Helioseismology over the solar cycle

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with thanks to Rachel Howe to show some of our unpublished results

Thanks also to Anne-Marie Broomhall and Deborah Haber for sharing results.
Outline

1. Introduction
2. Global results – the mean solar structure and rotation
3. Frequency variations over the cycle
4. Flow variations over the cycle
5. Local helioseismology – potential and issues
6. Conclusions
Helioseismology

Measure mode frequencies and other properties
Eigenfunctions / spherical harmonics

Frequencies $\nu_{nlm}(t)$ depend on conditions in solar interior determining wave propagation

$\nu_{nlm}$ – degeneracy lifted by rotation and by structural asphericities and magnetic fields

Inversion provides maps such as of c and $\rho$ and rotation and wave-speed asphericities

Spherical harmonics
Asphericities (rotation, magnetic field, etc.) raise m-degeneracy of mode frequencies. Commonly expressed as:

\[ \nu_{nlm} = \nu_{nl} + \sum_{k>0} a_k(n, l) P_k^{(l)}(m) \]

where \( P_k^{(l)} \) are orthogonal polynomials of degree \( k \).

Odd order coefficients \( a_k \) arise from rotation.

Even order coefficients arise \( a_k \) from magnetic fields and other asphericities (incl. centrifugal distortion) which do not distinguish between westward- and eastward-propagating waves.
Helioseismology over 3 solar cycles
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Inferred sound-speed differences

Fractional difference in squared sound speed (sun minus model)
Inferences from the sound speed

(Sound speed is in units of hundreds of km/s)
Helioseismology: base of convection zone at 0.713 +/- 0.003 R.
No temporal or latitudinal variation in this location.

Note that this measures the extent of the essentially adiabatically stratified region. Sun’s transition smoother than in models.
Revision of solar surface abundances

Pijpers, Houdek et al.

Z = 0.015
Rotation rate inferred from MDI data using two different analysis techniques
Estimating the shape and location of the tachocline

Kosovichev (1996) – fit to early data, characterizing the tachocline transition with the function

$$0.5 \left\{ 1 + \text{erf} \left[ \frac{2 ( r - r_0 )}{w} \right] \right\}$$

Obtained width $w = (0.09+/-0.05)R$ and central location $r_0 = (0.692+/-0.005)R$, i.e. just beneath base of convection zone.

Subsequent analyses have typically yielded substantially smaller width, e.g. Charbonneau et al. (1999):
width $w = (0.039+/-0.013)R$
Position $r_0 = (0.693+/-0.002)R$ at equator.
Prolate with location different by $(0.024+/-0.004)R$ at 60 degrees.

Extent of prolateness confirmed by Basu & Antia (2001), who further found no *temporal* variation in the tachocline properties.
Extent of the solar tachocline
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Frequency shifts observed over last 23 yrs
(compared with 10.7cm radio flux)

Broomhall et al. (2009)
Solar results

Mode-averaged $\langle a_k \rangle$ as a function of time

$\langle a_k \rangle$ (nHz)

$\langle a_k \rangle$ (nHz)

1995 2002 Date

1995 Date 2002

$\langle a_k \rangle$ (nHz)

$\langle a_k \rangle$ (nHz)

Antia et al. 2001
Solar results

Mode-averaged $\langle a_k \rangle$ as a function of time

The variation with time of the even a-coefficients is strongly correlated with the surface magnetic field.

Antia et al. 2001
\[ \langle a_k \rangle \text{ as a function of } B_k \]

where \[ B_k \propto \int |B(\theta)| \ [P_k(\cos \theta)]^2 \, d(\cos \theta) \]

Antia et al. 2001
The dominant term in the even $a$-coefficients is the surface term:

$$a_k = \text{contribution from solar interior} + \frac{\text{(surface effect)}}{\text{(mode mass)}}$$
Inferred latitudinal sound-speed variation as function of time

Antia et al. 2001
Frequency shifts observed over last 23 yrs
Broomhall et al. (2009)

- Minimum lower than 1996 (as was the previous minimum)
- Biennial oscillatory signal in the frequencies (and 10.7cm flux but only at high activity)
- Evidence of subsurface component?
Inferred wave-speed variations at base of convection zone

Variation in sound speed between solar minimum and solar maximum (min minus max)

Baldner & Basu 2008
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Temporal variations in inferred rotation
Temporal variations of the internal rotation possibly modulated by magnetic field

Differencing rotation inversions at different epochs reveals torsional oscillations …

… and possible 1.3-year quasi-periodic oscillations above and beneath the base of the convection zone
Torsional oscillations of whole convection zone

Differencing rotation inversions relative to solar minimum (1996) at successive 72-day epochs ...

... and at successive 1-year epochs
Torsional oscillation flows from helioseismology

Howe et al. 2009
... and the cycle length they imply

Howe et al. 2009
Near-surface zonal-flow variations over one solar cycle

45 degrees latitude

Blue: GONG   Red: MDI
Near-surface zonal-flow variations over one solar cycle

52 degrees latitude

Blue: GONG  Red: MDI
Near-surface zonal-flow variations over one solar cycle

60 degrees latitude
Blue: GONG  Red: MDI
Near-surface zonal-flow variations over one solar cycle

67 degrees latitude

Blue: GONG  Red: MDI
Near-surface zonal-flow variations over one solar cycle

75 degrees latitude
Blue: GONG  Red: MDI
Near-surface zonal-flow variations over one solar cycle

78 degrees latitude

Blue: GONG   Red: MDI
Near-surface zonal-flow variations over one solar cycle

82 degrees latitude

Blue: GONG   Red: MDI
Near-surface zonal-flow variations over one solar cycle

Blue: GONG  Red: MDI

86 degrees latitude

1995  2009
Variability in and near tachocline

1.3-yr variations in inferred rotation rate at low latitudes above and beneath tachocline

Signature of dynamo field evolution? Radiative interior also involved in solar cycle?

Link between tachocline and 1.3/1.4-yr variations in
- solar wind,
- aurorae,
- solar mean magnetic field?
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Varying Pattern of Meridional Circulation Cells

**SOUTH:**
- **2005:** DOUBLE CELL
- **2003:** SINGLE CELL
- **2001:** POLEWARD FLOW NEAR SURFACE
- **1999:** DOUBLE CELL
- **1997:** MULTI-ROTATION AVERAGES

**NORTH:**
- **2005:** SINGLE CELL
- **2003:** POLEWARD FLOW NEAR SURFACE
- **2001:** REVERSED FLOW AT DEPTH
- **1999:** DOUBLE CELL

*Courtesy D. Haber*
Sound-speed map and magnetogram of AR 10486 on October 25, 2003, 4:00 UT (depth of the lower panel: 45 Mm)
Observations of emerging active region by time-distance helioseismology

Sound-speed perturbation
(\sim 1 \text{ km/s}: 300 \text{ K} \text{ or} 3000 \text{ G})
Inferred wave-speed perturbation under AR 9787

Gizon et al. 2009
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Conclusions

• Helioseismology has produced unprecedented measurements of the Sun’s internal structure and dynamics over the past 25 years, including
  • Map of the solar internal rotation
  • Discovery of the tachocline
• The frequencies vary over the cycle
  • Changes in the odd a-coefficients reflect changes in the solar internal rotation in and possibly below the convection zone
  • Most of the changes in mean multiplet frequencies and even a-coefficients come from changes at or very close to the surface: caused by changes in the surface magnetic field (or something extremely highly correlated with the surface field)
• Frequencies are lower this minimum than last – may be that some subsurface differences in the two minima that accounts for this
• May be some small variation in wave speed at the base of the convection zone correlated with surface activity
• The behavior of the banded zonal flows (torsional oscillations) give a length of 12 years for Cycle 23
• Local helioseismology clearly detects temporal and spatial variations – but need improved forward models to make robust inferences about the physical causes of those variations.