Independent Junior Research Group "Helio- and Asteroseismology

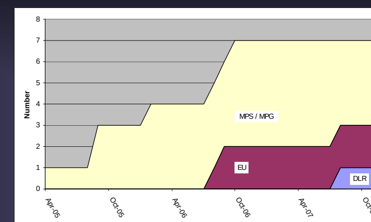
Laurent Gizon

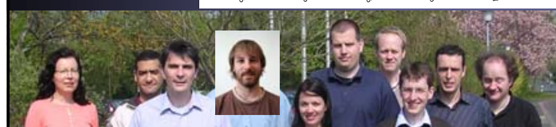
MPI for Solar System Research
Katlenburg-Lindau

2007 Fachbeirat

IJRG Staff

- Start date:
  1 Sept 2005
- Today:
  1 group leader
  4 postdocs
  2 PhD students





S. Deutsch | K. Daiffallah | L. Gizon | R. Burston | H. Schunker | T. Stahn | J. Jackiewicz | M. Roth | Y. Saidi | R. Cameron

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Why look inside stars?

- **Everything above the surface of stars is driven by what happens below the surface**
- **How do stars work?**
  → Internal structure, convection, rotation, evolution, nuclear chemistry
- **Why does the Sun have a magnetic cycle?**
- **Can we see solar active regions before they emerge on the surface?**
  → Can we predict surface activity and space weather?

Solar seismic waves

are used to probe the interior of the Sun

velocity images (1 min cadence)
measured from the SOHO spacecraft

Techniques:

1. Global helioseismology:
internal structure as a function of radius and latitude.

2. Local helioseismology:
Three dimensional maps of flows and temperature inhomogenities inside the Sun.

3. Sunspot seismology:
New! Forward modeling of wave propagation through model sunspots

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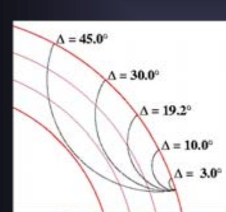
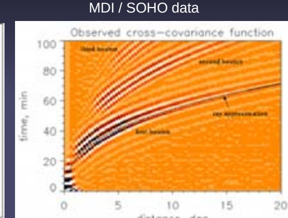
IJRG: Main topics of research (areas of expertise)

- Local helioseismology
  - Data analysis: travel time measurements (4)
    → poster (Roth et al.)
    → poster (Gizon & Rempel)
  - Linear forward modeling: sensitivity kernels (4)
    → poster (Saidi et al.), more posters upstairs
  - Linear inverse problem: 3D tomography (2)
    → poster and talk (Jackiewicz et al.)
- Sunspot seismology
  - Observational seismic signatures of the magnetic field (2)
    → poster (Schunker et al.)
  - Numerical forward modeling of wave propagation through model sunspots (3)
    → poster (Cameron et al.)

Solar seismograms



MDI / SOHO data



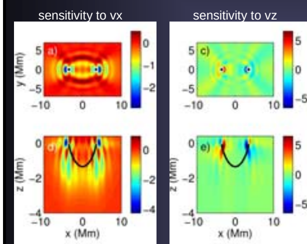
$$C(\mathbf{r}_1, \mathbf{r}_2, t) = \int dt' \, \phi(\mathbf{r}_1, t')\phi(\mathbf{r}_2, t'+t)$$

Sensitivity to T, rho, v, B...

Linear forward modeling

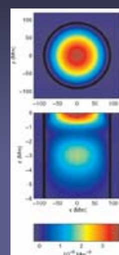
Needed for high-resolution tomography
(We are spending a lot of time on this)

Travel-time sensitivity kernels



Birch & Gizon, AN (2007)
Jackiewicz, Gizon, Birch & Duvall, ApJ (2007)
Lapole et al., in preparation

Kernels for ring-diagram analysis



Birch, Gizon, Haber & Hindman, ApJ (2007)

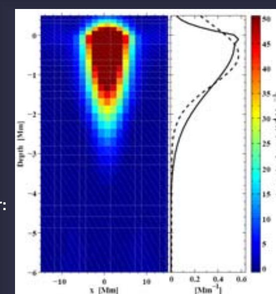
Linear inversions

2+1 dimensional Optimal Localized Averaging

Target depth
0.5 Mm

Target width:
7 Mm

Noise for 24 hr:
18 m/s



Jackiewicz, Gizon, Birch & Thompson, AN (2007) Jackiewicz et al., in preparation

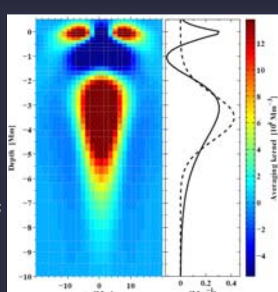
Linear inversions

2+1 dimensional Optimal Localized Averaging

Target depth:
3.5 Mm

Target width:
10 Mm

Noise for 24 hr:
40 m/s
(quite a lot)



Jackiewicz, Gizon, Birch & Thompson, AN (2007) Jackiewicz et al., in preparation

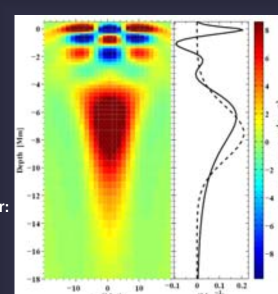
Linear inversions

2+1 dimensional Optimal Localized Averaging

Target depth:
7.5 Mm

Target width:
10 Mm

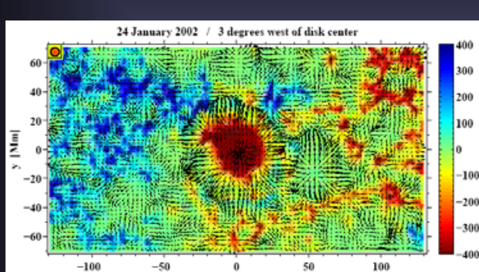
Noise for 24 hr:
57 m/s
(too much)



Jackiewicz, Gizon, Birch & Thompson, AN (2007) Jackiewicz et al., in preparation

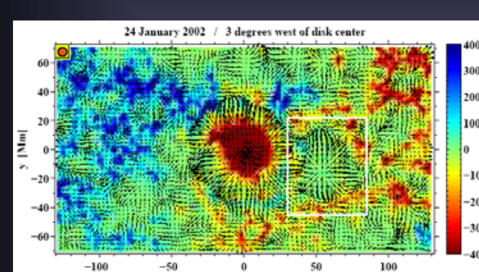
Horizontal flows

Modes: f, p1, p2, p3, p4 Depth: 1 Mm below the surface



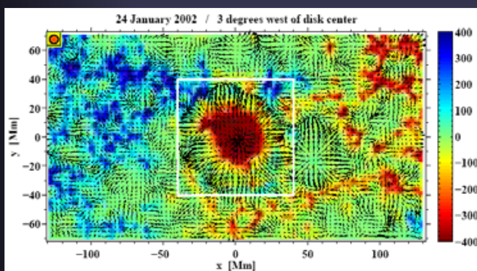
Large supergranule

Modes: f, p1, p2, p3, p4 Depth: 1 Mm below the surface

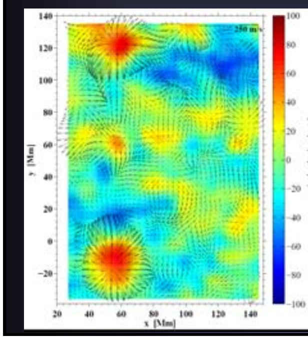


Moat flow around a sunspot

Modes: f, p1, p2, p3, p4 Depth: 1 Mm below the surface



First meaningful inversion for all three components of velocity



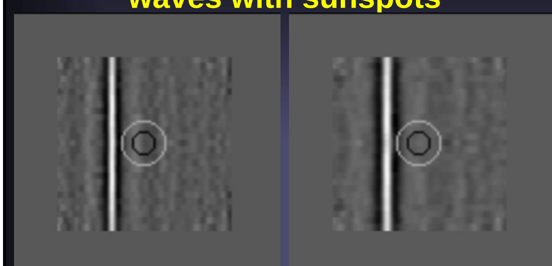
24 hr averages:

Noise:
15 m/s for Vx & Vy
25 m/s for Vz

$$V_z \sim H\,\mathrm{div}\mathbf{V}_h$$

Where the density scale height is H=0.7 Mm at z = -1.5 Mm

Imaging the interaction of solar waves with sunspots



Cross-correlation between the MDI signal averaged over a vertical line and the MDI signal at any other point in the map (Gizon 2007)

Left: f modes
Right: p1 modes

Can we do this properly?

MOVIE: Sound speed perturbations below a sunspot (Stanford University)

Sunspot seismology

- A different game:
  - The strong effect of B cannot be ignored
  - We cannot linearize with respect to a quiet-Sun reference solar model
- The only possible strategy:
  - Numerical forward modeling

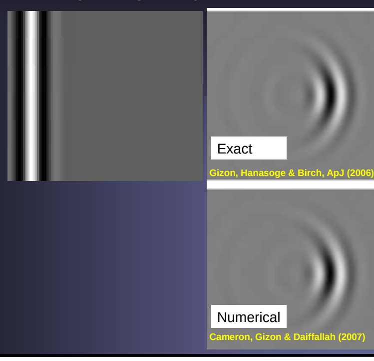
SLiM (Semi-spectral Linear MHD) code

- Developed at MPS; has no equivalent
- Numerical simulation of wave propagation through a general 3D magnetized solar atmosphere
- Initial value problem
- Spectral in the horizontal coordinates
- Finite differences in the z direction

Cameron, Gizon & Daiffallah, AN (2007)

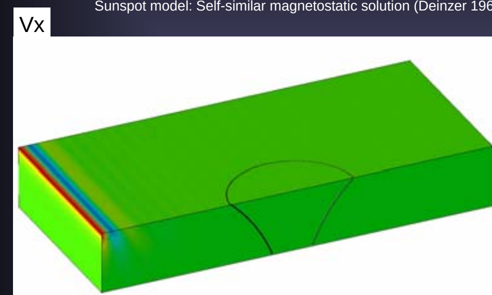
Testing SLiM with an exact solution:

Sound waves through a magnetic cylinder in a uniform medium



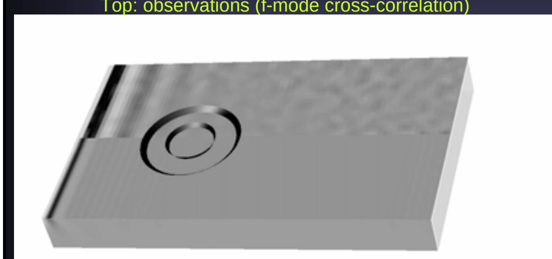
F-mode wavepacket through a "realistic" model sunspot

Sunspot model: Self-similar magnetostatic solution (Deinzer 1965)

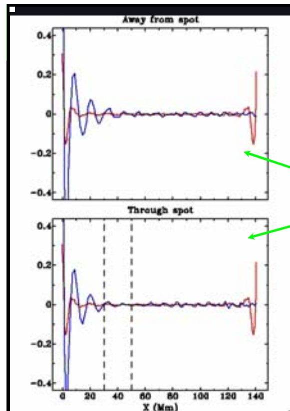


Comparison with observations

Top: observations (f-mode cross-correlation)



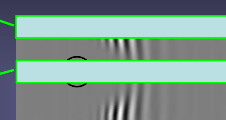
Bottom: SLiM numerical solution for Bz=3kG



Simulations

Observations

Movie duration is 144 min



The best match is obtained for Bz=3 kG at the surface.

→ First ever helioseismic constraint on a sunspot's magnetic field !

Achievements

- (Linear) local helioseismology
  - We have developed and implemented an independent procedure for the interpretation of helioseismic travel times.
  - This procedure is fully consistent
  - We have a good understanding of the propagation of noise
  - The first results are very promising (talk by J. Jackiewicz)
- Sunspot seismology
  - We have developed and tested a code (SLiM) that computes the interaction of solar waves with sunspots
  - Wave perturbations are large and caused mainly by the direct effect of B through the Lorentz force.
  - The comparison between observations and simulations is encouraging
  - First helioseismic constraint on B !
- Asteroseismology
  - Detection of solar-like oscillation on K giants (talk by M. Roth)
  - Fourier analysis of gapped time series (poster by T. Stahn)

IJRG Publications (as of Sept 25)

- 20 refereed publications (+5 submitted)
- One major review paper in *Living Reviews of Solar Physics* (120 pages)
- 16 conference papers
- 4 articles in popular magazines
- 11 articles in preparation for upcoming double topical issue of *Solar Physics.*

IJRG: International visibility

•Leading role in scientific organization and management of the HELAS FP6 European Helio- and Asteroseismology Network (MR Project Scientist, LG Chairman of Local Helioseismology Network Activity)

•Guest editors of a special issue of *Astronomische Nachrichten* on local helioseismology, and a double topical issue of *Solar Physics* on helio- and asteroseismology

•HELAS II Conference, 20-24 August, Goettingen, Germany (150 participants)

Helioseismology, Asteroseismology and MHD Connections
HELAS II Conference, 20-24 August, Goettingen, Germany

IJRG: Future plans

- Apply OLA inversions to all the MDI data
  - We will soon have the best vector flow maps over a full solar cycle
  - Study flow patterns and their relationship to active regions
  - Extend inversions to all other physical variables, incl. B
- Computational sunspot helioseismology
  - Infer the internal structure of sunspots using forward modeling
  - (Seek funding to acquire dedicated computational power)
- Prepare for the Solar Dynamics Observatory (SDO)
  - German data center for SDO (DLR project)
  - Clone the JSOC-Stanford data management system
  - Create software and data analysis pipeline
- Asteroseismology
  - Analysis of CoRoT data: solar-like stars

This is just the beginning!
An exploding field of research

- Future space missions for helioseismology:
  - SDO (2008, NASA) 2TB/day
  - Solar Orbiter (2015, ESA)
  - SOHO and GONG still work...
- Asteroseismology has just begun:
  - COROT (dec 2006, CNES/ESA)
  - ESO VLT (UVES)
  - Kepler (NASA)
  - Antarctica (Dome C)
  - Ground-based network (SONG)