Helioseismic Observations of Active Regions

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Data: P. Scherrer & *SOHO* MDI Team

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Outline

- p-Mode absorption in sunspots
  - Hankel analysis, theories & holography
- Travel-time perturbations in ARs
  - Agreements and controversies
  - Farside imaging
- What's next and what's needed?
  - Doppler diagnostics
  - Numerical modeling

Hankel analysis

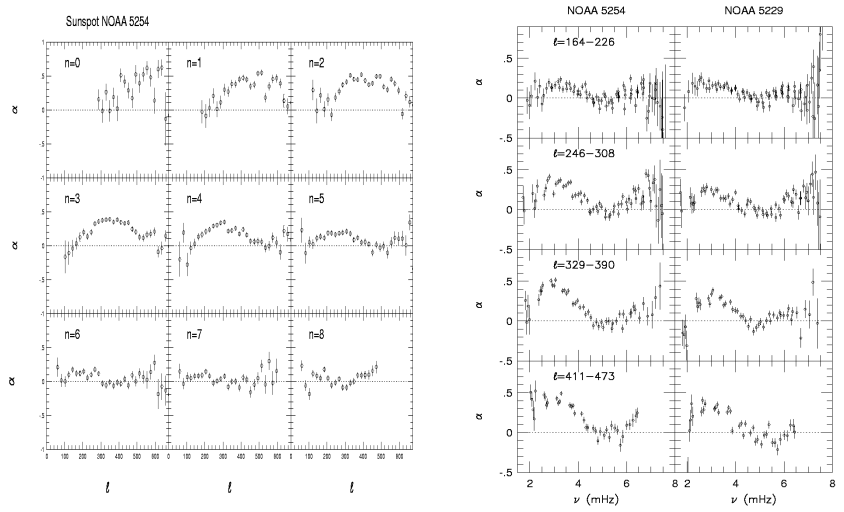
"in-coming"(A_{lmn}) and "out-going" (B_{lmn}) mode amplitudes determined from Fourier-Hankel decomposition of surface wave field

Absorption coefficient $$\alpha \equiv 1 - \frac{|B_{lmn}|^2}{|A_{lmn}|^2}$$

Phase-shift $$\delta \equiv \arg(B_{lmn}) - \arg(A_{lmn})$$

p-Mode absorption

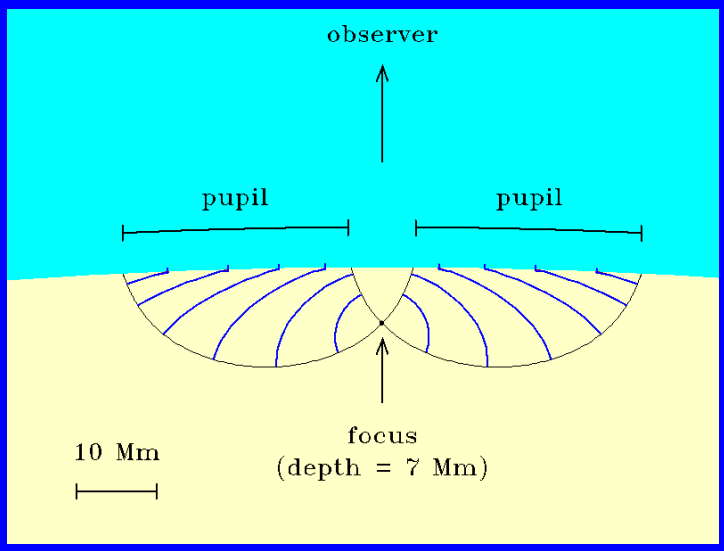
Braun (1995, *ApJ*, **451**, 859)



Theories of p-Mode Absorption

- Resonance absorption (1988-1994)
  - Hollweg, Lou, Chitre, Davila, Rosenthal, Sakurai, Goosens, Poedts, Keppens, Bogdan
- Slow-mode conversion (1991-present)
  - Spruit, Bogdan, Cally, Zweibel, Barnes, Rosenthal, Julien

Helioseismic holography



$H_-(z,\mathbf{r},t)$= ingression

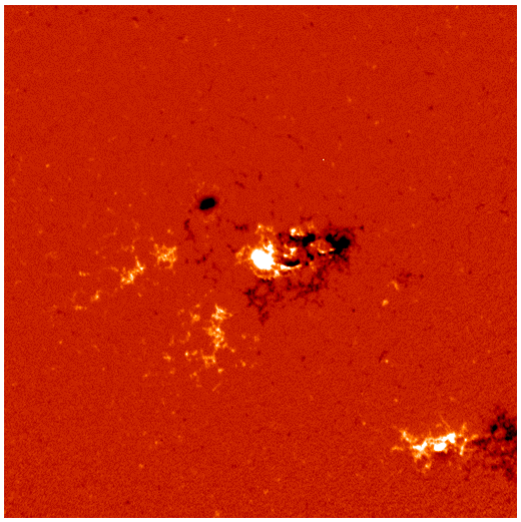
$H_+(z,\mathbf{r},t)$ = egression

Holographic depth diagnostics

depth:

0

20 Mm



5 mHz
egression
power

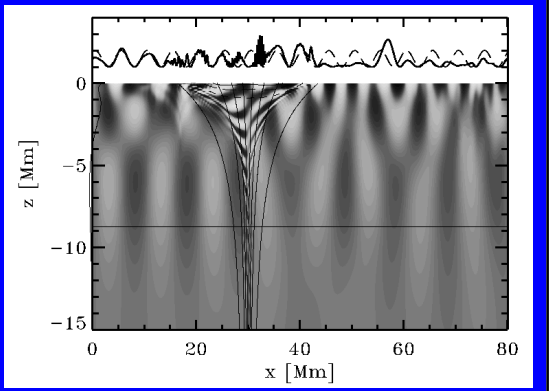
Braun & Lindsey, 1999, *ApJ*, **513**, L79

s-Mode coupling

Cally (2000, *Sol Phys*, **192**, 395)

Conditions for efficient absorption:

- $c_a \approx c$
- Horizontal (spreading) magnetic field



600×200 SIMULATION

Incoming wave + OW on left, OW on right

External Enhanced Polytrope, m = 1.5

p_1−mode

Magnetic Flux = 45000 Gauss Mm

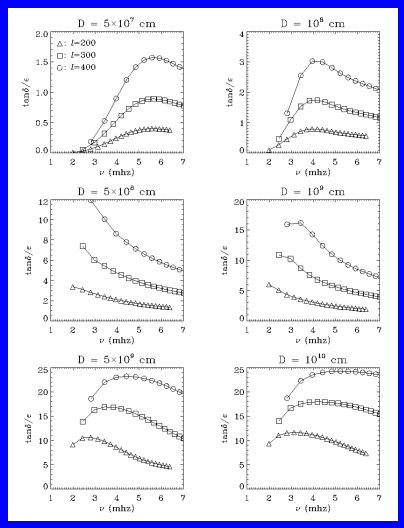
BC = [7,4,3,0]

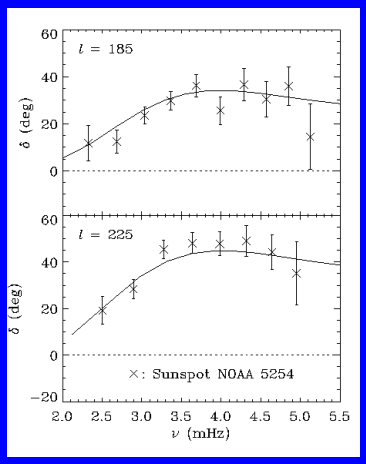
AR travel-time perturbations observed by 4 local helioseismic diagnostics:

- Hankel analysis (Braun et al. 1992)
  ~20-60° phase-shifts in sunspots
- Time-distance (Duvall et al. 1996)
  ~1^{min} travel-time *decrease* in spots
- Holography (Braun & Lindsey 2000)
  20-60^{s} *decrease* in spots, 5-15^{s} in plages
- Ring-diagrams (Hindman et al. 2000)
  – *positive* "frequency-shifts" in magnetic regions $\delta\nu/\nu \sim 10^{-3} - 10^{-2}$

Modeling (Hankel) phase-shifts

Fan, Braun & Chou (1995, *ApJ*, **451**, 877)





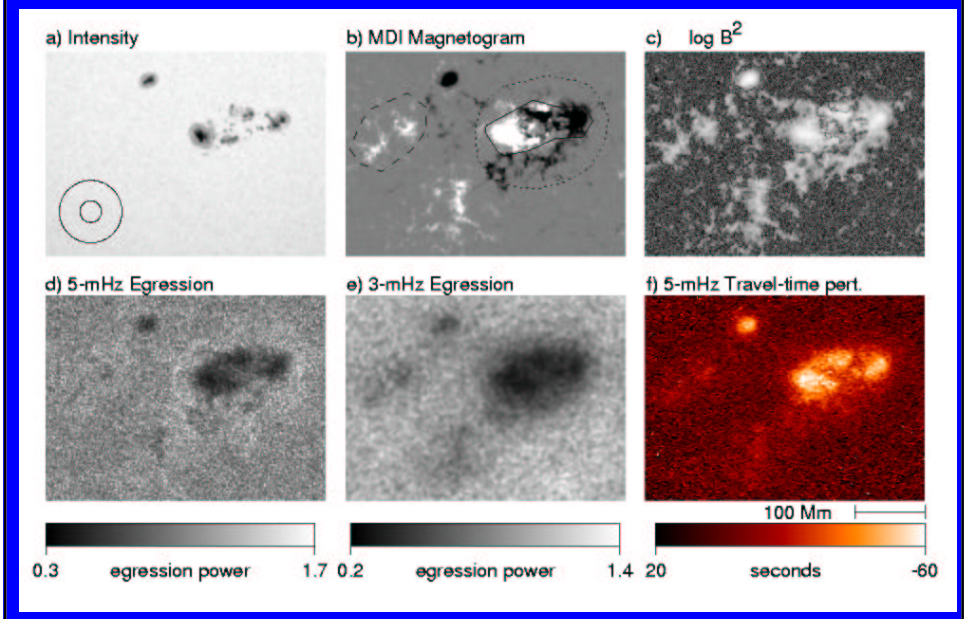
$\frac{\delta c}{c} \approx 0.4$ Depth = 1 Mm

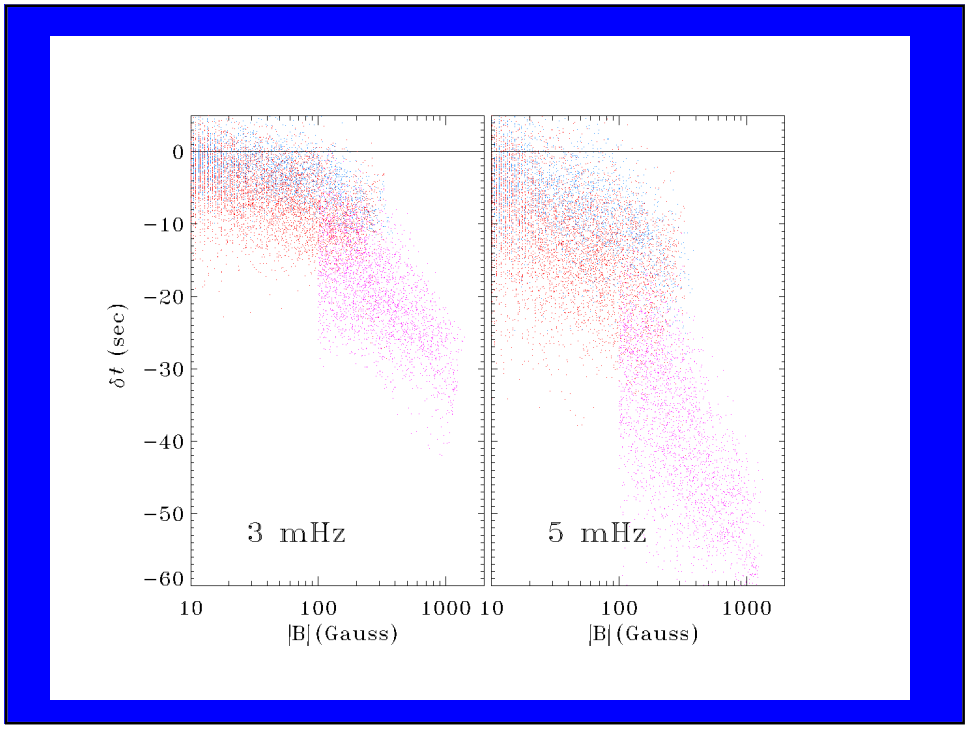
Phase-sensitive holography

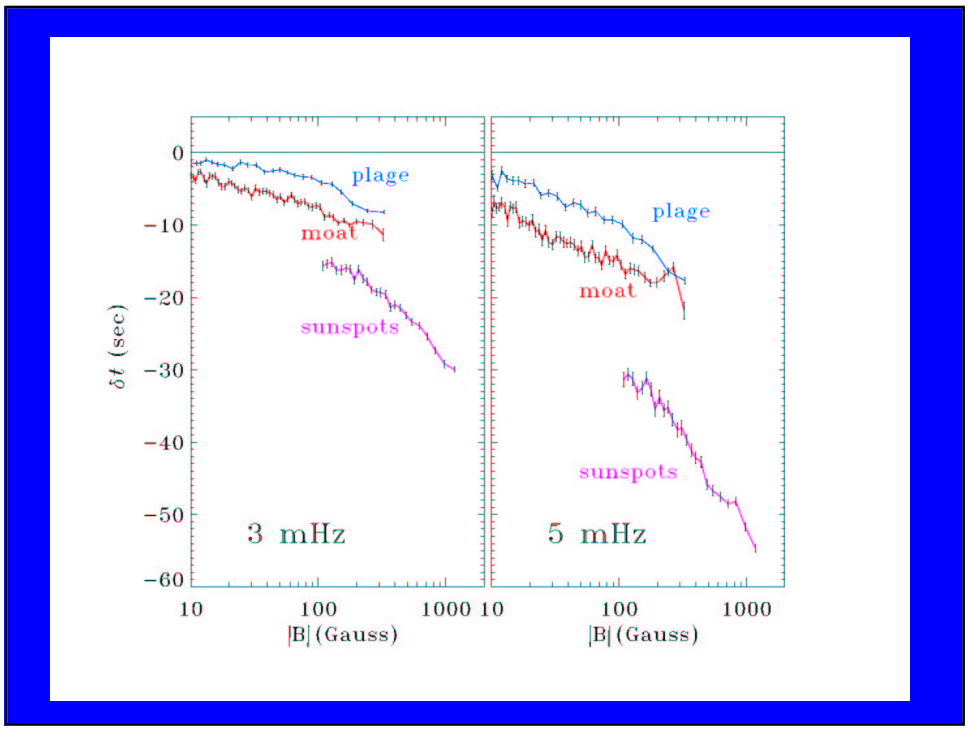
Refractive perturbations produce temporal delays or speed-ups of egressing waves with respect to ingressing waves:

$$\delta t(\mathbf{r}, z) \rightarrow \max \left(C(\delta t) = \int dt\, H_{-}(z, \mathbf{r}, t)\, H_{+}(z, \mathbf{r}, t + \delta t) \right)$$

Braun & Lindsey 2000 *Solar Phys.* **192**, 307



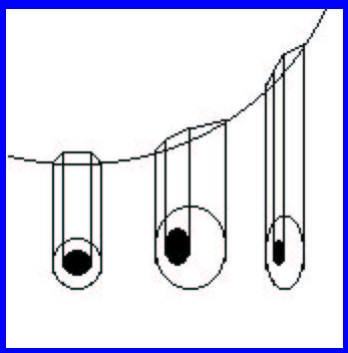

0
−10
−20
−30
−40
−50
−60
δt (sec)
3 mHz
5 mHz
10
100
1000
|B| (Gauss)


0
−10
−20
−30
−40
−50
−60
δt (sec)
plage
moat
sunspots
3 mHz
5 mHz
10
100
1000
|B| (Gauss)

Wilson depression

Sunspots: $\delta t \approx \frac{z_w}{c} \approx \frac{500 km}{9 km/s}$

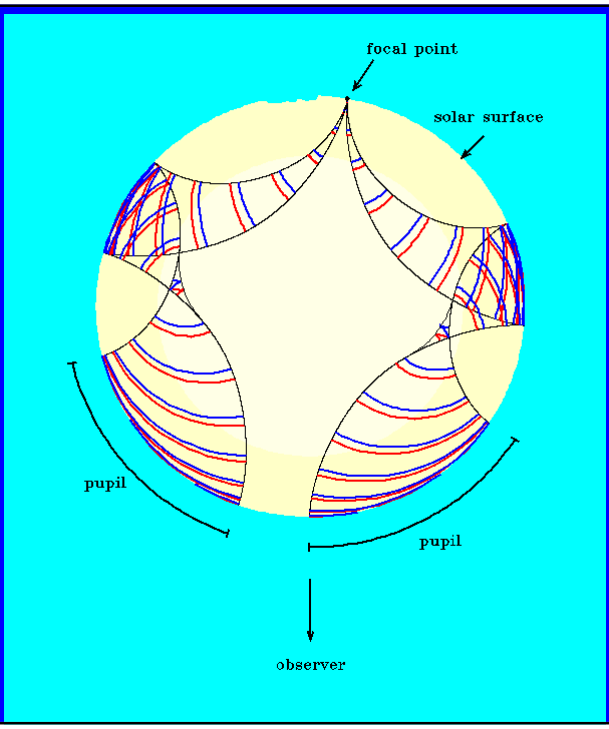
$$z_w \approx H_p \ln\left(\frac{B^2}{8\pi P_e} + 1\right)$$



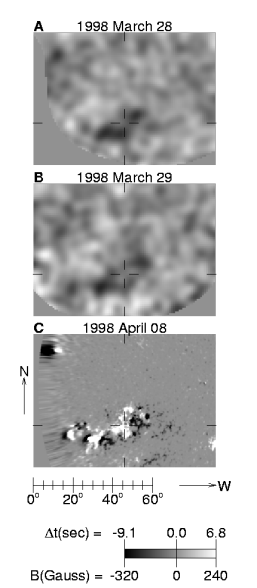
Implications of travel-time perturbations

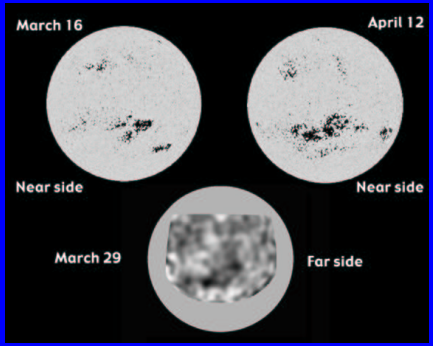
- Wilson-like depression?
- Thermal perturbation?
- Magnetic wave-speed perturbation?
- Cause of global-mode frequency variations with solar cycle
- Enable farside imaging

Farside imaging

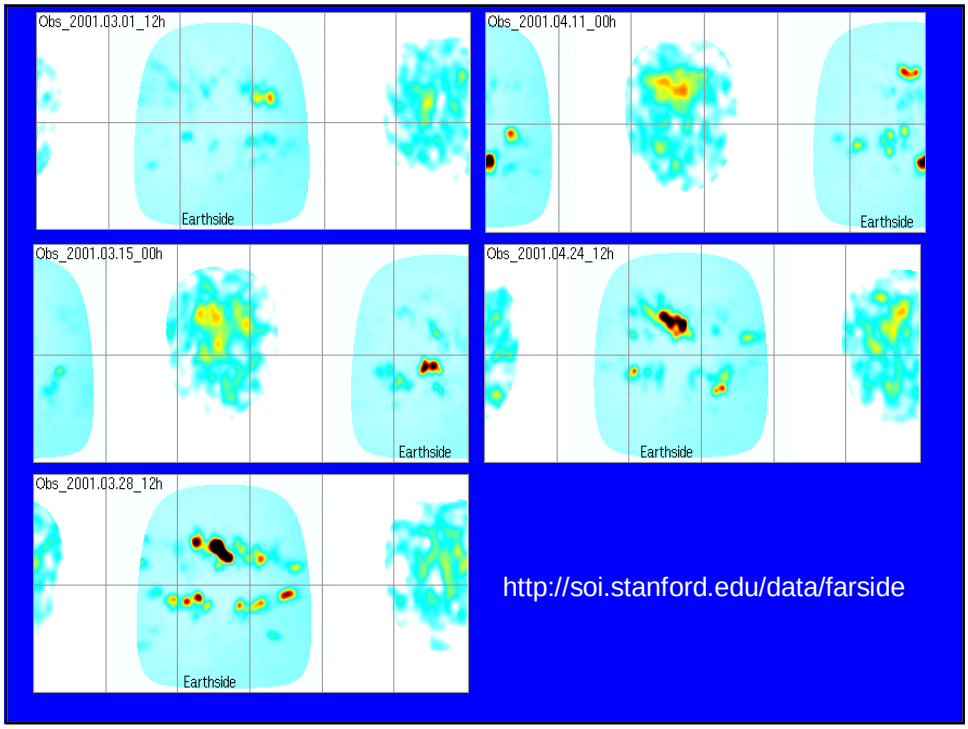


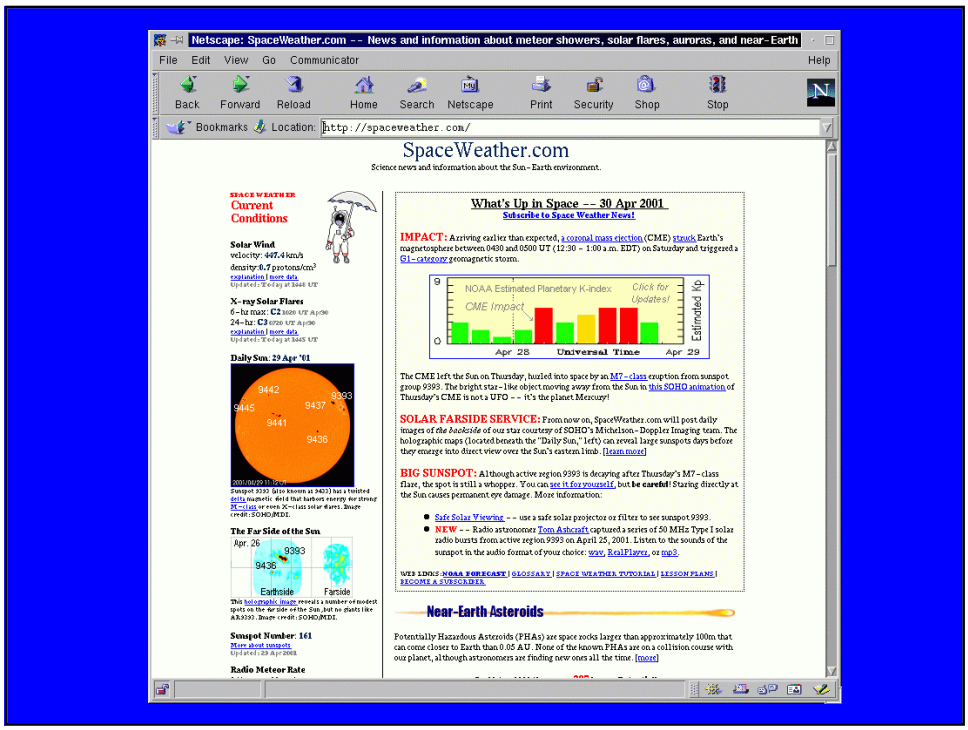
First images of the solar far side





Lindsey & Braun 2000 *Science*, **287**, 1799


Obs_2001.03.01_12h
Earthside
Obs_2001.04.11_00h
Earthside
Obs_2001.03.15_00h
Earthside
Obs_2001.04.24_12h
Earthside
Obs_2001.03.28_12h
Earthside
http://soi.stanford.edu/data/farside


Netscape: SpaceWeather.com -- News and information about meteor showers, solar flares, auroras, and near-Earth
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Bookmarks Location: http://spaceweather.com/
SpaceWeather.com
Science news and information about the Sun-Earth environment.
Current Conditions
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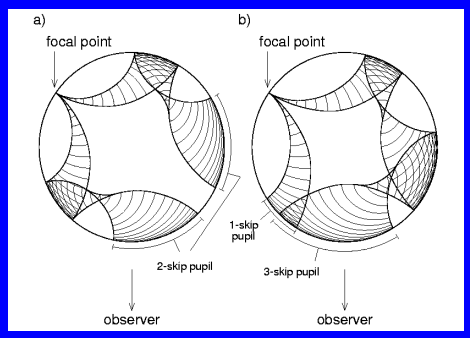
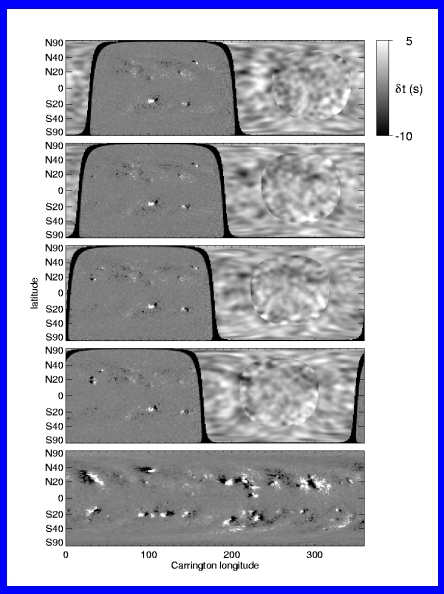
IMPACT: Arriving earlier than expected, a coronal mass ejection (CME) struck Earth's magnetosphere between 0430 and 0500 UT (12:30 - 1:00 a.m. EDT) on Saturday and triggered a G1-category geomagnetic storm.
NOAA Estimated Planetary K-index
Click for Updates!
CME Impact
Estimated Kp
Apr 28 Universal Time Apr 29
The CME left the Sun on Thursday, hurled into space by an M7-class eruption from sunspot group 9393. The bright star-like object moving away from the Sun in this SOHO animation of Thursday's CME is not a UFO -- it's the planet Mercury!
SOLAR FARSIDE SERVICE: From now on, SpaceWeather.com will post daily images of the backside of our star courtesy of SOHO's Michelson-Doppler Imaging team. The holographic maps (located beneath the "Daily Sun," left) can reveal large sunspots days before they emerge into direct view over the Sun's eastern limb. [learn more]
BIG SUNSPOT: Although active region 9393 is decaying after Thursday's M7-class flare, the spot is still a whopper. You can see it for yourself, but be careful! Staring directly at the Sun causes permanent eye damage. More information:
Safe Solar Viewing -- use a safe solar projector or filter to see sunspot 9393.
NEW -- Radio astronomer Tom Ashcraft captured a series of 50 MHz Type I solar radio bursts from active region 9393 on April 25, 2001. Listen to the sounds of the sunspot in the audio format of your choice: wav, RealPlayer, or mp3.
WEB LINKS: NOAA FORECAST | GLOSSARY | SPACE WEATHER TUTORIAL | LESSON PLANS | BECOME A SUBSCRIBER.
Near-Earth Asteroids
Potentially Hazardous Asteroids (PHAs) are space rocks larger than approximately 100m that can come closer to Earth than 0.05 AU. None of the known PHAs are on a collision course with our planet, although astronomers are finding new ones all the time. [more]
Daily Sun: 29 Apr '01
The Far Side of the Sun
Sunspot Number: 161
Radio Meteor Rate

Increasing farside coverage



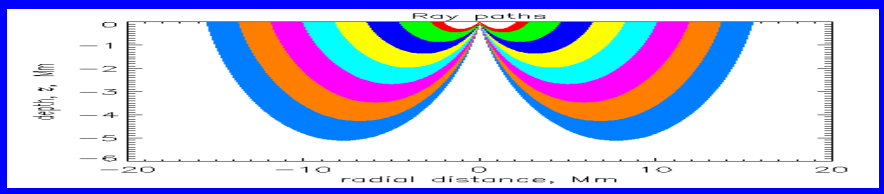


Braun & Lindsey (2001, *ApJ*, **560**, L189)

Time-distance Modeling

Ray Approximation (Kosovichev 1996, *ApJ*, **461**, L55)

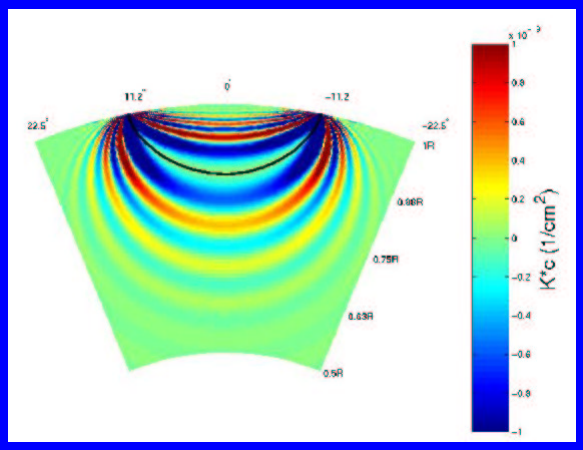
$$\delta t = -\int_{\Gamma} \frac{\delta w}{w}\left(\frac{k}{\omega}\right) ds \qquad \frac{\delta w}{w} = \frac{\delta c}{c} + \frac{1}{2}\frac{c_a^2}{c^2} + \cdots$$



Born approximation

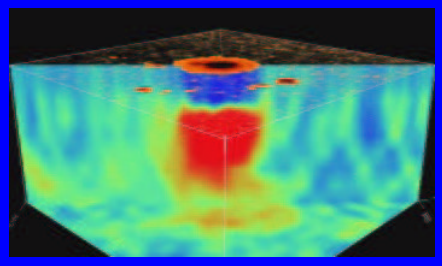
Birch & Kosovichev (2000, *Sol Phys* **192**, 193)

$$\delta t = \int_V K(\mathbf{x}) \frac{\delta w}{w} d^3\mathbf{x}$$



Ray-approximation inversions

Kosovichev, Duvall & Scherrer (2000, *Sol Phys*, **192**, 159)

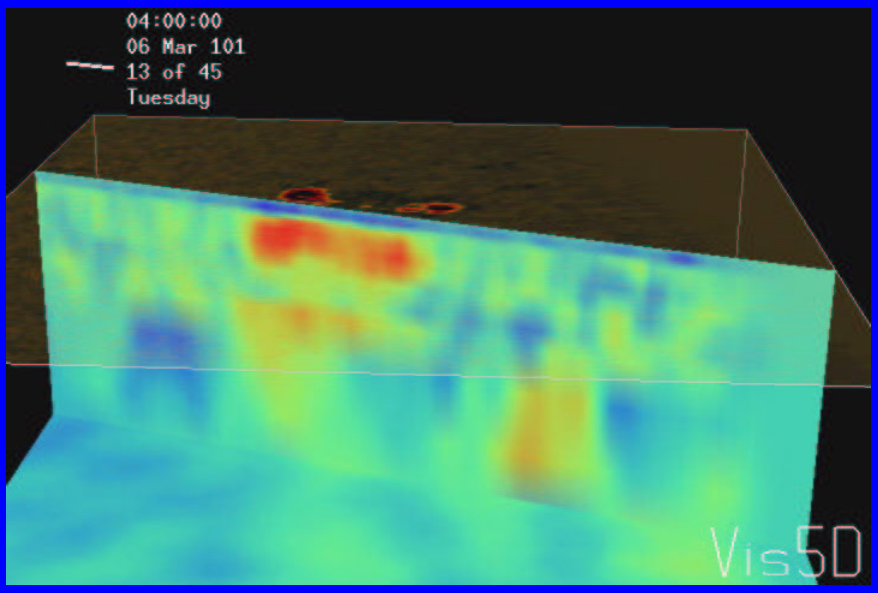


15 Mm

150 Mm

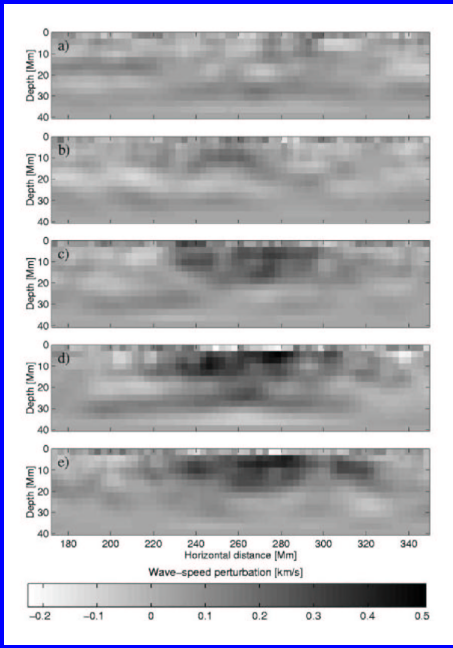
δw ~ 1 km/s at 4 Mm depth: δT ~ 3000K or B ~ 20,000 G

Kosovichev, et al. (2001 Fall AGU meeting, San Francisco)



Emerging Active regions

Jensen, et al. (2001 *ApJ*, **553**, L193)



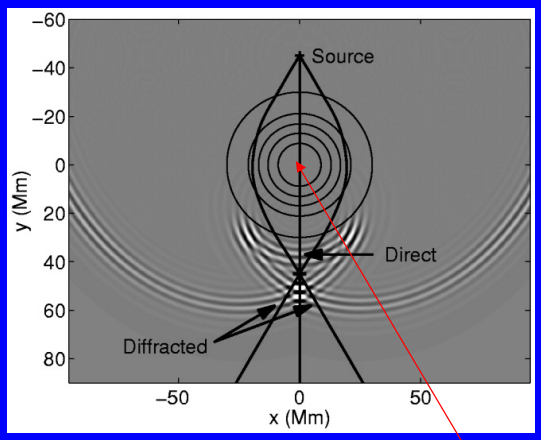
Controversies

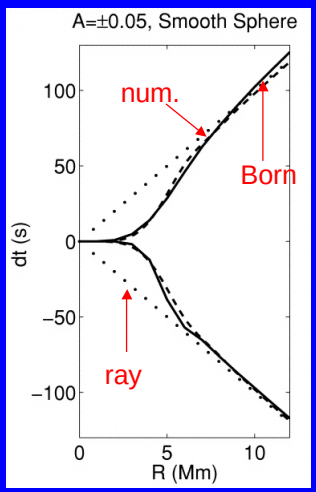
- Acoustic stalactites
- No isolated subsurface perturbations
- Deep perturbations seem too big
- Contamination of sunspot signal
- Oversimplified models & assumptions

Numerical analyses

- Predict and understand seismic signatures
  - e.g. p-mode absorption
- Test basic assumptions
  - Born, ray approximations
- Provide artificial data
  - Hare and hounds exercises

Test of Born and ray approximations

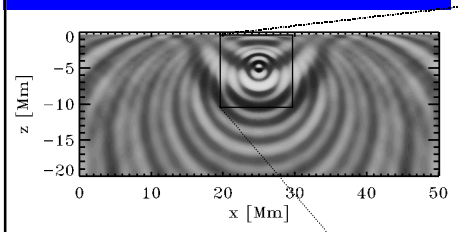


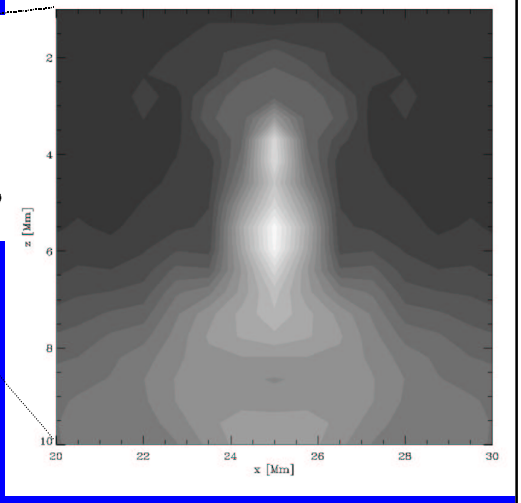


Birch, et al. (2001, *ApJ* **561**, L229)

δc/c=cosine-bell perturbation with peak amplitude=A, HWHM=R

Numerical simulations of holography





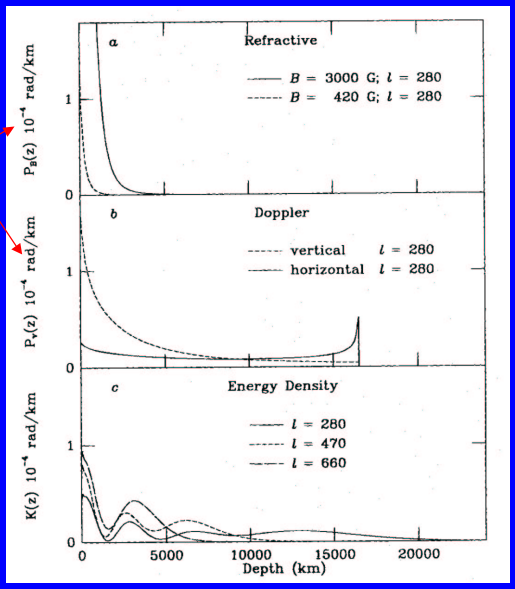
Barnes & Cally (2001, *Publ. Astron. Soc. Aust.*, **18**, 243)

Doppler diagnostics

Lindsey et al. (1996, ApJ, **470**, 636)

Phase-contribution functions

horizontal Doppler diagnostics are relatively less (more) sensitive to surface (subsurface) perturbations than refractive or vertical flow diagnostics



Conclusions

- Observations (mostly) robust
- Interpretations (sometimes) controversial
- Understand forward problem before inversions
- Doppler signatures may provide best subsurface diagnostic
- Numerical analyses will likely be crucial in testing and improving methods