just 2 m/s in the lower half of the convection zone.

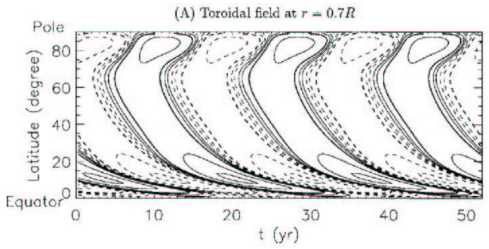
A 2 m/s flow would carry magnetic flux from the middle latitudes to the equator in about 10 years!

It is important to measure the meridional flow at the base of the convection zone.

Meridional Circulation and the Solar Cycle

The deep Meridional circulation has been largely neglected in dynamo models until fairly recently (Dikpati and Choudhuri, 1994; Durney, 1997; Dikpati and Charbonneau, 1999)





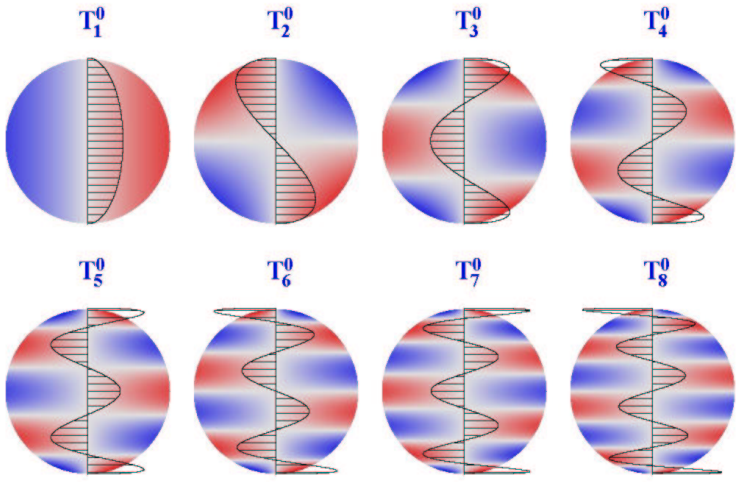
Dikpati and Charbonneau (1999) have produced a dynamo model using reasonable differential rotation and meridional circulation profiles. The period of the cycle is largely determined by the strength of the meridional flow:

$$\text{Period} \sim V_{\theta}^{-0.89}$$

A surface flow speed of 20 m/s give a period of about 17 years.

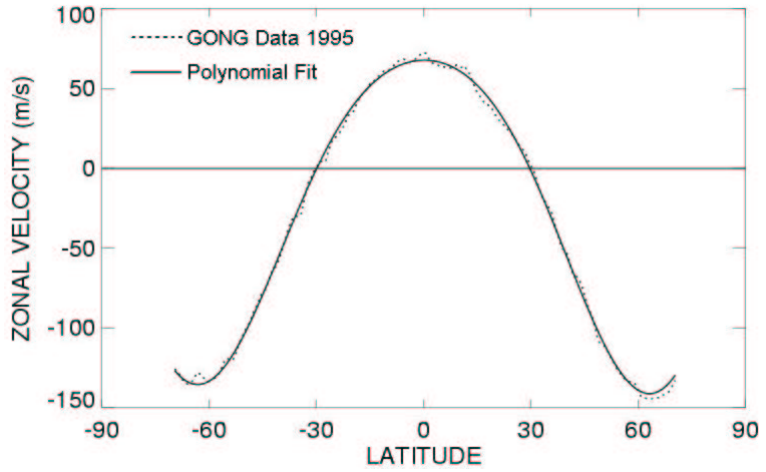
Rotation Components

The axisymmetric zonal flow can also be fully represented by a series of components based on the spherical harmonic functions.



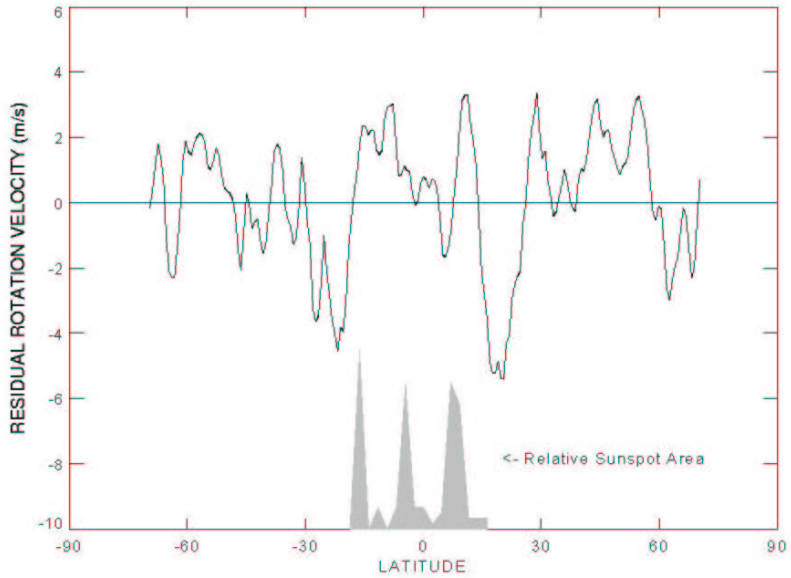
Torsional Oscillations

Torsional oscillations (Howard and LaBonte, 1980) are latitude bands of slightly faster and slower rotation. These bands propagate toward the equator on a solar cycle time scale giving an alternating prograde and retrograde motion at a given latitude.



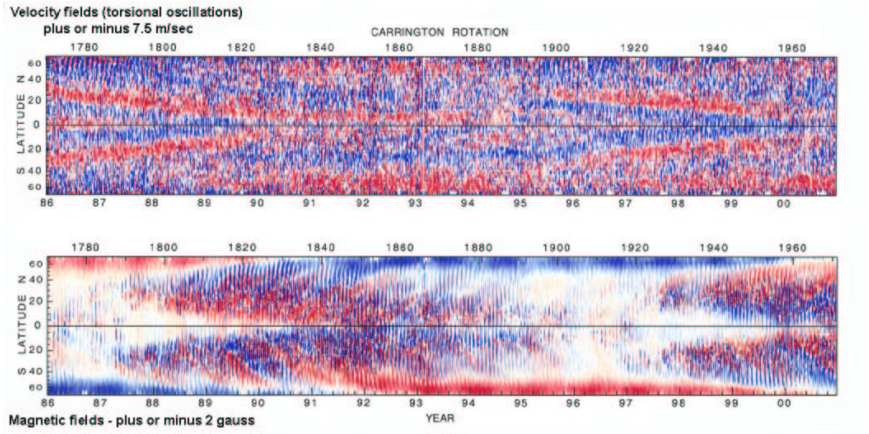
Torsional Oscillations

GONG Surface measurements fall 1995



Torsional Oscillations

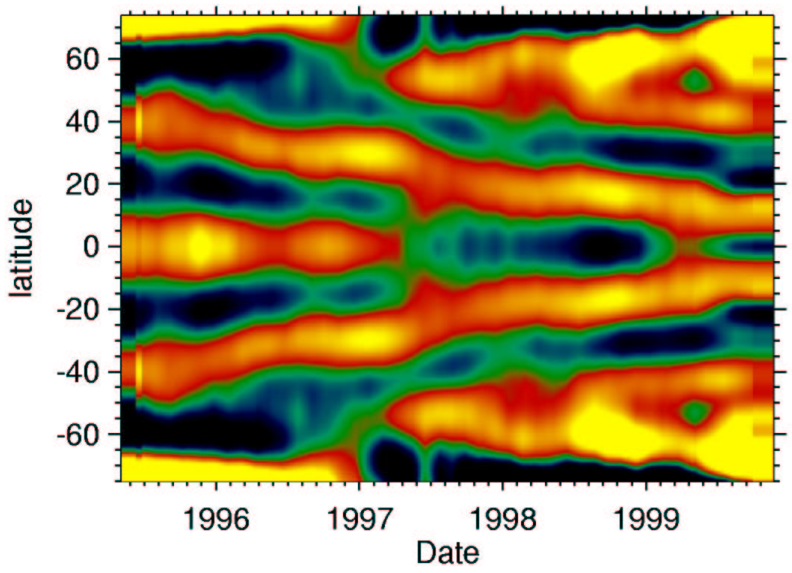
The fast and slow streams that comprise the torsional oscillations drift toward the equator in step with the equatorward motion of the sunspot latitudes. The sunspots and active regions themselves tend to form where the latitudinal shear is enhanced – poleward of the fast streams.



From Ulrich (2001) Red is faster than average velocity.

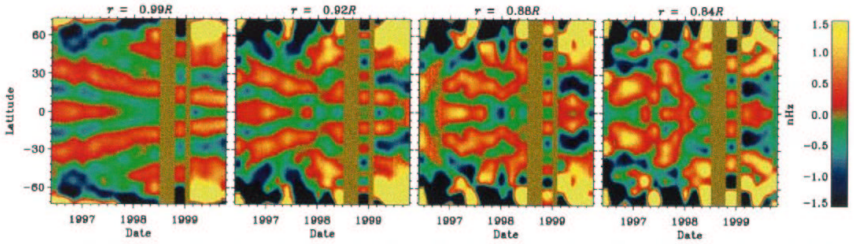
Torsional Oscillations

GONG near surface measurements 1995-2000.



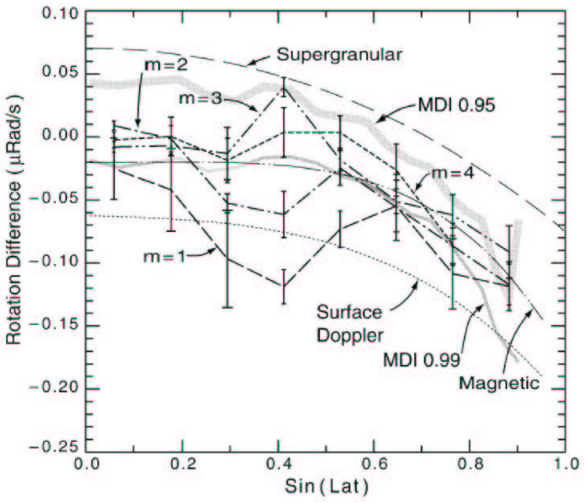
Torsional Oscillations

GONG interior measurements of the Torsional Oscillation Signal



The near surface features can be still be seen nearly half way through the convection zone. (Howe *et al.*, 2000; Toomre *et al.*, 2000; Komm, Hill, and Howe, 2001).

Source of the Torsional Oscillations

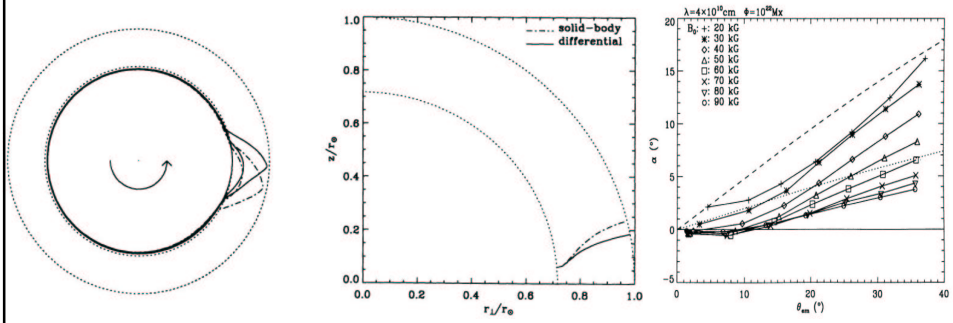


Sunspots and other magnetic features are observed to rotate more rapidly than the photospheric plasma.

The Torsional Oscillations may be produced by the Lorentz force acting magnetic flux tubes moving through the convection zone (Schüssler, 1981; Yoshimura, 1981).

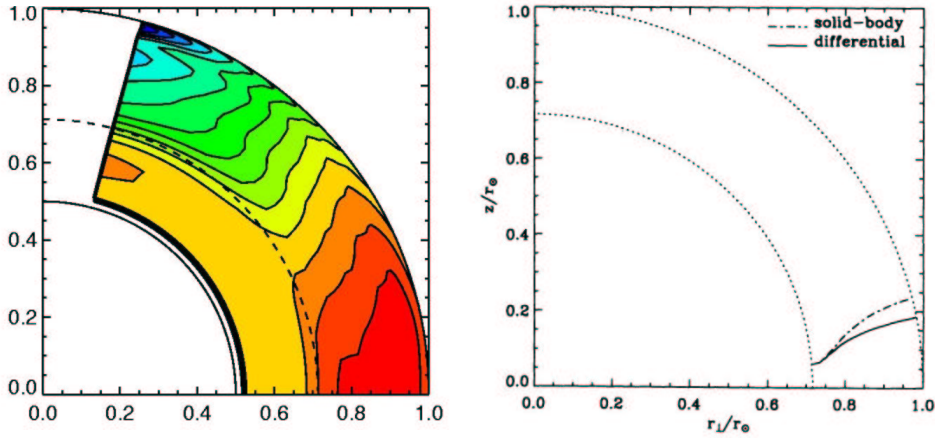
Dynamics of Buoyant Magnetic Flux Tubes

Flux tubes rising from the tachocline move to slightly higher latitudes (where the rotation rate is slower), are twisted slightly by the Coriolis force (as in Joy's Law), and produce asymmetries between the preceeding and following legs as it emerges through the photosphere (Fan, Fisher, & McClymont, 1994).



Rotation Rate of Buoyant Flux Tubes

As flux tube rise they pass through layers with different rotation rates. How do the tubes rotate as they erupt through the surface? How do the differences in rotation rate between flux tube and plasma feed back on the plasma?



Conclusions Concerning the Flows

- The Meridional Circulation is largely poleward from the equator at about 20 m/s and extends deep into the convection zone from the surface.
- The equatorward return flow should have a speed similar to that of the equatorward drift of the active latitudes – ***suggesting a causal link between the two but the return floe hasn't been measured***.
- The Torsional Oscillation bands also display the same equatorward flow speed and extend deep into the convection zone.
- Torsional Oscillations are likely due to the effects of magnetic flux tubes threading through the convection zone and rotating at a different rate than the plasma.

Conclusions Concerning the Solar Dynamo

- The solar dynamo mechanism (IMHO) likely includes:

1. The production of toroidal magnetic fields by shear in the zonal flow (differential rotation) in the tachocline (giving Hale's Law).
2. The production of poloidal magnetic field by the twist imparted by the Coriolis force on rising flux ropes (giving Joy's Law).
3. The transport of magnetic flux by the Meridional Circulation and diffusion at the surface (giving polar field reversals near cycle maximum).
4. The transport of magnetic flux by the Meridional Circulation at the tachocline (giving the equatorward drift of the active latitudes and the 11-year period of the sunspot cycle).