Observed Properties of the Solar Magnetic Cycle

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Thanks to

Karen Harvey
David Hathaway
Frank Hill
Bob Howard
Rachel Howe
Harry Jones
Stuart Jordan
Judit Pap
Barbara Thompson

Goals

- Emphasize the big picture (mostly).
- Discuss recent advances …
- … but recall basic results.
- Characterize results by
  - Reliability
  - Accuracy
  - Stability
- Minimize explicit theoretical ties.
  - Is it a cyclical property or not?
  - Does it seem to be a “primary” or a “derived” property?

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Topics

Covered

- Global properties
  - Sunspots and groups
  - Magnetic flux
  - Irradiance
  - T_e, R
- Spatially resolved properties
  - Sunspots, active regions, complexes
  - Rotation, flows, twists

Omitted

- Without regret:
  - Frequency of every do-dad that varies with the cycle (flares, live births in Novisibirsk, …)
  - Ice cores, tree rings, …
  - Most heliospheric properties (although important in themselves)
- With the hope that others here will expound:
  - Cycle dependence of flux and helicity loss

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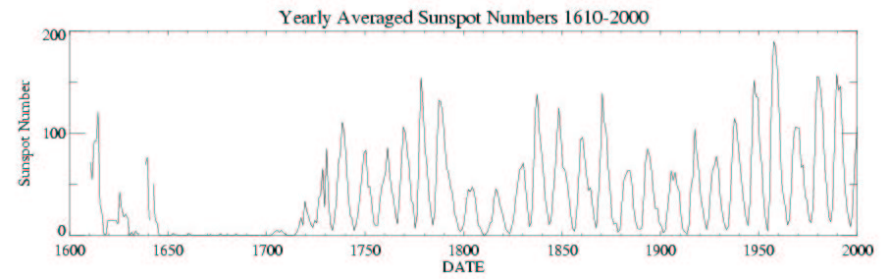
The Classics

- The sunspot cycle
- Spörer's law (Maunder's butterfly diagram)
- Joy's law
- The Hale-Nicholson rules

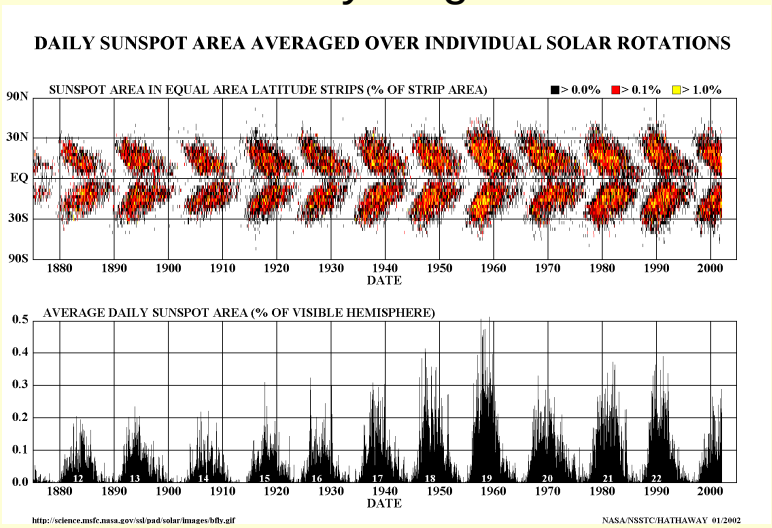
The sunspot cycle



Zűrich sunspot number

$$R_Z = k(10g + f)$$

Butterfly diagram



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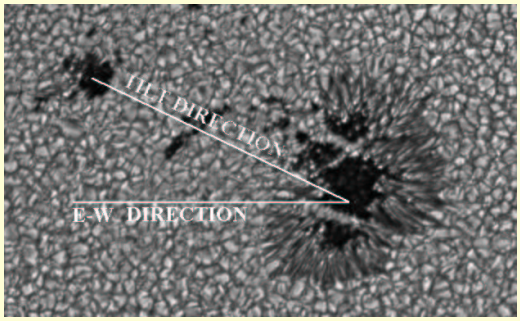
Joy's Law



- Varies with latitude (Joy):
  - ~6–7° at 30°
  - ~1–2° at equator
- But there is more to it:
  - Size, age, …
  - We'll return to this.

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Hale-Nicholson rules

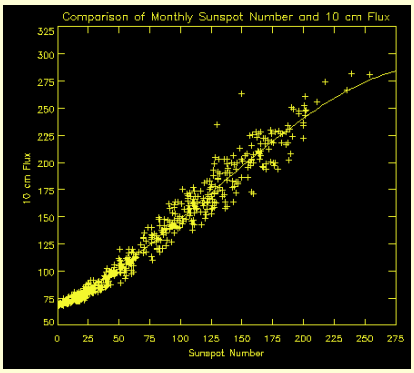
1. The leader spots in each hemisphere are generally of one polarity, the follower spots of the opposite polarity.
2. The leader polarity is opposite in opposite hemispheres.
3. The magnetic axes of the bipoles are inclined, with the leader closer to the equator.
4. Late in the cycle, bipoles appear at high latitudes with polarity reversed relative to lower latitudes.
5. After the sunspot minimum, the prevailing leader polarity in each hemisphere is opposite to the pre-minimum sense.

Global properties

- 10-cm flux (the battle of the proxies)
- Photospheric magnetic flux, weak and strong
- Total solar irradiance
- Effective temperature and radius

10-cm radio flux

(the battle of the proxies)



Dominated by diffuse thermal free-free above ARs and gyroresonance emission from electrons in magnetic fields above sunspots

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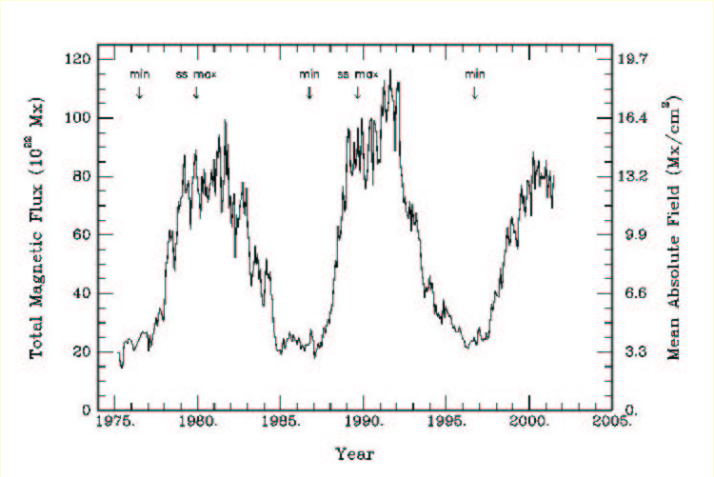
Photospheric magnetic flux



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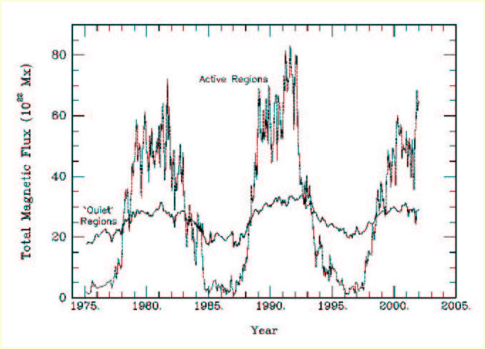
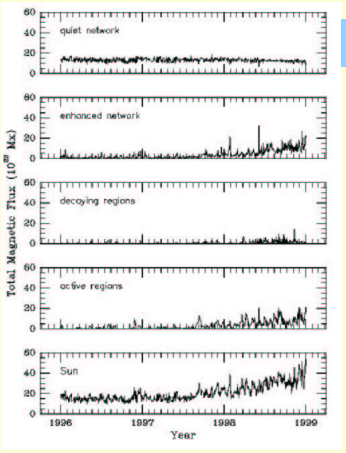
Weak and strong flux



Harvey 1993



Flux recycling

Harvey & White 2002

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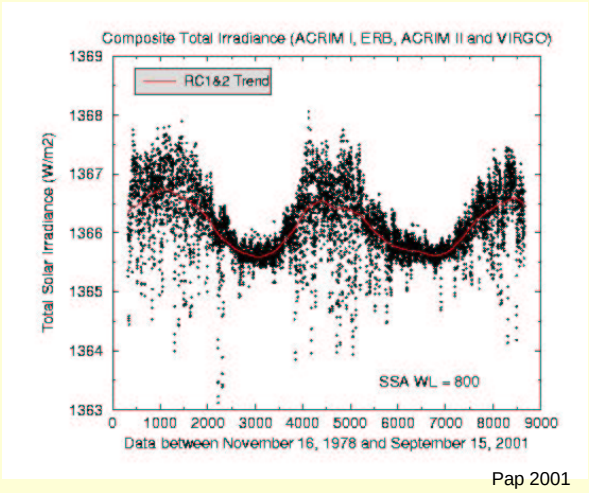
Total solar irradiance



Pap 2001

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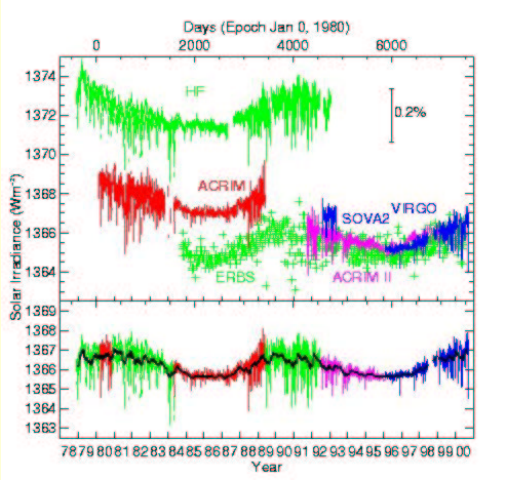
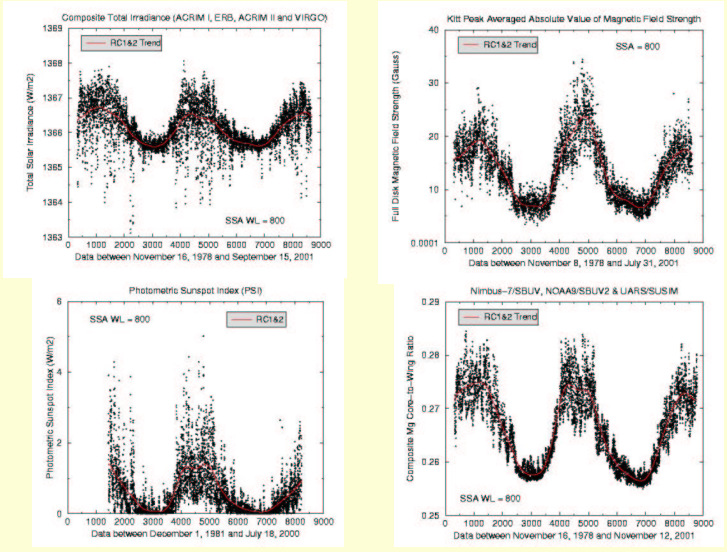
Irradiance: under the hood



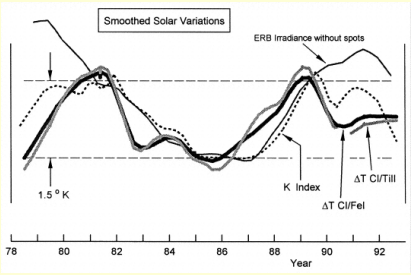
Pap 2001

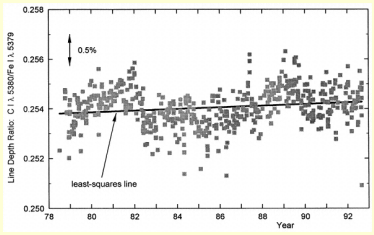
Some indices compared



Pap 2001

Effective temperature





The C I 5380 line in the solar flux spectrum was measured over the 1978–1992 interval. Analysis of the data shows seasonal and instrumental effects, but after allowance for these, the ratios of spectral line depths, C I 5380 to Fe I 5379 and to Ti II 5381, are shown to be robust indicators of effective temperature. These data show the solar temperature to have varied systematically during the activity cycle and nearly in phase with other indicators of the cycle. The amplitude of the variation is 1.5 K ±0.2 K, similar to but slightly less than the range implied by the variations of the sunspot-corrected irradiance. There is also evidence for a secular trend amounting to +0.014 K per year.

Gray & Livingston 1997

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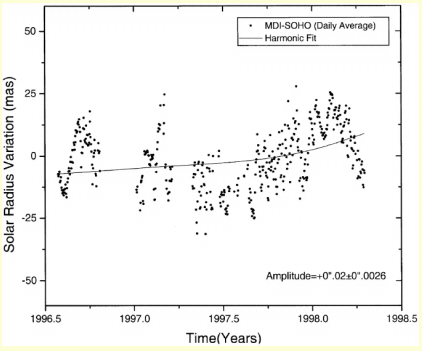
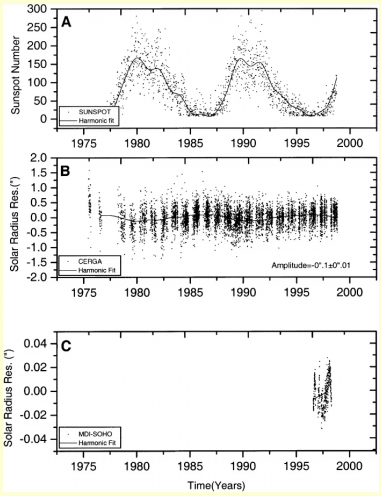
Radius



The residual linear variation in the Sun's radius is 8.1 ± 0.9 mas yr^{-1}.

Emilio et al. 2000



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Spatially resolved properties

- Sizes of spots and regions
- Motions of sunspots
- Joy and More Joy
- Inclination of field lines
- Complexes of activity
- Butterflies
- Rotation in the large
- Latitude zonal flows
- Meridional flows
- Other interior dynamics
- A peak at the heliosphere

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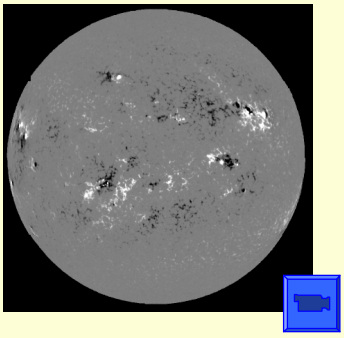
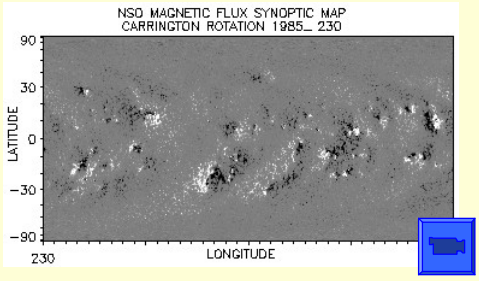
Spatially resolved properties



Jones movie



Hathaway movie

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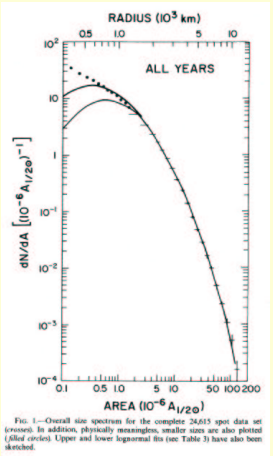
Caution …

The spatial and temporal properties of sunspots, sunspot groups, and plages are often different (i.e., "More different than one might expect").

Some of these differences are definitely intrinsic. Others may be partly or wholly caused by observational difficulties or differences in definition.

Sizes of spots and regions



Bogdan et al. 1988

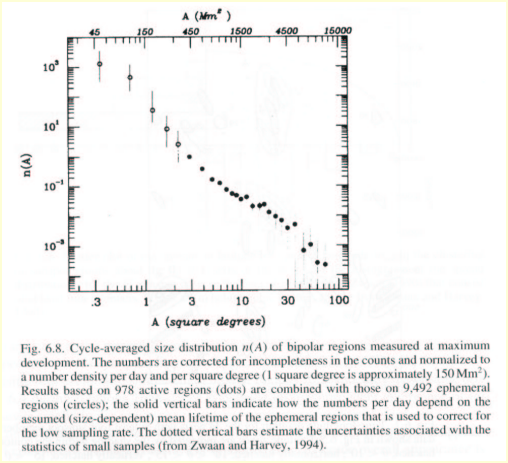
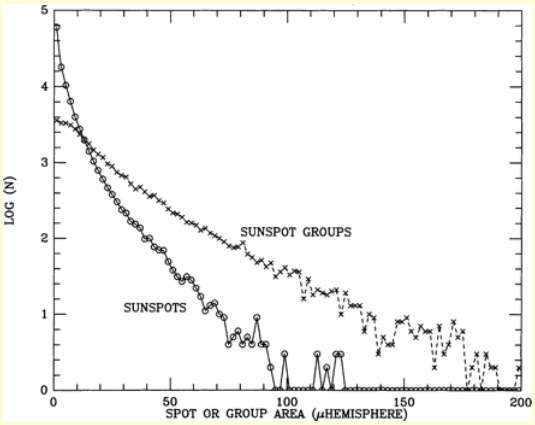


Fig. 6.8. Cycle-averaged size distribution $n(A)$ of bipolar regions measured at maximum development. The numbers are corrected for incompleteness in the counts and normalized to a number density per day and per square degree (1 square degree is approximately 150 Mm^2). Results based on 978 active regions (dots) are combined with those on 9,492 ephemeral regions (circles); the solid vertical bars indicate how the numbers per day depend on the assumed (size-dependent) mean lifetime of the ephemeral regions that is used to correct for the low sampling rate. The dotted vertical bars estimate the uncertainties associated with the statistics of small samples (from Zwaan and Harvey, 1994).

Zwaan & Harvey 1994

More sizes

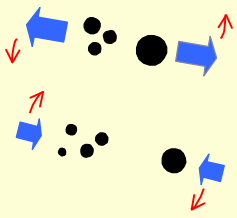


Howard 1996

Sunspot motions

It's shorter in words:

- Largest spots rotate 1–2% slower than smallest.
- At all latitudes, leaders rotate about 0.6% faster than followers.
  - But this is a time-average of evolutionary behavior:

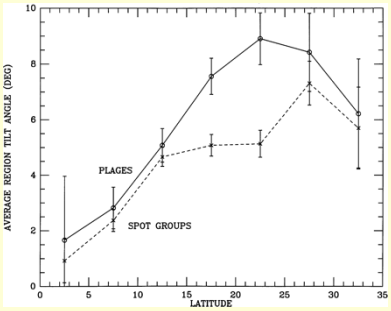


Young groups expand rapidly.

Old groups contact slowly.

Other latitude-longitude covariances? Murky …

Oh Joy …



Howard 1996

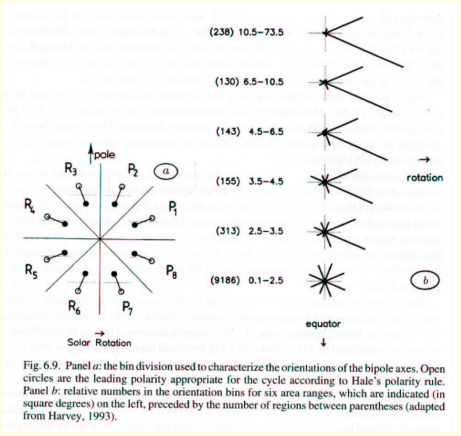
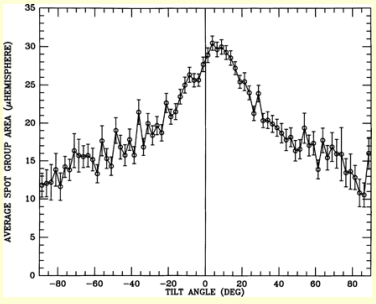


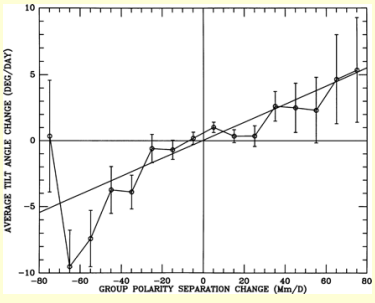
Fig. 6.9. Panel *a*: the bin division used to characterize the orientations of the bipole axes. Open circles are the leading polarity appropriate for the cycle according to Hale's polarity rule. Panel *b*: relative numbers in the orientation bins for six area ranges, which are indicated (in square degrees) on the left, preceded by the number of regions between parentheses (adapted from Harvey, 1993).

Larger regions obey Joy's law better. Harvey 1993

And more Joy



The penalty for flouting Joy



On average, a contracting group rotates CCW in the North, CW in the South

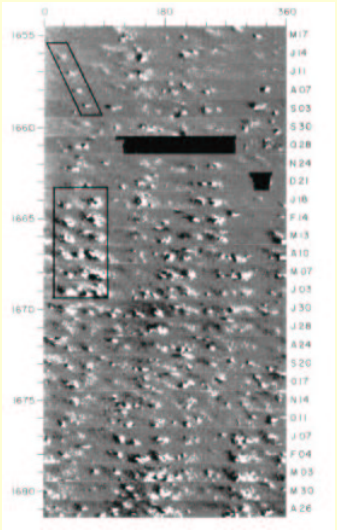
Howard 1996

Inclination of field lines to vertical

Again it's easier in words:

- On average, the *field lines* of both sunspots and plages *trail rotation* by a few degrees.
- The leading and following polarities of
  - *spot groups* are inclined *away* from each other by a degree or so.
  - *plages* are inclined *toward* each other by about 15°.
- Again, these time averages blur evolutionary behavior:
  - Growing plages *lead* rotation by 25° on average.
  - Decaying plages *trail* rotation by about 5°.

Complexes of activity



Strips of latitude between 10° and 40° for Carrington rotations 1655–1681 (May 1977 –May 1979. West to the right (Gaizauskas et al. 1983)

➡ Per area, active regions are >20 times more likely to emerge within an existing region than outside of one (Zwaan & Harvey 1994).

Extending the butterfly's wings

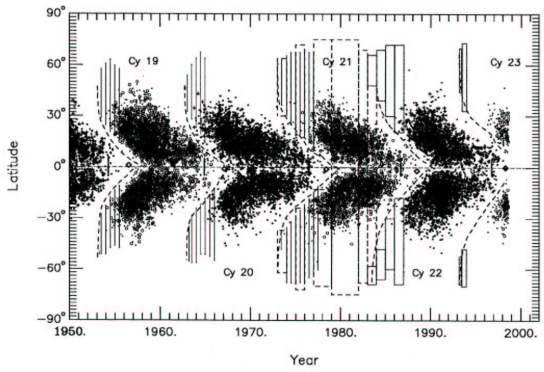


Fig. 6.3. A Maunder butterfly diagram. The sunspot cycle numbers are indicated; sunspot groups of odd cycles are shown as open circles, those of even cycles by pluses. The large/small symbols stand for sunspot areas larger/smaller than 100 millionths of the solar hemisphere. Vertical bars on the equator indicate the times of sunspot minima. The heavy dashed curves mark the boundaries between successive sunspot cycles. During the early phases of the cycles, the light solid lines indicate latitude ranges where small active regions without sunspots were seen as small Ca II K plages; dotted boxes mark the ranges of ephemeral regions (figure provided by K. L. Harvey).

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The butterfly flies high

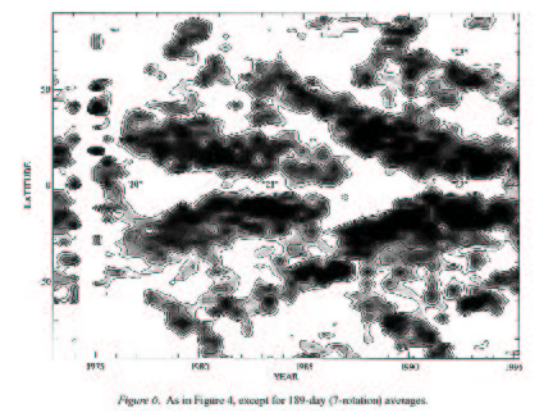

Figure 6. As in Figure 4, except for 189-day (7-rotation) averages.

Fe XIV emission at 1.15 R$_\odot$ Altrock 1997

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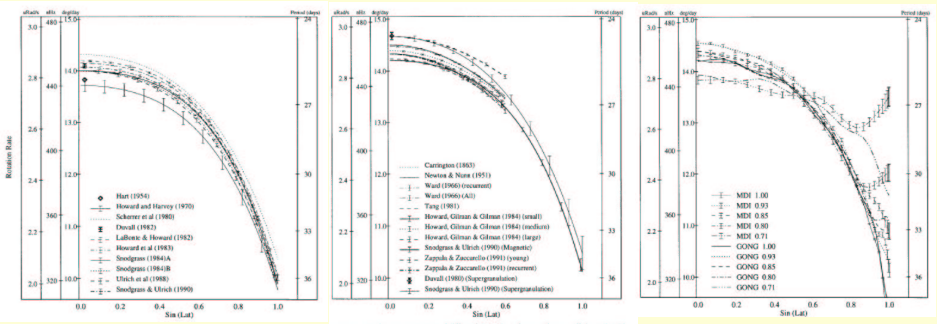
Rotation in the large

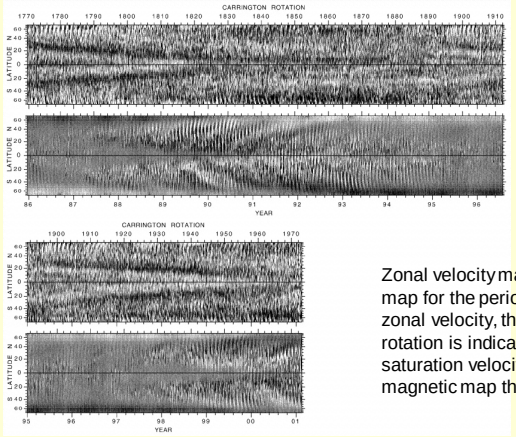


Recent measurements of the rotation of the plasma at the solar surface are converging to a well determined rate which is slower than the rotation within the convection zone. Further, magnetic and Doppler tracers rotate faster than does the solar surface.

Beck 1999

Latitude zonal flows

(aka torsional oscillations)



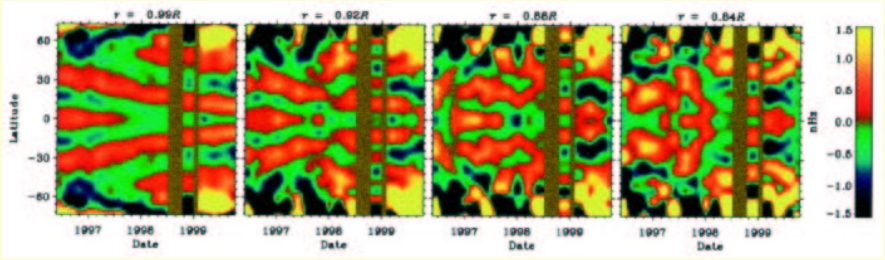
zonal velocity

magnetic flux

Zonal velocity map together with a magnetic map for the period 1986 to 2001. For the zonal velocity, the faster than average rotation is indicated by the black areas. The saturation velocity is 7.5 m s^{-1}, and for the magnetic map the saturation levels are 2 G.

Ulrich 2001

Latitude zonal flows



OLA inversion of GONG data Howe et al. 2000

Zonal flows extend about 60 Mm below the surface.

Meridional Flows

Still a murky subject!

Almost settled:

The prevailing time-averaged fluid flow is poleward at about 20 m s^{-1} to a depth of at least 20 Mm.

Likely true but not settled:

Superimposed on the “steady” flow is a cycle-dependent pattern of similar magnitude in which flow is directed away from the latitudes of maximum activity.

Not observed (or observable?):

Deep return flow.

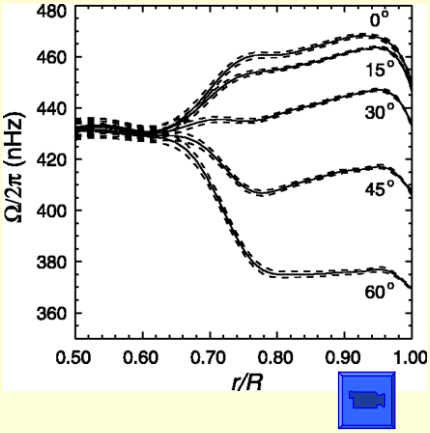
Interior properties more generally

- Many aspects of interior dynamics, as revealed by oscillation properties, are time-dependent.
- Surface activity plays a major role in modulating the oscillations.

Some results

- From solar minimum to maximum, mode line widths Γ increase by about 3%, mode amplitudes *A* decrease by about 7% (both frequency dependent), but energy supplied to the modes (~ $A \times \Gamma^2$) varies little or may be constant (Komm et al. 2000).
- Cycle-dependent variations in mode width, amplitude, and even-order splitting coefficients can be localized in space and time to active regions (Hill et al. in press).
- Inversions have not established the influence of subsurface magnetic fields on the local sound speed (except under strong surface features).

Interior dynamics



Does the rotation rate near the tachocline oscillate with period ~1.3 yr and amplitude ~6 nHz?

Howe movie

Upper CZ
Fast Neutral Slow

Lower CZ
Fast Neutral Slow

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What about the heliosphere?

- Inner magnetic structure determined by active regions and ephemeral regions.
- Observed photospheric magnetic fields satisfactorily account for coronal holes.
- $\int B \cdot ds \approx \text{const}$ over cycle? [E. Smith]

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Summary

I don't think so!