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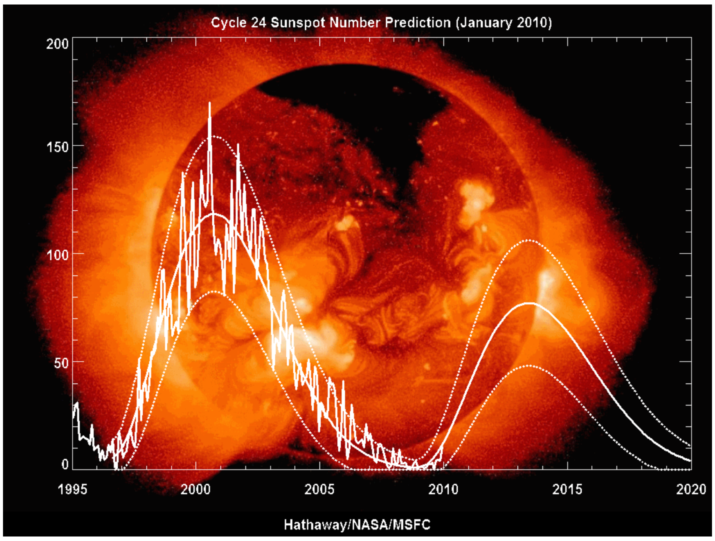
Helioseismology

Bill Chaplin, School of Physics & Astronomy
University of Birmingham, UK

STFC Advanced Summer School, 2012 Sep 4



http://solarscience.msfc.nasa.gov/predict.shtml

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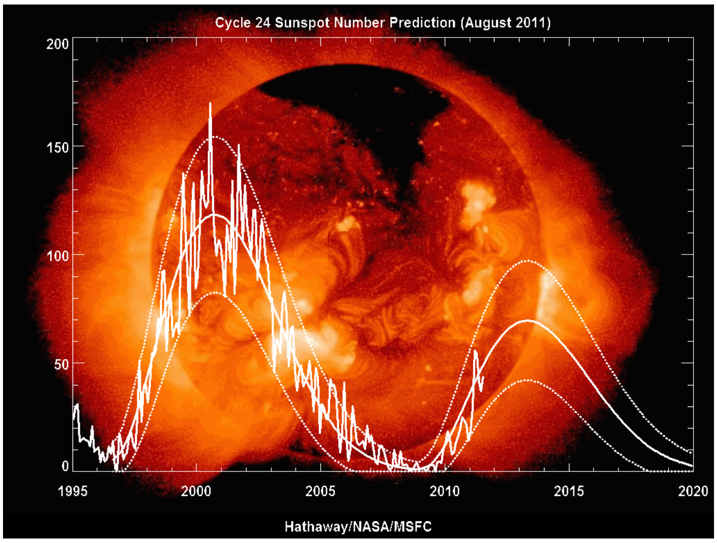

http://solarscience.msfc.nasa.gov/predict.shtml

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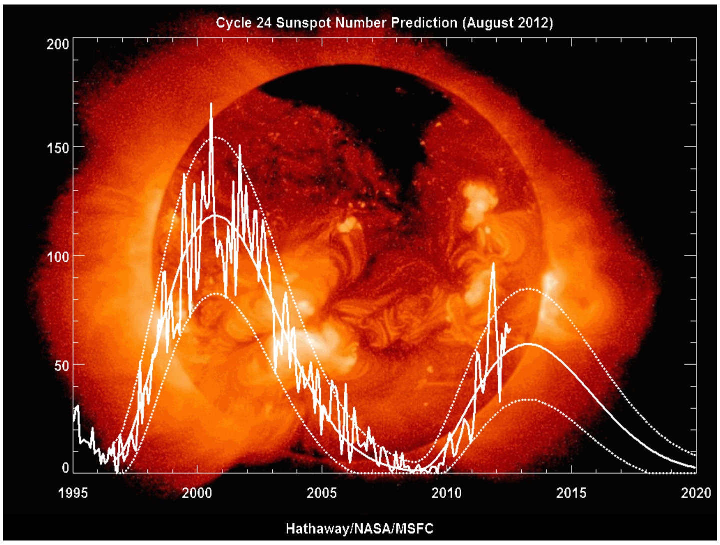

http://solarscience.msfc.nasa.gov/predict.shtml

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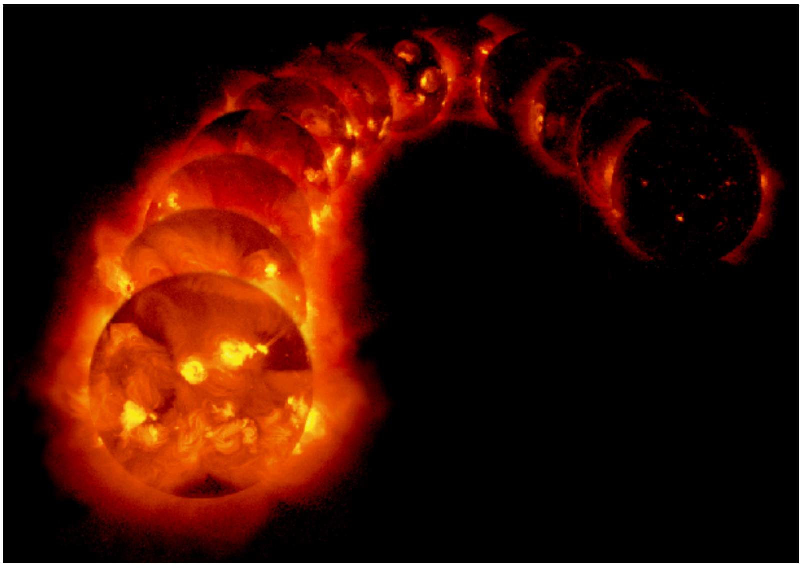
Seismology as a probe of the solar cycle

Bill Chaplin, School of Physics & Astronomy
University of Birmingham, UK

STFC Advanced Summer School, 2012 Sep 4



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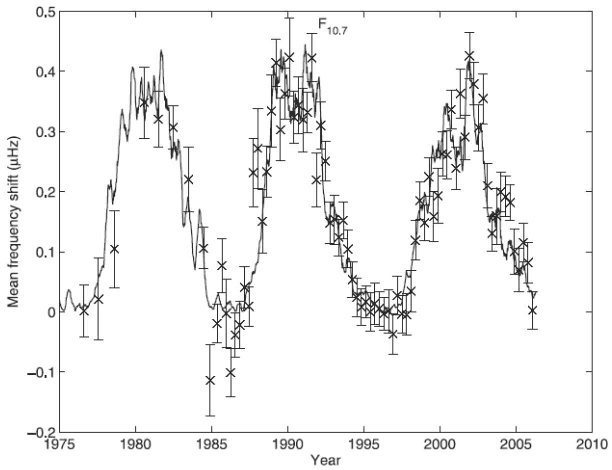
Three solar cycles with BiSON



Chaplin et al. 2007, ApJ, **659**, 1749

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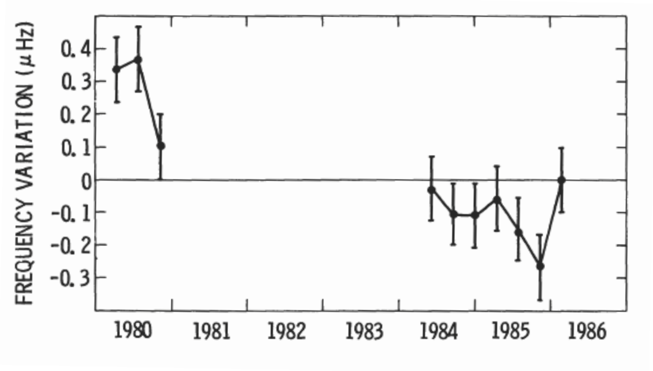
Acoustic signatures of the solar cycle: where it all started…

SMM/ACRIM data



Woodard & Noyes 1985, Nature; 1988, IAU123

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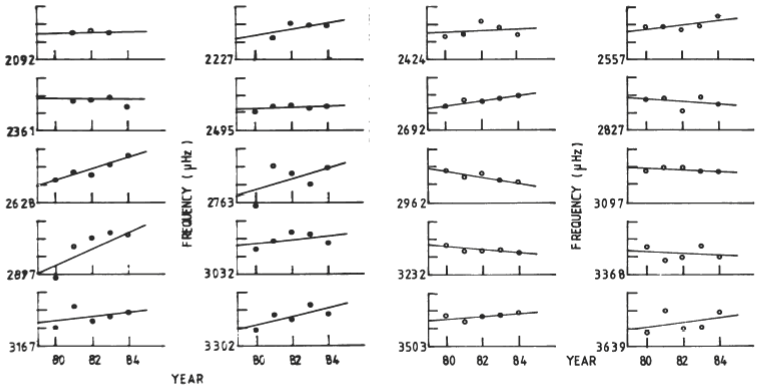
Early BiSON data (Data: Tenerife & Haleakala)

l=0 l=1



Isaak et al. 1988, IAU123

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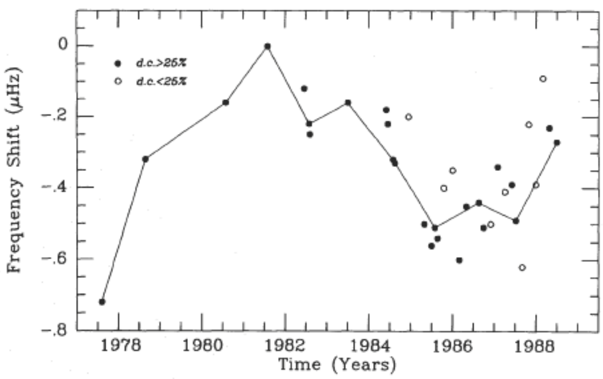
Cross-correlation analysis



Pallé et al., 1989, A&A, **224**, 253

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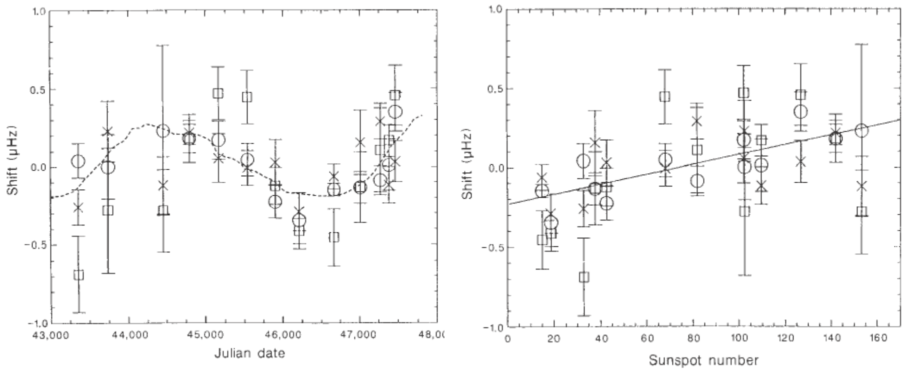
Clear correlations with surface measures of activity



Elsworth et al. 1990, Nature, **345**, 322

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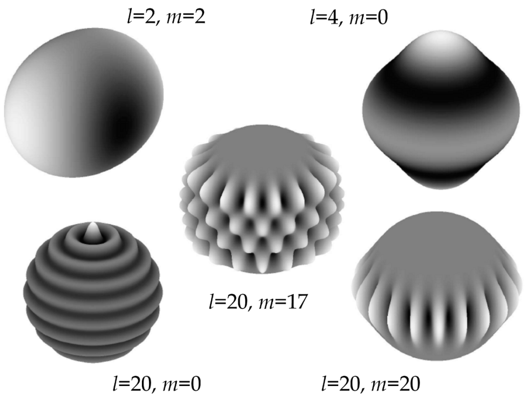
Behave like spherical harmonics

l: number of nodal lines

m: number of azimuthal nodal lines



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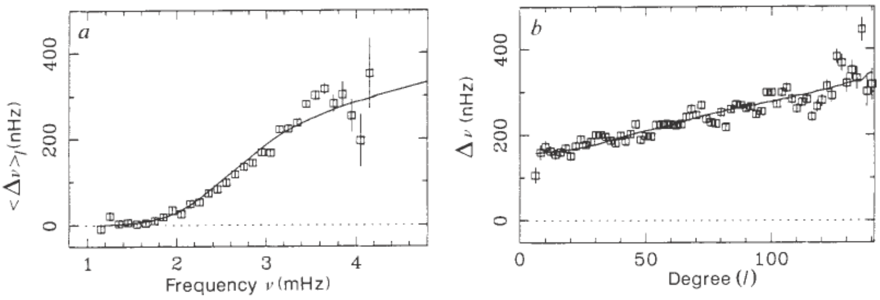
Frequency and degree dependence of shifts…



Libbrecht & Woodard 1990, Nature, **345**, 779

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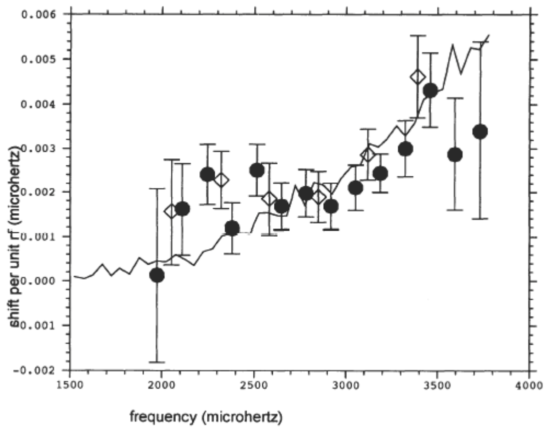
Frequency dependence at low degree



Elsworth et al. 1994, ApJ, **434**, 801

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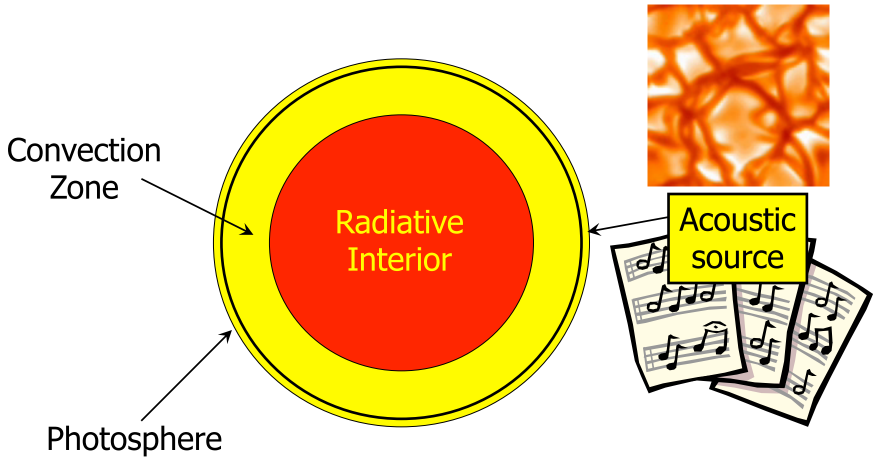
Sound waves generated at top of Convection Zone...



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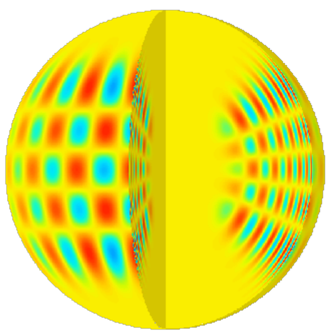
The Resonant Sun

The Sun resonates like a musical instrument...



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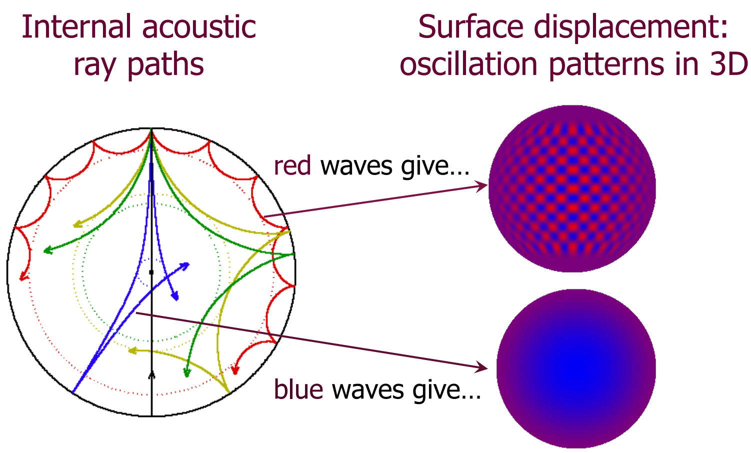
Standing acoustic wave patterns...



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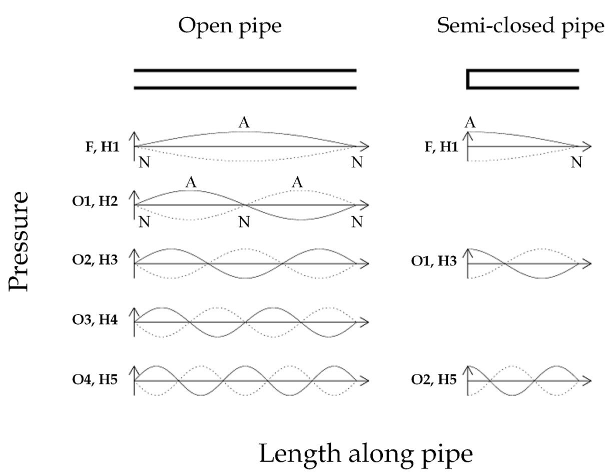
Resonance in simple 1-D pipes



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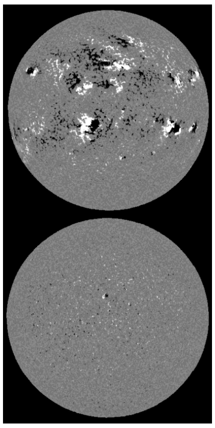
Changes in Mode Properties...



Magnetic fields can act as agents of change:

- Directly, by action of Lorentz force
- Indirectly by changing stratification

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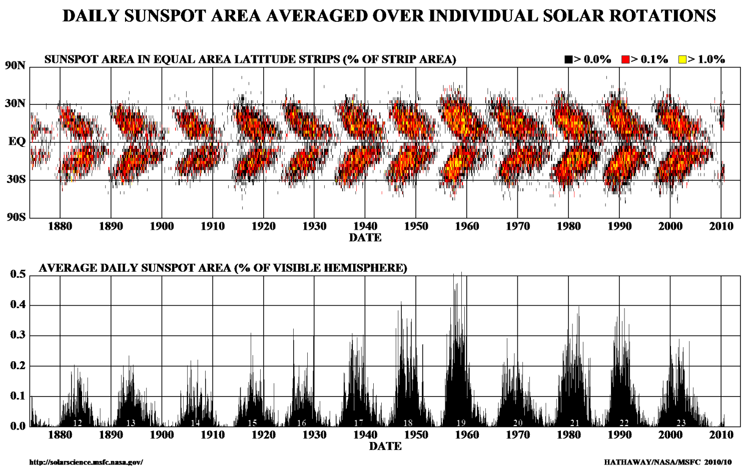
The Solar Activity Cycle



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Dispersion relation

- Simple $\omega = ck$ relation modified:
    - Interior stratified under gravity
    - Total internal reflection implies existence of cut-off frequency
    - Radial (*r*) and horizontal (*h*) wave numbers required

Dispersion relation

- Allow for different types of internal wave:
    - Acoustic waves: compression dominates
    - Buoyancy waves: displacement dominates

Dispersion relation

- Simple $\omega = ck$ relation modified to:

$$k_r^2 = \frac{\omega^2 - \omega_{\mathrm{ac}}^2}{c^2} + \frac{k_h^2(N^2 - \omega^2)}{\omega^2}$$

ω_{ac}: acoustic cut-off frequency

N: Brunt Väisälä frequency (characterises oscillation of fluid element displaced from rest position)

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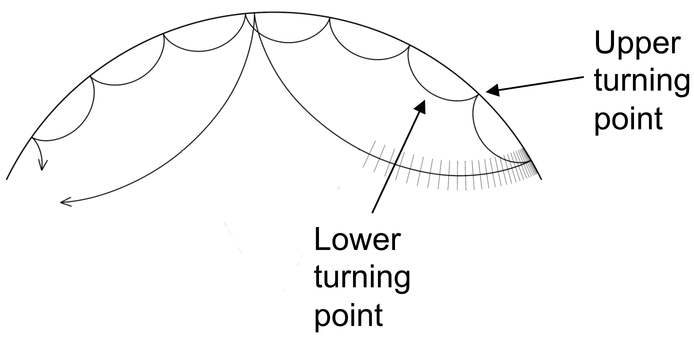
Trajectories of acoustic waves in interior



Courtesy J. Christensen-Dalsgaard

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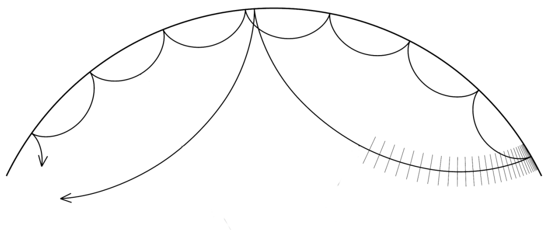
Trajectories of acoustic waves in interior



Waves launched at steeper angle to radial direction penetrate more deeply!

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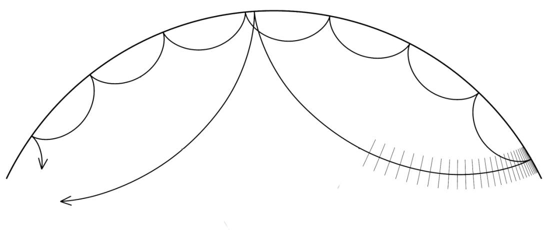
Trajectories of acoustic waves in interior



These more-deeply penetrating waves have longer horizontal wavelengths: bigger skip distance goes with longer λ_h [smaller k_h]

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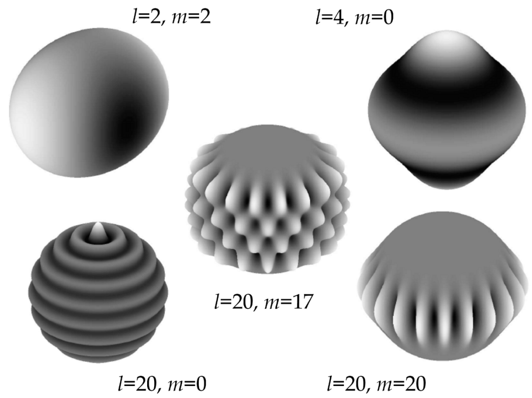
Behave like spherical harmonics

l: number of nodal lines

m: number of azimuthal nodal lines



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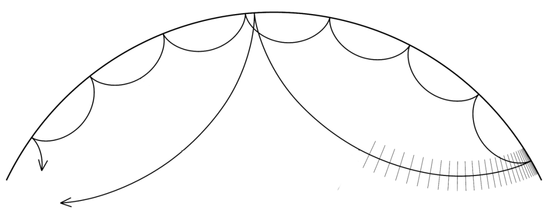
Trajectories of acoustic waves in interior



Longer [illegible]$_h$ [smaller k_h] = lower degree, l

So the lower the degree, the more deeply penetrating the mode; and the larger the associated mode inertia

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Frequency dependence of shifts

Mode inertia and mode mass

$$E_{nl} = M_{\odot}^{-1} \int_V |\xi|^2 \rho \, dV = M_{nl} / M_{\odot}$$

$$\frac{1}{2} M_{nl} v_{nl}^2 = \frac{1}{2} E_{nl} M_{\odot} v_{nl}^2$$

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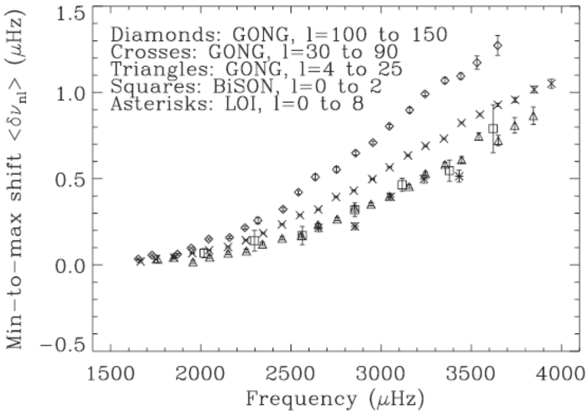
Frequency dependence of shifts



Chaplin et al. 2001, MNRAS, **324**, 910

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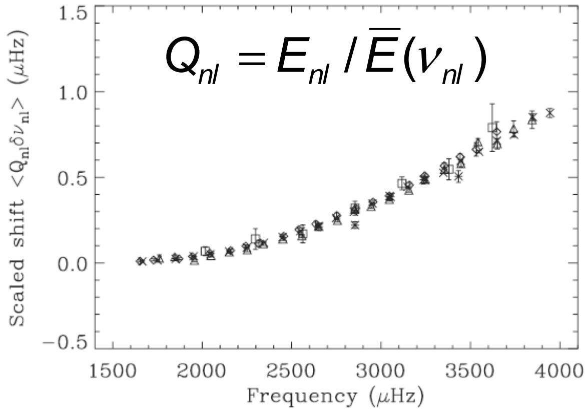
Frequency dependence of shifts

$\overline{E}(\nu_{nl})$: inertia an l=0 mode would have at frequency ν_{nl}



Chaplin et al. 2001, MNRAS, **324**, 910

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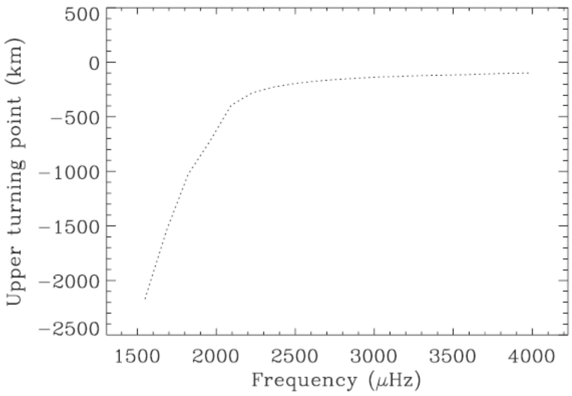
Frequency dependence of shifts



UTP for radial modes (model ‘S’)

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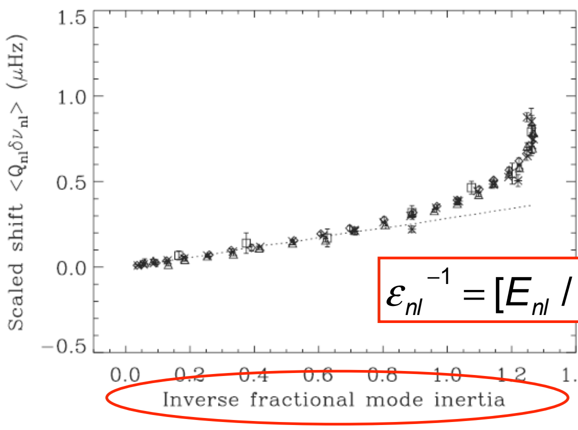
Frequency dependence of shifts

$$\delta\nu_{nl} \propto \frac{(\nu_{nl})^{\alpha}}{E_{nl}}$$

$$\propto \frac{(\nu_{nl})^{\alpha}}{\varepsilon_{nl}}$$

Frequency dependence of shifts



$$\varepsilon_{nl}^{-1} = [E_{nl} / \overline{E}(3000)]^{-1}$$

Chaplin et al. 2001, MNRAS, **324**, 910

Frequency dependence of shifts

- What do we expect for ?
  - Change confined close to surface (but in the interior): = 0
  - Change confined to photosphere (within one pressure scale height): = 3

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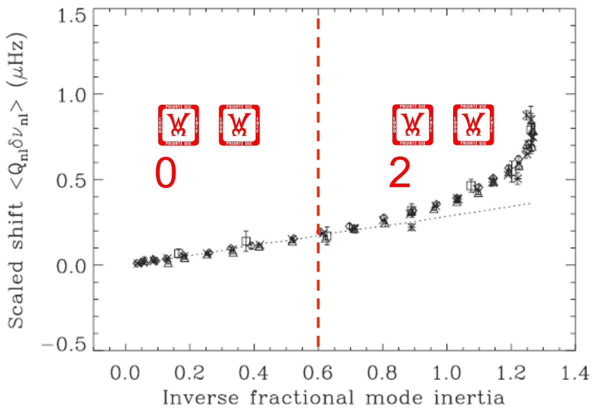
Frequency dependence of shifts



Chaplin et al. 2001, MNRAS, **324**, 910

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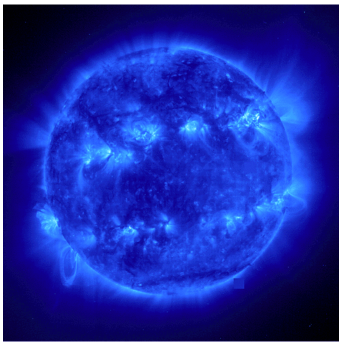
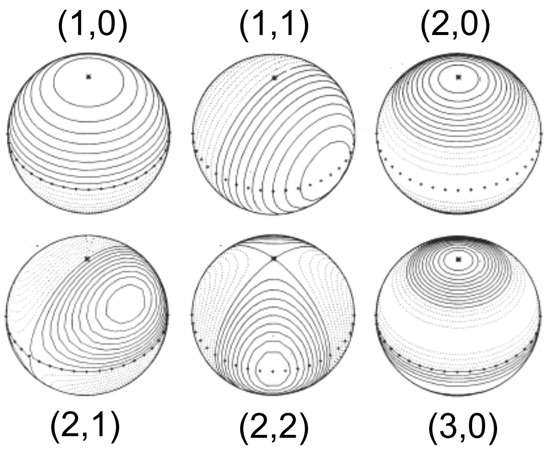
Effects of near-surface activity on modes

Depends on spherical harmonic of mode (l, m)





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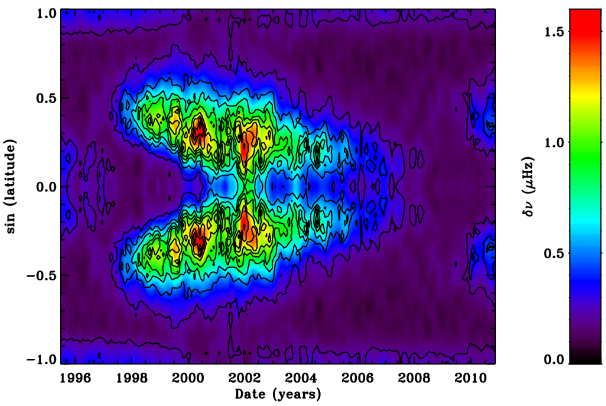
Global Frequency Shifts in GONG data: as Function of Solar Latitude



Spatial dependence correlates strongly with active regions

Dependence of shifts on mode degree, l, and mode frequency, suggests near-surface effect

Courtesy R. Howe

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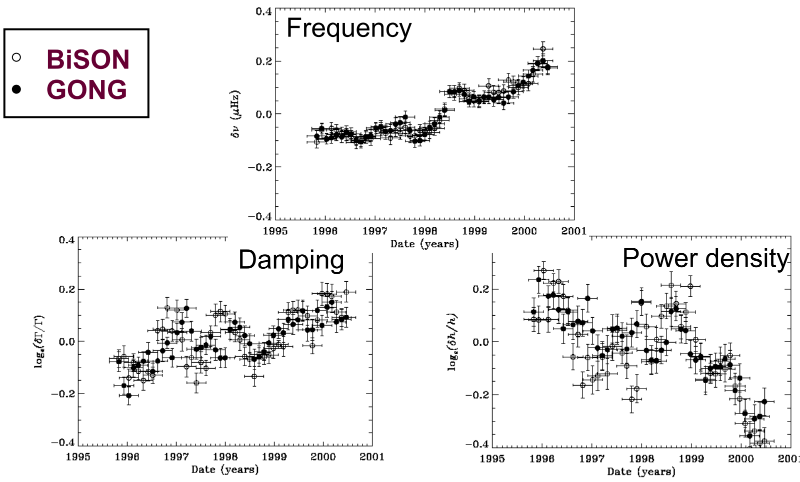
Solar Cycle Variations

Howe et al., 2003, ApJ, **588**, 1204

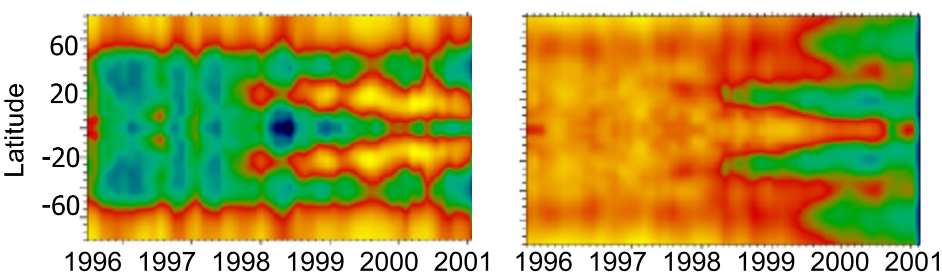


Variations in Global Mode Damping and Energy

Inference on changes to convection, which excites and damps modes

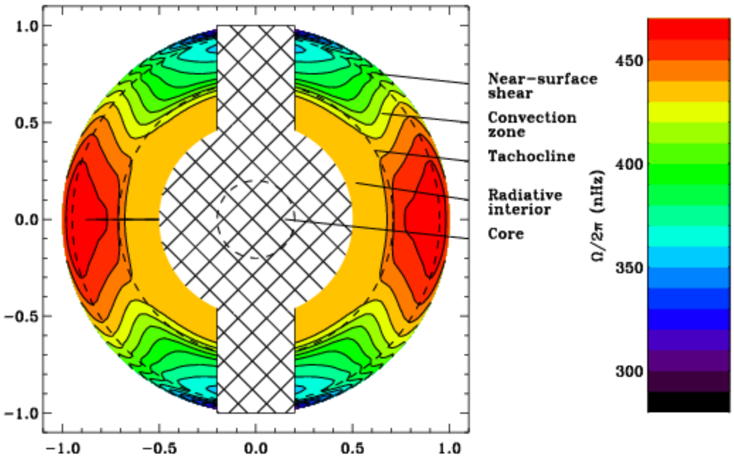
Mode Damping

Energy (forcing/damping)



Komm, Howe & Hill, 2002

Internal Solar Rotation



GONG data

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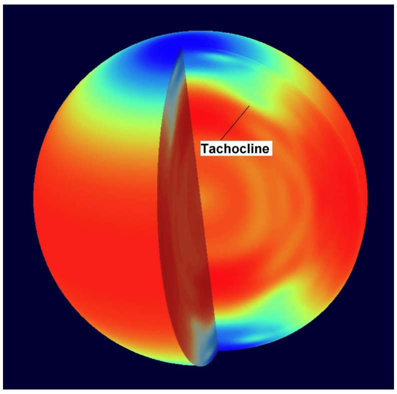
The Tachocline ('speed slope')



Located just beneath base of convection zone

Key for dynamo action!

Courtesy P. H. Scherrer, SOI Stanford

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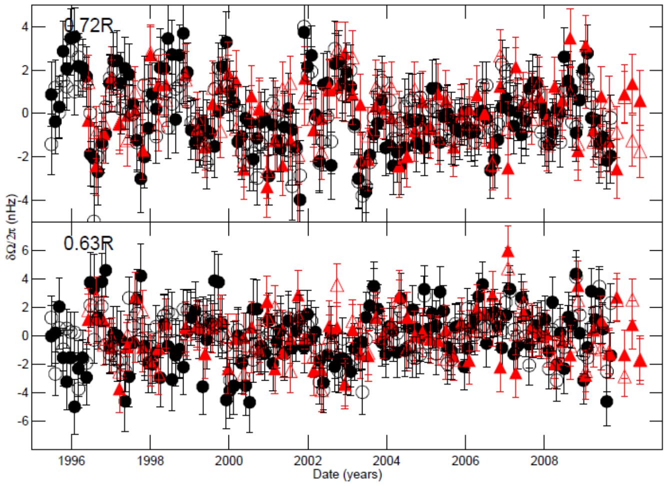
Tachocline oscillations

GONG and MDI data



Above tachocline

Beneath tachocline

Howe et al. 2011, JPCS

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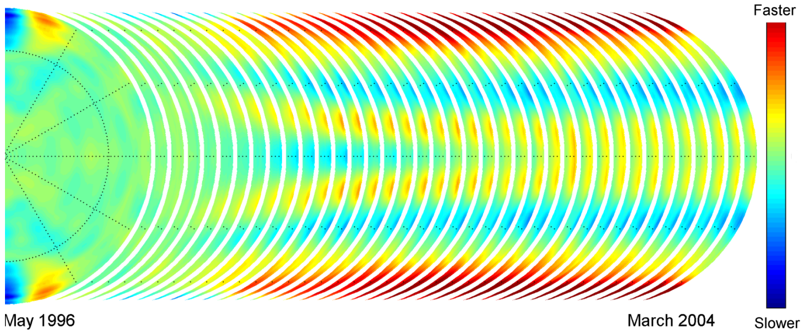
Torsional oscillations of the whole convection zone

Difference in successive 72-d rotation inversions of MDI data

Migrating bands of flow penetrate interior!



Courtesy S. Vorontsov and collaborators

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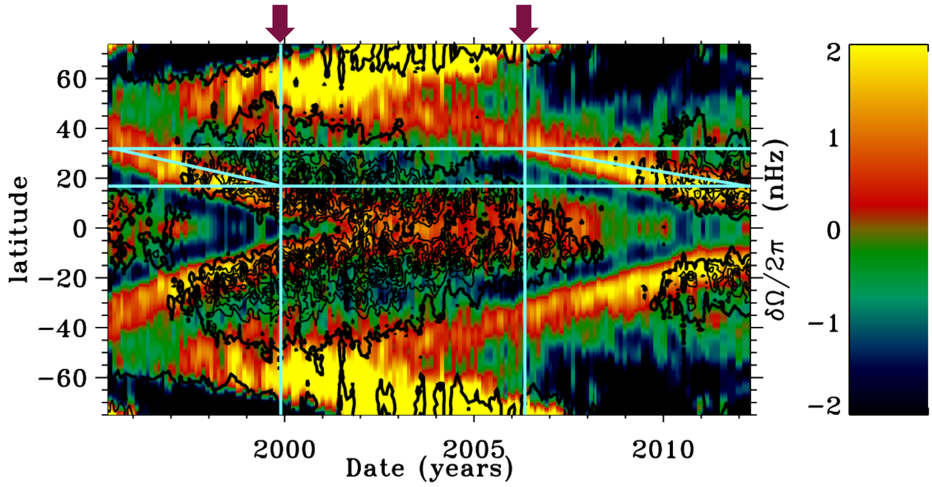
Slow start to cycle 24

Near-surface flows: GONG, MDI, HMI



Howe et al. (2009), updated to 2012

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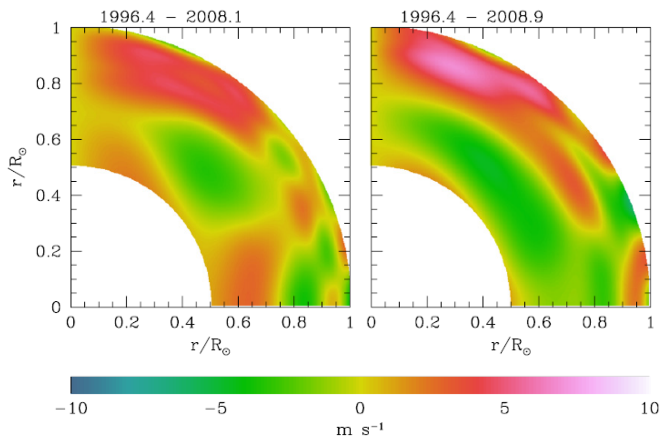
Dynamics: comparing solar minima

MDI & GONG data: cycle 24 – cycle 23



Antia & Basu (2010)

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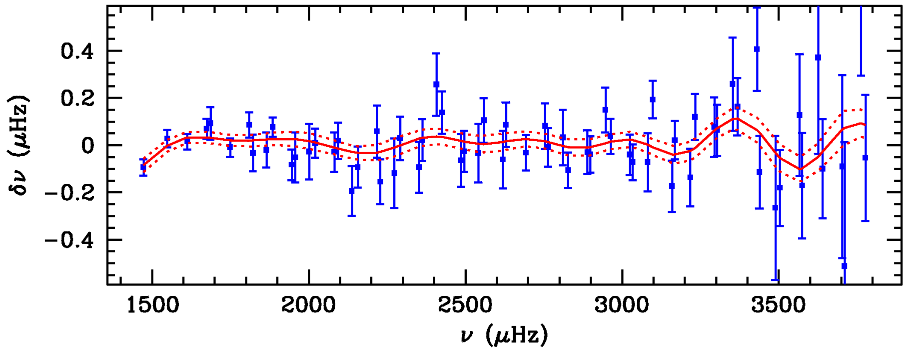
Structure: comparing solar minima

BiSON frequencies: cycle 24 – cycle 23



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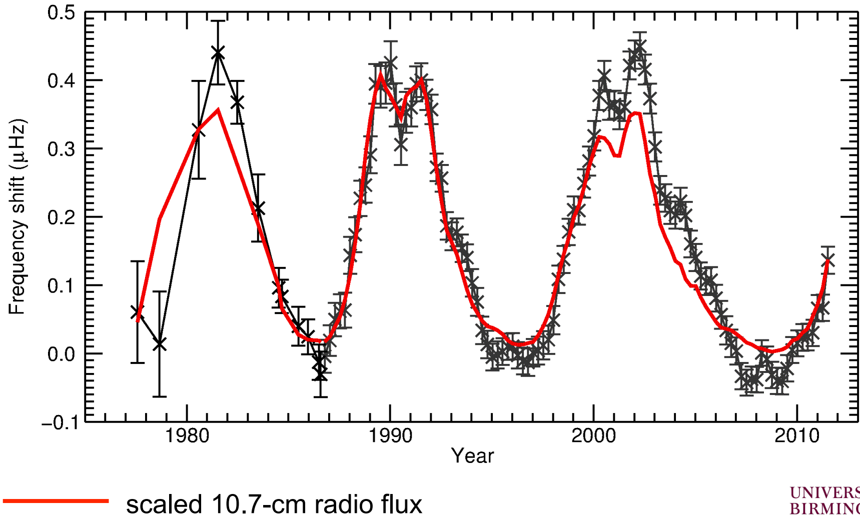
"Sounding" stellar activity cycles: Sun

Three solar cycles with BiSON Sun-as-a-star data



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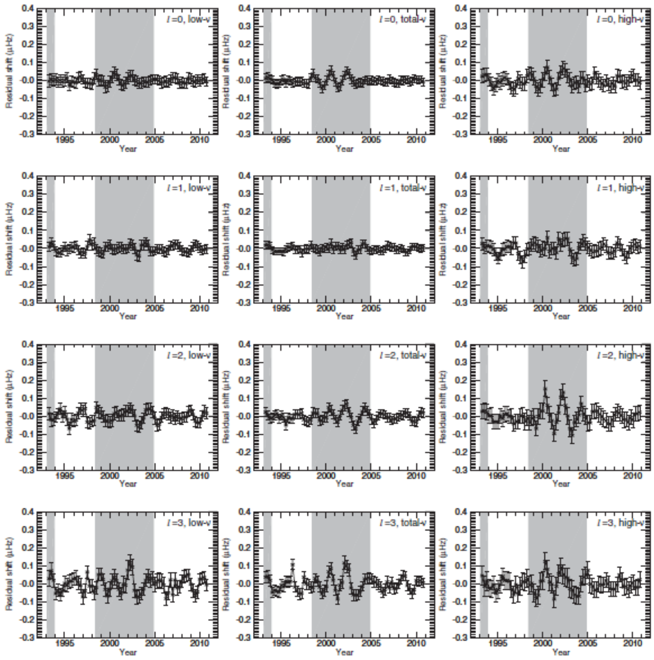
Quasi-biennial variation

After removal of 11-yr cycle signature



Broomhall et al., 2012, ApJ, 420, 1405

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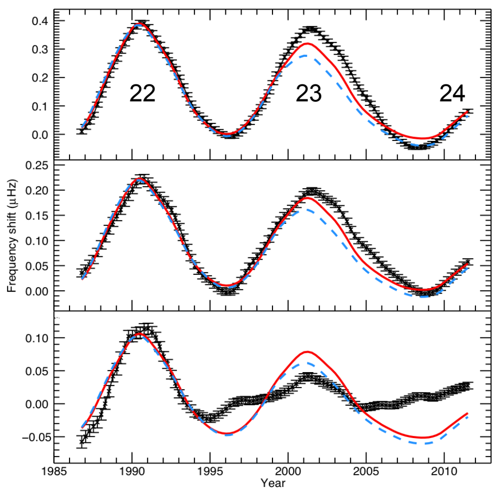
Cycles 22, 23… and rise of 24

BiSON Sun-as-a-star data



High-frequency modes

Intermediate-frequency modes

Low-frequency modes

scaled 10.7-cm radio flux — scaled ISN

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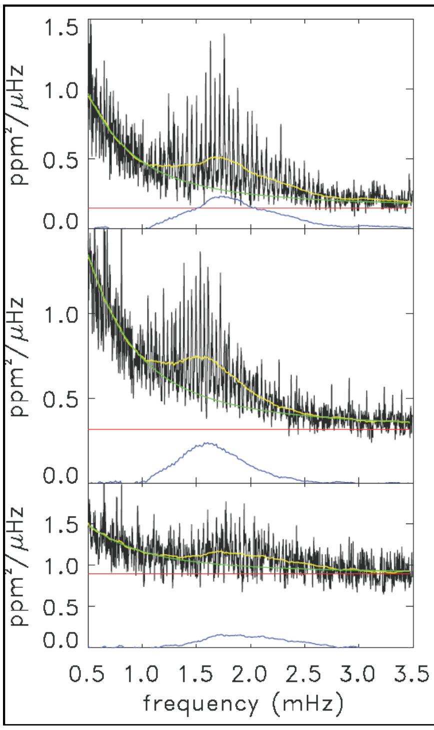
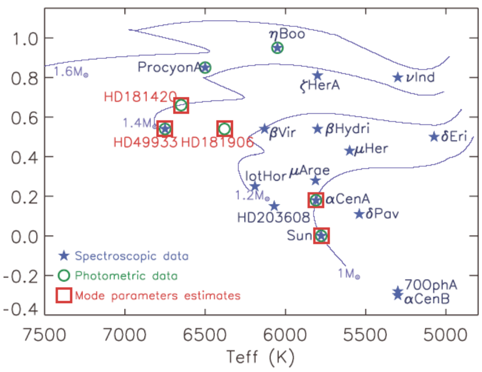


CoRoT sounds F type stars

Michel et al. 2008



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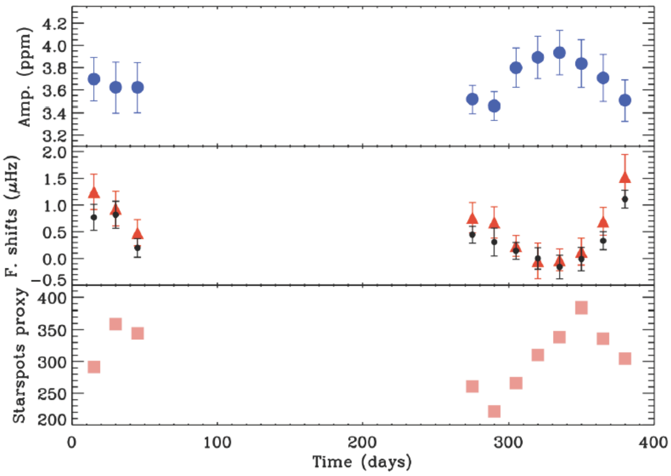
CoRoT reveals a short activity cycle in HD49933



García et al., 2010, Science

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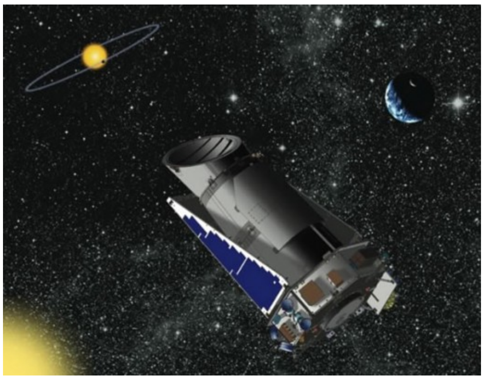
Kepler Asteroseismic Science Consortium (KASC)



NASA *Kepler* Mission

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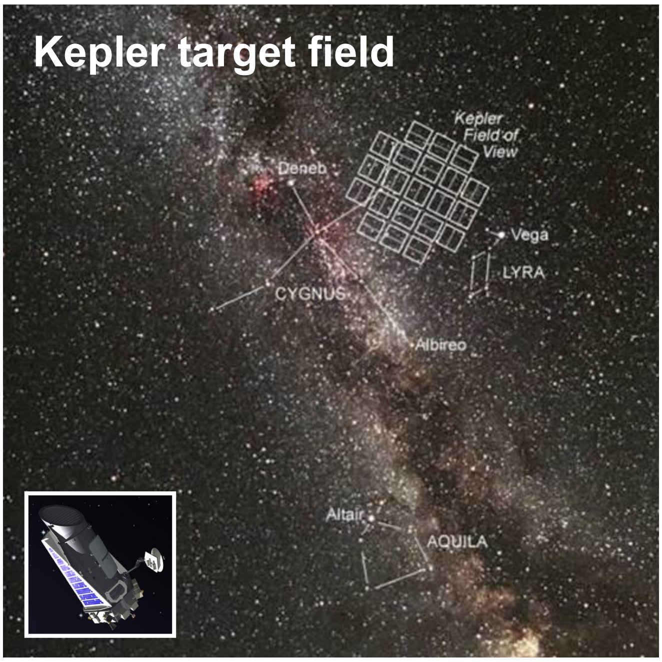

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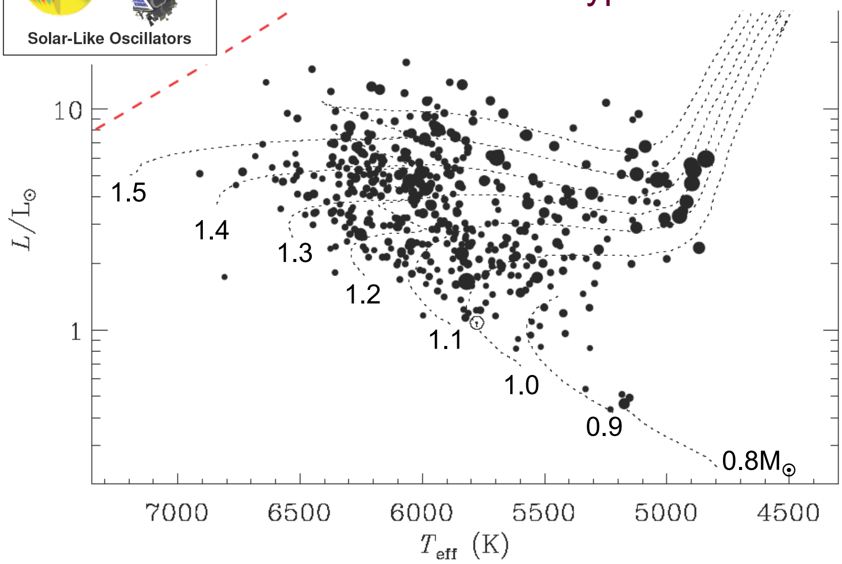
KASC asteroseismic survey

More than 600 solar-type stars



Chaplin et al., 2011, Science, 332, 213

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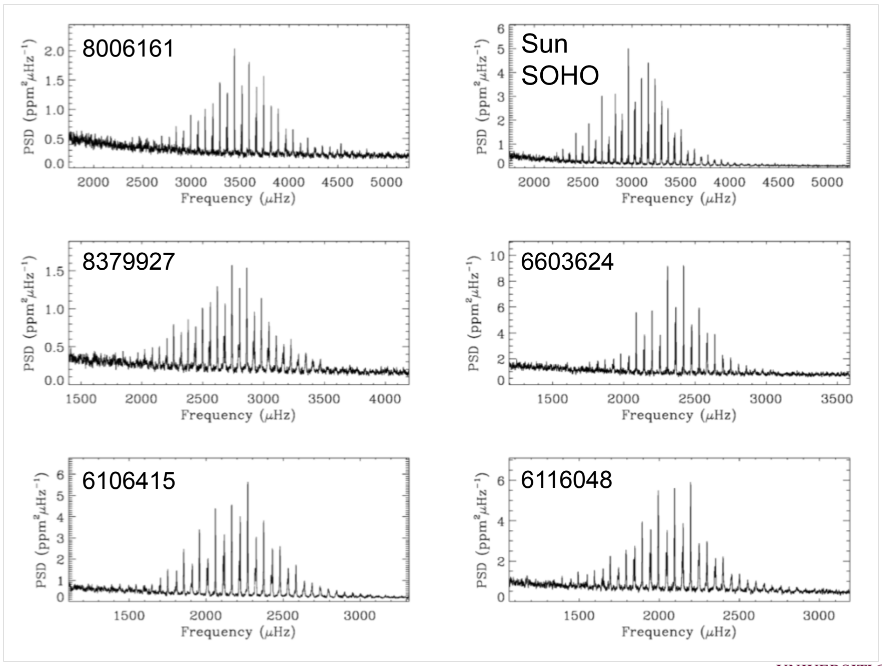
GHAM



The asteroseismic ensemble

Inferences on stellar activity, dynamo theories

- "Sound" stellar cycles
- Accurate inference on depths of convective envelopes
- Internal rotation

Seismic evidence for a rapidly rotating core in a lower-giant-branch star observed with *Kepler*

S. Deheuvels[1,2,3], R. A. García[3,4], W. J. Chaplin[3,5], S. Basu[1], H. M. Antia[6], T. Appourchaux[7], O. Benomar[8], G. R. Davies[4], Y. Elsworth[5], L. Gizon[9,10], M. J. Goupil[2], D. R. Reese[11], C. Regulo[12,13], J. Schou[14], T. Stahn[9], L. Casagrande[15], J. Christensen-Dalsgaard[16], D. Fischer[1], S. Hekker[17], H. Kjeldsen[16], S. Mathur[18], B. Mosser[2], M. Pinsonneault[3,19], J. Valenti[20], J. L. Christiansen[21], K. Kinemuchi[22], F. Mullally[21]

Deheuvels et al. 2012, ApJ, in the press

The asteroseismic ensemble

Inferences on stellar activity, dynamo theories

- “Sound” stellar cycles
- Accurate inference on depths of convective envelopes
- Internal rotation
- Constrain surface distribution of active regions

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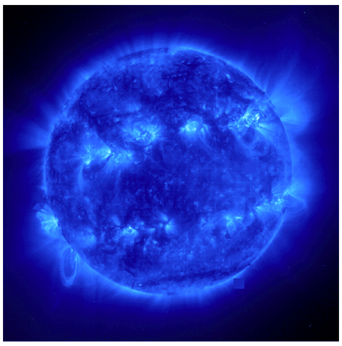
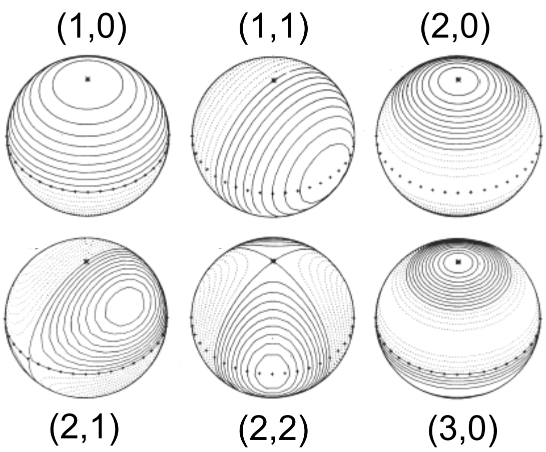
Effects of near-surface activity on modes

Depends on spherical harmonic of mode (*l*, *m*)





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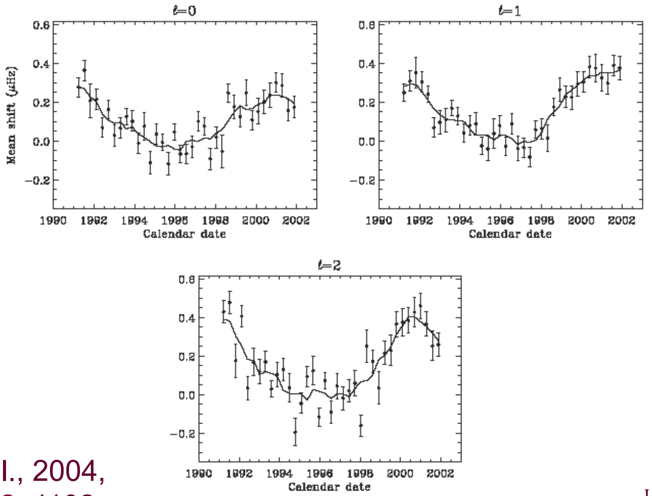
Spatial dependence of the frequency shifts

Sun-as-a-star
BiSON data



Chaplin et al., 2004, MNRAS, **352**, 1102

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