Helioseismic probes of the solar interior
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Outline

- Time-averaged conditions in the solar interior
  - The surface term
  - Solar abundance problem
  - Rotation
  - Gravity modes
- Variations with solar cycle
  - Variations in helioseismic mode properties
  - Evidence for solar cycle structure variations
  - Variations in flows
What is helioseismology?

• At any one time there are thousands of oscillations trapped in the solar interior.
• Dominant modes are acoustic p modes.
• Enable us to build up profiles of internal sound speed, $c_s$.
• $c_s^2 \propto \Gamma_1 T/\mu$
  ($\Gamma_1=1^{st}$ adiabatic exponent, $\mu=$ mean molecular weight).
Harmonic degree, $\ell$

- Intermediate or high degree ($\ell$)
- Low degree ($\ell$)
- $\ell = 0$
- $\ell = 2, m = 2$
Frequency-power spectrum

- Modes with largest amplitudes have frequencies around 3000$\mu$Hz or periods ~5min.
- Period of fundamental radial mode ~1hr.

BiSON data
l=0-3
At 3000$\mu$Hz n~20

SOHO (ESA & NASA)
Structure and flows in the solar interior
Testing solar models

- Comparisons can be made between model and helioseismic observations
- But discrepancies are observed.

Observed-model frequency ($\mu$Hz) vs. $\nu$ ($\mu$Hz)
The ‘surface term’

- Corrections based on parametric fit to Sun-as-a-star frequencies.
- 3D hydrodynamical simulation, nonadiabatic effects, and a consistent treatment of the turbulent pressure.
- See Lionel Bigot’s talk

e.g. Gough, 1990; Ball et al., 2016

Houdek et al. 2017

- Improved model
- Standard model
Solar abundance problem

- Numerous attempted solutions include modified opacities, gravitational settling, enhanced diffusion, dark matter…

Z/X:
- GS98 – 0.023
- AGS05 – 0.016
- AGSS09 – 0.018
- C+11 – 0.0209

Basu, 2016, LRSP
Internal rotation profile

- Differential rotation extends over outer 30%
- Two regions of shear
  - Tachocline & near surface shear layer
  - Most estimates place tachocline around $0.69R_\odot$, with a thickness of $0.05R_\odot$ (Howe, 2009).
- See talks by Yuhung Fan & Roxanne Barnabé

Courtesy of Michael Thompson
Near-surface shear layer

- Gradient of shear not what expected from conservation of angular mom’m (i.e. -2).
- Presence of NSSL not fully explained:
  - Cunnyngham et al. (2016): radiation $\rightarrow$ angular mom’m loss $\rightarrow$ torque (like Poynting-Robertson drag).

Barekat, Schou & Gizon, 2014
Limitations of p modes

- Inversions of core conditions poorly constrained by p modes.
- Gravity modes far more sensitive to solar core.
Detections of gravity modes

- No independently confirmed detections of individual g modes.
- Some evidence in periodogram of periodogram.

Garcia et al., 2007
Helioseismology and the solar cycle
Solar cycle variations in p modes

Unresolved BiSON data
Seismic frequencies and the solar cycle

- Seismic frequencies respond to changes in the surface activity (Woodard & Noyes, 1985).

- Causes:
  - Direct – Lorentz force.
  - Indirect – change in cavity properties.

Shifts from BiSON

Scaled 10.7cm flux

shift $\approx 0.01\%$ of mode frequency

Shift of $\approx 0.03 \mu$Hz G$^{-1}$
Shorter term variations in the seismic frequencies

• Persistent shorter-term variations are visible in frequency shifts – quasi-biennial oscillation (QBO).

Broomhall & Nakariakov, 2015
Empirical Mode Decomposition of QBO

Kolotkov, Broomhall & Nakariakov (2015)
Max-min frequency shift

GONG data \(10 \leq \ell \leq 150\)

Change in frequency between cycle max. and min.

Broomhall, 2017, in press
Max-min frequency shift

- Mode inertia given by $M_{n,l}/M_{\text{sun}}$

GONG data  $10\leq l \leq 150$

Change in frequency between cycle max. and min.

Broomhall, 2017, in press
Frequency shift inversions

- Howe et al. (2002) localized the frequency shifts in latitude.

Courtesy of Rachel Howe
The unusual solar cycle – smoothed

Basu et al. (2012)
Changes in the magnetic layer

- The upper turning point of the low-$\nu$ modes are beneath the magnetic layer in cycle 23.
- The changes must occur above $0.9965R_\odot$ (upper 2Mm).
Is there any evidence for the influence of magnetic field deeper in the solar interior?
Cycle variations at $0.98R_\odot$

- Helium ionization causes a discontinuity in the sound speed.
- The discontinuity causes oscillatory component in mode frequencies.
- Basu & Mandel looked at amplitude of oscillation through solar cycle.
Cycle variations at 0.98$R_\odot$

- Christensen-Dalsgaard et al (2011) found no evidence for it.
A change in sound speed at the base of the convection zone?

- Limits on strength of magnetic field at BCZ e.g.
  - magnetic field < 300kG (Basu, 1997; Antia et al, 2000).
- First evidence Serebryanskiy & Chou (2005)
  - $\delta c/c = 1-3 \times 10^{-5}$
  - 170-290kG change in field strength.
- Baldner et al. (2009): Change in field strength of 390kG.
Torsional Oscillation

Courtesy of Rachel Howe
Torsional Oscillation

Courtesy of Rachel Howe
Time variation of near-surface shear

- Results consistent with theoretical impact of strong magnetic fields (Kitchatinov, 2016).
- Possible probe of sub-surface strong magnetic field.

Barekat, Schou, & Gizon (2016)
Summary

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  - Many of these have applications for stellar physics as well.
- Helioseismic observations offer important constraints for standard solar and stellar models and dynamo models.
- We now at the stage where we can start comparing different activity cycles.
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Thank you for listening!