Future Prospects for Helioseismology

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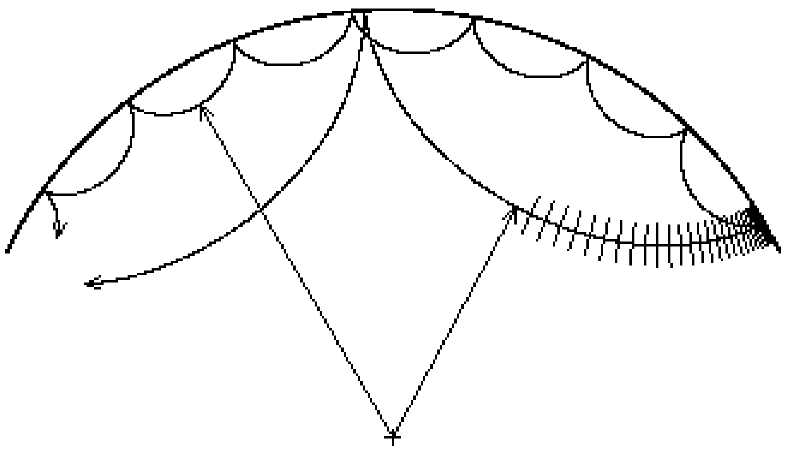
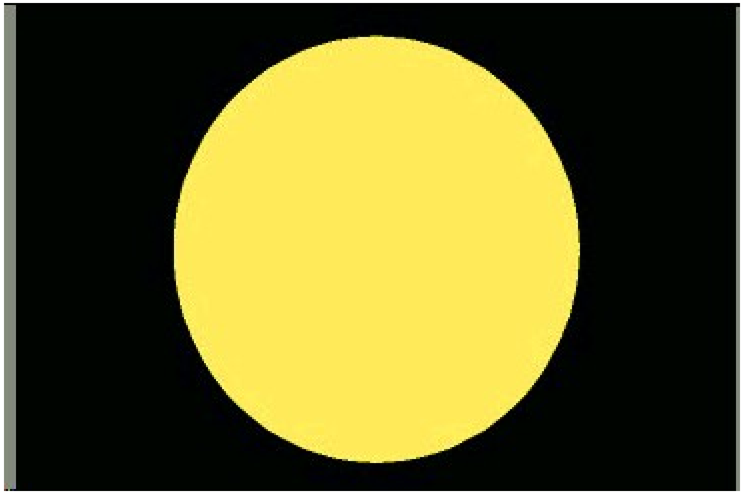
Abstract

Helioseismology has been spectacularly successful at revealing many aspects of the Sun's internal structure and dynamics. What then are the new challenges and opportunities for the field? In this talk I will briefly review the current state of helioseismology, and will then discuss science opportunities and future directions for observations from the ground and space.

Solar oscillations: sound waves in the Sun

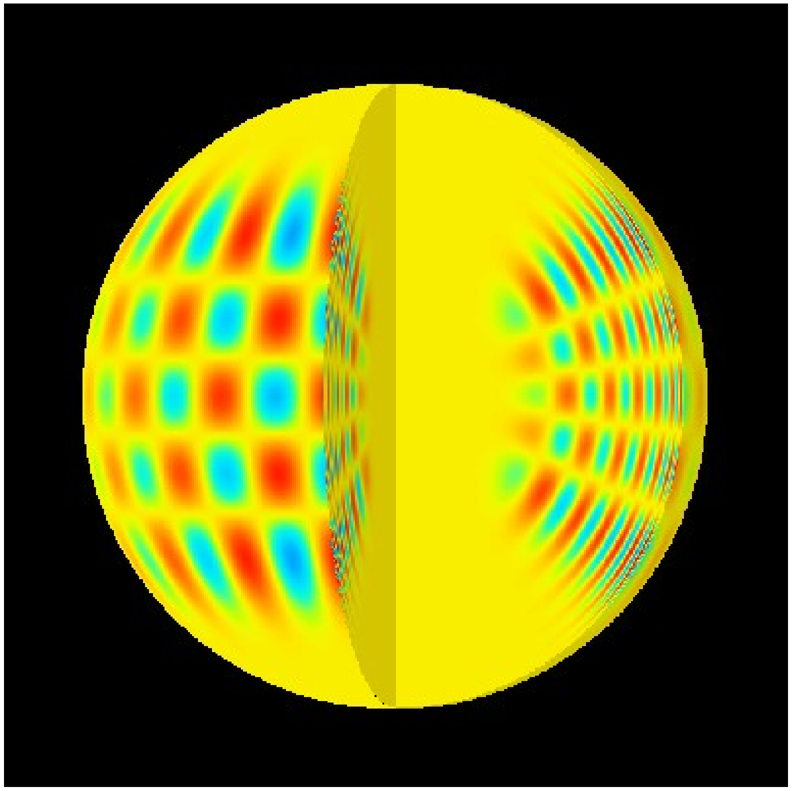


Refraction of waves provides lower boundary of resonant cavity

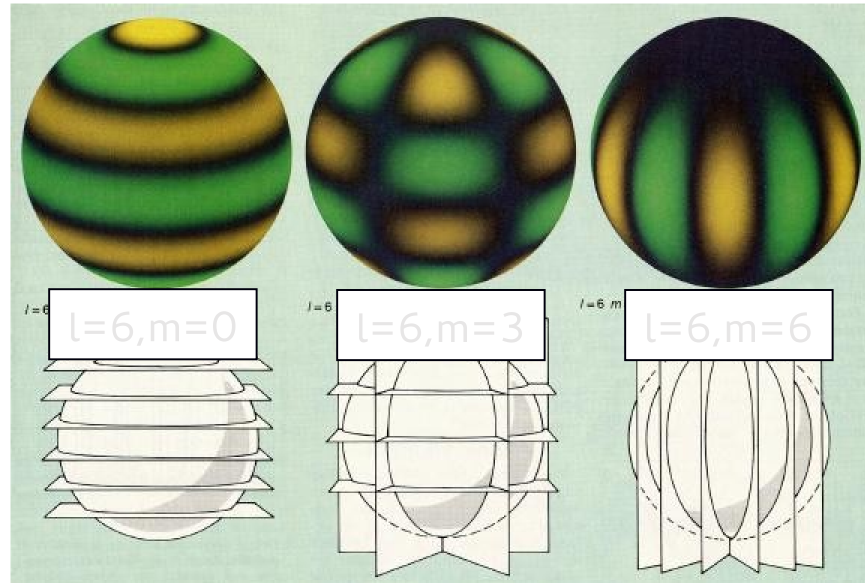


Resonant cavities are of differing extent

Resonant modes the sun

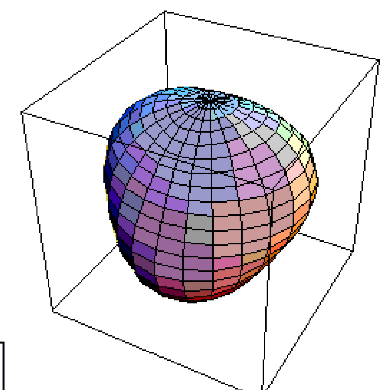


Schematic of a resonant mode of the sun



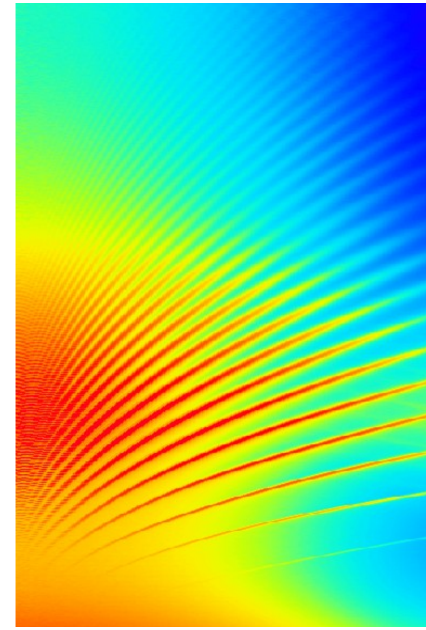
Examples of spherical harmonics

Spherical harmonic
degree l, order m



l=3,m=2

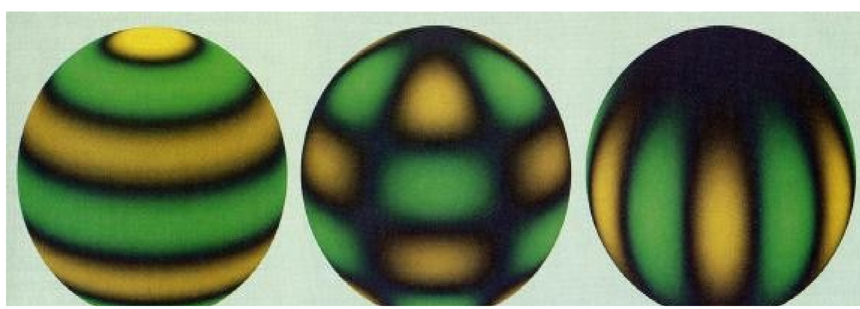
Helioseismology



Measure mode frequencies and other properties
Eigenfunctions / spherical harmonics

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

Inversion provides maps such as of sound speed, density and rotation

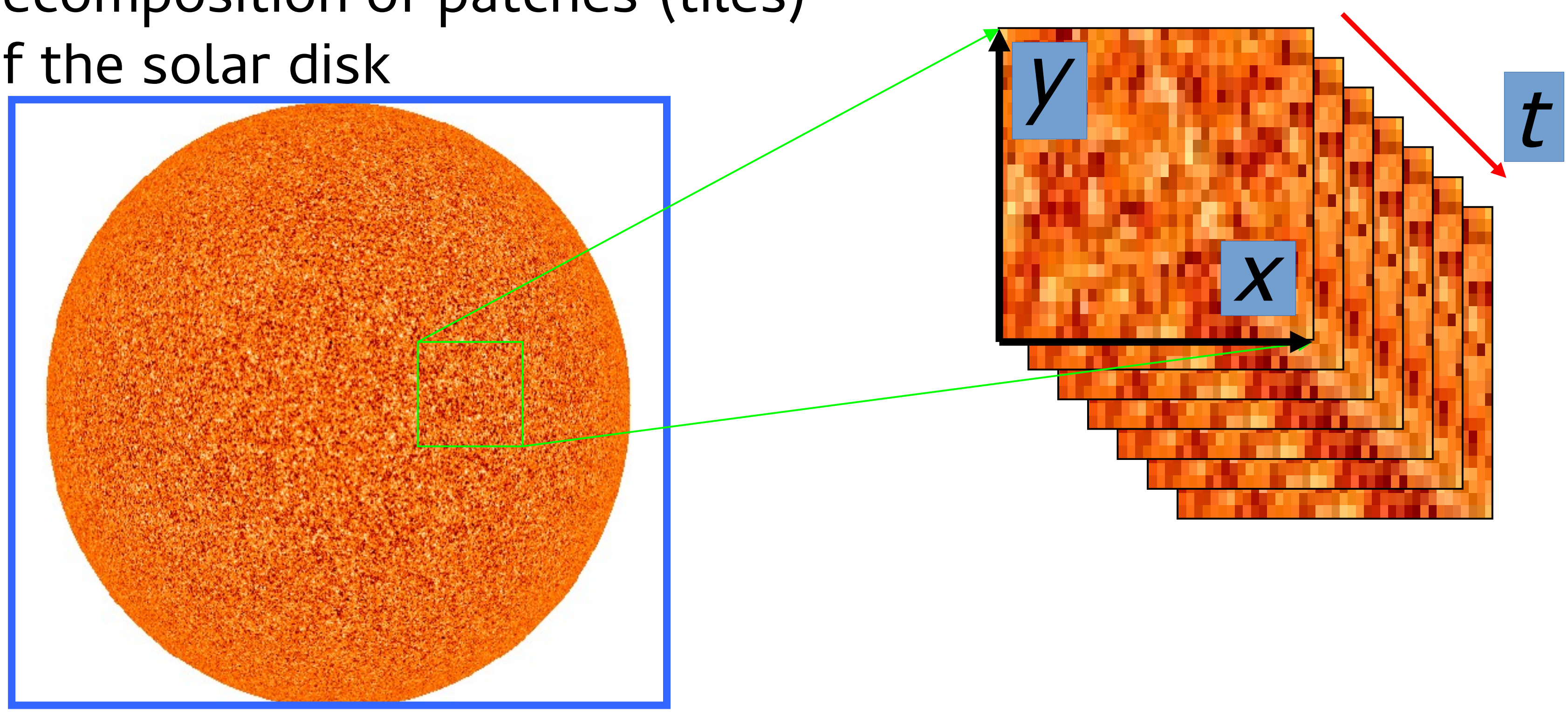


Spherical harmonics

Ring-Analysis Helioseismology

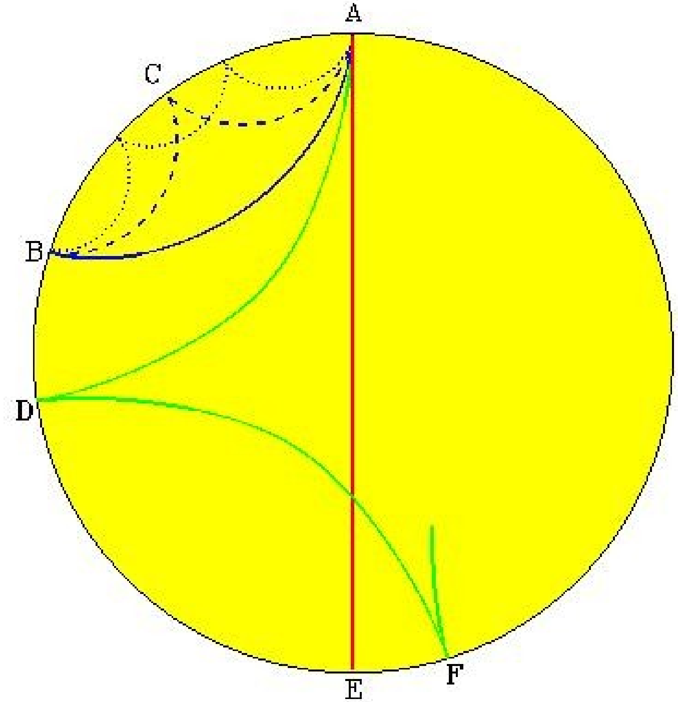
- Observe line-of-sight velocity (Dopplergrams).
- Make plane-wave decomposition of patches (tiles) of the solar disk

- Data used in this talk are from SOHO/MDI

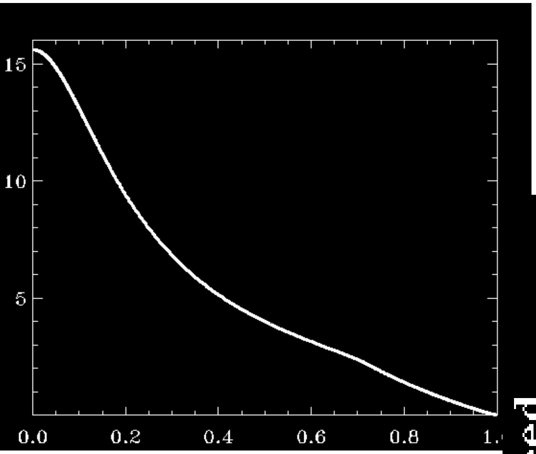


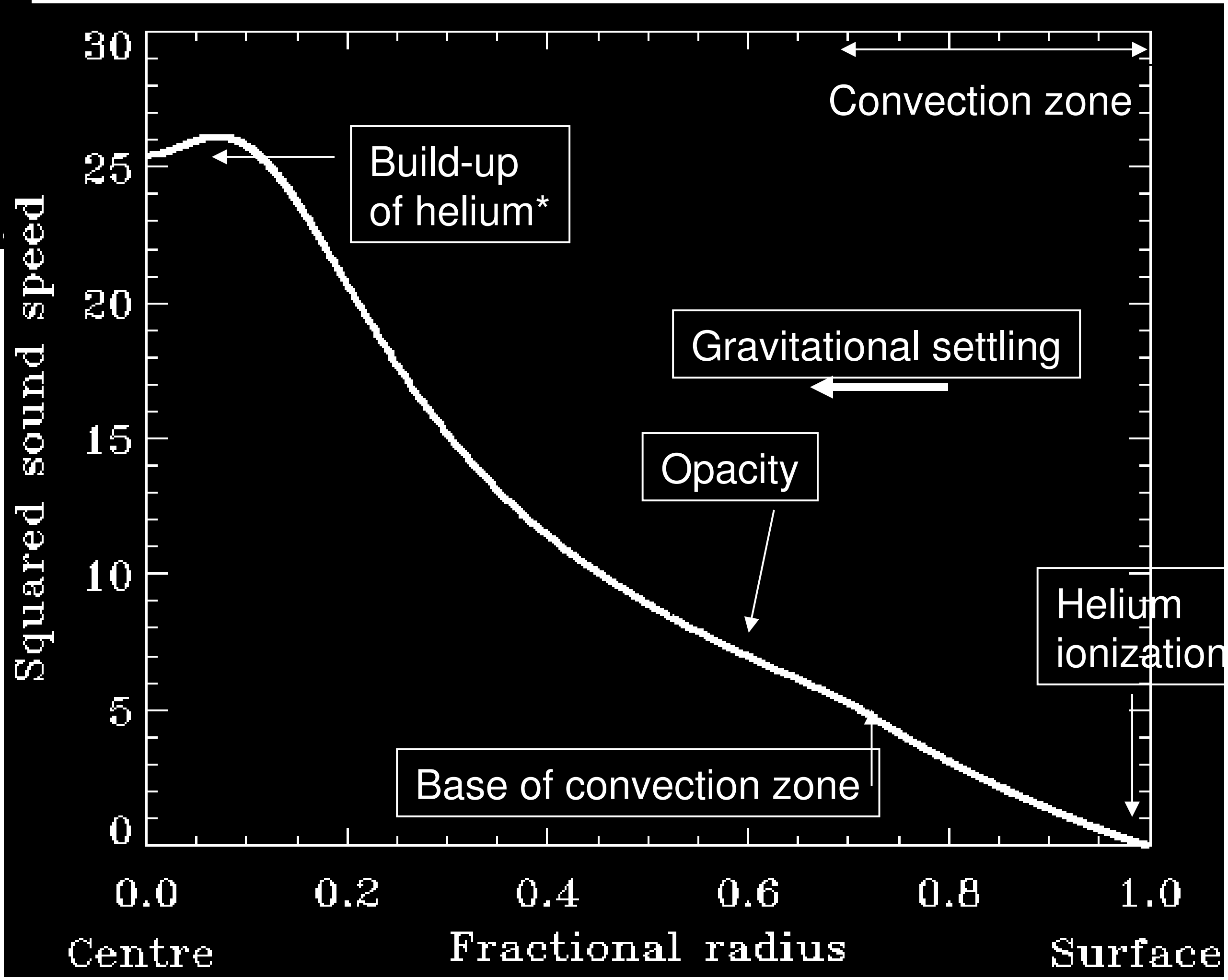
Tomography

- Make surface observations at end-points of ray paths of waves propagating through the solar interior
- Cross-correlating the observational signal at the two end-points reveals the wave travel time between the two points
- Inversions of those travel times then reveal the subsurface structure and dynamics (and magnetic field)



Sound-speed inferences





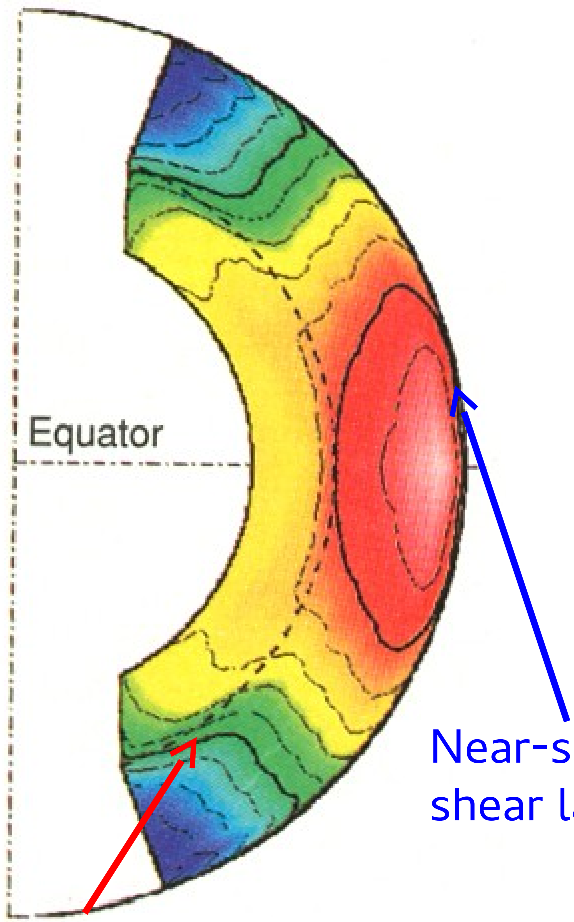
$$c^2 \propto \Gamma_1 T / \mu$$

(Sound speed is in units of hundreds of km/s)

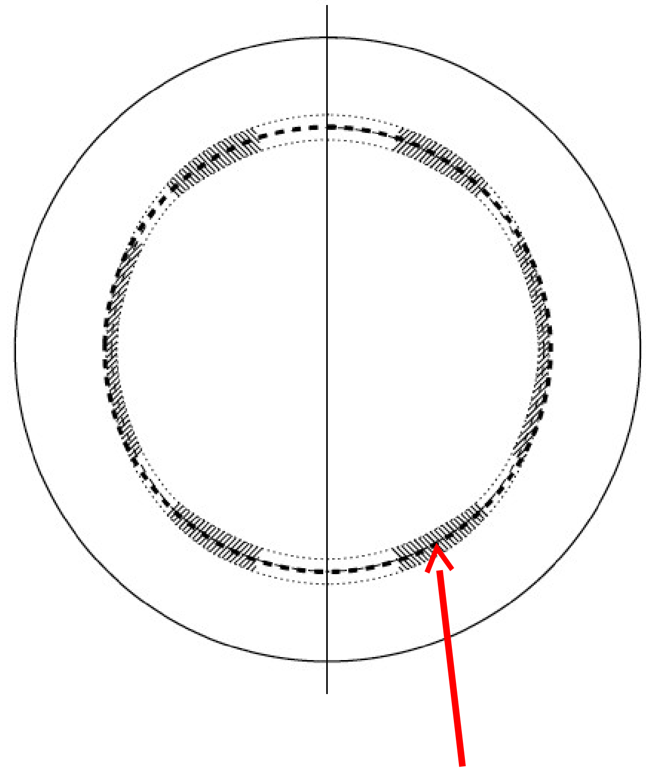
*Indirect inference from small frequency separations

Solar Rotation and the Tachocline

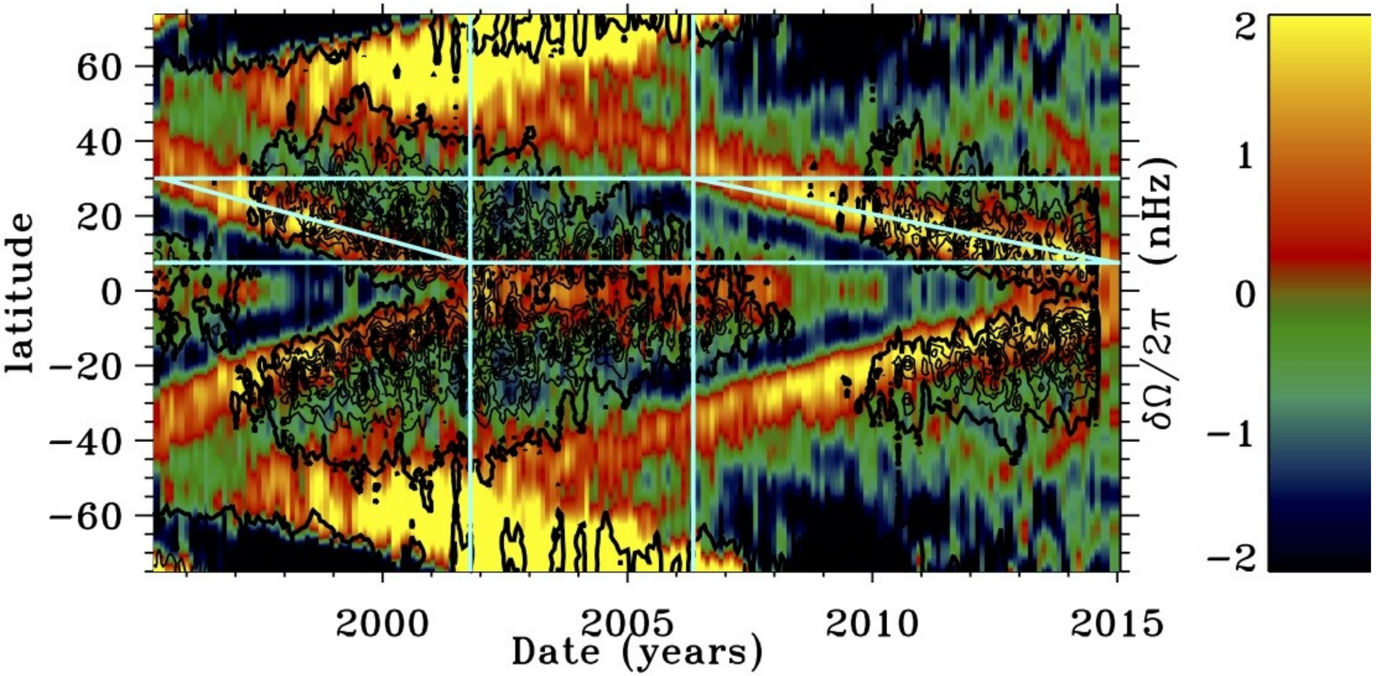
Solar rotation



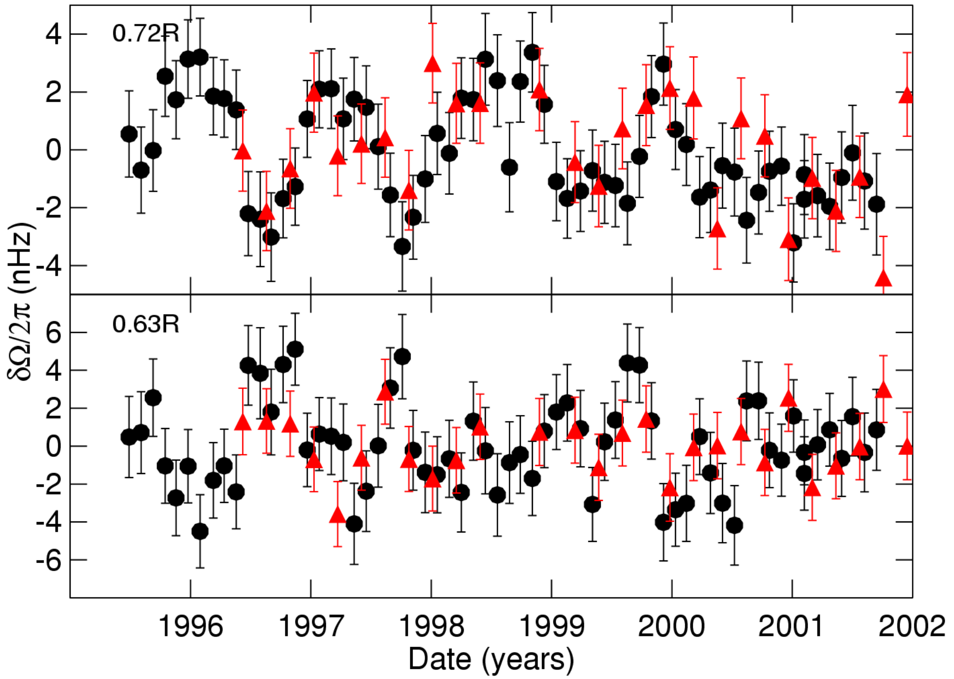
Solar tachocline



Tachocline lies substantially beneath
the base of the CZ at low latitudes:
covers stable convective overshoot layer

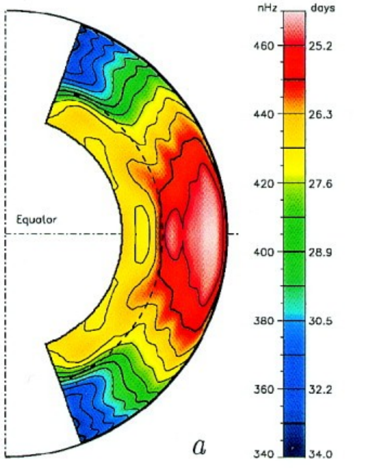


Temporal variations in the rotation rate

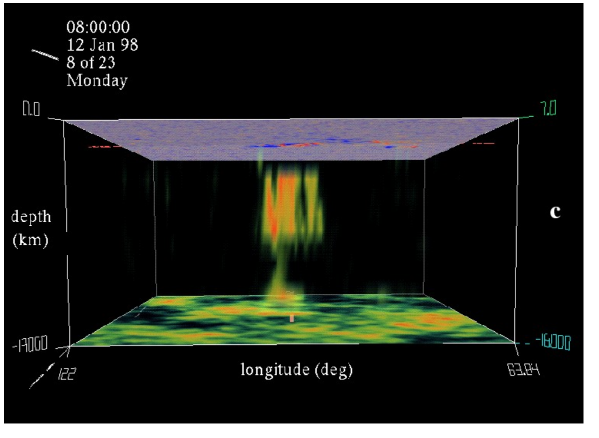


Limitations of helioseismology from a single vantage point

- Global helioseismology has been remarkably successful at revealing the Sun’s internal radial structure and its internal rotation as a function of radius and latitude; but global helioseismology can give no information about longitudinal variation of the solar interior.



- Local helioseismic techniques such as time-distance helioseismology give longitudinal information, but are restricted to probing the upper third of the convection zone when the Sun is viewed from a single vantage point.



Challenges & Opportunities

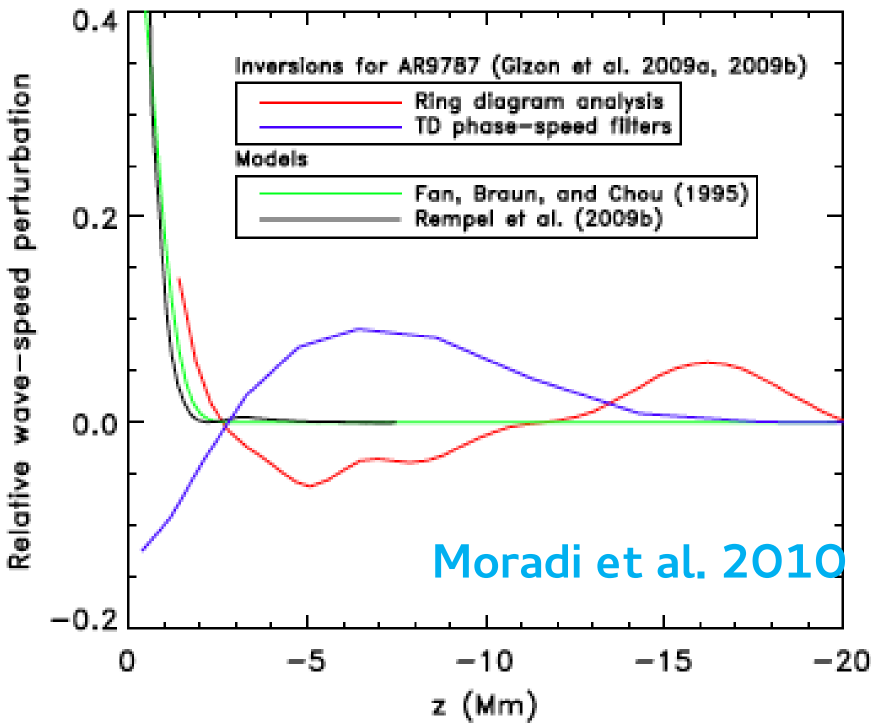
- Improving on resolution / noise of inversions (in particular global-mode inversions)

- We are dominated by systematic errors, not random errors – inadequate modeling of mode physics, mode leakage, etc.

- S. Jefferies and S. Vorontsov proposed in the early 2000s an approach to simultaneously fit the modes and the internal structure dynamics all at once – but this has not been pursued to completion

Challenges & Opportunities

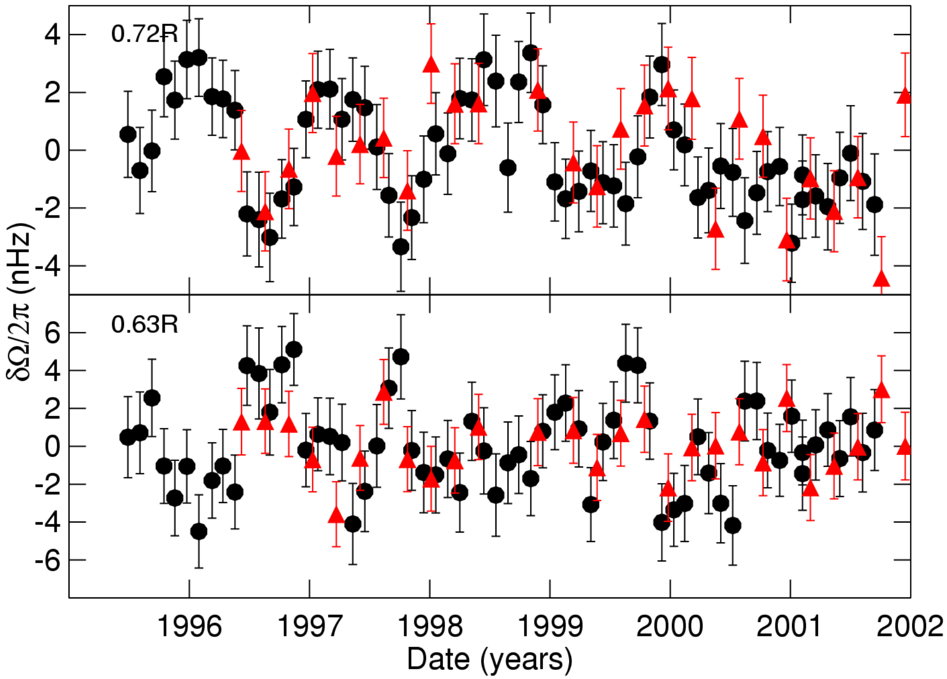
- Determine flow/structure under active regions
- Different local helioseismic techniques give contradictory results!



- One problem is that we are not modeling mode conversion caused by presence of magnetic field

Challenges & Opportunities

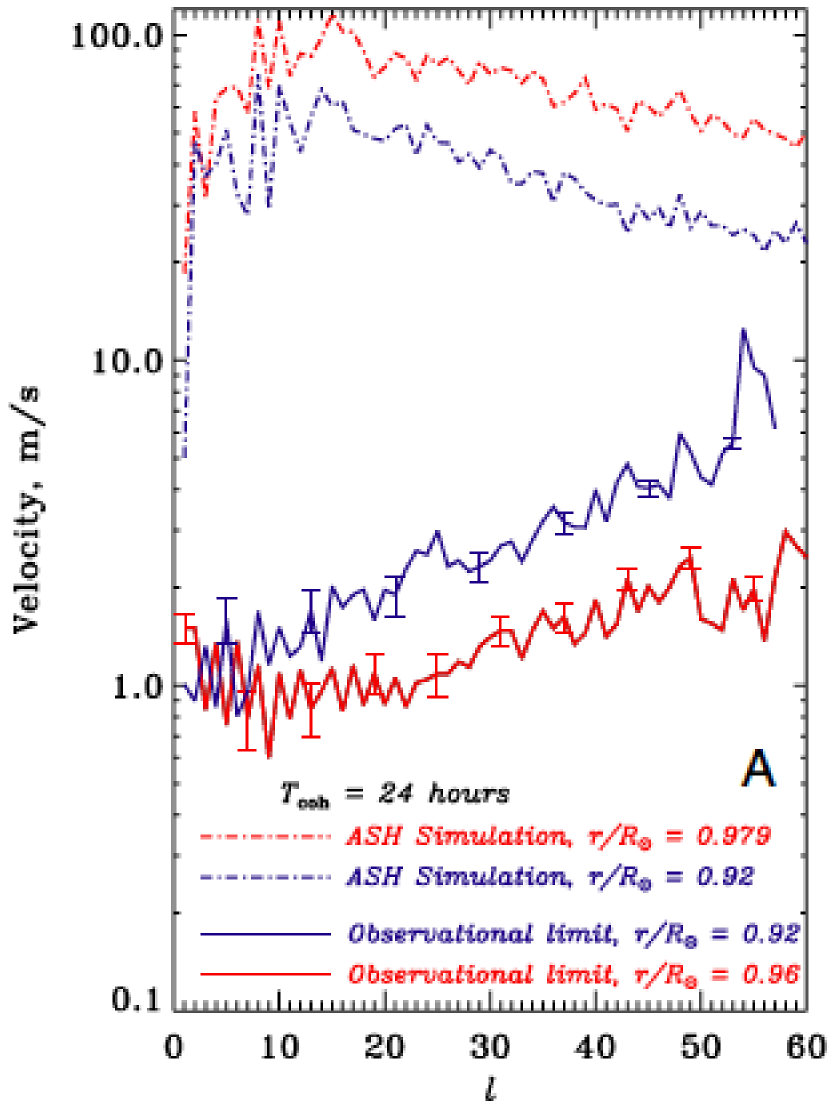
- Things that are “just” out of reach
  - Characterization of structure/flow at base of convection zone



  - Limits of p-modes in the core

Challenges & Opportunities

- Convective velocities in convection zone – disagreement between models and seismic inferences



  - Maybe our models have the background structure of the convection zone wrong? Can we determine that better?

Hanasoge et al. 2012

Challenges & Opportunities

- Latitudinal/longitudinal structures in or near the tachocline
- Such structures are predicted / invoked by some models of the solar dynamo
- May also be seat of active longitudes ("hotspots")

Importance of imaging the tachocline and its longitudinal variations

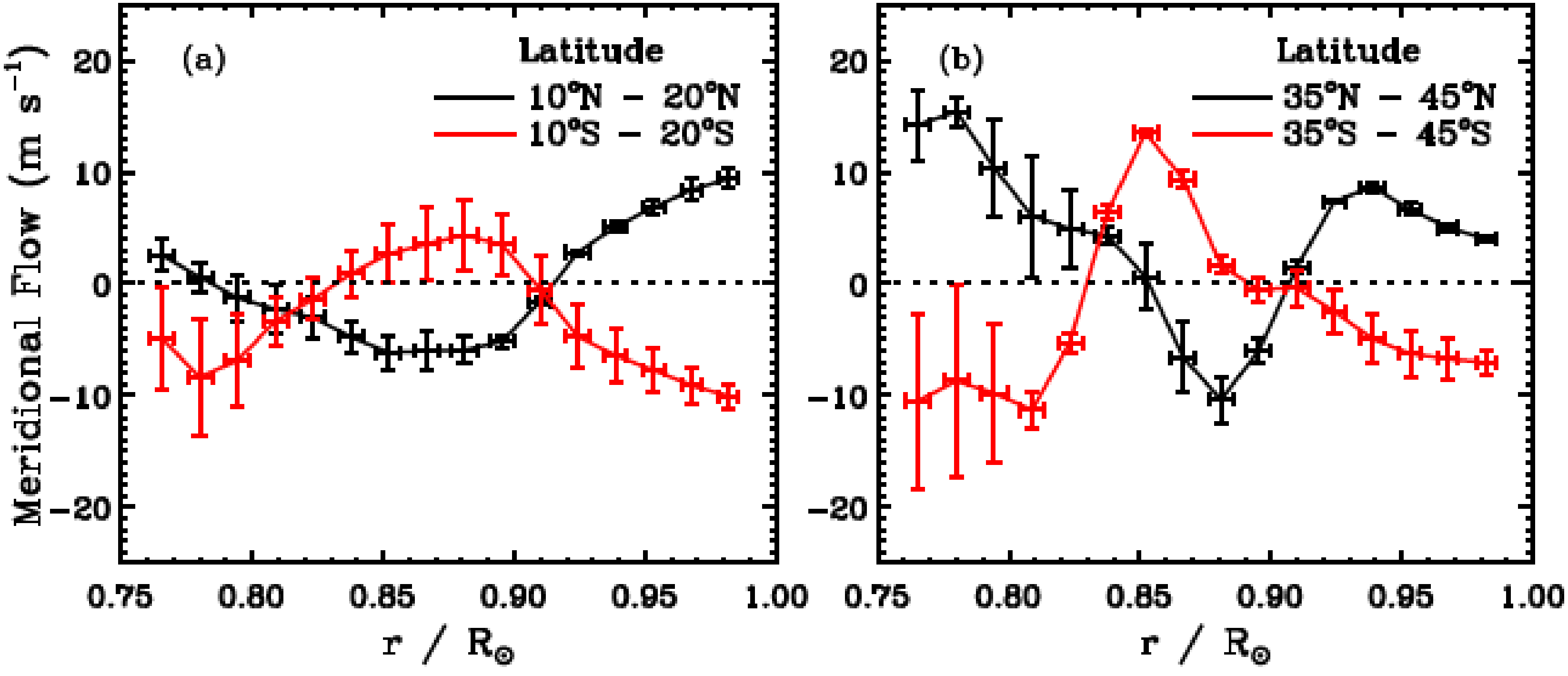
- Understanding the solar dynamo is one of the outstanding challenges of solar physics. The tachocline shear layer at the bottom of the Sun convective envelope is believed to be the seat of the solar dynamo. Direct detection of the magnetic field in tachocline is extremely challenging; but associated thermal anomalies and bulk flows are accessible to helioseismology, with the right observational datasets.

- Calculations of magnetoshear instabilities of the tachocline region, by Gilman, Cally, Dikpati and collaborators, predict longitudinal variations as signatures of the magnetic field present there.

- Active longitudes and hotspots of persistent surface magnetic activity of many rotations or even over more than one solar cycle are also likely associated with hotspots in the tachocline region which will only be revealed once with longitudinal resolution of this region.

Challenges & Opportunities

- Meridional circulation
- Key ingredient of flux-transport dynamo models, but challenging to determine beneath the outer ~0.05 – 0.1 R_{sun}



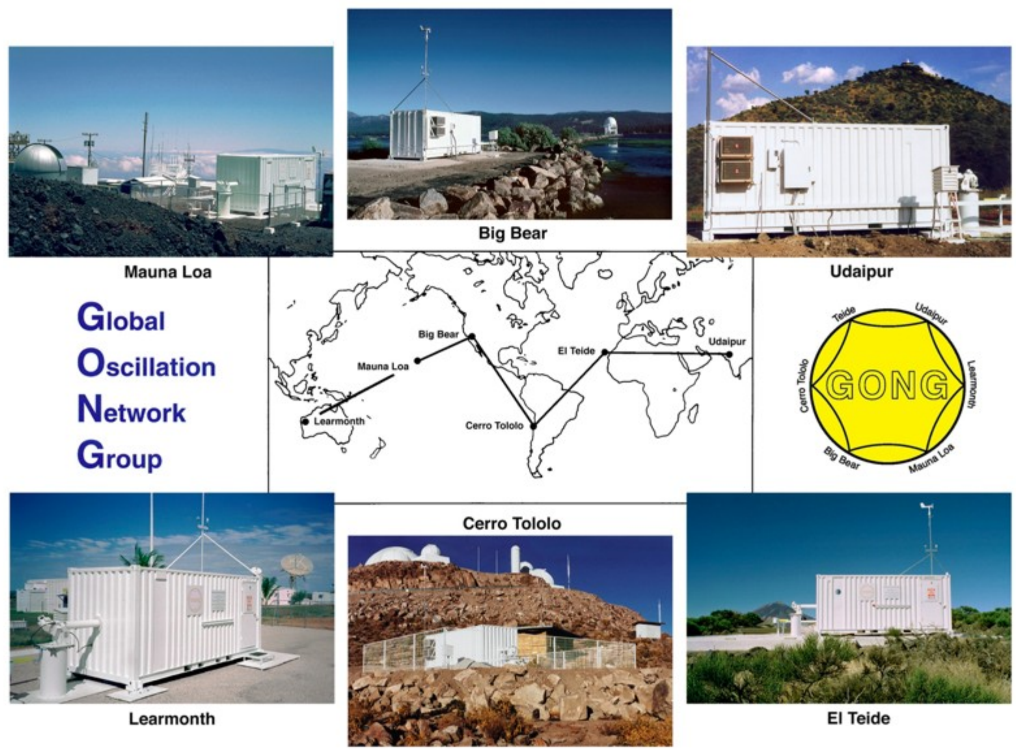
Zhao et al. 2013

Future Observational Platforms

- Next-generation ground-based network(s)
    - Multi-height measurements in the solar atmosphere

Solar Physics Research Integrated Network Group (SPRING)

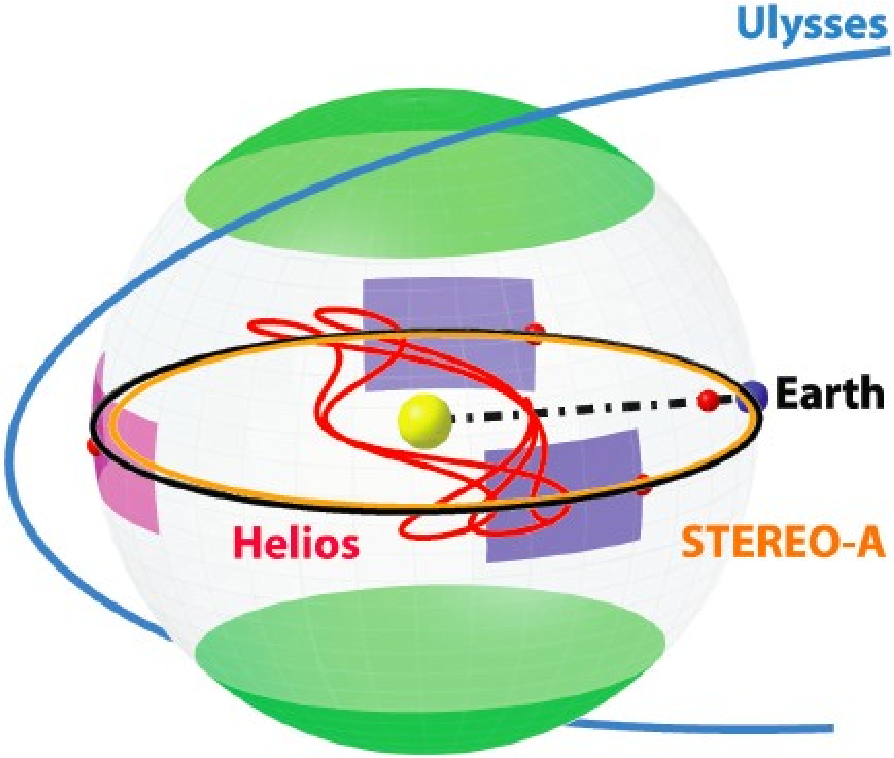
Successor to GONG



Future Observational Platforms

- Space mission(s) to make helioseismic observations away from the Sun-Earth line
- Farside, Polar, or L4/L5

Previous inner-heliosphere missions that have explored away from the Sun-Earth line



Science Path Forward

Beating down systematic errors in global-mode inversions for structure and evolution better spatial resolution, smaller error bars, larger domain of reliable inversions

- Improved analysis of global mode observations (Jefferies/Vorontsov)
- Simultaneous observations made at Earth and away from the Earth-Sun line (better coverage of whole Sun)

Determining structure/flows/magnetic field in Active Regions

- Multi-height observations (SPRING)
- Better modeling of oscillations and mode conversion in strongly magnetized regions (ARs)
- Iterative approaches to inversions in ARs

Science Path Forward

Detecting longitudinal structures in and near the tachocline

- Observations “in quadrature” (e.g. from L5 point) and from far-side

Improved determination of high latitudes and latitudinal structures in and below the convection zone

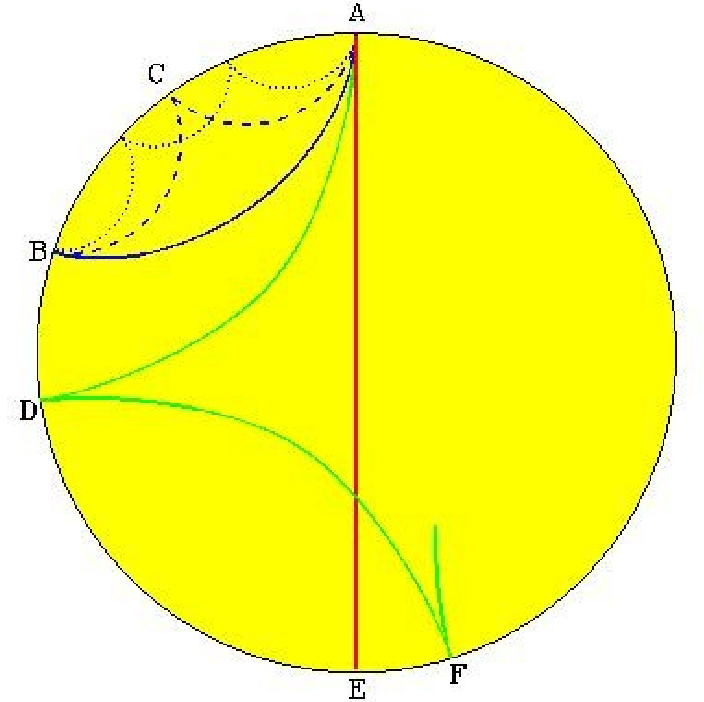
- Observations from over the poles

Better determination of structure and rotation of core

- g mode detection (maybe recent breakthrough)

Role of an L5 mission

- Simultaneous helioseismic observations from the Earth and from the L5 point enable both ends of long, deep wave raypaths to be seen. Such rays penetrate to the tachocline. By measuring wave travel times along such raypaths, the thermal anomalies and flows in the tachocline will be resolved in longitude for the first time. The resolution will be about 0.1 solar radii, resolving azimuthal variations up to about wavenumber m=30.



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Solar Physics from Unconventional Viewpoints

Sarah E. Gibson [1,*], Angelos Vourlidas [2], Donald M. Hassler [3], Laurel A. Rachmeler [4], Michael J. Thompson [1], Jeffrey Newmark [5], Marco Velli [6], Alan Title [7], and Scott W. McIntosh [1]

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