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FOR SOLAR SYSTEM RESEARCH

30 Years of SOHO - Internal Structure and Dynamics

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***Work mostly done by others.**

Introduction

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- **I will only show results**
  - Mostly pretty pictures
  - No technical details
  - Not in depth
  - Sometimes I will include data from other sources
  - Sometimes original results, sometimes later, sometimes both
- **I will only show a few results**
  - With apologies to others

- **I was a postdoc (actually RA) when SOHO was launched**
  - With SOI/MDI at Stanford
  - Then instrument scientist for HMI
  - Now at MPS
  - I did see the SOHO launch!

Solar Structure – Overview

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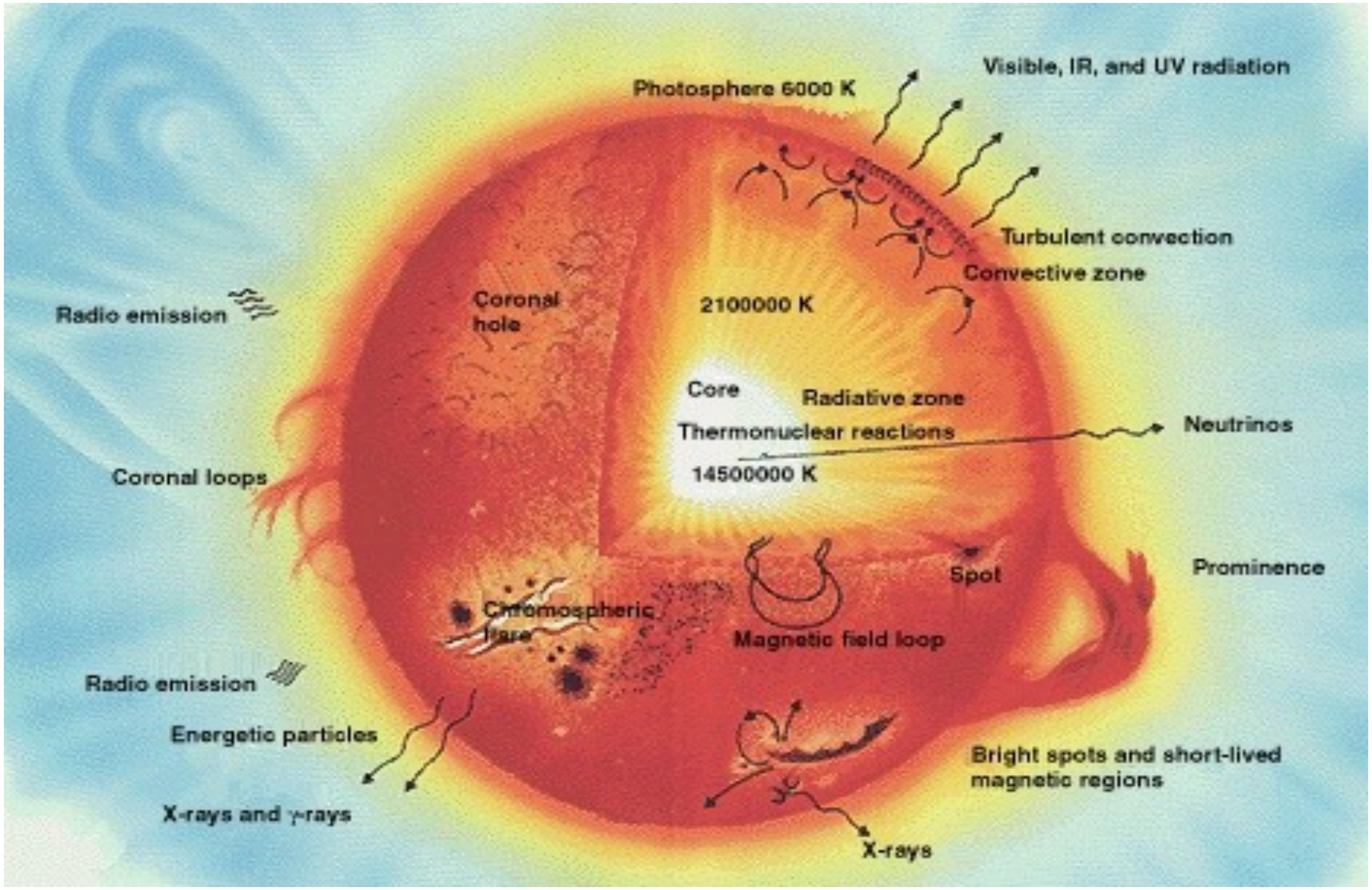
- **The Sun is a ball of hot gas!**



NASA/Wikipedia

Helioseismology - Global Mode Eigenfunction

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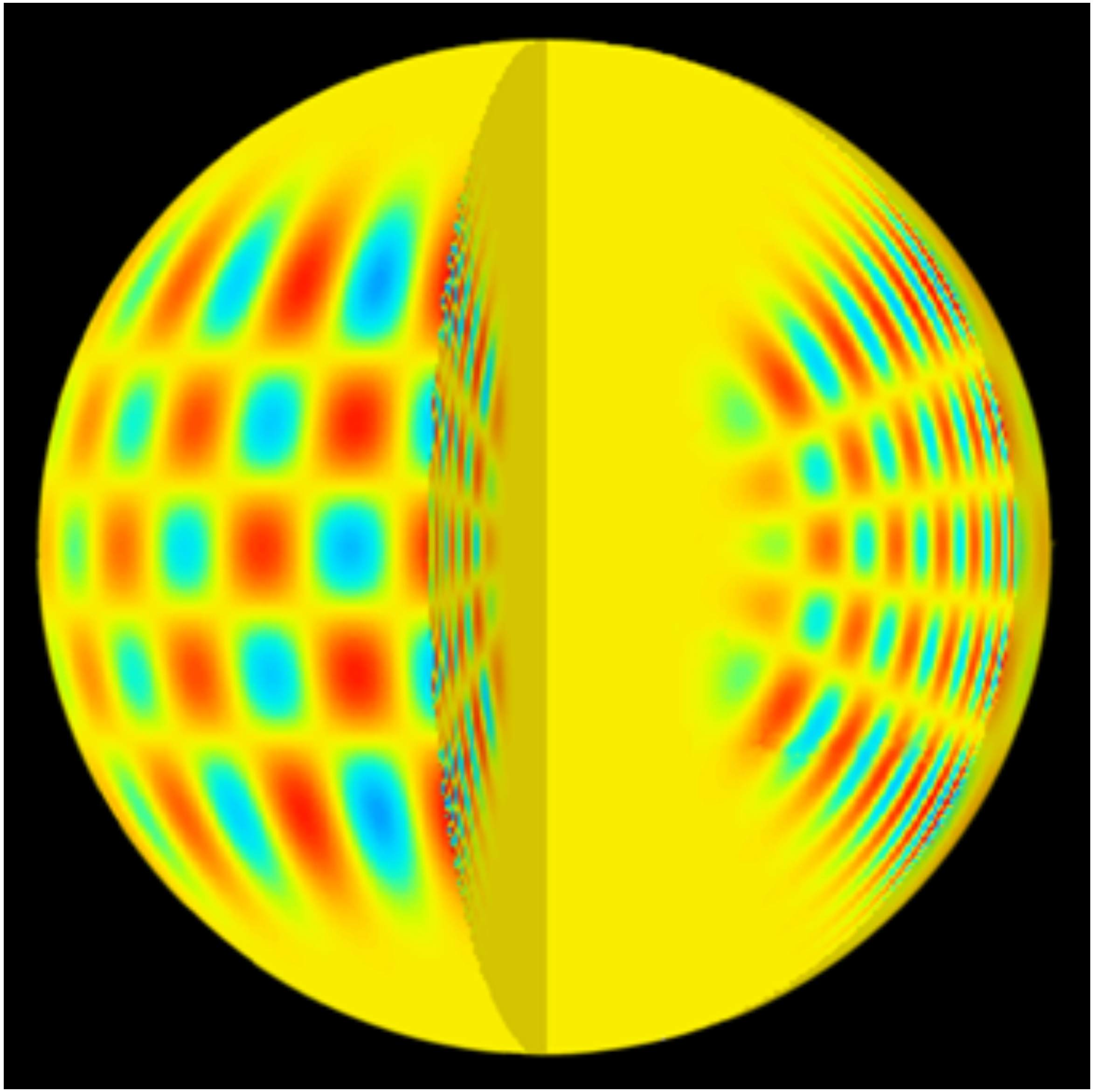

Wikipedia

Example HMI Velocity Image (Dopplergram)

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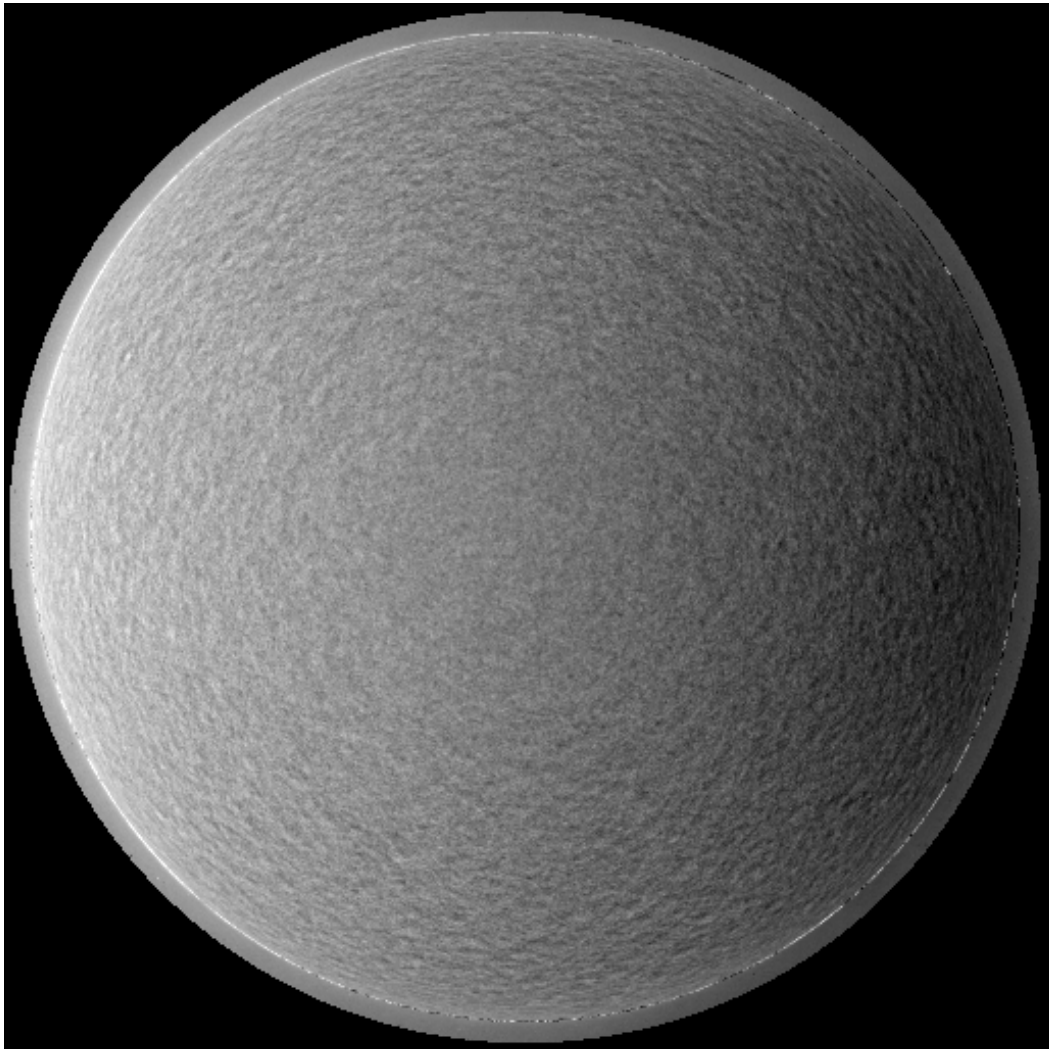

J. Schou

Dopplergram Movie

Very Precise Measurements!

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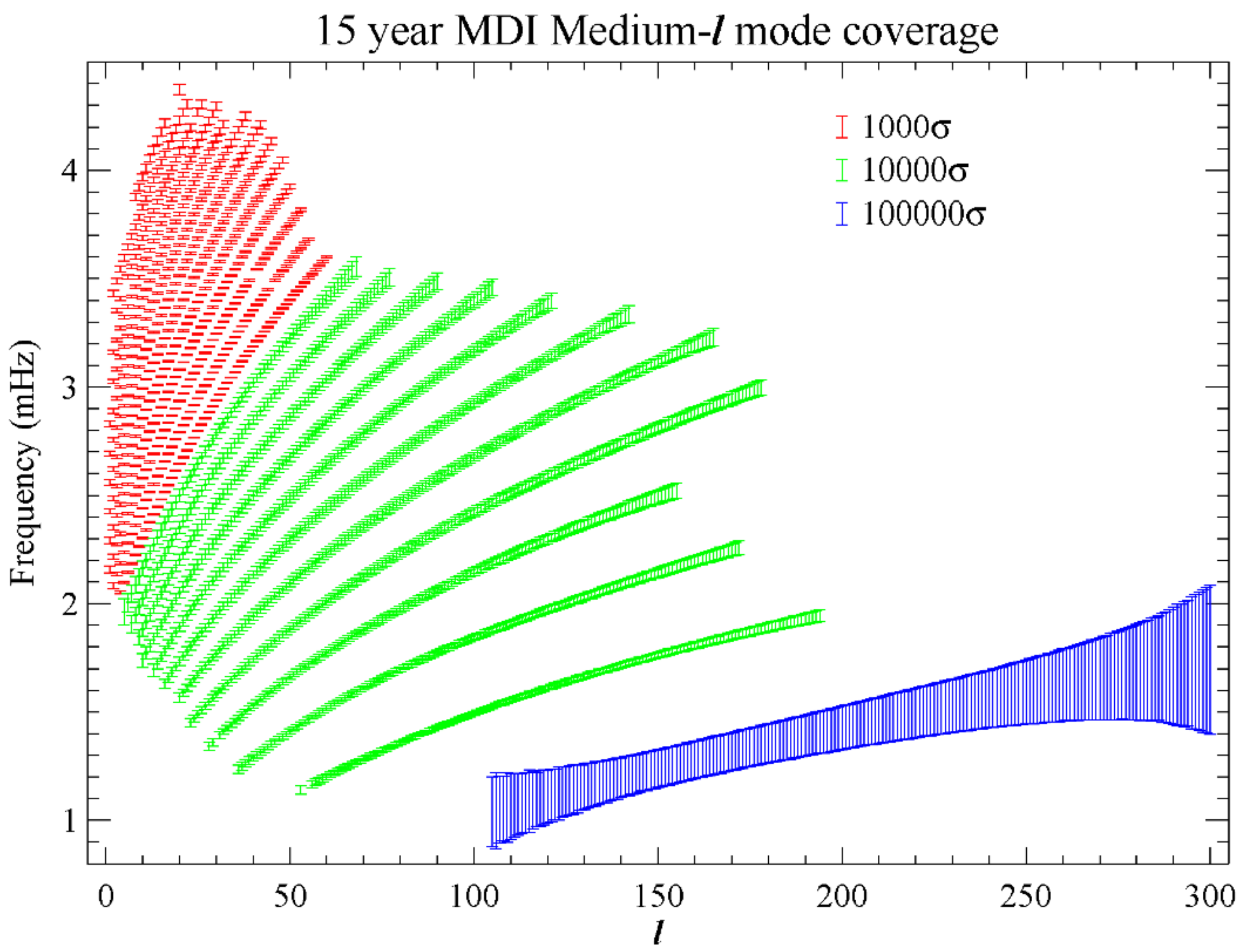


74x72 days. Present 75% of time. Fractional error is 1 part in 50 million, for f-modes: 16 million

Internal Structure

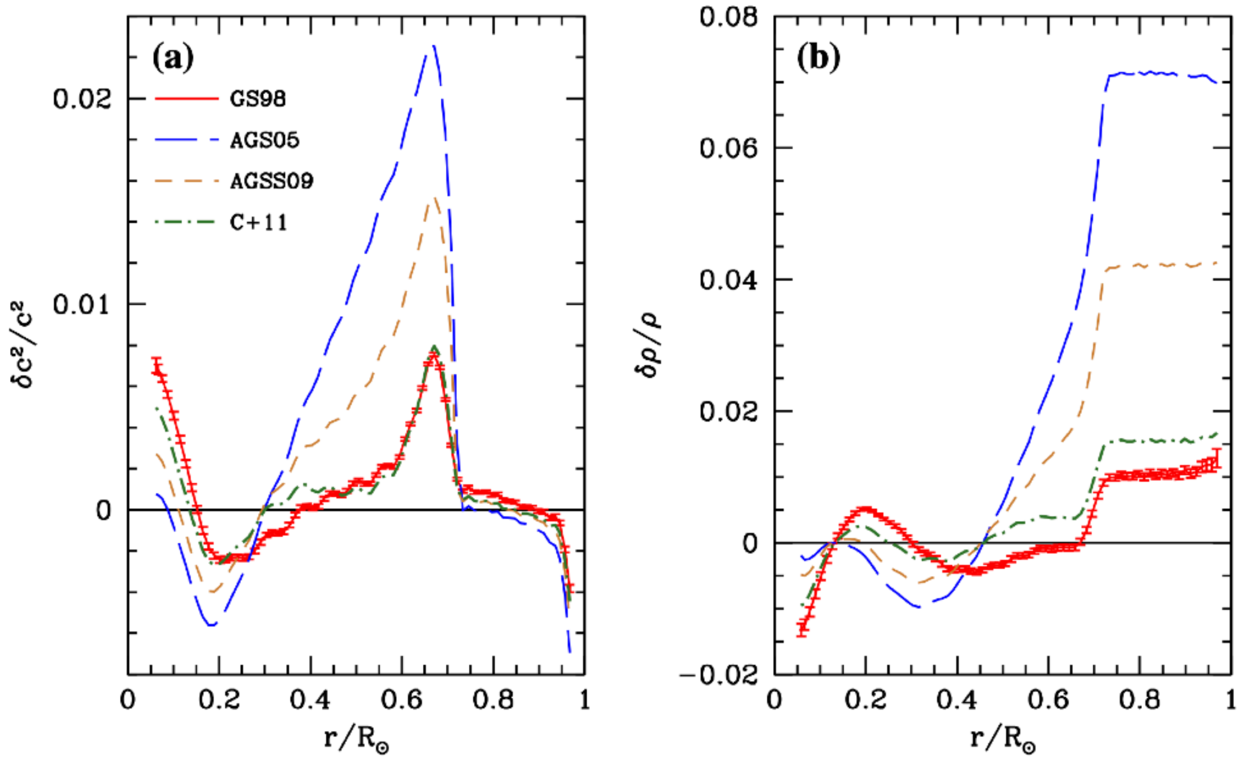
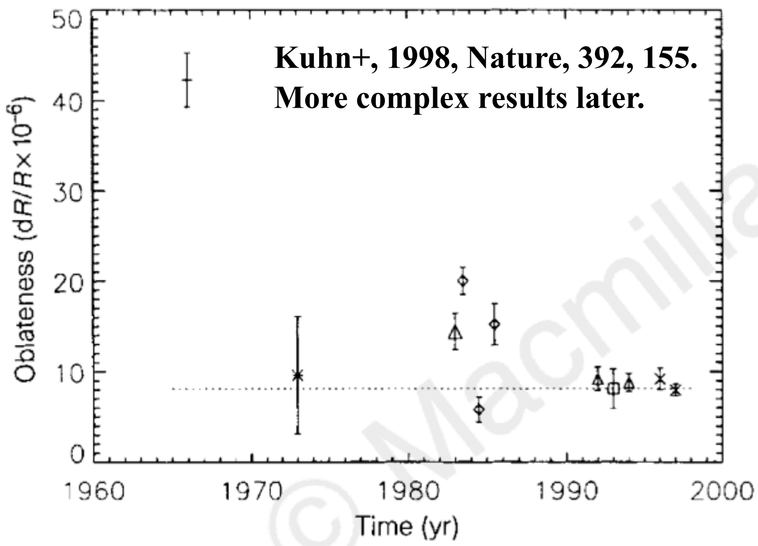


Fig. 23 The relative sound-speed and density differences between the Sun and four standard models constructed with different heavy-element abundances but otherwise identical physics inputs. The model GS98 was constructed with Grevesse and Sauval (1998) abundances, AGS05 with Asplund et al. (2005a) abundances, AGSS09 with Asplund et al. (2009) abundances, and models C+11 was constructed with Caffau et al. (2010, 2011) abundances supplemented with abundances from Lodders (2010)

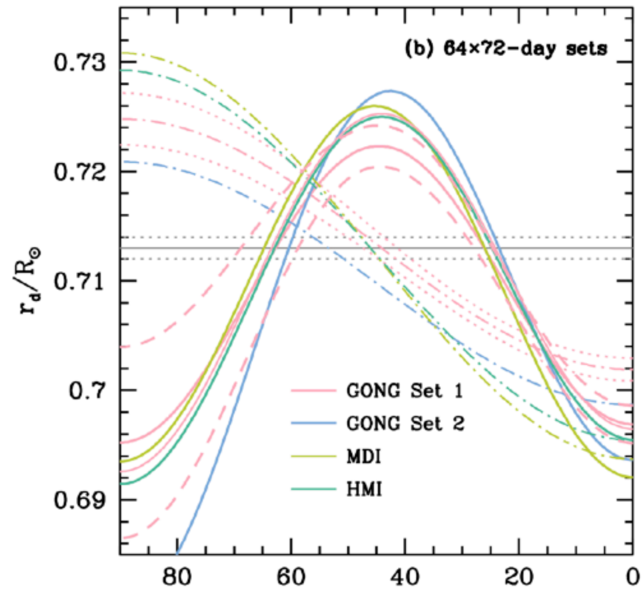
S. Basu (2016), LRSP 13:2

The Sun is not Round!

- **We have measured the solar (surface) oblateness**
  - Consistent with general relativity!



- **The tachocline is also not round**
  - Radiative/convection zone boundary



Basu & Korzennik, 2025, ApJ accepted

Solar Neutrino Problem

- **Neutrinos are created in the solar core**
  - Directly in proportion to the energy production rate
    - So the expected rat is known very accurately
  - Rarely interact with matter - Travel almost unimpeded through the Sun
    - But can be measured on the Earth with a large enough detector
- **First measurement was made around 1970 using a large (380m^3) tank of C_2Cl_4**
  - Too few (about 1/3) were found
    - 2002 Nobel Prize (also for a later experiment)
  - Bad solar model?
    - Major reason for SOHO and GONG
    - Solar models largely consistent with results from helioseismology
  - Bad measurement?
    - More experiments were made
    - No solar structure errors could explain all
  - Bad neutrino physics?
    - Turns out that neutrinos transform on the way to the Earth
    - 2015 Nobel Prizes came out of this
  - Helioseismology got Kavli Prize in 2022
    - And Crafoord Prize in 2024

Farside Imaging

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- **Can image the far side using waves observed on the near side bouncing off the far side**
- **Pioneered by C. Lindsey and D. Braun**
- **Now routinely used for space weather forecasting**

solar equator, easily resolving a moderately large plage. The computations made here were devised to image an area on the solar far side that included a large, multipolar magnetic region, NOAA AR 8194 (*16*), which we reference to Carrington longitude 29.8° and latitude −22.8°, about 18 hours before its passage through the far-side meridian. The result is a signature that renders the active region on the far side of the sun by a local reduction in the one-way sound-travel time of about 6 s over an area covering about 300 degree² (Fig. 2A). This is consistent with the sign and magnitude of signatures that typically characterize plages imaged on the near side of the sun (*17*).

When the aforementioned computation on the near side of the sun just inside the east limb (Fig. 2C). Control computations to test the effects of near-side magnetic regions in the computational pupil show no artifacts of large near-side active regions at their far-side antipodes or thereabout (*19*).

The seismic imaging of the far side of the sun has important implications for research on the acoustic properties of the sun's magnetic regions and of the sun as a whole. The far-side images directly demonstrate the influence of active regions on global modes. Because these waves travel from the near side of the sun to the far side and back, they interfere with their multiple reflections. The result is a standing wave with a sharply defined frequency, called a *p*-mode, similar to

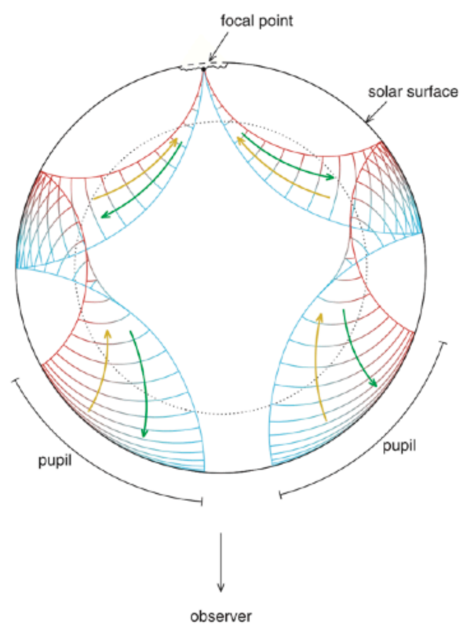

Fig. 1. Cross section of the solar interior showing the wave configuration for two-skip far-side seismic holography. Wavefronts emanating from a far-side point source (focal point) at intervals of 286 s (1/3.5 mHz) within the corridor of trajectories that are shown reflect once from the solar surface (right and left sides) and arrive in an annular pupil on the near surface (bottom) of the sun. Waves coherently emanating from the focal point (green arrows) are represented by the acoustic egression, reconstructed for each focal point in the image from the surface disturbance it creates on the near surface. Its time-reverse signature, the ingression (yellow arrows), represents identical waves coherently converging into the focal point to contribute to the local disturbance there. A local acoustic depression at the focal point will shift the phase of the ingression-egression correlation. In the case of a quasi-specular reflection at the focal point, the outside of the ingression pupil on one side (red part of wavefronts) correlates with the outside of the ingression pupil on the other (also red). Likewise for the inside of the pupil (blue part of wavefronts). Thus, the loss of either side of the pupil destroys the phase correlation for the entire pupil. For this reason, phase-sensitive holography of far-side solar activity is only practical for regions within ~50° of the antipode of disk center. The dotted circle indicates the depth of the base of the solar convection zone.

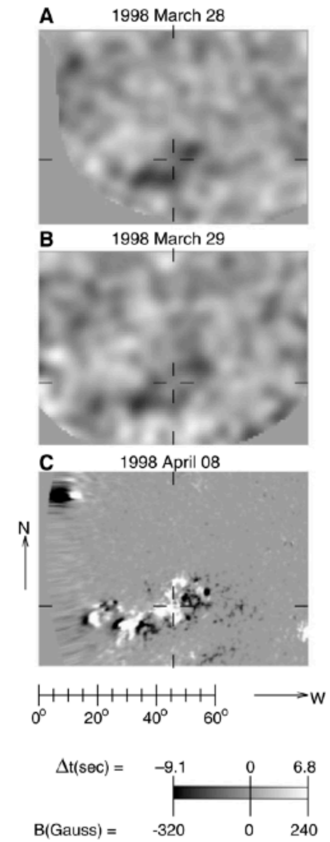

Fig. 2. Maps of one-way sound–travel time perturbation, Δt, in the neighborhood of NOAA AR 8194 just before (**A**) and during (**B**) its passage through the far-side solar meridian. Vertical fiducials in the center of each frame mark Carrington longitude 29.78°. Horizontal fiducials cross that meridian at solar latitude −22.82°. (**C**) An NSO/Kitt Peak magnetogram of the same location 10 days later, as the magnetic region becomes visible just inside the east limb. All three maps are overhead-view Postel projections centered on the aforementioned reference location with radial distance from the reference point indicated by the rule just beneath the bottom frame.

Lindsey+Braun, 2000, Science, 287, 1799

10 MARCH 2000 VOL 287 SCIENCE www.sciencemag.org

Farside Imaging

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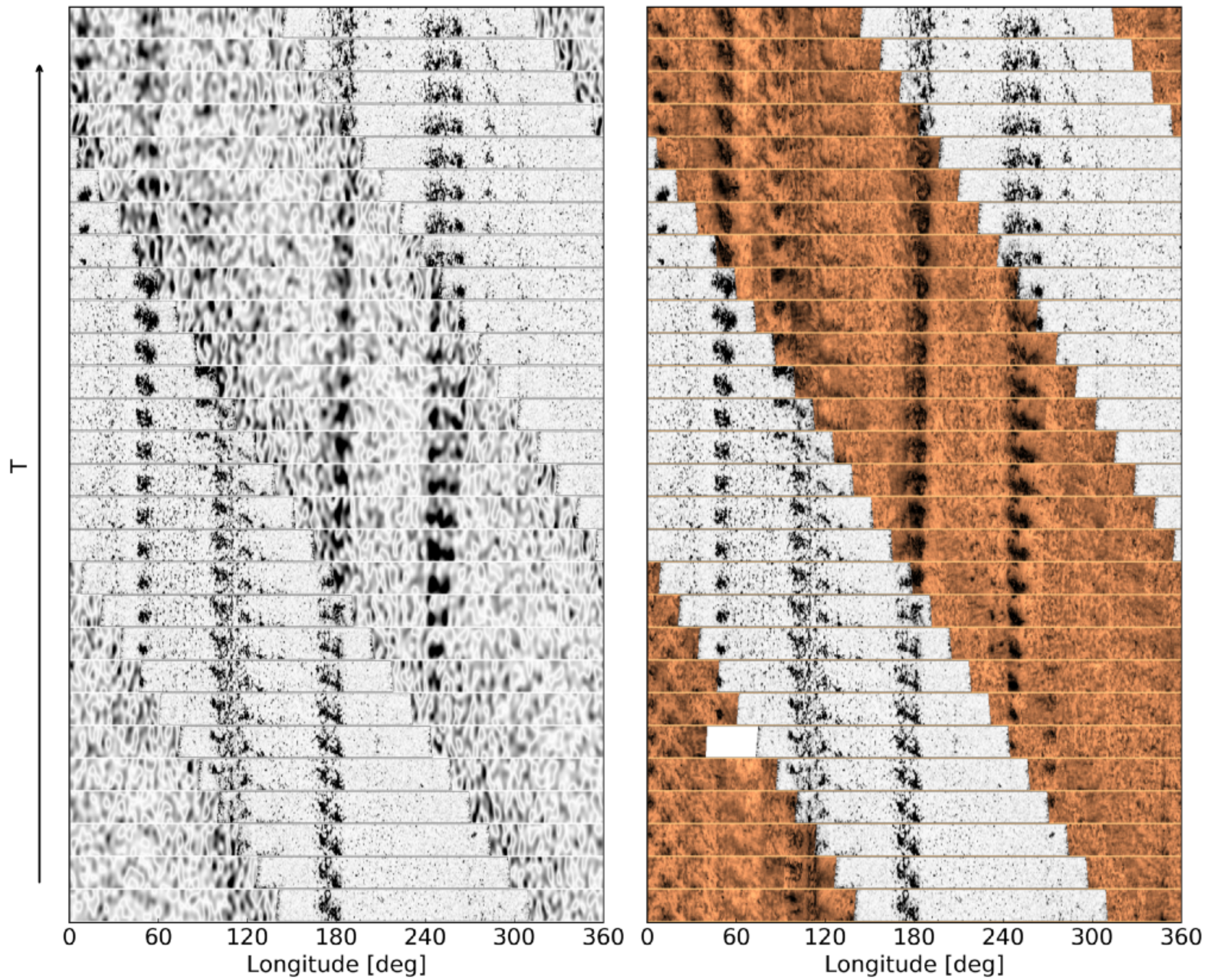
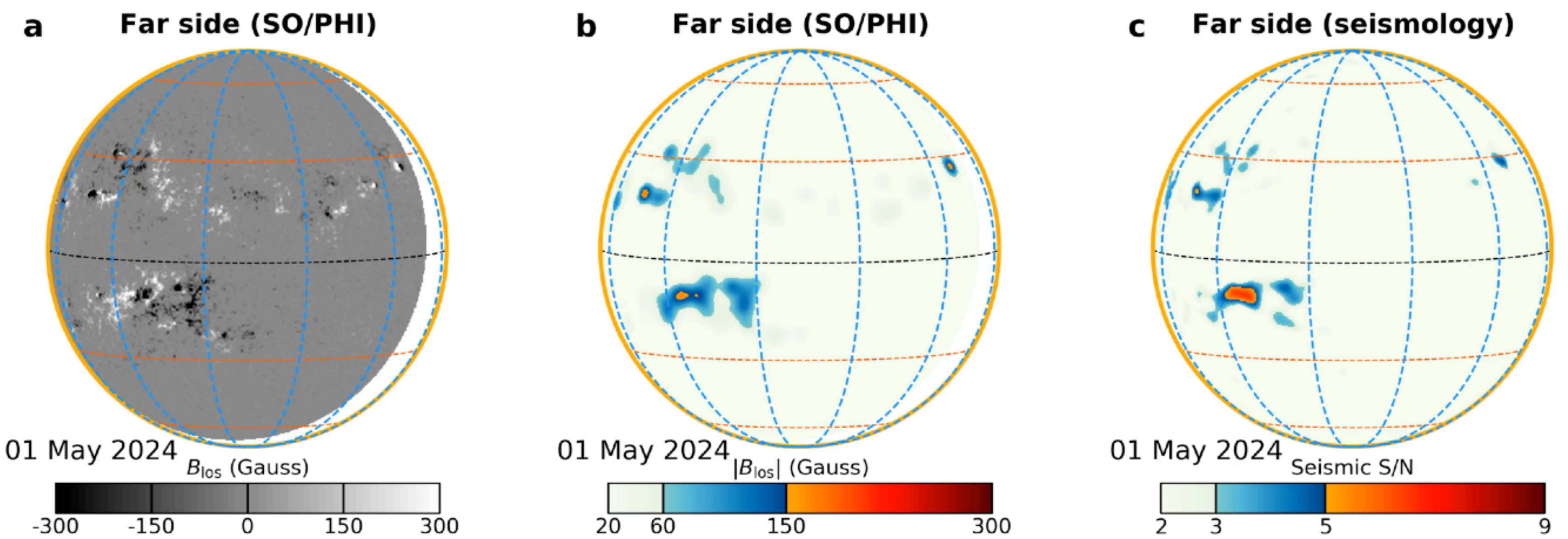


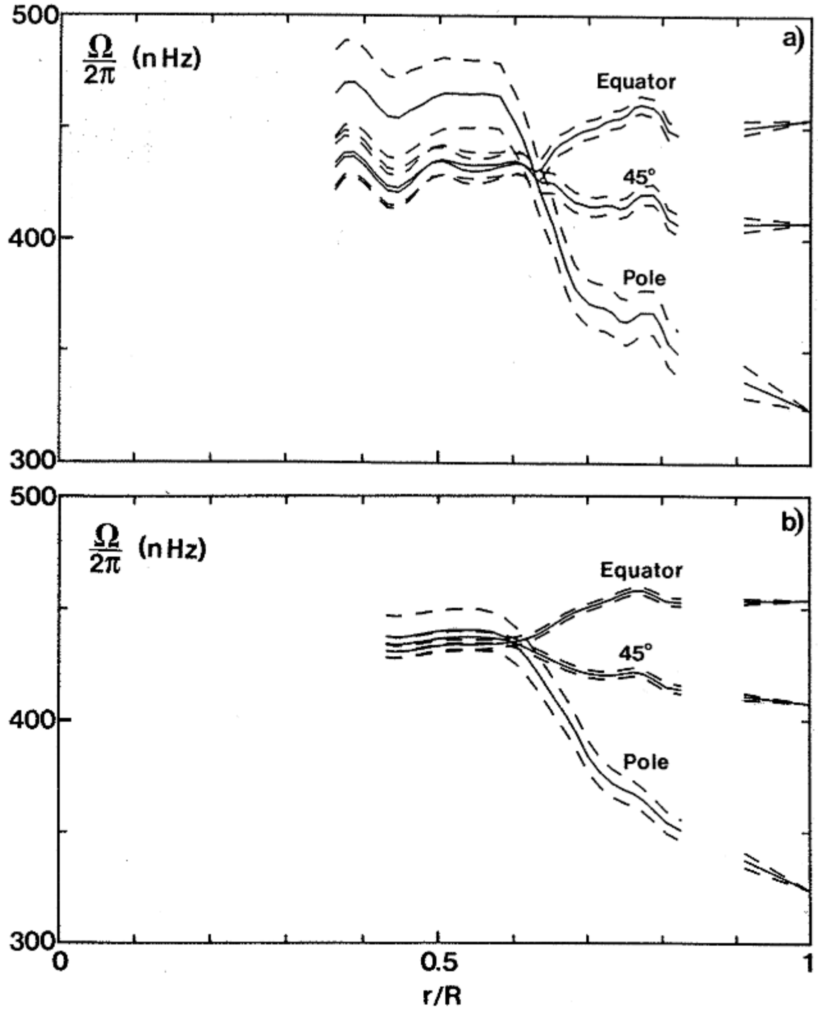
Farside images (HMI) and STEREO/EUVI 304Å.
Courtesy of Dan Yang (private communications).

Farside Imaging



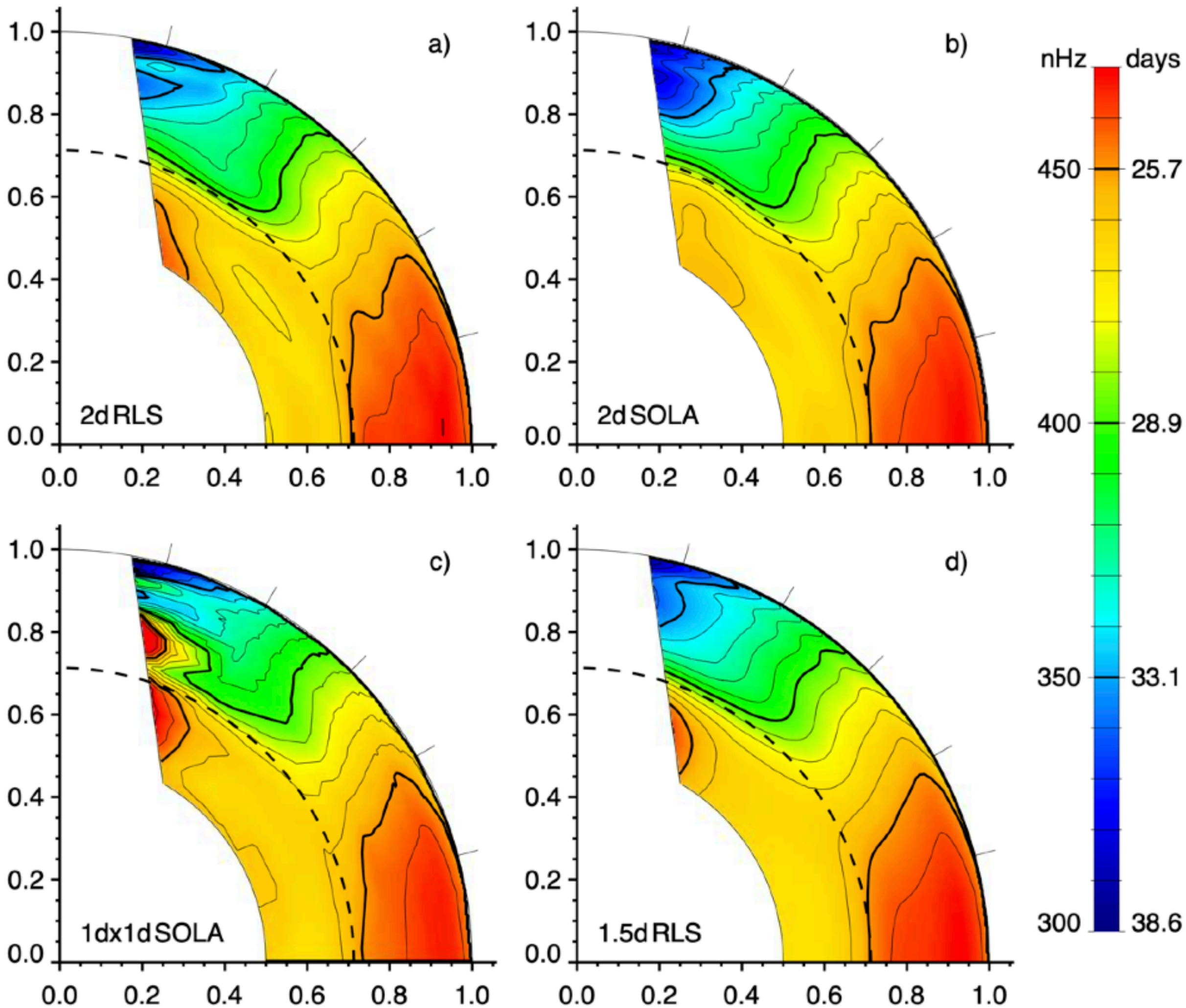
HMI farside images and PHI data. Courtesy of D. Yang.

Rotation - Before



Schou & Christensen-Dalsgaard, 1988, ESASP, 286, 149

Rotation - After



Schou+, 1998, ApJ, 505, 390

Rotation - Long After

Larson & Schou, 2018, Solar Physics, 293, 29
Also note near surface shear layer, Barekat+, 2014, A&A 570, 12

Torsional Oscillation

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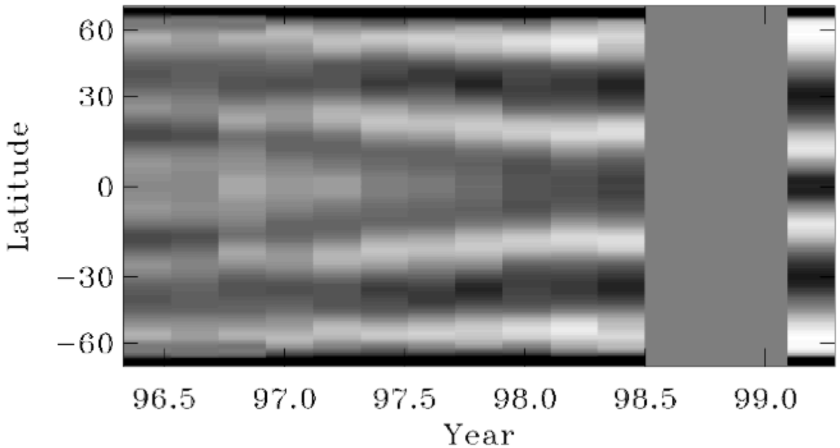
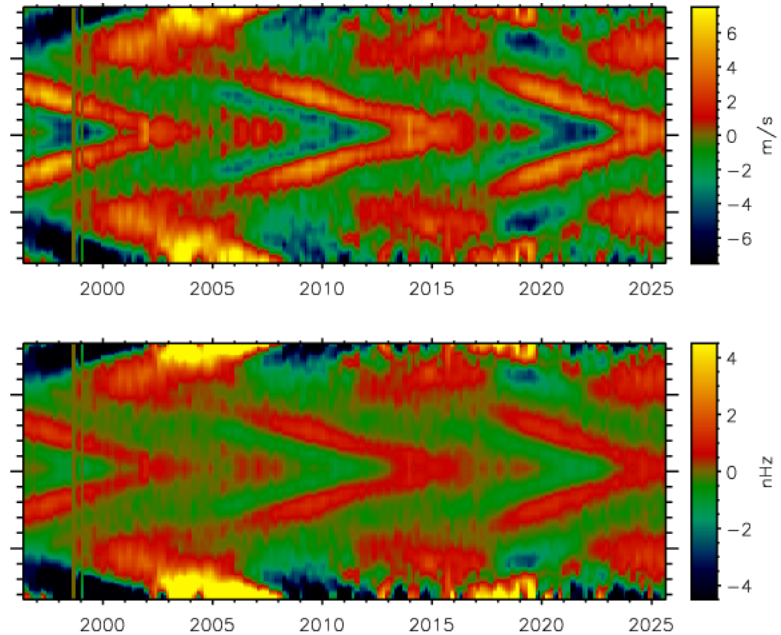
Rotation near 0.99R minus smoothed temporal average

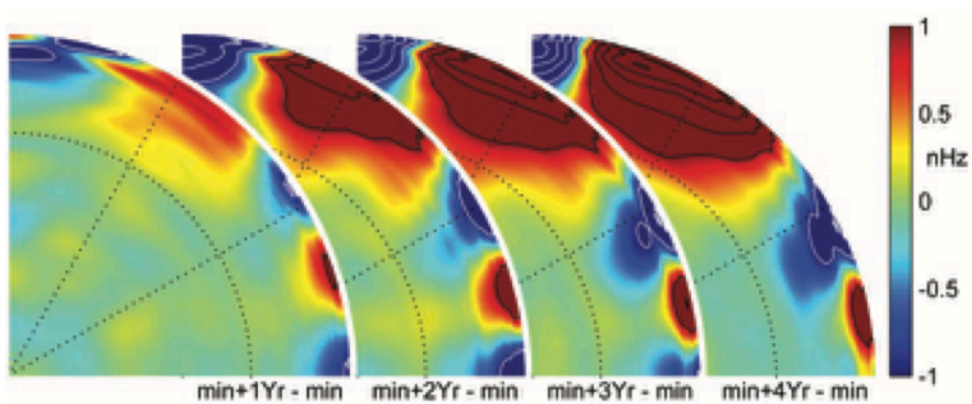


Schou, 1999, ApJ, 523, 181



Courtesy of T. Corbard

Also varies with depth



Vorontsov+, 2002, Science, 296, 101

Meridional Circulation

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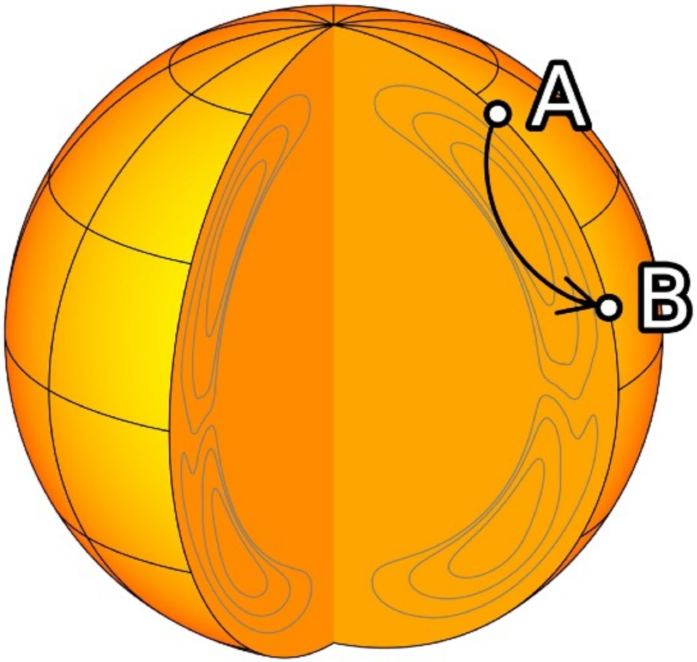
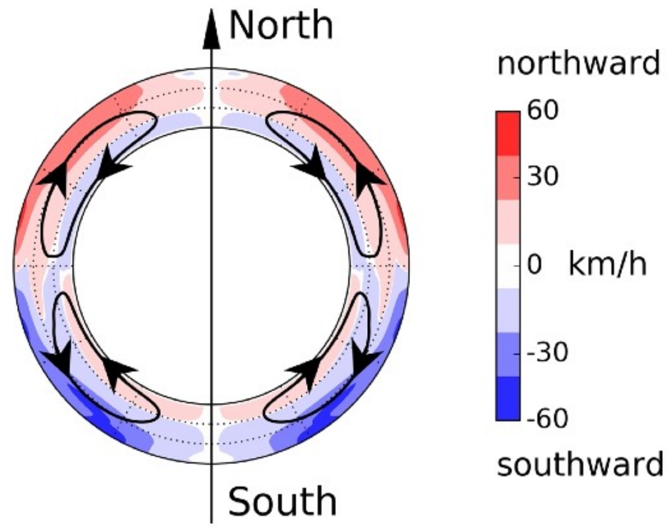
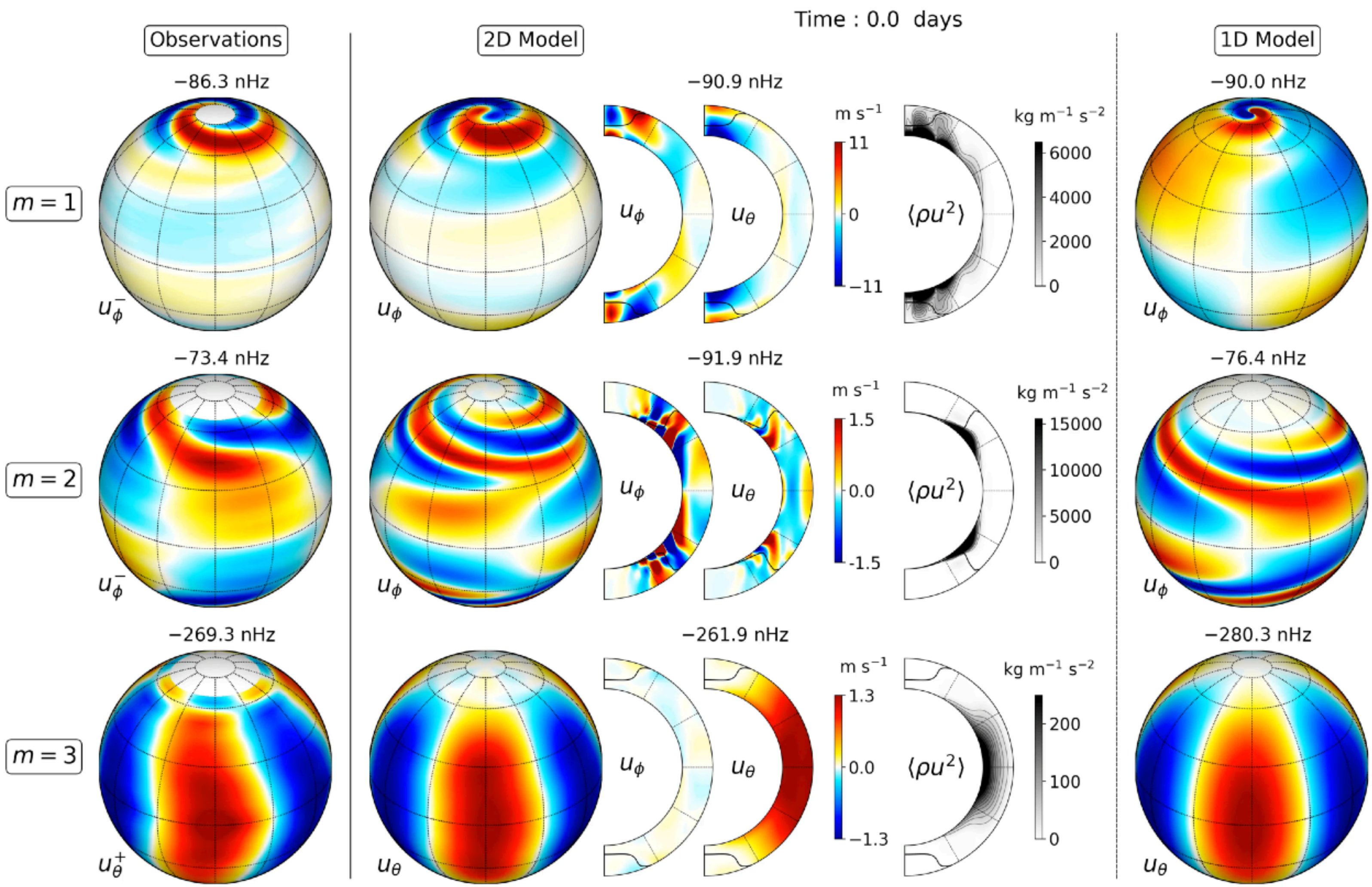




Müller+ 2025, Nature Astronomy/ Courtesy of Z-C. Liang

Inertial Modes



HMI. Gizon+, 2021, A&A, 652, L6

g-mode Detection: The Orthodox and Dissident Churches slides by Appourchaux and Garcia

Orthodox church (No detection)

- **Appourchaux et al (2000), Observational Upper Limits to Low-Degree Solar g-Modes: upper limit < 10 mm.s^{-1}**
- **Gabriel et al (2002), A search for solar g modes in the GOLF data: upper limit < 6 mm.s^{-1}**
- **Broomhall et al (2010), A comparison of frequentist and Bayesian inference: searching for low-frequency p modes and g modes in Sun-as-a-star data: No detection**

Dissident church (Detection)

- **Turck-Chièze et al (2004), Looking for Gravity-Mode Multiplets with the GOLF Experiment aboard SoHO: 7 modes detected between 150 µHz to 250 µHz with an amplitude of 2 mm.s^{-1}**
- **Jiménez and Garcia (2009), On the Solar Origin of the Signal at 220.7 µHz: A Possible Component of a g-Mode?: detection of one g mode**
- **Garcia et al (2007), Tracking Solar Gravity Modes: The Dynamics of the Solar Core: dipole (*l*=1) quasi-periodic pattern detected**

The concord !

Appourchaux et al (2010), The quest for the solar g modes: "At the time of writing, there is indeed a consensus amongst the authors of this review that there is currently no undisputed detection of solar g modes."

New schism

- **Schunker et al (2018), Appourchaux et al (2019), Scherrer and Gough (2019): no detection in Fossat et al (2017)**
- **Fossat et al (2017), Asymptotic g modes: Evidence for a rapid rotation of the solar core: detection of asymptotic g modes**

HMI – Offspring of MDI

With JS for scale

Conclusion

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- **SOHO is the greatest solar physics mission ever!**
  - Thanks to lots of people!