What Helioseismology Can Tell Us About Changes In The Solar Interior

Rachel Howe
National Solar Observatory
Tucson, Arizona, USA
Synopsis

- Introduction
- Convection zone dynamics over the solar cycle
- Solar-cycle changes in mode properties (frequency, width and amplitude)
- The search for interior structural change
Introduction

- Helioseismology uses acoustic waves to probe the solar interior.
- The history of systematic helioseismic observations goes back more than 30 years.
- Good-quality, continuous observations are available from GONG and MDI for most of Cycle 23.
- The observations uncover changing flow patterns deep inside the convection zone.
- Structural change is still hard to see.
History (schematic)
Convection-Zone Dynamics

- So-called ‘torsional oscillation’ is a pattern of weak slower and faster zonal flows migrating from mid-latitudes to the equator and poles over the solar cycle.
- First observed by Howard and Labonte (1980) in surface observations
- Surface Doppler measurements from Mt Wilson go back to 1986. (Ulrich 2001).
Helioseismic Detections of the Torsional Oscillation

- Woodard and Libbrecht (1993) saw hints in BBSO data.
- Seen in early MDI f-mode data by Kosovichev & Schou (1997)
Helioseismic Detection of the Torsional Oscillation

- Seen in 4 years of GONG and 3 years of MDI data by Toomre et al. (2000), Howe, Komm & Hill (2000), Howe et al. (2000)
- Penetration depth at least $0.92R$. 

![Diagram showing helioseismic detection](image-url)
Torsional Oscillation

- Antia and Basu (2001) drew attention to high-latitude, poleward-moving part of phenomenon.

Fig. 3.—Rotation rate residuals at \( r = 0.98 \, R_\odot \) plotted as a function of time for different latitudes. The latitudes are marked in the figure. The results were obtained using two-dimensional RLS inversion of GONG (left) and MDI (right) data.
Vorontsov et al (2003) showed that the phenomenon involves much of convection zone, and analyzed the signal in terms of 11-year sinusoidal variations.
Torsional Oscillation

- Vorontsov et al, 2002
- Extrapolation using 11-yr sinusoid
Zonal Flow Pattern

- MDI OLA $\tau = 0.80R$
- MDI RLS $\tau = 0.80R$
- GONG OLA $\tau = 0.80R$
- GONG RLS $\tau = 0.80R$
Zonal Flow Patterns (Time-Radius)

MDI OLA
MDI RLS
GONG RLS

Howe et al 2005
A Complete 11-year Solar Cycle

• Zonal flows from combined GONG and MDI data
Torsional Oscillation: Latest

- We now have a full 11yr cycle of observations!
- Animation based on 11+11/2 year sinusoids.
Comparison of near-surface flow observations

Howe et al, 2006
Variations at the Tachocline

See Howe et al. (2000; Science 287, 2456)
Tachocline oscillations

$\delta \Omega_1$ (nHz)

Date


Basu & Antia (2001; MNRAS 324, 498)
The ‘1.3 year oscillation’

A. 0.71, eq. residuals
B. Power spectrum
C. Power in max. power frequency bin, vs latitude
D. Power in max. power frequency bin, vs radius.
Solar-cycle Variation of Meridional Flow

Converging residual flow (flows into active regions?)

solid: 4 Mm, dash-dot: 7 Mm

Zhao & Kosovichev 2004
Mean zonal and meridional flows

Zonal bands

Meridional cells

Haber

Hindman
Can helioseismic measurements help predict solar cycle strength?

- Dikpati et al. 2006
- Prediction of strength of next cycle using flux-transport dynamo model (calibrated with helioseismic data) and sunspot area data.
- Using time-varying measured meridional flow gives different prediction from using mean value alone.
- Prediction now looking less likely!
Frequency shifts with solar cycle

- BiSON, Mark I (Palle et al. 1989, Elsworth et al. 1990)

Chaplin et al. 2007
Frequency shifts with solar cycle

Figure 18. Frequency shift as a function of frequency, using frequencies from 1986 as a reference. The frequency dependence was obtained by averaging over modes in the range $4 \leq l \leq 140$ in degree. Data from 1988 are denoted by circles, data from 1989 by squares. From Woodard and Libbrecht (1991).
Localized Global Frequency Shifts

(Howe, Komm & Hill 2002)
High-degree Frequency Shifts

- Mode frequencies are higher in active regions
- (Hindman et al, 2000).
What Causes Frequency Shifts?

- Shifts are obviously well correlated in time and space with surface magnetic activity, but what’s the mechanism?
- Magnetic fields:
  - Chromospheric
  - Photospheric (fibril)
  - Submerged at tachocline
- Kuhn – temperature
- Dziembowskki and Goode 2005 – geometry
Mode Energy and Width

- Komm, Howe and Hill 2002
Summary

• Mode frequency, lifetime, amplitude are affected by surface magnetic features.
• Mechanism of frequency changes still unclear, but seems to be close to surface.
• Energy supplied to mode may be invariant, suggesting features affect damping only.
• Amplitude, lifetime changes related to mode absorption by sunspots?
The Search for Subsurface Structural Changes

• Pattern of frequency shifts is consistent with near-surface effects.
• Surface layers are poorly resolved, modeled.
• Surface effects liable to mask more subtle changes in deeper layers.
Search for Structural Change

- Antia et al. 2001 – sound speed change is all in ‘surface term’, but near-surface layers not resolved.
Search for Structural Change

- Eff-Darwich et al. 2002 – upper limit of 3e-5 on stratification change at base of convection zone
Subsurface Structure Changes?


Fig. 1.- Radial variation as a function of the fractional radius, obtained as a solution of the inversion of f-mode frequencies by a least-squares regularization technique. The reference year is 1996. The error bars are the standard deviation after averaging over a set of random noise added to the relative frequencies. The averaging kernels for this inversion are well localized between 0.985 and 0.996, with a typical half-width of 0.003.
Subsurface Structure Changes?

Subsurface Structure Changes

Conclusions

• Helioseismology reveals changes in dynamics deep in the convection zone.
• Improved knowledge of convection-zone dynamics may help predict future cycles.
• Solar activity at the surface influences mode parameters.
• Detection of interior structural change is still difficult.