

Physics 681: Solar Physics and Instrumentation – Lecture 20

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Internal Angular Velocity

- ❑ Angular velocity $\Omega(r, \theta)$ and meridional circulation
- ❑ Solar rotation removes the $(2l + 1)$ -fold degeneracy of the frequencies of non-radial p -mode of degree l
- ❑ Inversion of the frequency splitting \Rightarrow angular velocity as a function of depth $\Omega(r)$
- ❑ Multiplets with non-equidistant frequency spacing \Rightarrow angular velocity as a function of latitude $\Omega(\theta)$
- ❑ Strong gradients of $\Omega(r, \theta)$ near the surface $r_{\odot} = 0.95$ and at the bottom of the convection zone $r_{\odot} = 0.7$
- ❑ Transition from solid-body rotation of the radiative core to differentially rotating convection zone \Rightarrow solar tachocline
- ❑ The angular velocity of the core matches the surface rotation at about $\pm 30^{\circ}$ (≈ 435 nHz)
- ❑ Shear results from non-uniform rotation \Rightarrow converts poloidal to toroidal magnetic fields $\Rightarrow \alpha\Omega$ dynamo \Rightarrow solar activity

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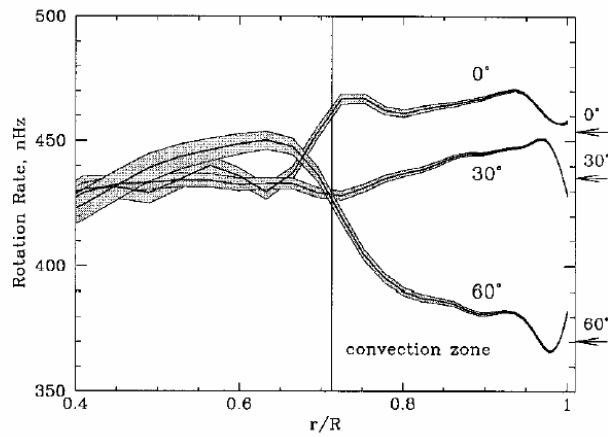


Figure 13. Solar rotation rate inferred from 2 months of MDI medium- l data as a function of radius at three latitudes, 0° , 30° , and 60° . The formal errors are indicated by the shaded regions. The arrows indicate the Doppler rotation rate directly measured on the surface.

Kosovichev et al. (1997)



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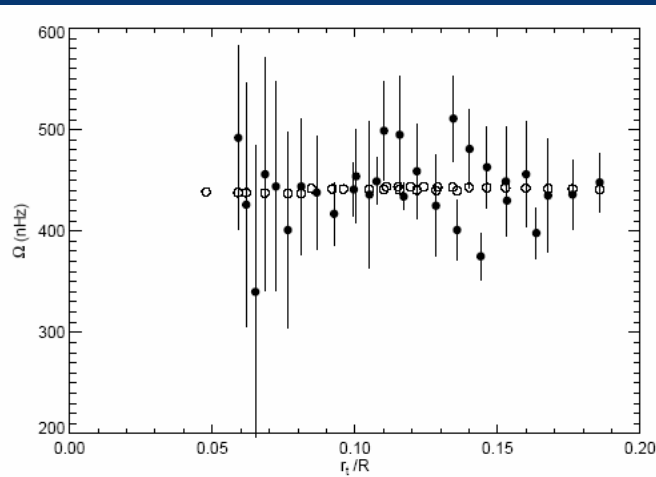


FIG. 8.—Comparison between the GOLF sidereal splitting results (*filled circles*) and the rotational splittings calculated for a model of solar rotation inferred from the MDI medium- l data by the two-dimensional RLS inversion (*open circles*) as functions of radius.

Bertello et al. (2000)

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Angular Velocity at the Surface

- ❑ Measuring the solar surface rotation is complicated by the presence of other velocity fields
- ❑ Surface rotation is represented in the form

$$\Omega = A + B \sin^2 \psi + C \sin^4 \psi$$
- ❑ The coefficients A , B , and C are determined by a least-square fit to the measurements
- ❑ Gegenbauer and Legendre polynomials
- ❑ A represents the equatorial rotation rate ($\approx 14.5^\circ/\text{day}$)
- ❑ Old (recurrent) sunspots rotate slower than the average sunspot
- ❑ The parameter C corresponds to high latitudes \Rightarrow not meaningful for sunspots, which do not occur at latitudes higher than $\approx 40^\circ$
- ❑ Tracers include prominences, EUV bright points, coronal holes, ...
- ❑ Coronal holes seem to rotate rigidly



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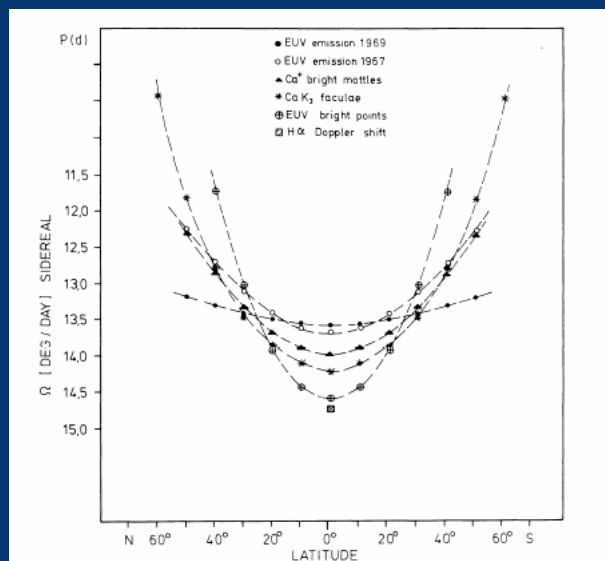


Fig. 2. Comparison of various determinations of the solar differential rotation obtained from small-scale short-lived and large-scale long-lived features of the chromosphere (rescaled figure from Antonucci *et al.*, 1977).

Schröter (1985)



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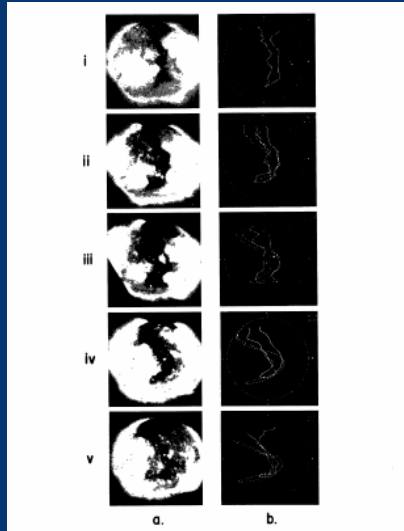


Fig. 9. Comparison of the position of CMI as seen (a) in soft X-ray wavelengths 3-32 Å and 44-54 Å and (b) its extrapolated position calculated using the Newton and Nunn (1951) differential sunspot rotation rates. Images are shown in five successive rotations for: (i) June 1, 1973; (ii) June 28, 1973; (iii) July 25, 1973; (iv) August 21, 1973; and (v) September 29, 1973. The solid line on each schematic represents the outline of the hole as measured on that rotation, the dotted line shows the extrapolated position of the hole measured on the first rotation and rotated through the appropriate time interval.

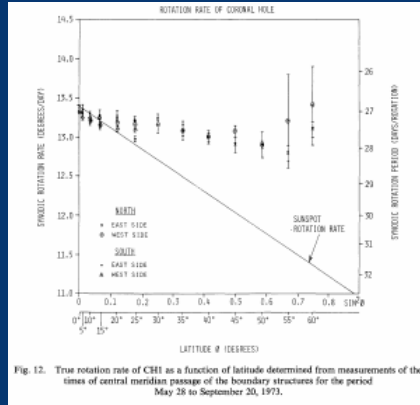


Fig. 12. True rotation rate of CMI as a function of latitude determined from measurements of the times of central meridian passage of the boundary structures for the period May 28 to September 20, 1973.

Timothy et al. (1975)

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Variability

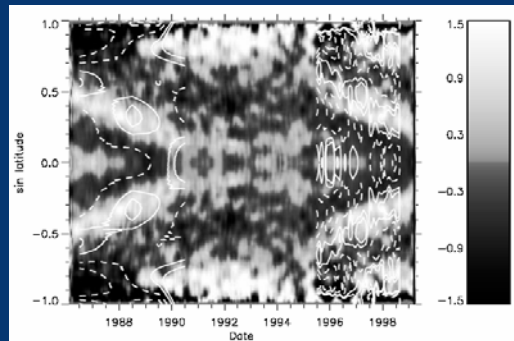


Figure 6. Doppler measurements of zonal flow measured from Mt. Wilson observations. The overlaid contours show the angular velocity residuals from BBSO and GONG. The contours are at -1.5 , -0.5 , 0.5 , 1.5 nHz, with dashed lines denoting negative values. The Doppler data have been symmetrized about the equator and smoothed by a running mean over 108 days to reflect the resolution of the helioseismic data.

Howe, Komm, & Hill (2000)

- Variations of the Sun's angular velocity (small effect $\approx 0.1^\circ/\text{day}$)
- The whole solar surface slowly speeds up and slows down in unison
- "Torsional Oscillator" (equatorial retardation $\approx 0.04^\circ/\text{day}$ and wave-like periodic variation)
- 11-year periodicity

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Meridional Circulation

- ❑ Axisymmetric longitudinally averaged north-south and radial velocity components
- ❑ LOS component of meridional circulation ≈ 10 m/s, same order of magnitude as measurement errors
- ❑ Equatorward flow at latitudes lower than $\approx 25^\circ$
- ❑ Poleward flow at higher latitudes
- ❑ Dividing line corresponds to the central latitude of the sunspot zone
- ❑ Antisymmetric component: northward flow around $\pm 15^\circ$
- ❑ Same symmetries a visible in giant cell patterns and large-scale magnetic field
- ❑ Meridional flow patten extends to a depth of $\approx 10^7$ m
- ❑ No proper theoretical description, yet!



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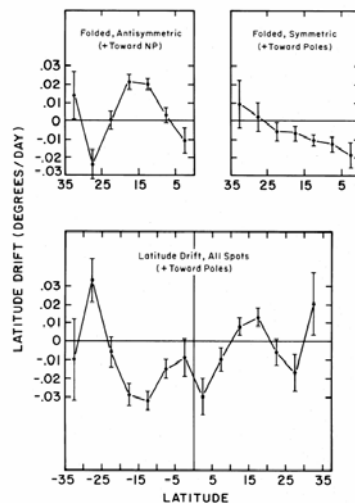


FIG. 1.—The latitude motions of all individual sunspots measured on the Mount Wilson data in the interval 1917 to 1983 in degrees per day. In the lower panel the full latitude dependence is plotted. In the upper right we plot the latitude drift folded about the equator. This maintains the same sign convention—positive indicating a poleward motion in each hemisphere. At the upper left is an antisymmetric folding of the data. The sign of the southern data is reversed in the average at each latitude, so that a positive sign denotes northward motion. The error bars plotted in this paper represent $\pm 1\sigma$.

Howard & Gilman (1986)



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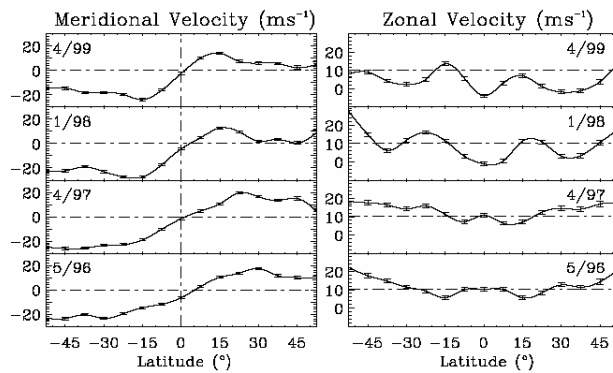


Figure 7. Meridional and zonal flows at a depth of 2.0 Mm. Each curve is constructed by a weighted average over all longitudes of the Dense-Pack for nine days from each Dynamics Program. The intervals observed are: 23–31 May 1996, 15–23 April 1997, 21–29 January 1998, and 6–11 April 1999. The crosshairs on the meridional flow diagram are reference lines for the equator and for a flow velocity of zero. The reference line on the zonal flow diagram denotes the latitudinal and temporal average of all four years. The error bars are as described in Figure 5. Notice that the gradient in the meridional flow as a function of latitude gets much steeper as the cycle progresses. In the zonal flows we see bands of increased flow at around 30° latitude move toward the equator as magnetic activity increases and see a rise in the amplitude of the southern band with respect to the northern one.

Haber et al. (2000)

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