

# What Helioseismology Can Tell Us About Changes In The Solar Interior

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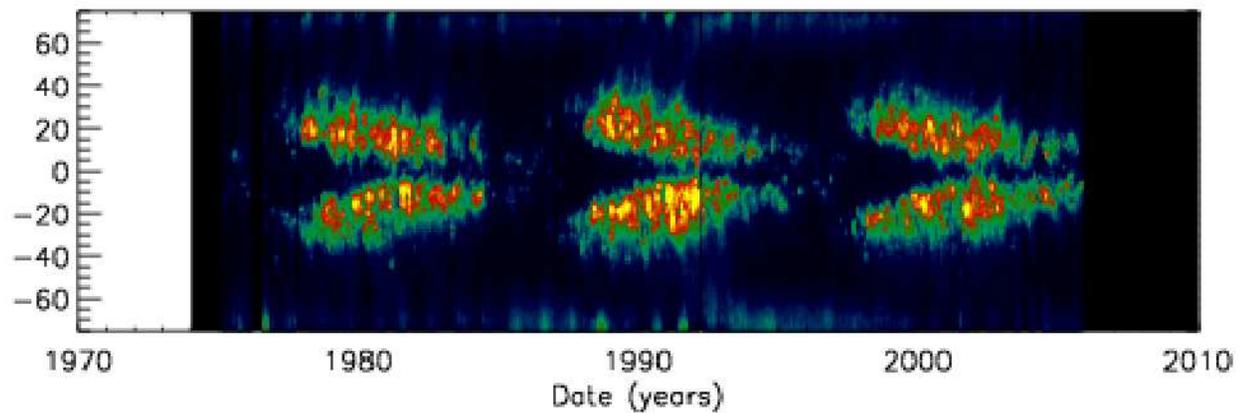
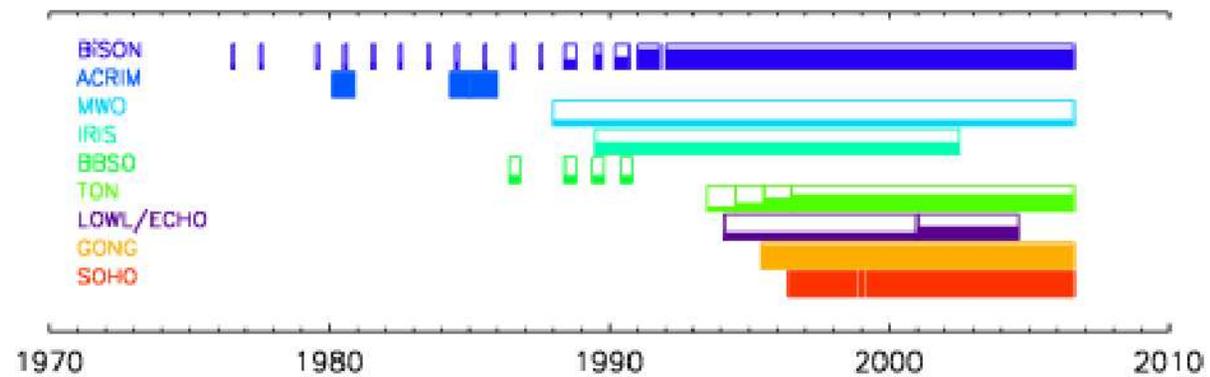
# Synopsis

- 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

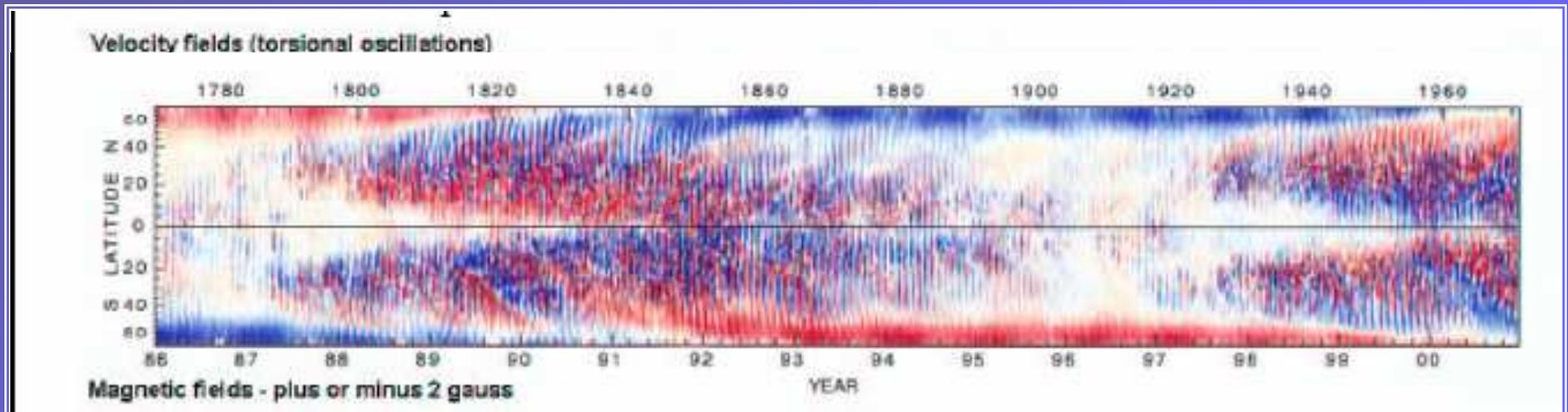
- Helioseismology uses acoustic waves to probe the solar interior.
- The history of systematic helioseismic observations goes back more than 30 years.
- Good-quality, continuous observations are available from GONG and MDI for most of Cycle 23.
- The observations uncover changing flow patterns deep inside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

# History (schematic)



# Convection-Zone Dynamics

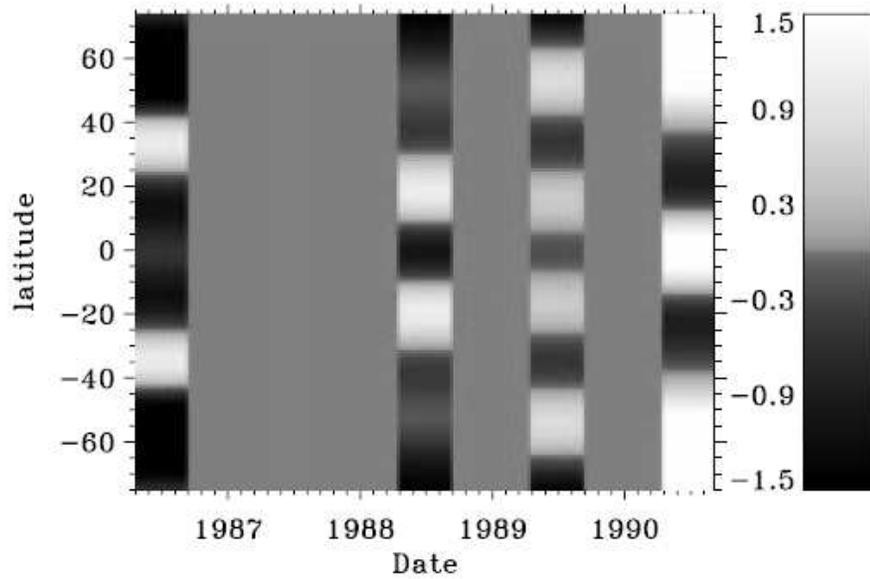
- So-called 'torsional oscillation' is a pattern of weak slower and faster zonal flows migrating from mid-latitudes to the equator and poles over the solar cycle.
- First observed by Howard and Labonte (1980) in surface observations
- Surface Doppler measurements from Mt Wilson go back to 1986. (Ulrich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



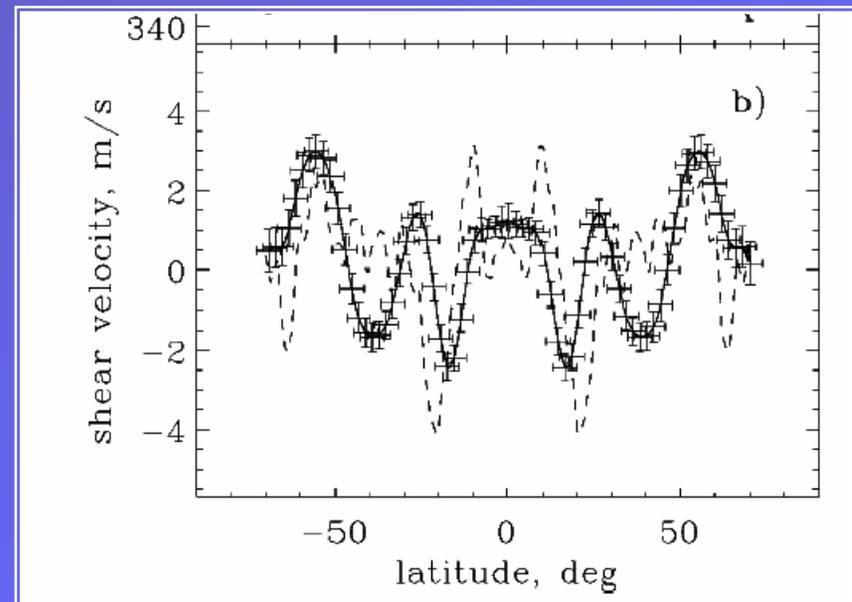
# Helioseismic Detections of the Torsional Oscillation

- Woodard and Libbrecht (1993) saw hints in BBSO data.
- Seen in early MDI f-mode data by Kosovichev & Schou (1997)

R. HOWE, R. KOMM, AND F. HILL

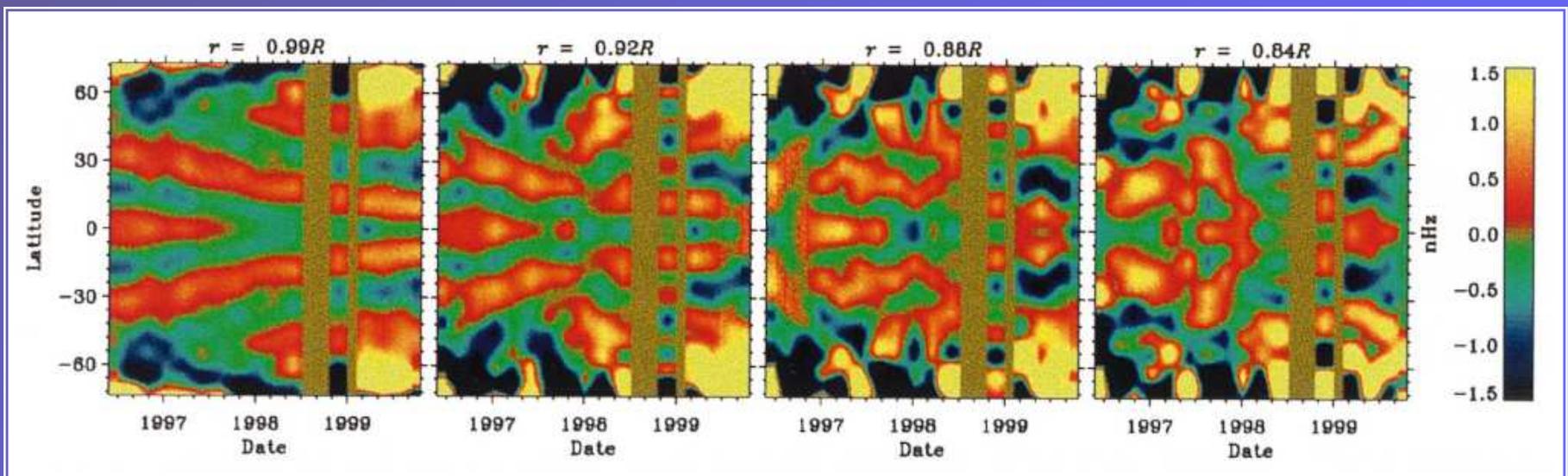


Residual angular velocity from BBSO data at  $0.99 R_{\text{Sun}}$  plotted as a function



# 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  $0.92R$ .



# Torsional Oscillation

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

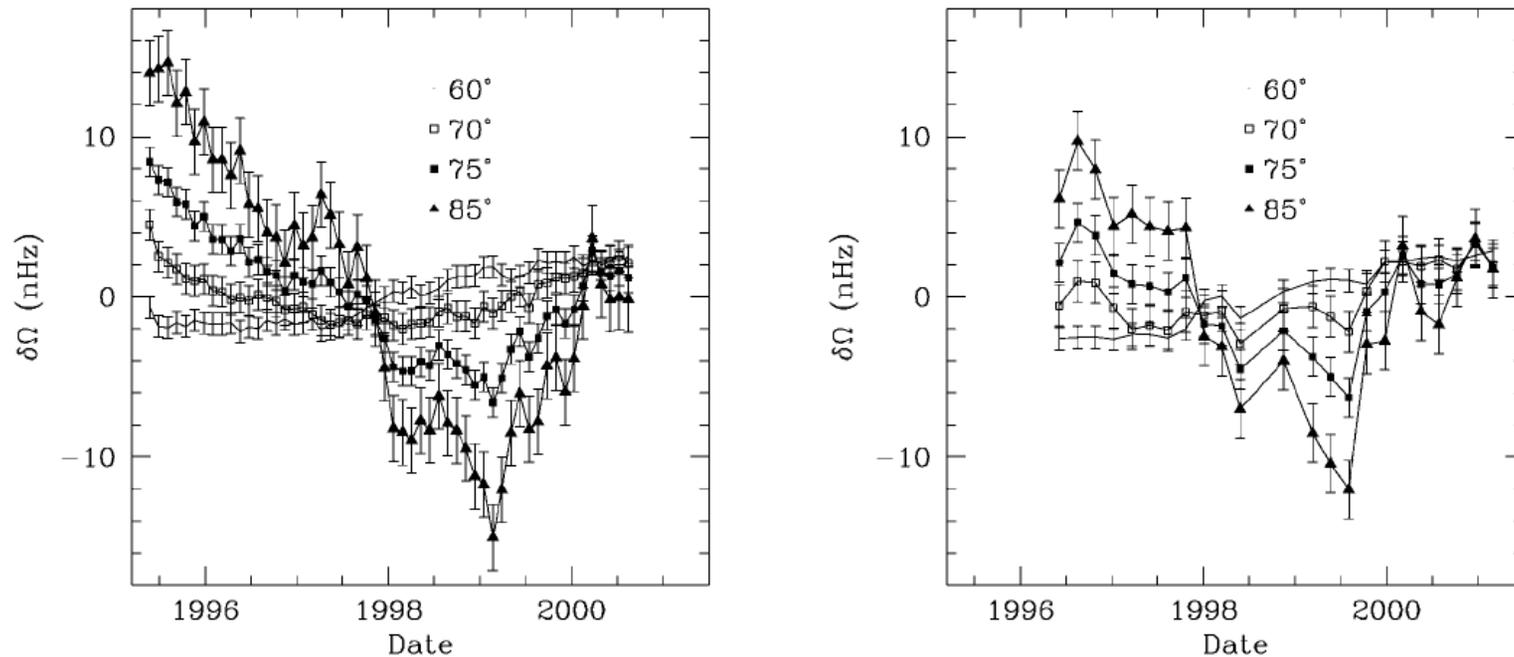
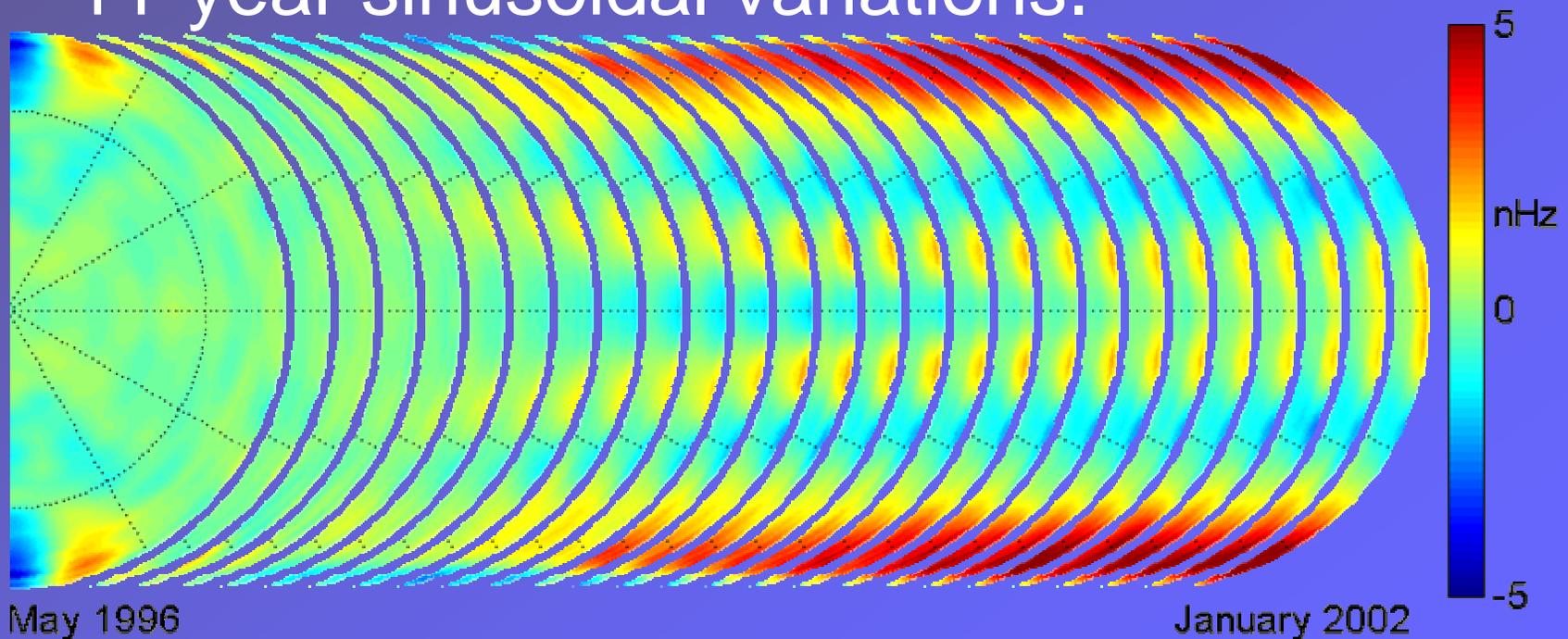


FIG. 3.—Rotation rate residuals at  $r = 0.98 R_{\odot}$  plotted as a function of time for different latitudes. The latitudes are marked in the figure. The results were obtained using two-dimensional RLS inversion of GONG (*left*) and MDI (*right*) data.

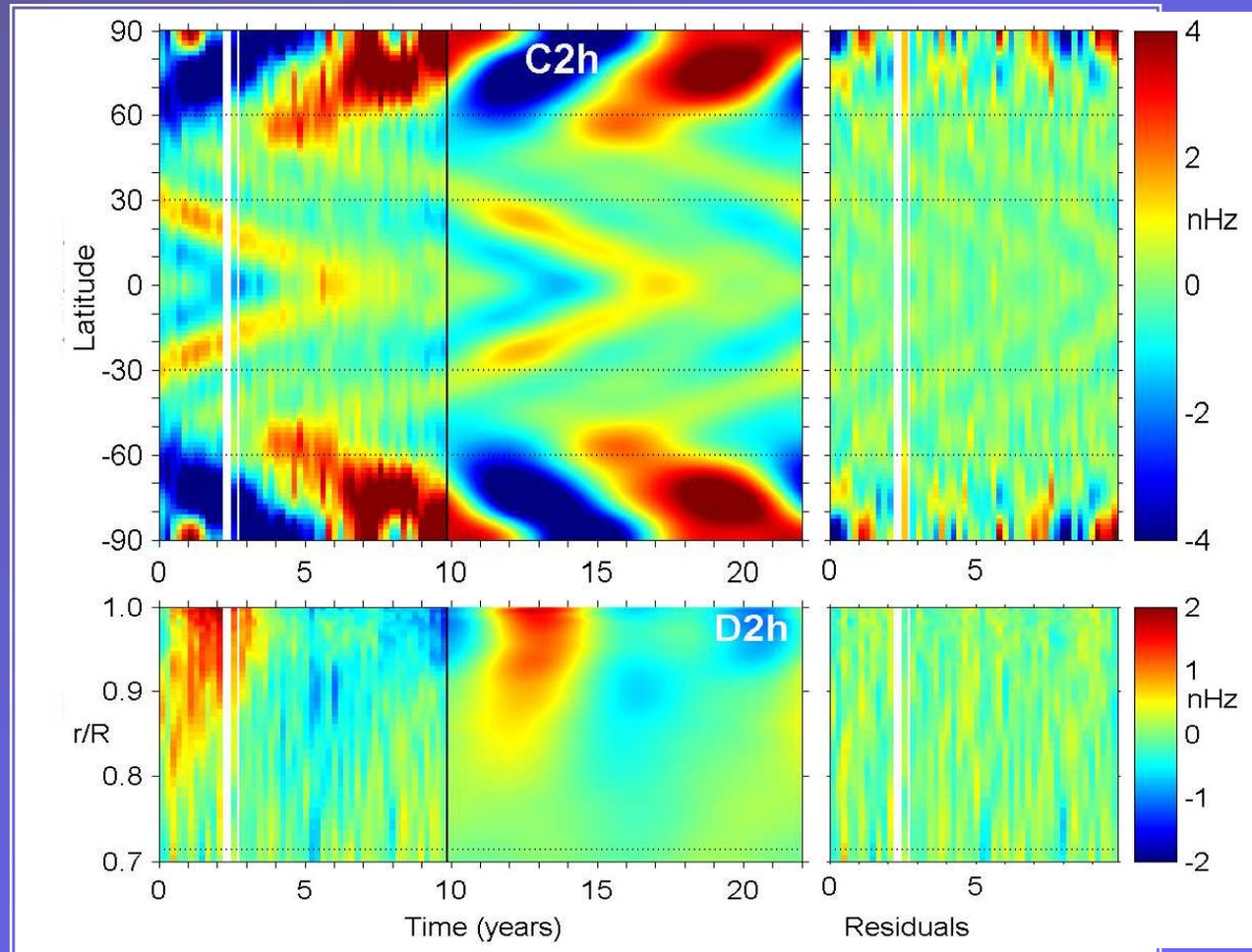
# Torsional Oscillation

- Vorontsov et al (2003) showed that the phenomenon involves much of convection zone, and analyzed the signal in terms of 11-year sinusoidal variations.

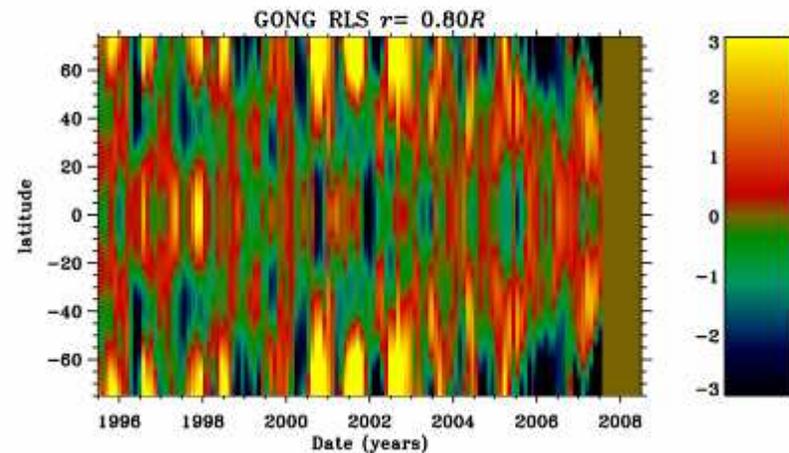
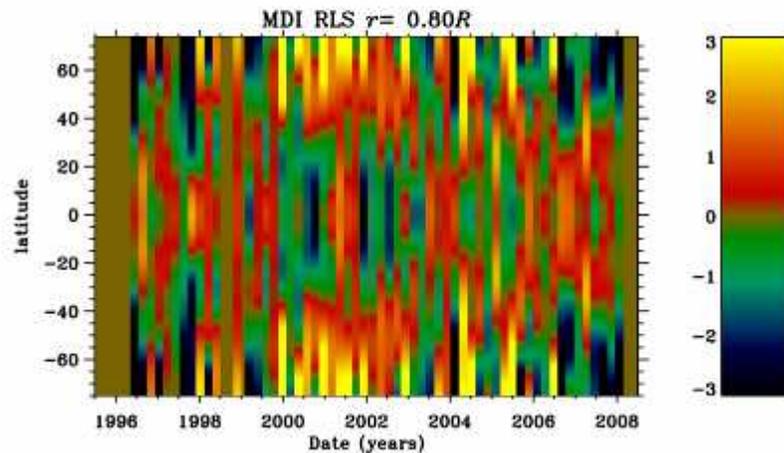
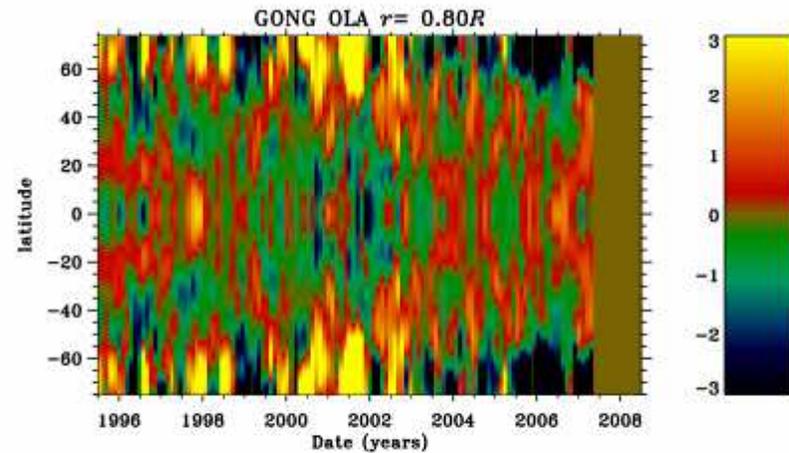
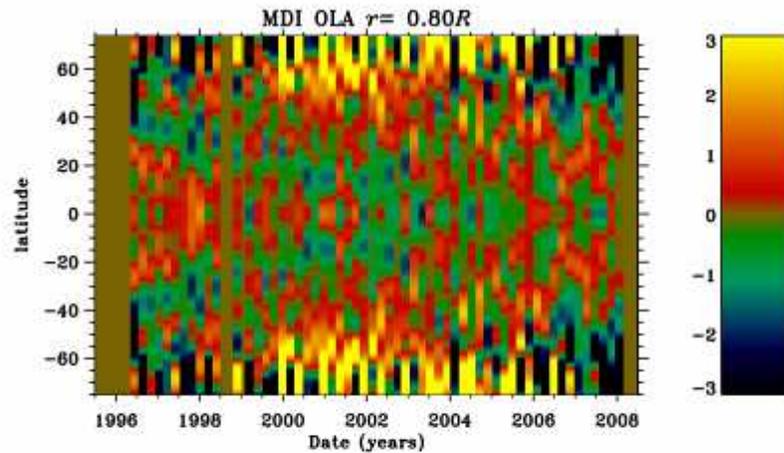


# Torsional Oscillation

- Vorontsov et al 2002
- Extrapolation using 11-yr sinusoid



# Zonal Flow Pattern



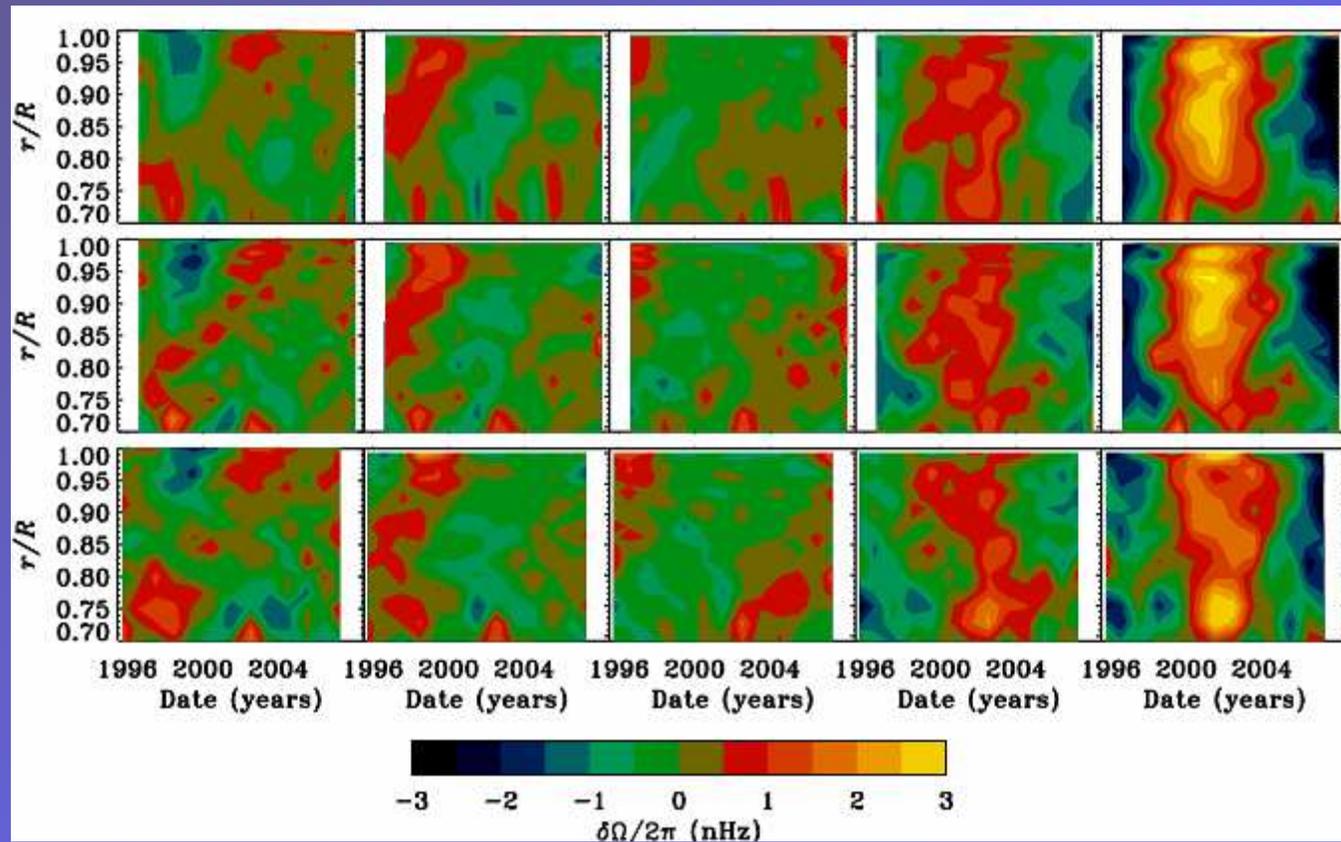
# Zonal Flow Patterns (Time-Radius)

0                      15                      30                      45                      60

MDI OLA

MDI RLS

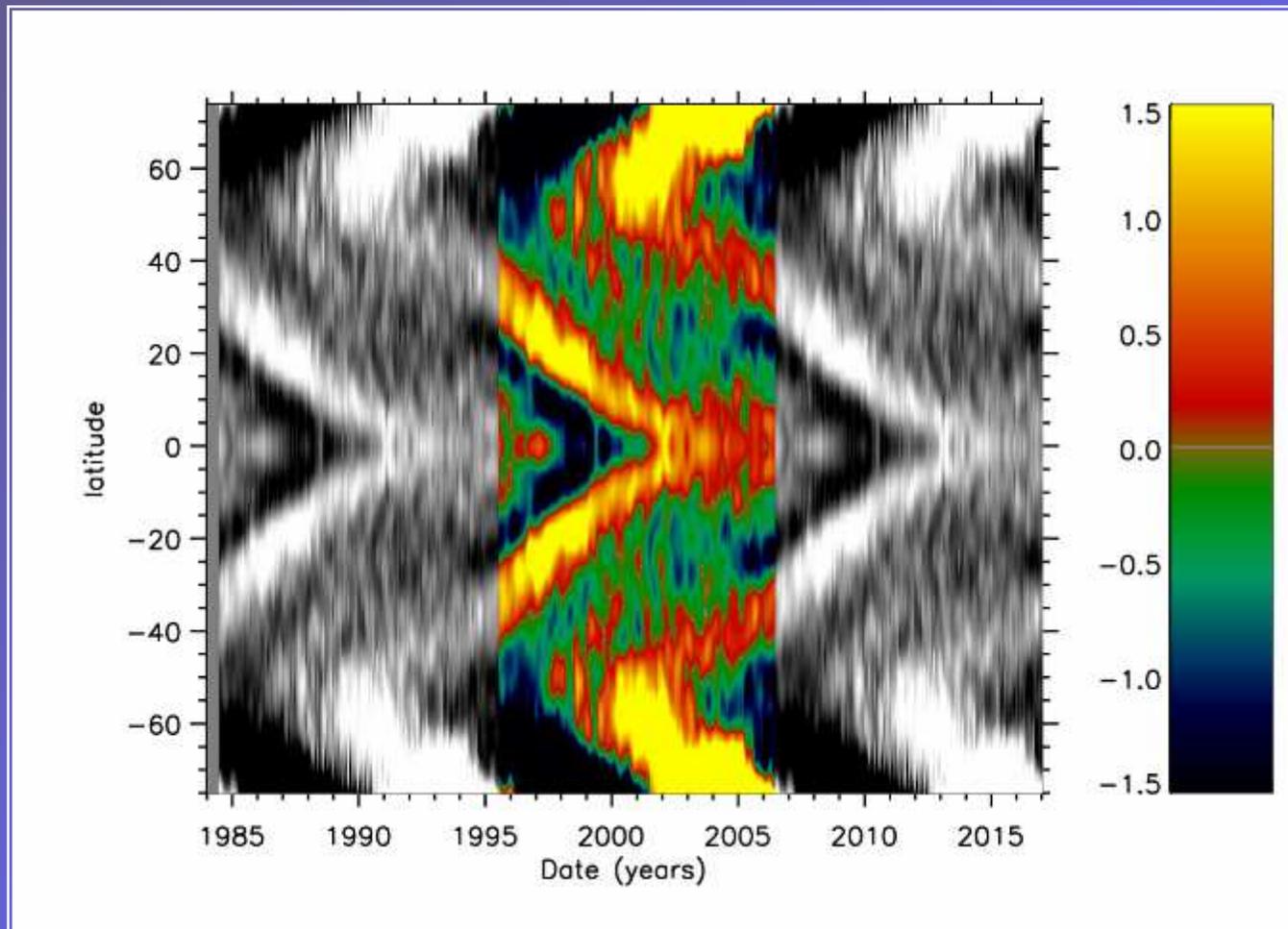
GONG RLS



Howe et al 2005

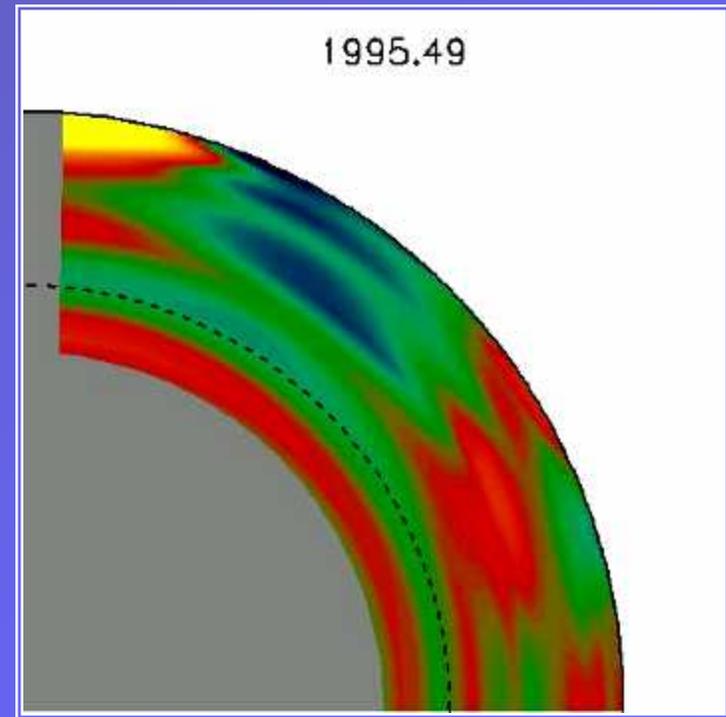
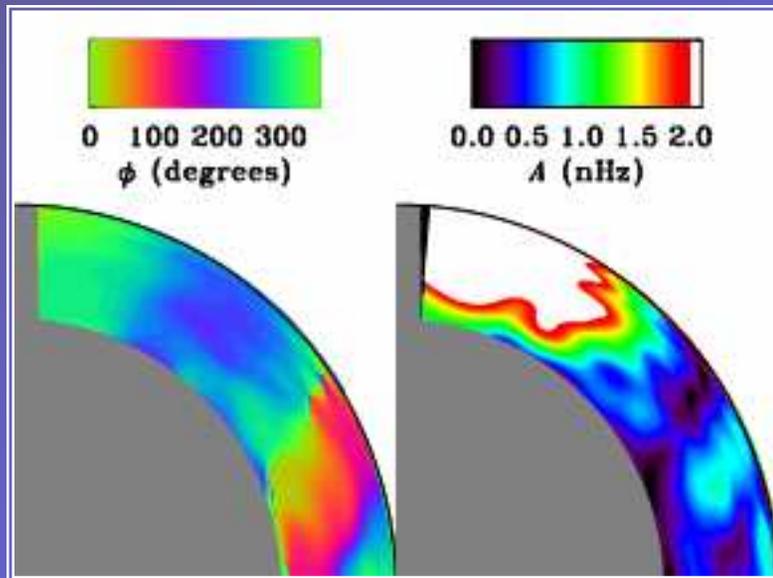
# A Complete 11-year Solar Cycle

- Zonal flows from combined GONG and MDI data

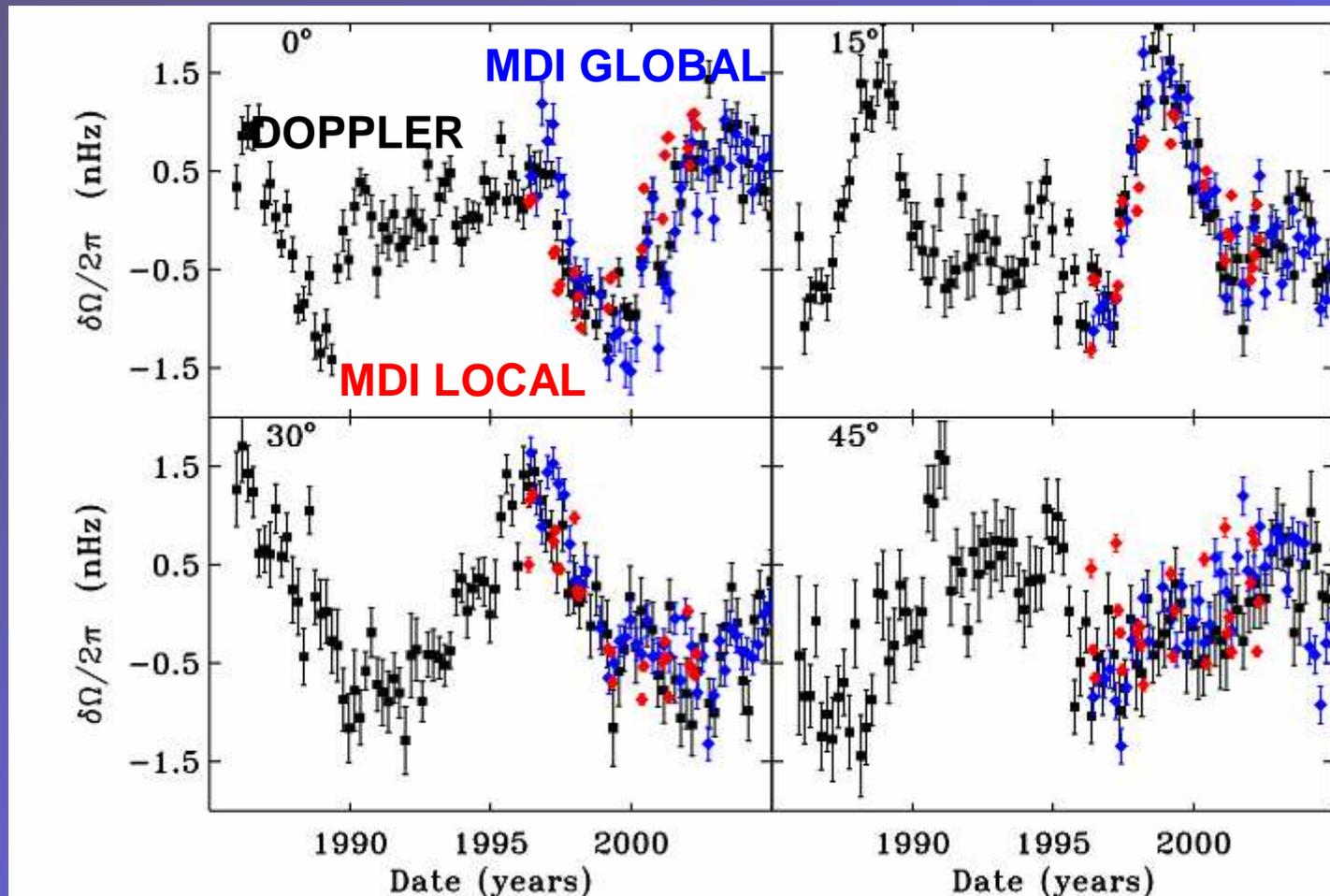


# Torsional Oscillation: Latest

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

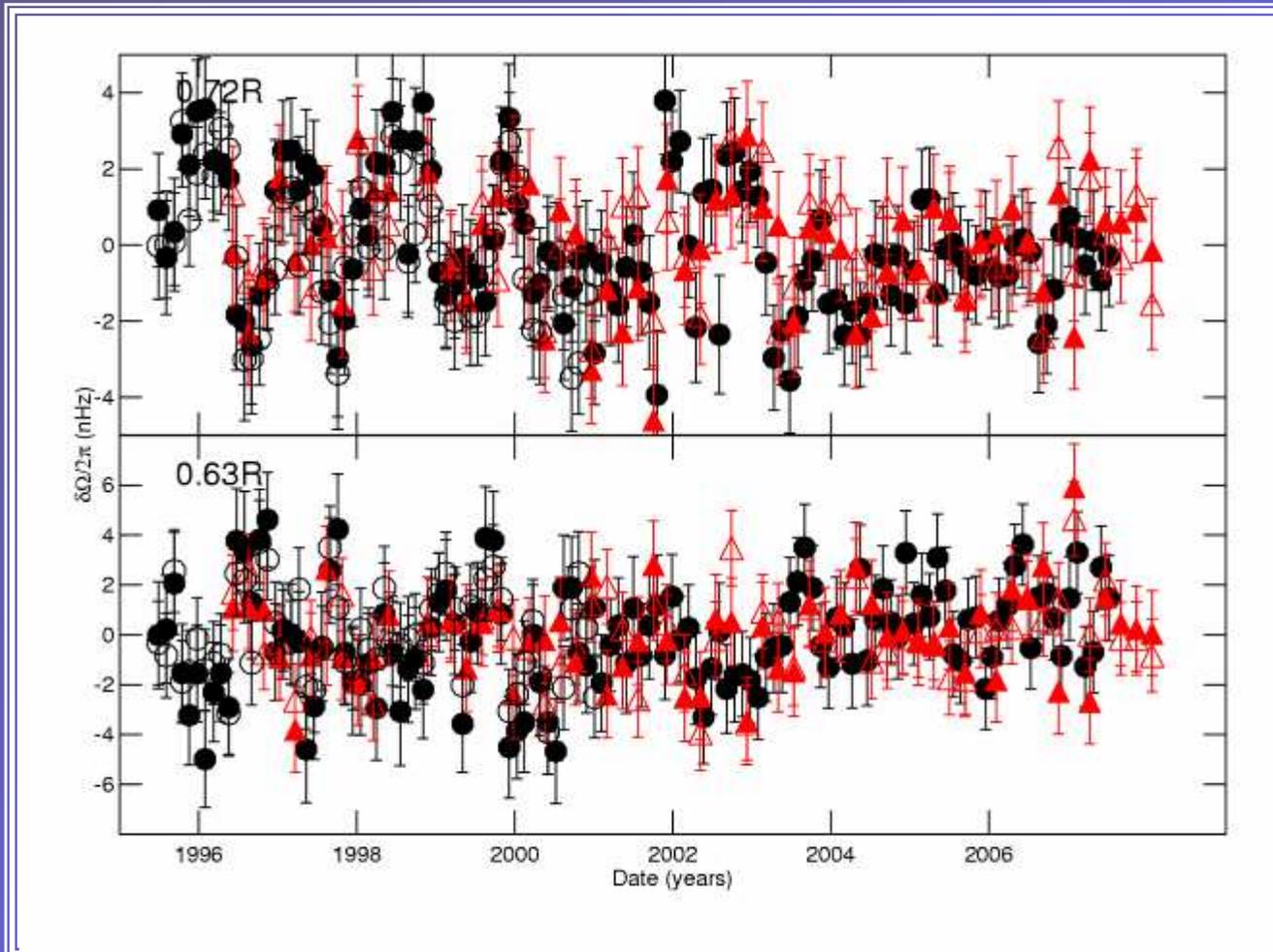


# Comparison of near-surface flow observations



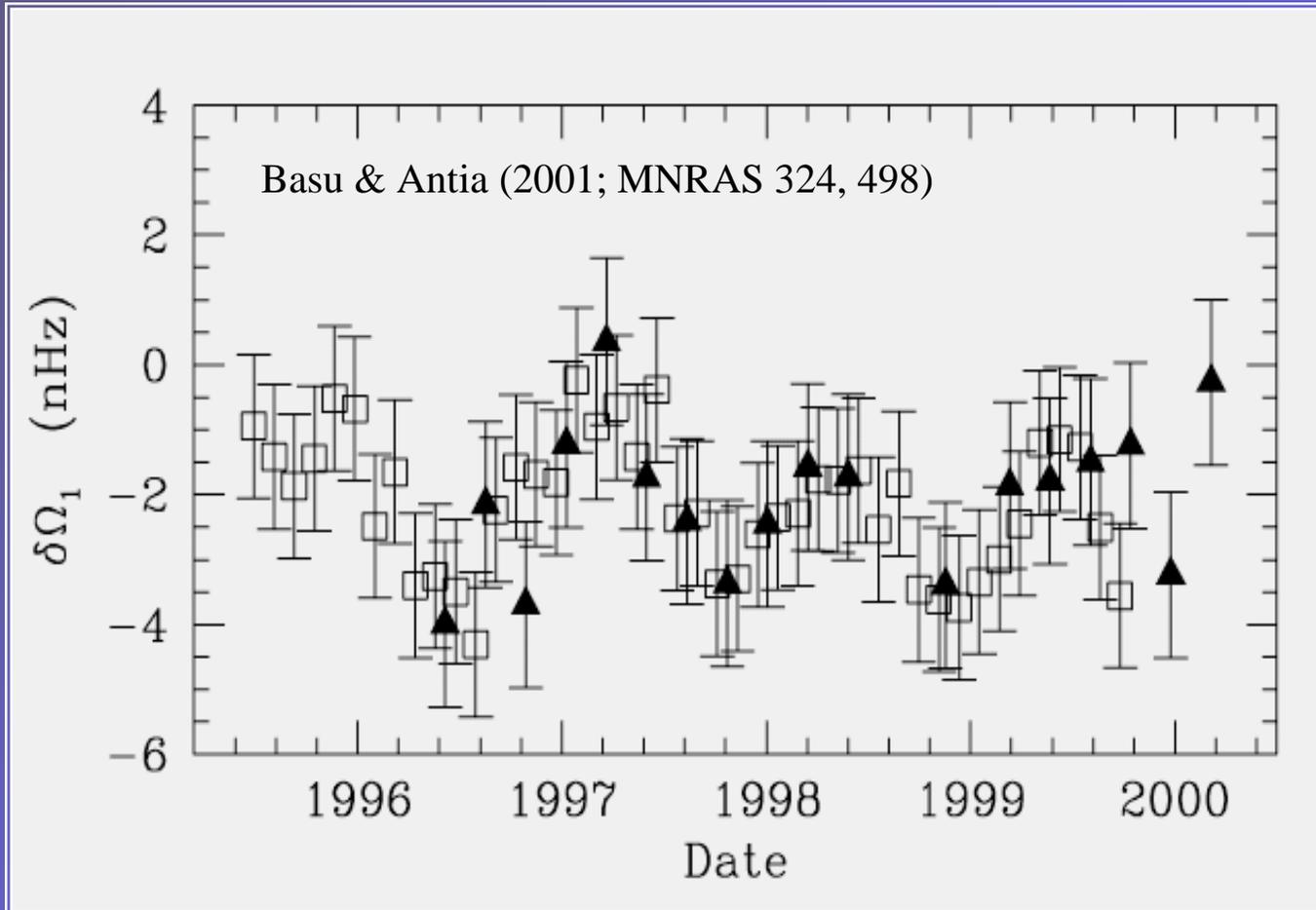
Howe et al, 2006

# Variations at the Tachocline

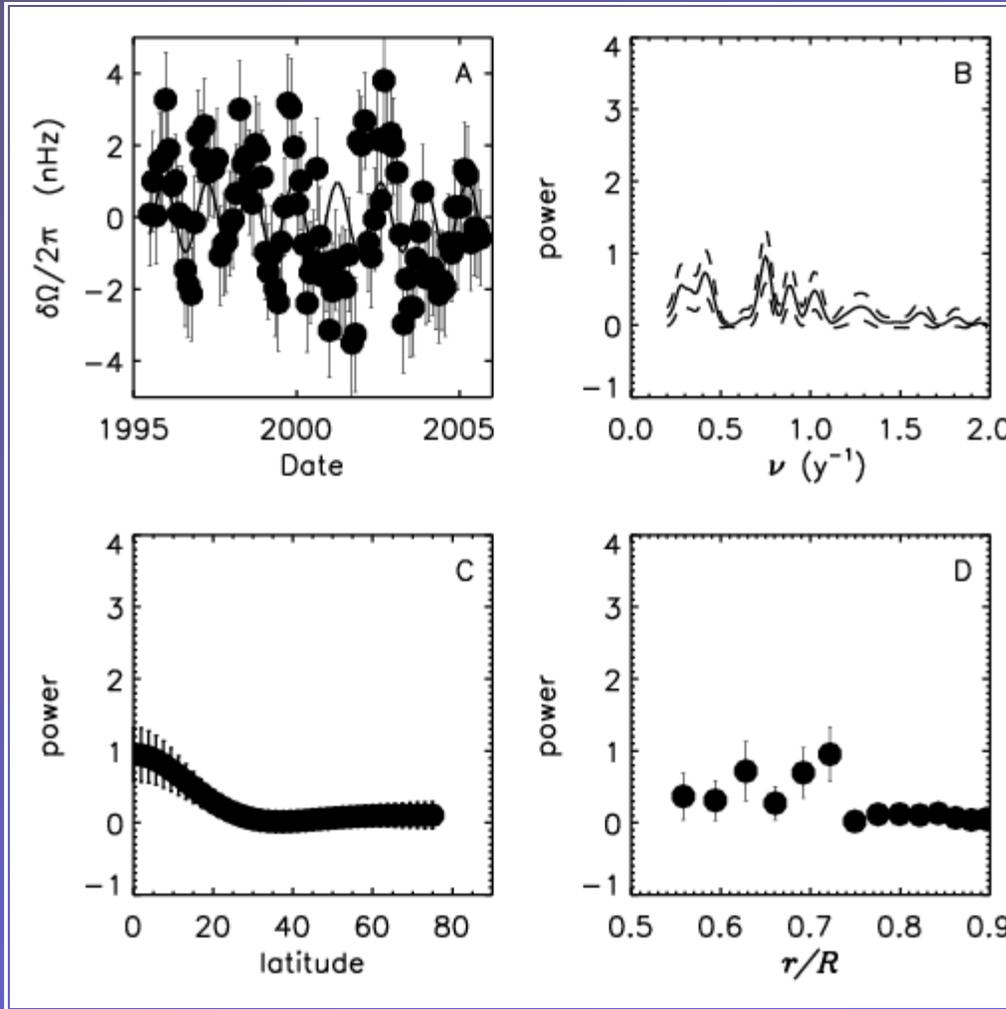


See Howe et al. (2000; Science 287, 2456)

# Tachocline oscillations



# 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

2002

2001

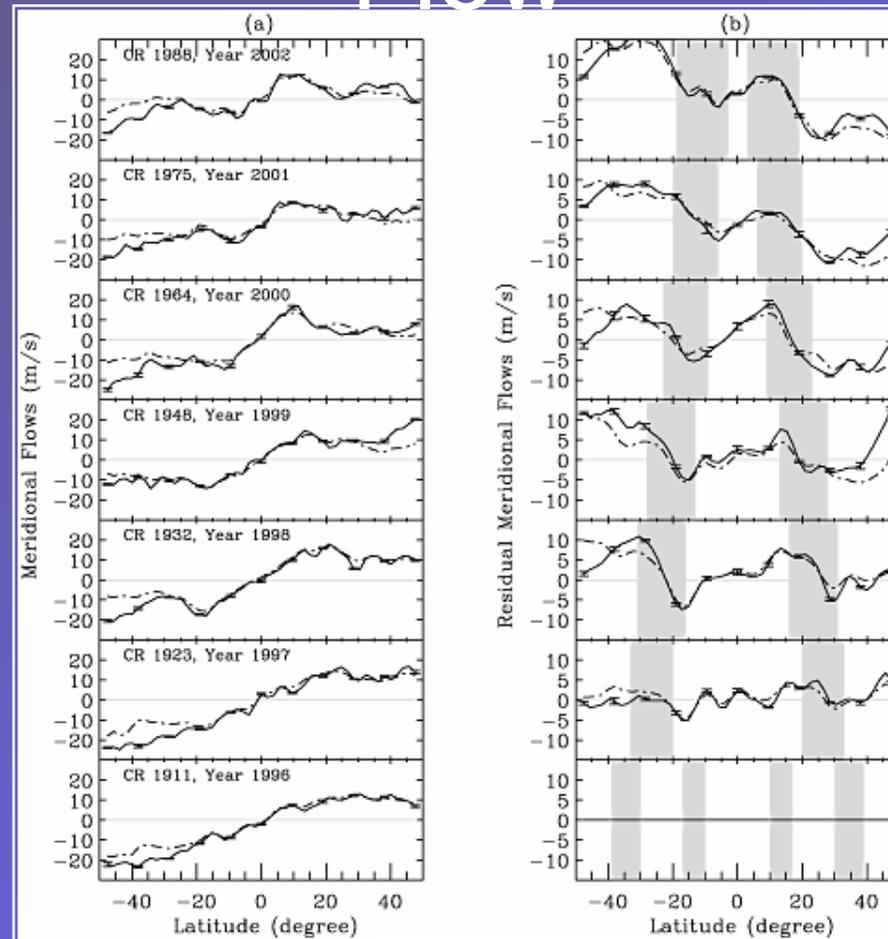
2000

1999

1998

1997

1996



Converging  
residual flow

(flows into  
active  
regions?)

solid: 4 Mm,  
dash-dot: 7 Mm

Zhao & Kosovichev 2004

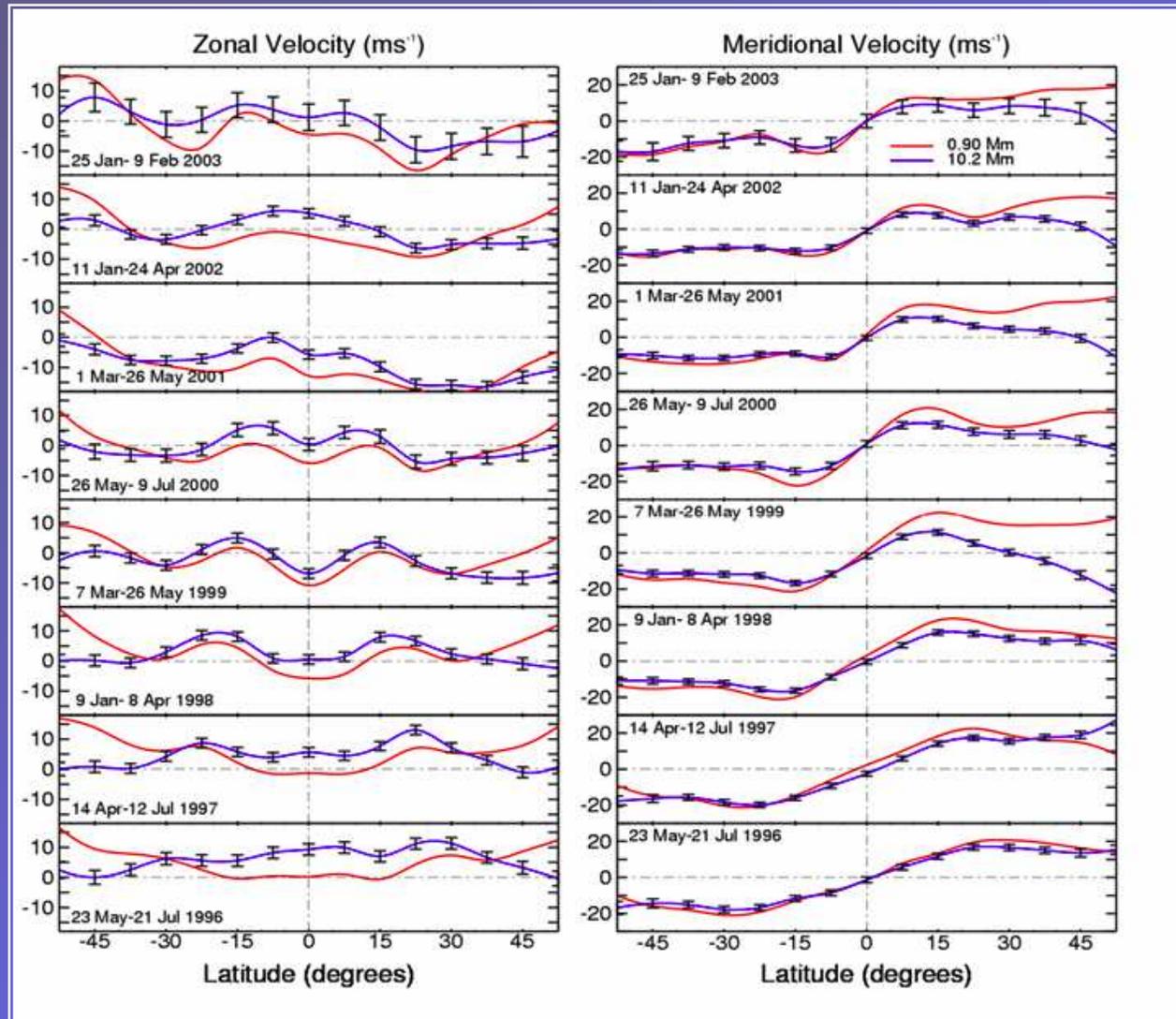
# Mean zonal and meridional flows

2003

2001

1999

1997

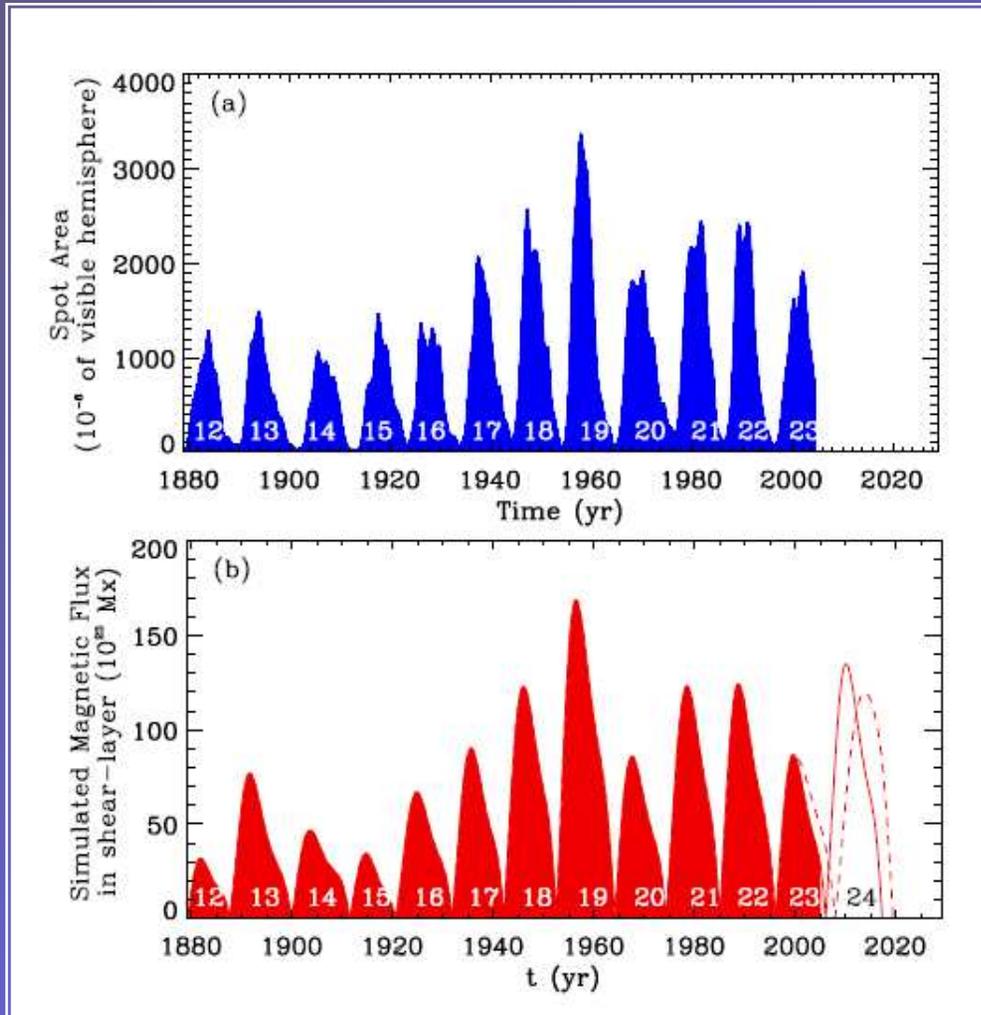


Zonal bands

Meridional cells

Haber  
Hindman

# Can helioseismic measurements help predict solar cycle strength?

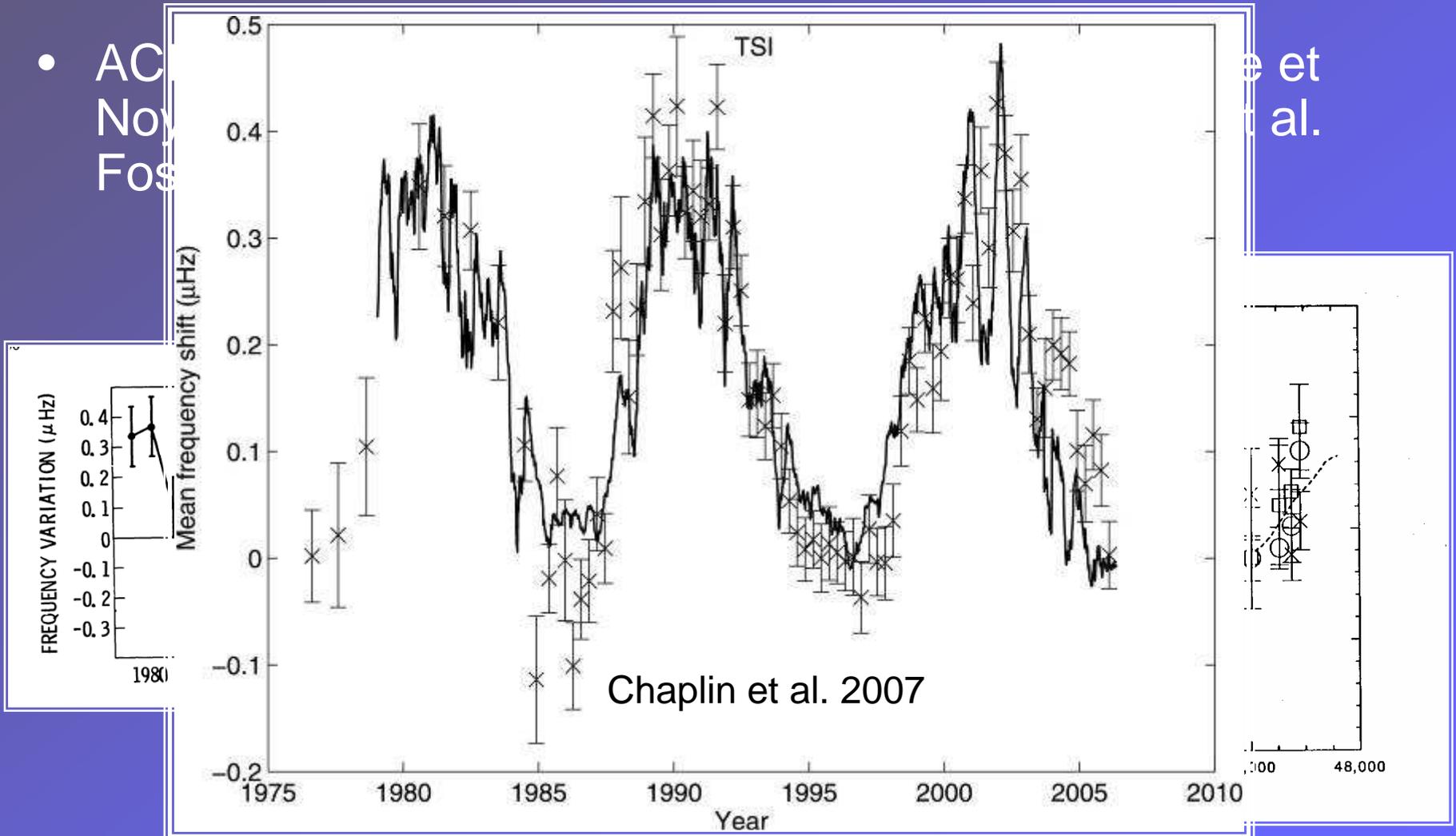


- Dikpati et al. 2006
- Prediction of strength of next cycle using flux-transport dynamo model (calibrated with helioseismic data) and sunspot area data.
- Using time-varying measured meridional flow gives different prediction from using mean value alone.
- Prediction now looking less likely!

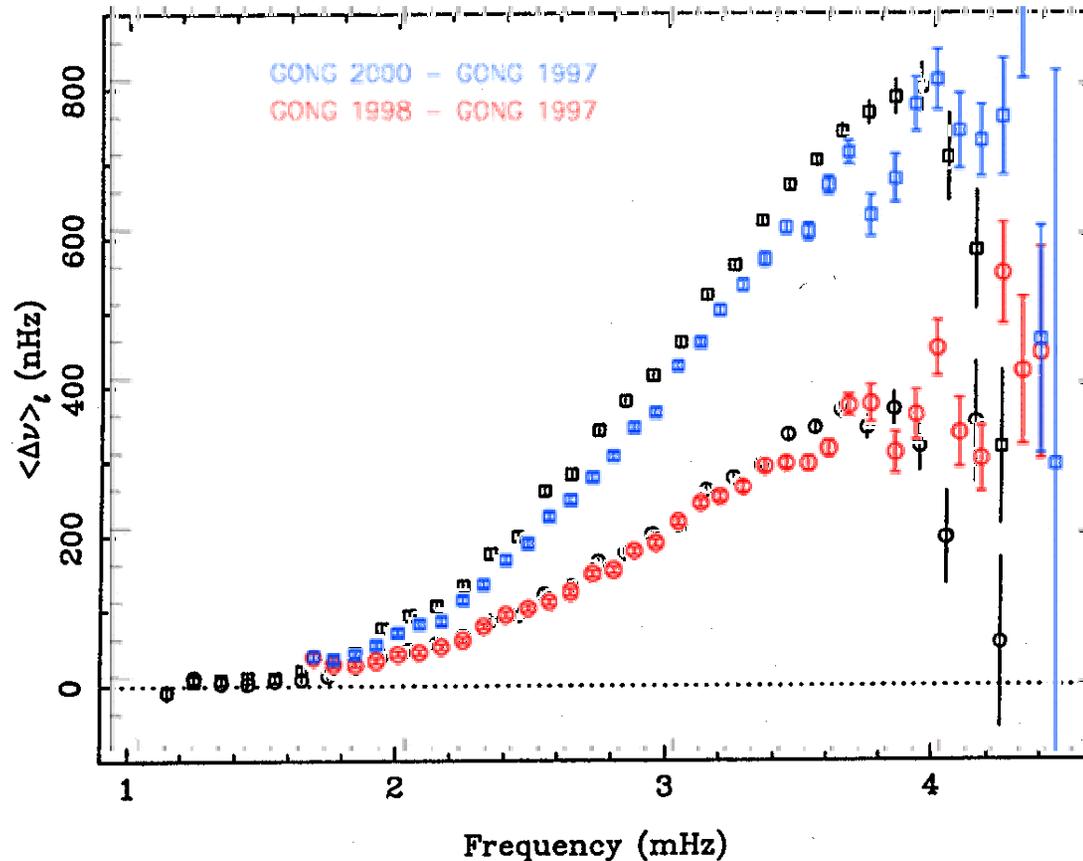
# Frequency shifts with solar cycle

- AC  
Noy  
Fos

e et  
al.

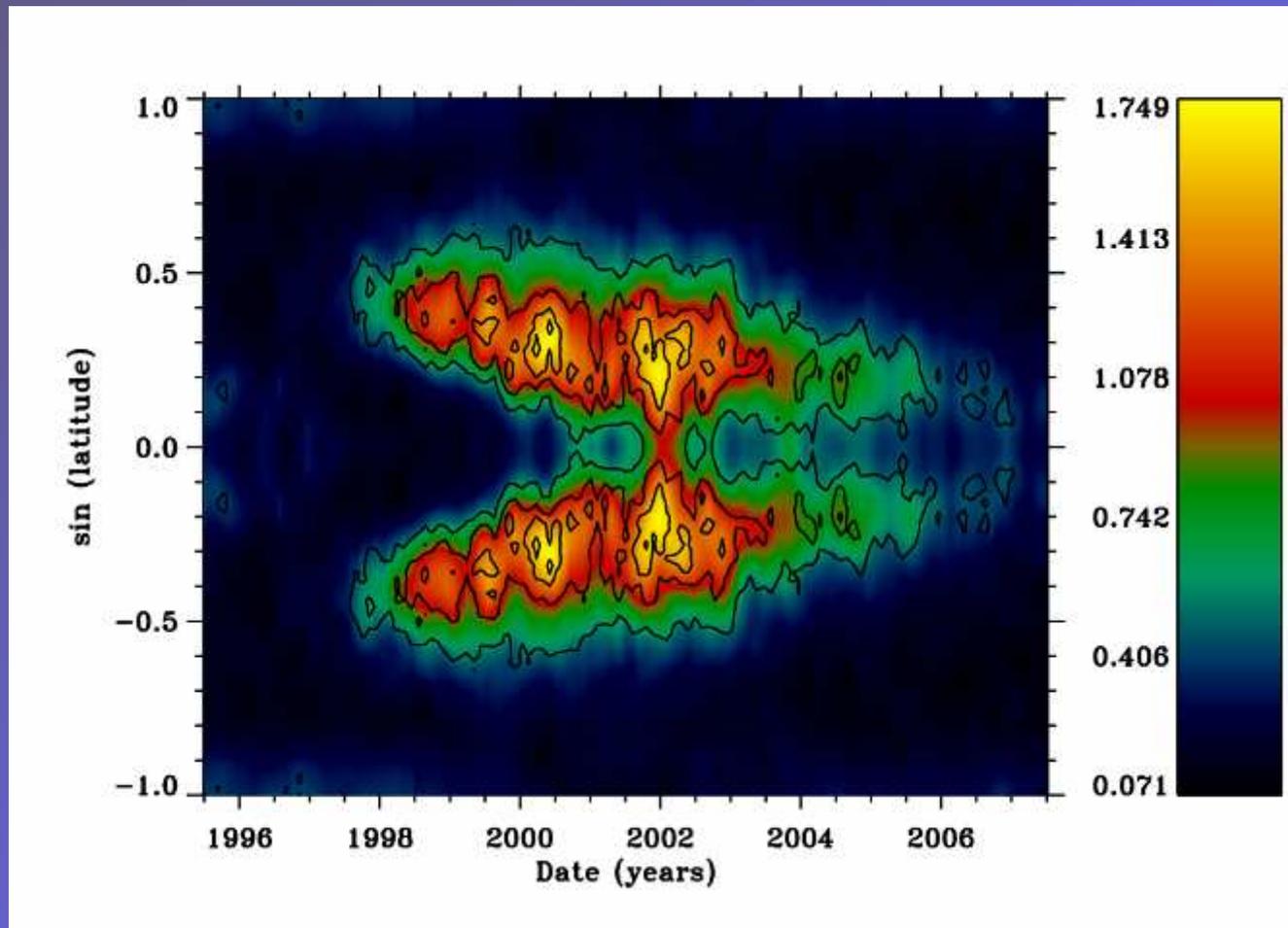


# Frequency shifts with solar cycle



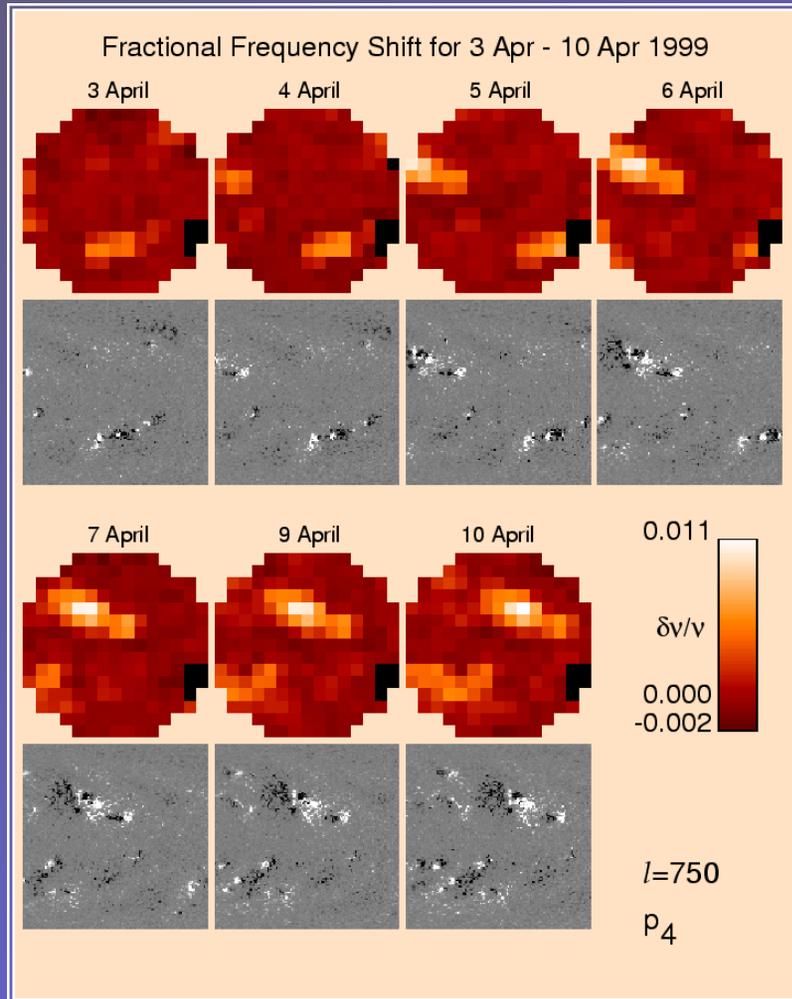
**Figure 18.** Frequency shift as a function of frequency, using frequencies from 1986 as a reference. The frequency dependence was obtained by averaging over modes in the range  $4 \leq l \leq 140$  in degree. Data from 1988 are denoted by circles, data from 1989 by squares. From Woodard and Libbrecht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

# Localized Global Frequency Shifts



(Howe, Komm & Hill 2002)

# High-degree Frequency Shifts

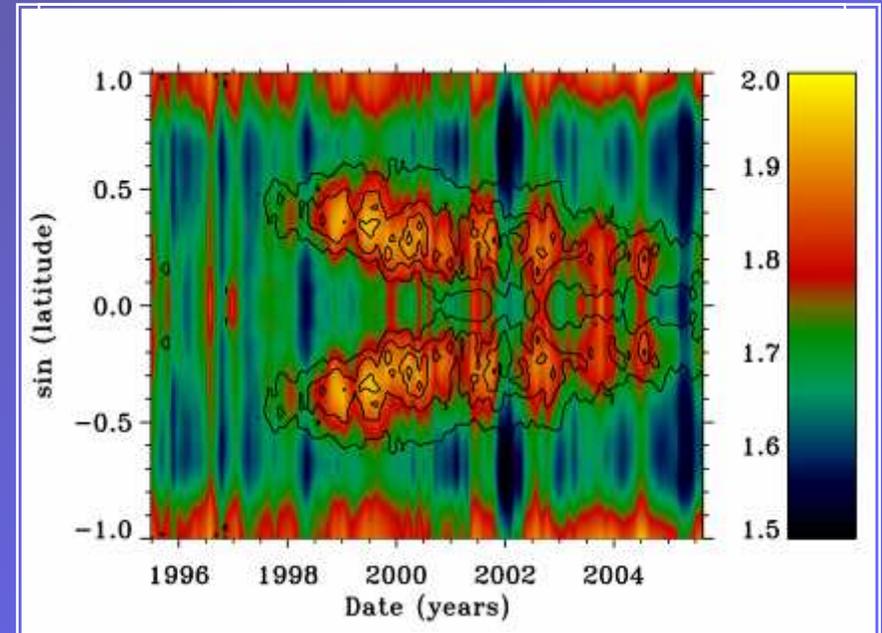
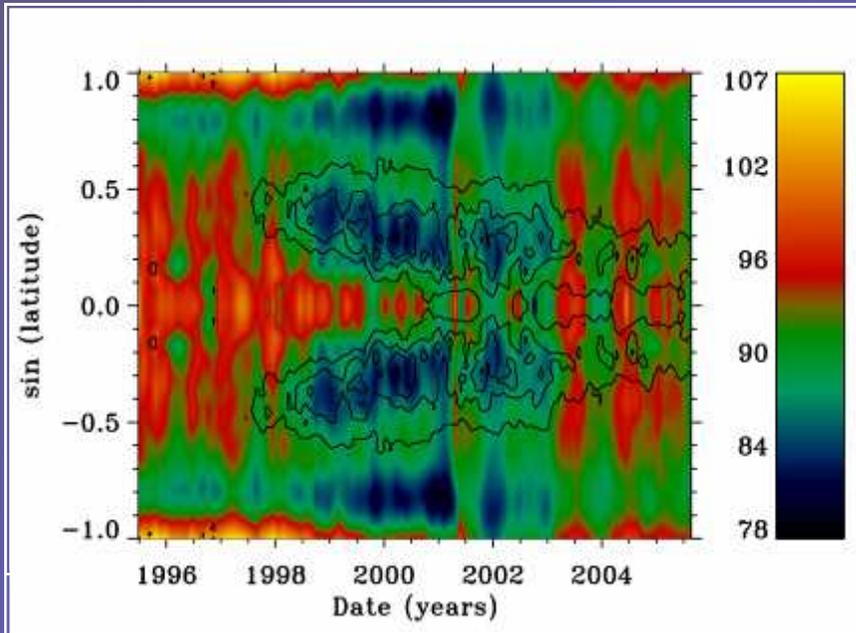


- Mode frequencies are higher in active regions
- (Hindman et al, 2000).

# 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
- Dziembowski and Goode 2005 – geometry

# Mode Energy and Width



- Komm, Howe and Hill 2002

# Summary

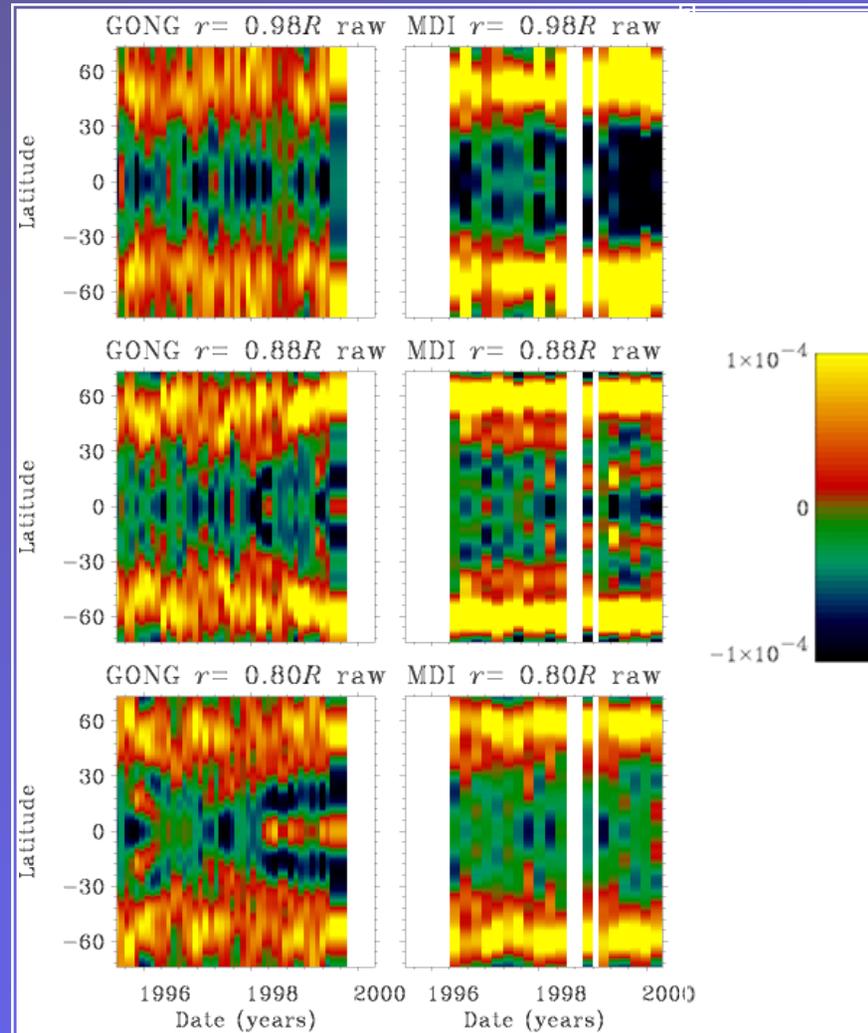
- Mode frequency, lifetime, amplitude are affected by surface magnetic features.
- Mechanism of frequency changes still unclear, but seems to be close to surface.
- Energy supplied to mode may be invariant, suggesting features affect damping only.
- Amplitude, lifetime changes related to mode absorption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

# The Search for Subsurface Structural Changes

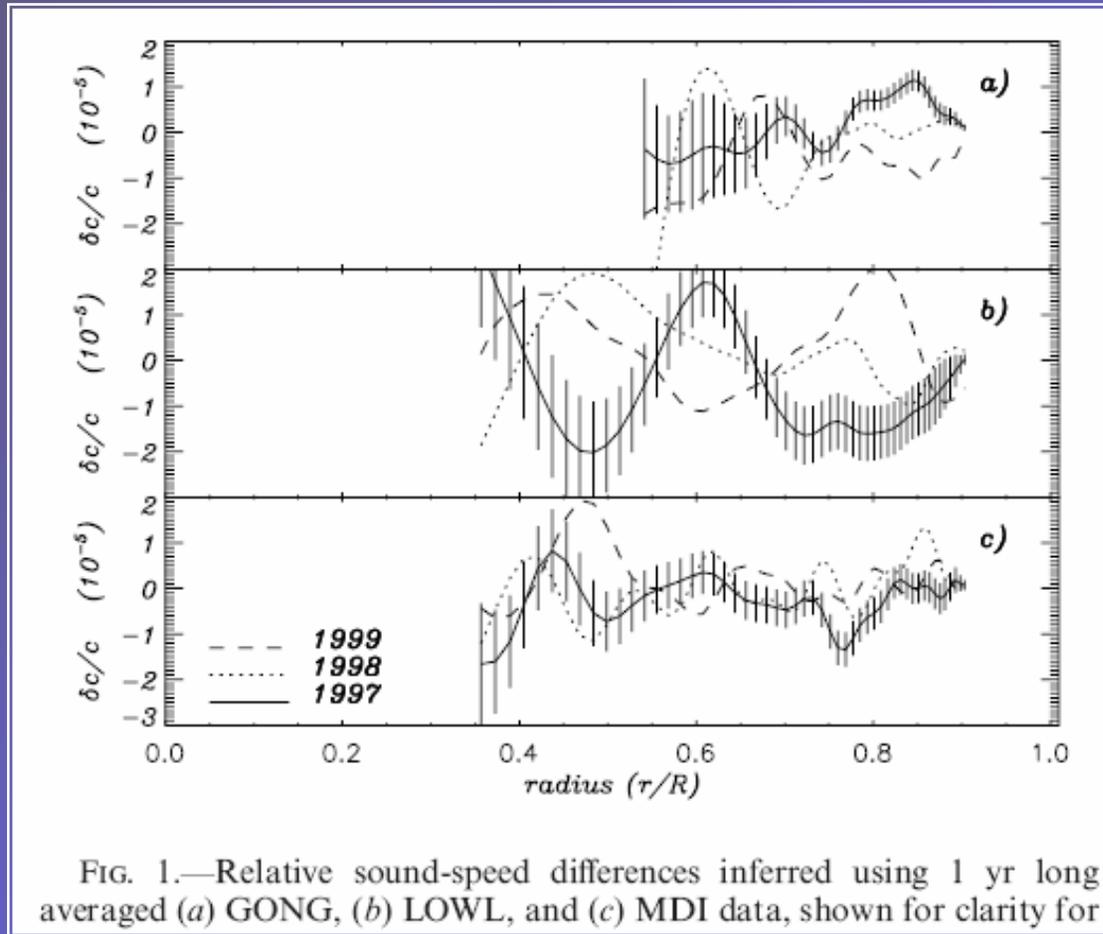
- Pattern of frequency shifts is consistent with near-surface effects.
- Surface layers are poorly resolved, modeled.
- Surface effects liable to mask more subtle changes in deeper layers.

# Search for Structural Change

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

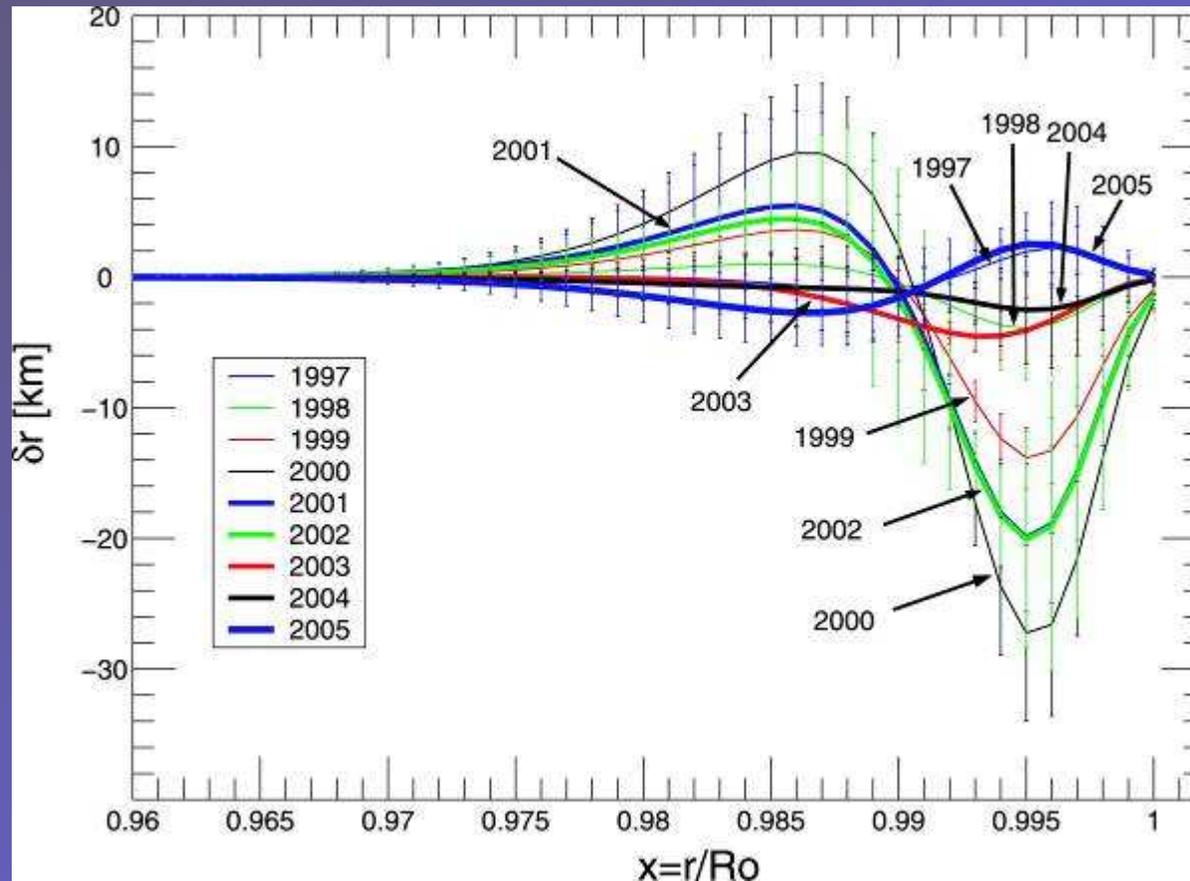


# Search for Structural Change



- Eff-Darwich et al 2002 – upper limit of  $3e-5$  on stratification change at base of convection zone

# Subsurface Structure Changes?

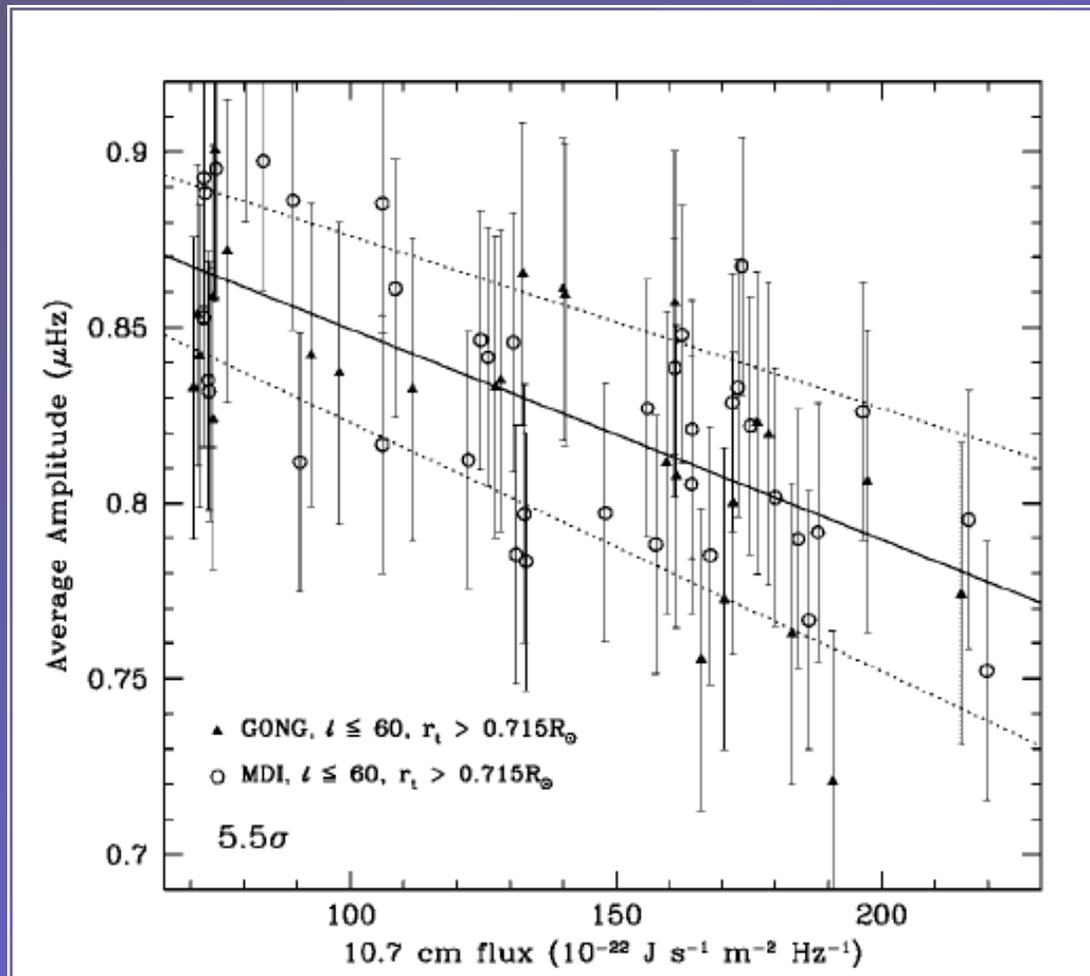


- Lefebvre & Kosovichev 2005, Lefebvre, Kosovichev & Rozelot 2007 – radius change in shallow subsurface layers.

Fig. 1.-

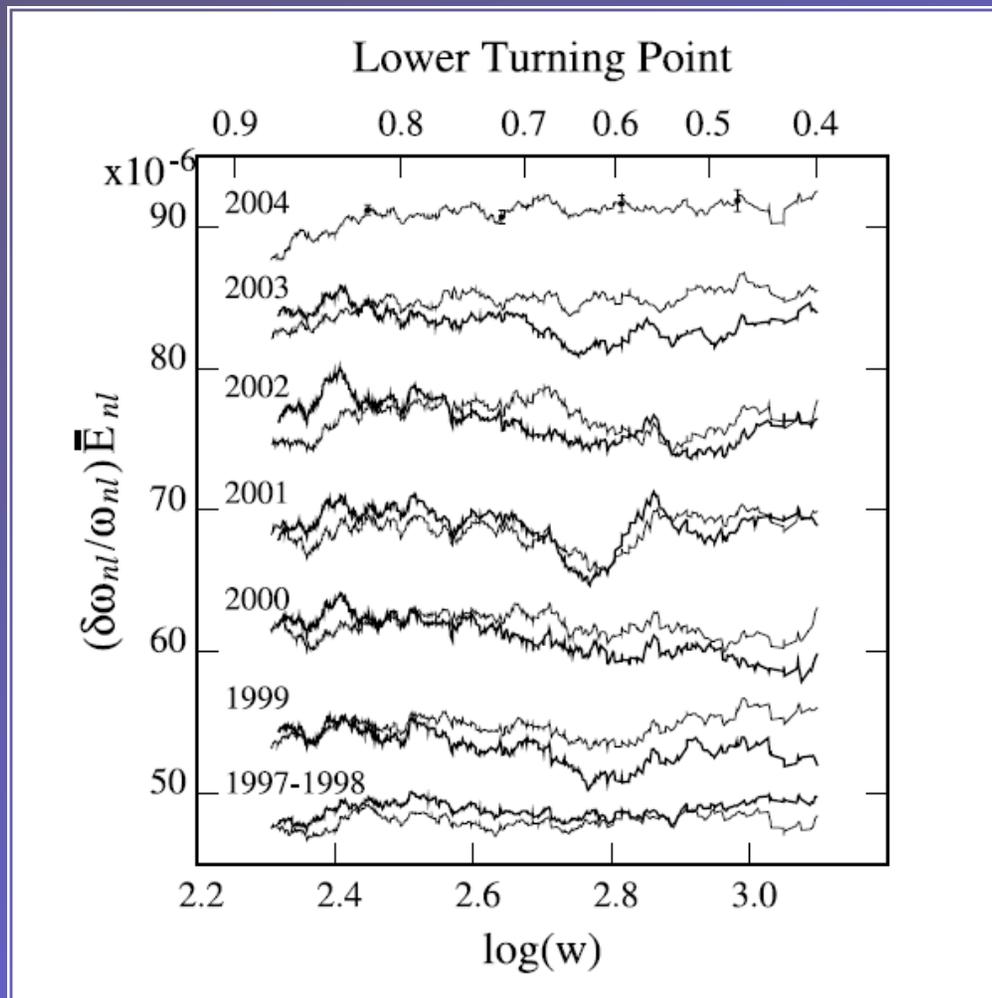
Radial variation as a function of the fractional radius, obtained as a solution of the inversion of f-mode frequencies by a least-squares regularization technique. The reference year is 1996. The error bars are the standard deviation after averaging over a set of random noise added to the relative frequencies. 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?



- Basu & Mandel (2004), Verner, Chaplin & Elsworth (2006) – evidence for solar-cycle change in amplitude of He ionization zone signature ( $0.98R$ ) from GONG, MDI, BiSON data.

# Subsurface Structure Changes



- Chou & Serebryanskiy 2005, Serbryanskiy & Chou 2005 – possible wave speed change near bottom of convection zone.

# 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.