Seismology of sunspots: old needs, new ~~ideas~~ and new needs.

developments

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Introduction - old ideas and needs

Discussion of existing results and issues --
'surface magnetic effects'

Some new time-distance helioseismic measurements --
deep focus geometry

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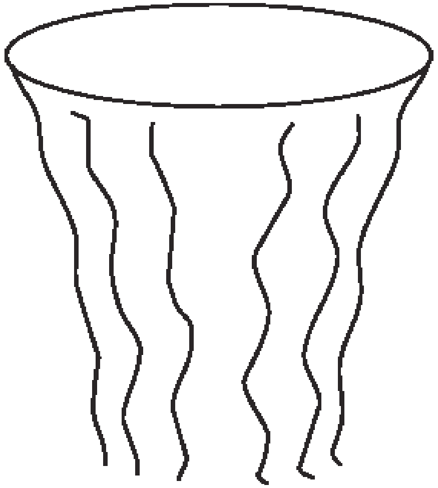
Introduction

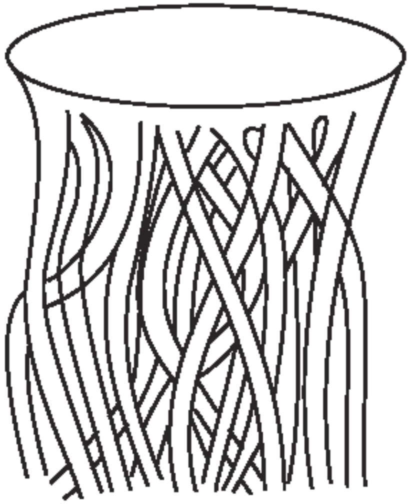
Old ideas - origin of sunspot seismology

The suggestion (Thomas et al. 1982, Nature) that the sunspot - p mode interactions could be used to probe the sub-surface structure of sunspots gave birth to the field of sunspot seismology.

Old needs:

monolithic flux tube ? or a cluster of flux tubes?

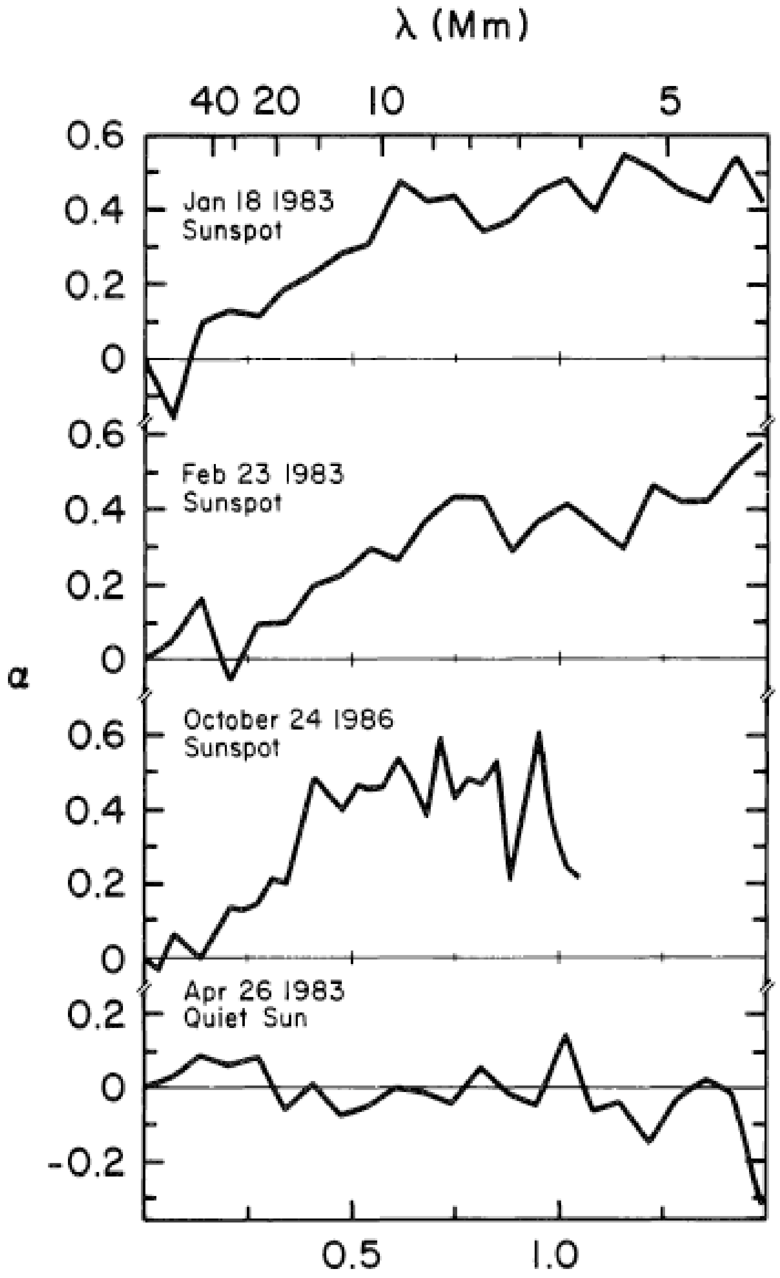

Cowling (1957)


Parker (1979)

- analyses mainly based on changes in the freq. - wavenumber spectrum (ν - k) and changes in modal power
- absorption of p modes by sunspots (Braun, Duvall & LaBonte 1987)
- efforts to model the magnetic field - p mode interactions

Introduction (contd.)

Absorption of p modes by sunspots (Braun, Duvall & LaBonte 1987)



$$\alpha = [P_{\rm in}(k) - P_{\rm out}(k)]/P_{\rm in}(k)$$

Much of the early work (Spruit, Bogdan and Thomas, 90's) focussed on understanding and explaining the mechanisms responsible for the absorption of p modes by sunspots.

Introduction (contd.)

Major developments:

Introduction of time-distance helioseismology (Duvall et al. 1993, Nature) made possible 3-dimensional tomographic inversion of subsurface layers of sunspots (Kosovichev et al. 2000, Sol. Phys., Zhao et al. 2001, ApJ). Large positive sound speed perturbations extending down to about 18 Mm were imaged.

Subsequent development of helioseismic holography (Lindsey & Braun, 1990's) has contributed to emphasising the dominant magnetic and shallow contributions to seismic measures.

Recently, ring diagrams (Antia, Basu, Howe, Hindman et al.), i.e. 3-d power spectra, have been used to analyse sunspot regions, and 1-d inversions for sound speed and flows have been performed (Basu, Antia and Bogart 2007)

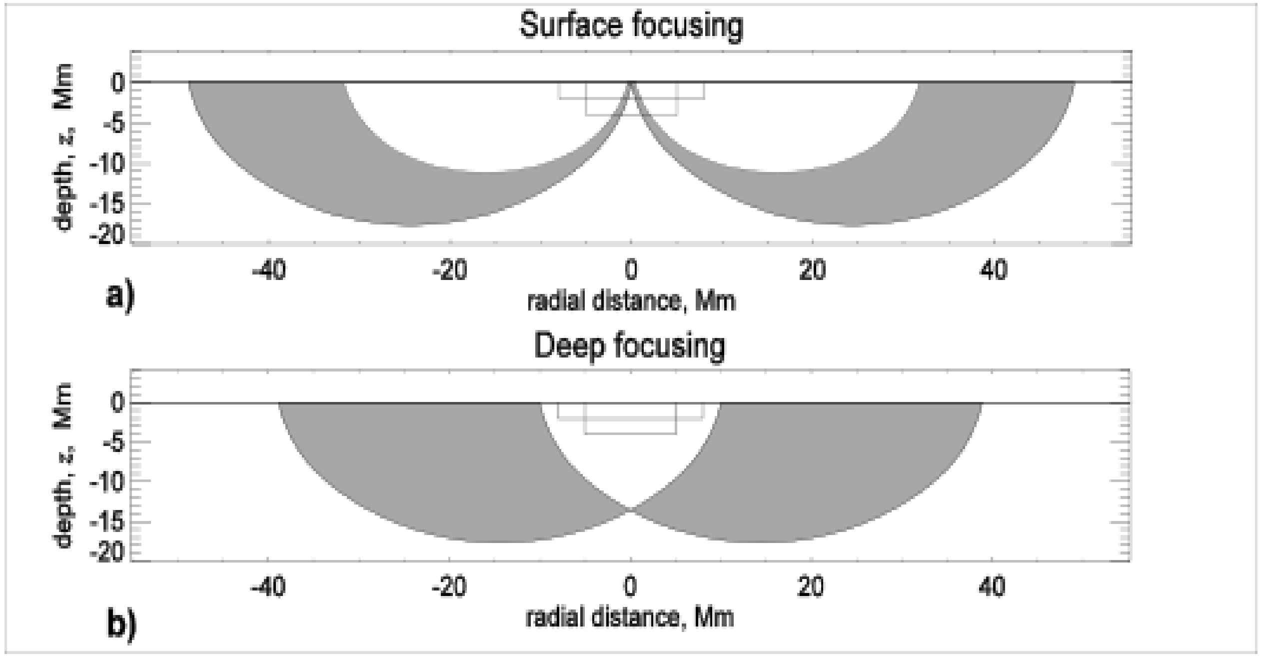
Time-distance helioseismology

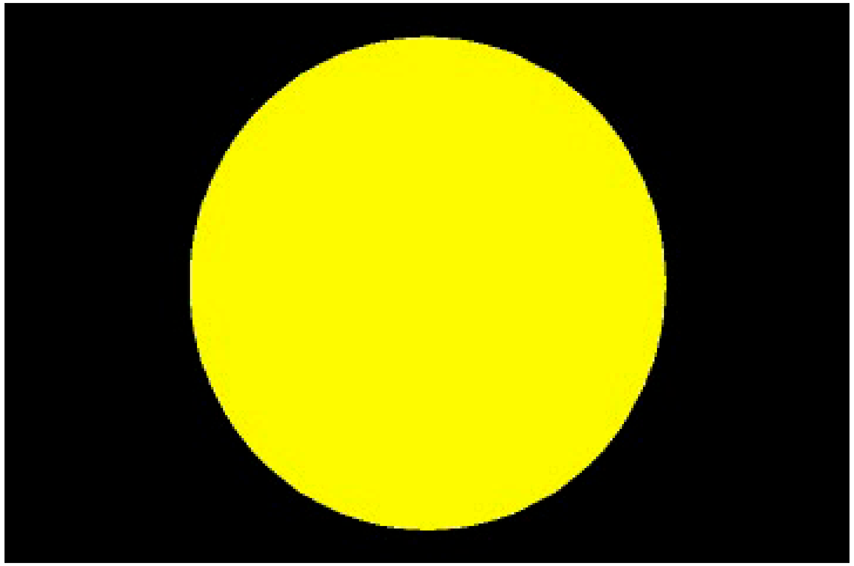
Basic measures are travel times of acoustic wave packets – formed out of resonant p-modes – travelling between two surface locations via a curved path through the interior.

The basic data are time-series of Doppler images of target regions.

Travel times are estimated from the temporal cross-correlation of oscillation signals observed at separated surface locations.

Map the travel times over a region of interest and invert them using models of wave-propagation perturbation in sound speed and flow.





Cross-Correlations and Travel times

Centre-Annulus correlations,

$$C(\tau, \Delta) = \int_0^T f(t) f(t + \tau, \Delta)\, dt$$

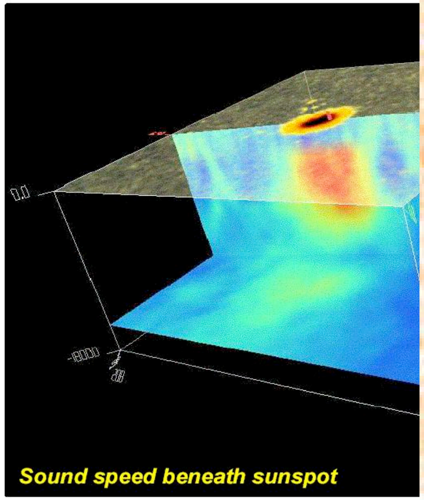
f(t) - oscillation signal at the centre point
f(t + τ, Δ) – signal averaged over an annulus of radius Δ

Travel times are measured by fitting a Gabor wavelet to C(t,Δ),

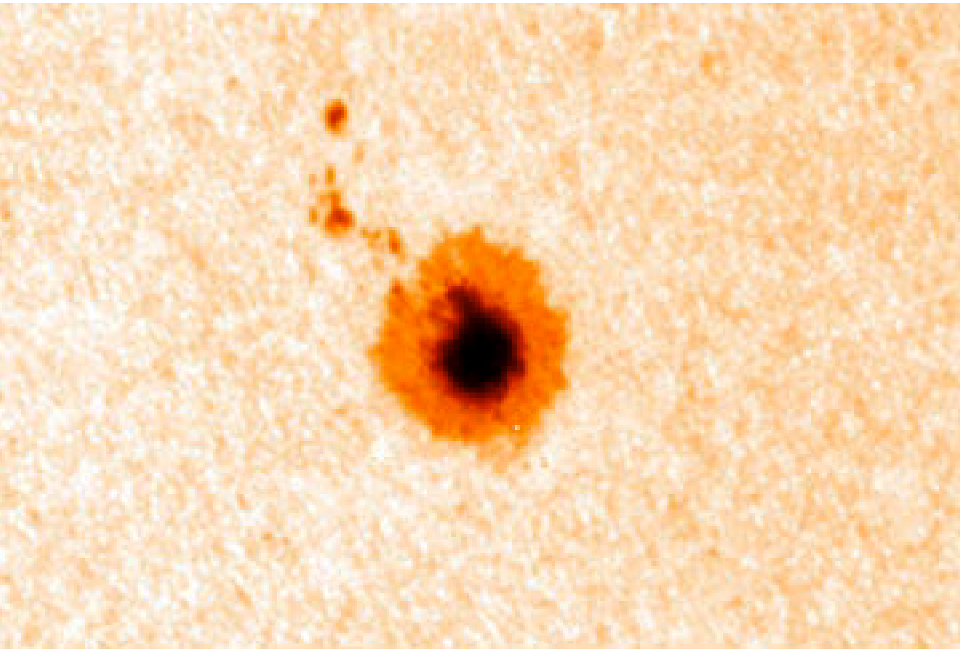
$$G(\tau) = A \cos\left[2\pi\nu(\tau - \tau_{\mathrm{ph}})\right] \exp\left[-\frac{(\tau - \tau_{\mathrm{en}})^2}{2\sigma^2}\right]$$

Existing Results and Problems

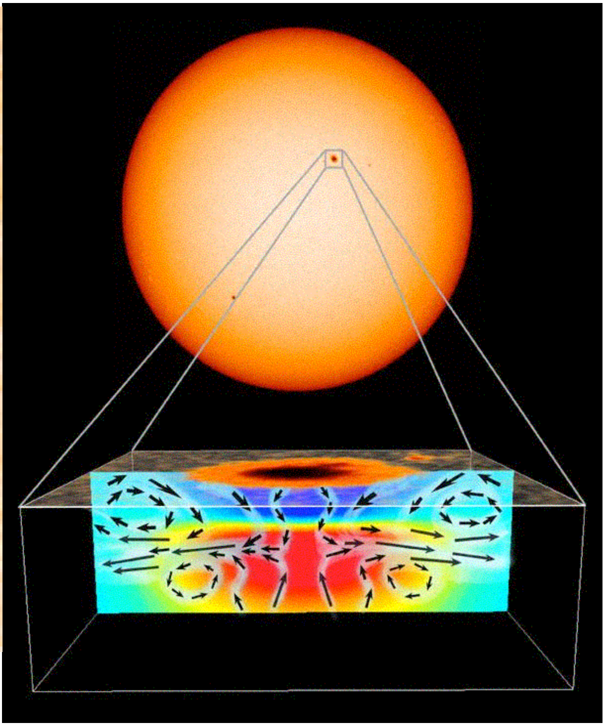
Sound speed perturbation



Sunspot data from MDI High Resoluti



Flows



A two-region structure:

a smaller sound speed shallow region above a faster sound speed region that extends down to about 18 Mm.

Converging surface flow feeds a downflow beneath the spot.

From: Kosovichev et al. 2000, Sol.Phys. and Junwei Zhao et al. 200,
Movies from URL: http://soi.stanford.edu

Problems: new developments and ideas

- ‘surface magnetic effects’, mostly from helioseismic holography measurements (Schunker et al. 2005, Lindsey & Braun 2006, Zhao & Kosovichev 2006, Braun & Birch 2006).

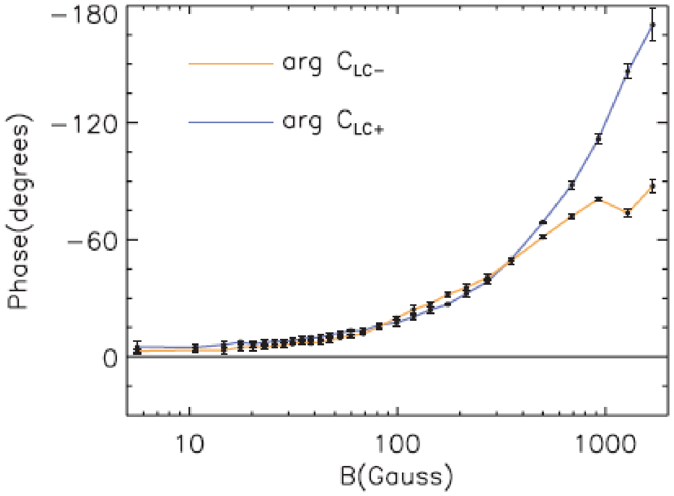
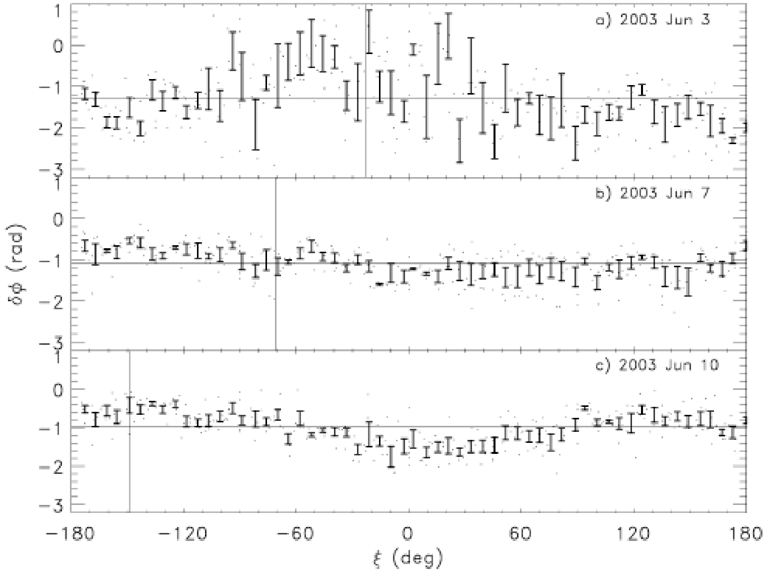


Fig. 7.—Plots of the arguments of C_{LC-} (*yellow*) and C_{LC+} (*blue*) from the diagnostic curves plotted in Figs. 4 and 5.



Schunker et al. 2005 ApJL.

Freq. dependent travel times.

(Braun & Birch, 2006 ApJL)

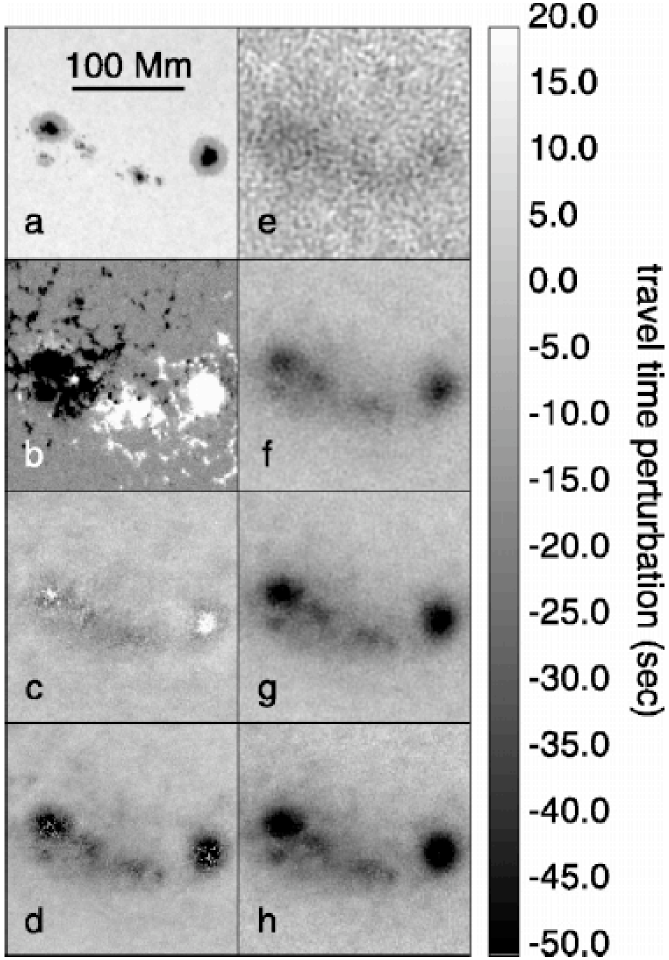


FIG. 1.—(*a*) MDI intensity, (*b*) line-of-sight magnetogram, and (*c*–*h*) sample maps of the mean travel-time perturbation covering a portion of the region studied and showing sunspot group AR 9885. Panels *c* and *d* show travel-time maps for filter C at 3 and 4 mHz, respectively (see Table 1). Panels *e*–*h* show the travel-time maps for filter E at 2, 3, 4, and 5 mHz, respectively.

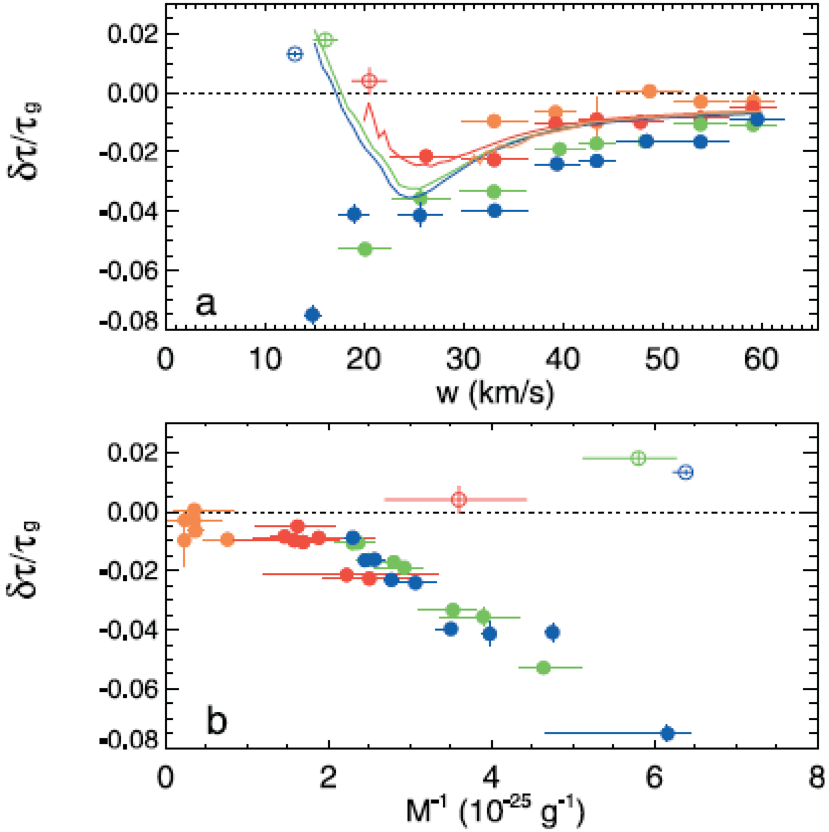
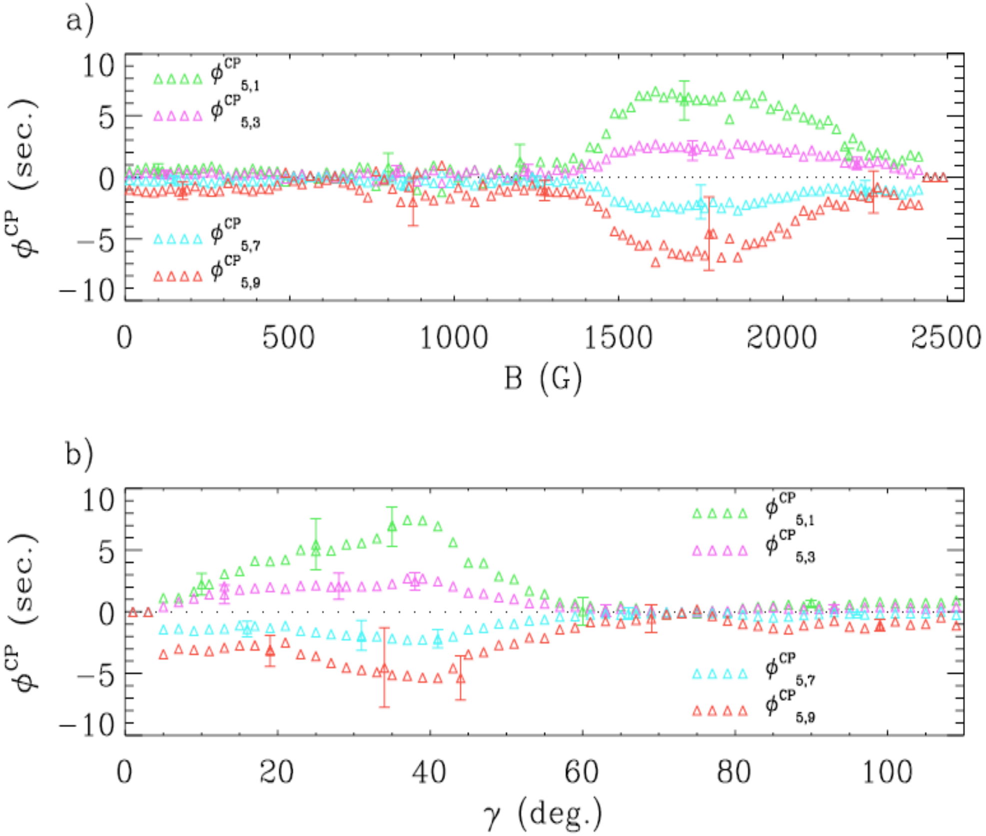
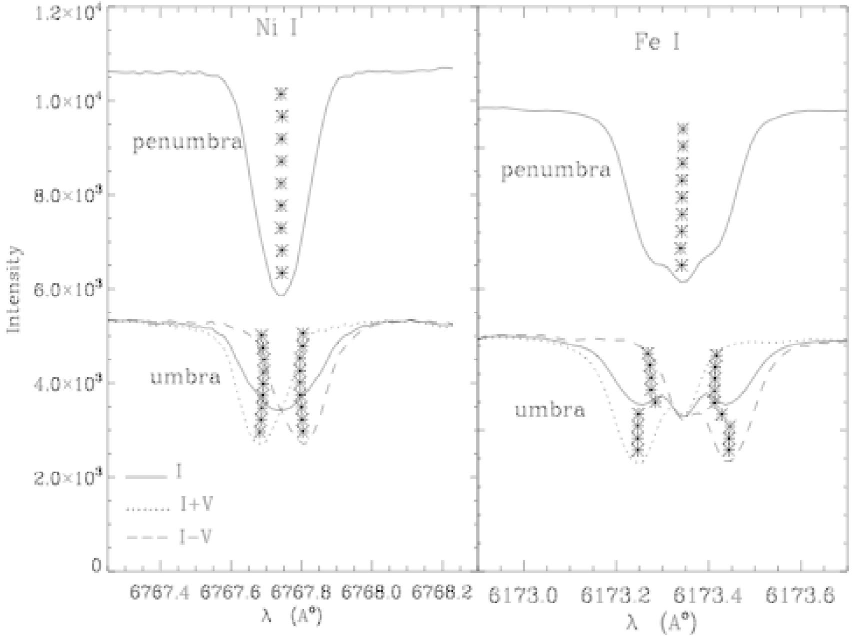


FIG. 3.—(*a*) Mean travel-time perturbations, averaged over all sunspot umbrae in the four spot groups observed, divided by the group travel times as functions of the phase speed w, where the orange, red, green, and blue symbols indicate results for $\nu_0 = 2$, 3, 4, and 5 mHz, respectively. The open circles indicate the filter and frequency combinations which are dominated by the p_1-mode. Horizontal bars indicate the range of w present within the filter and frequency bandpass, and the vertical bars indicate the standard deviation of the mean. The colored lines indicate the predicted values computed from a sound-speed proxy (see text), where the colors indicate the same ν_0 as the observations. (*b*) Fractional travel-time perturbations as a function of the inverse of the mean mode mass.

- radiative transfer effects on Doppler measurements (Rajaguru et al. 2007)

Phase shifts between mid-level (5) and other bisector levels in CP against B and gamma





Propagating waves in the observable layers introduce additional phase-shifts, which if not accounted for, could manifest as sub-surface physical signals in helioseismic inversions.

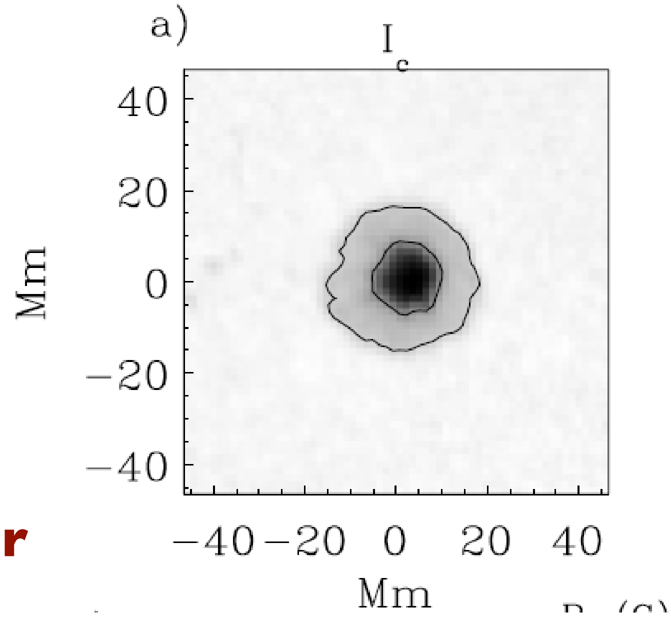
- phase speed filter effects that couple strong amplitude variation over a sunspot region with Fourier fltering procedure leading to artificial travel time signals (Rajaguru et al. 2006)

All of the above listed effects are not due to seismic or sub-surface perturbations!

So, all local helioseismic inferences, which do not account for them in the inversion procedures, i.e. all existing results on sub-surface structure and dynamics of sunspots, have serious flaws.

New time-distance helioseismic measurements

Frequency dependence of travel times

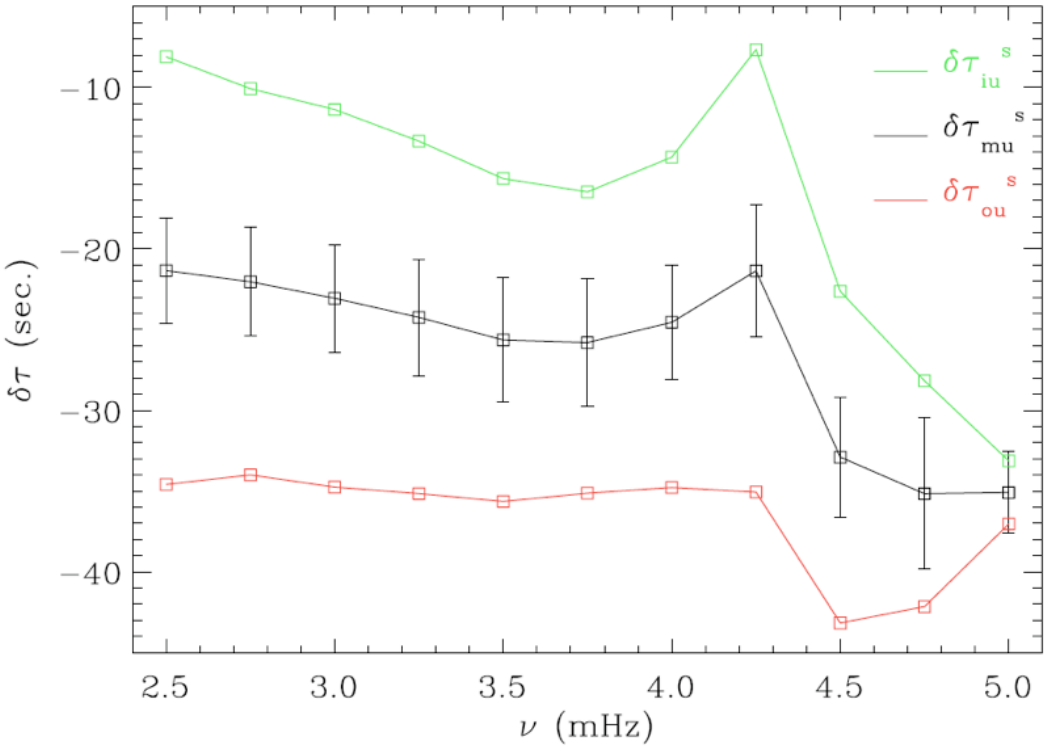


A large sunspot in NOAA AR9057,
observed by SOHO/MDI on 28 Jun, 2000.

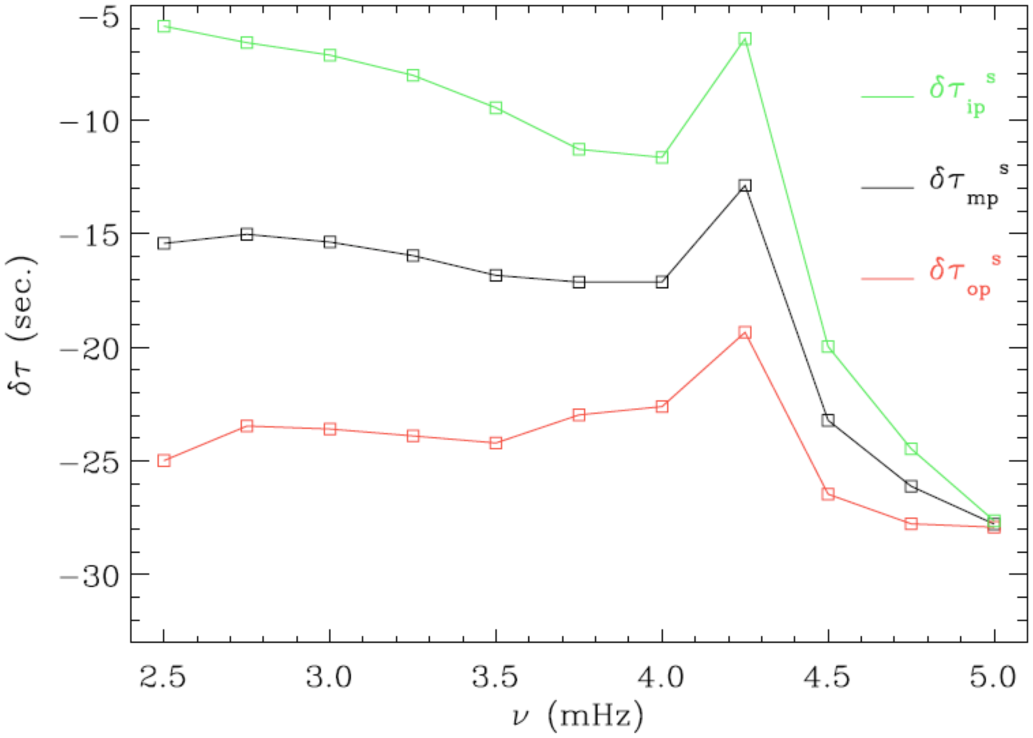
Travel time perturbations for a travel distance Δ = 50 Mm

Signatures of freq. dependent p mode absorption? or just leakage of p modes?

Umbral Averages



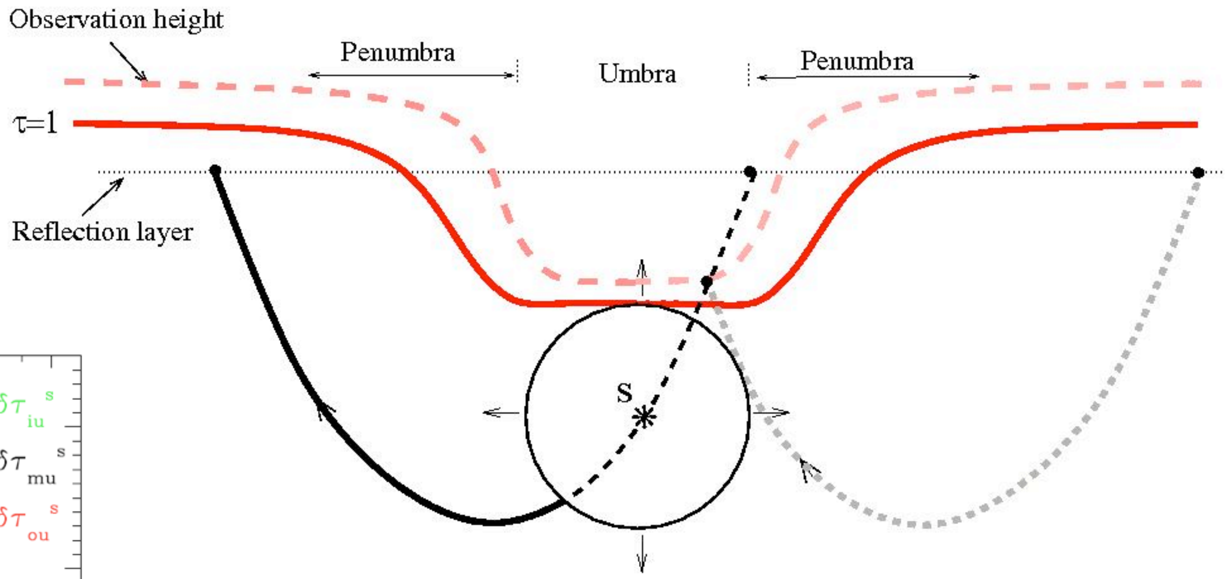
Penumbral Averages

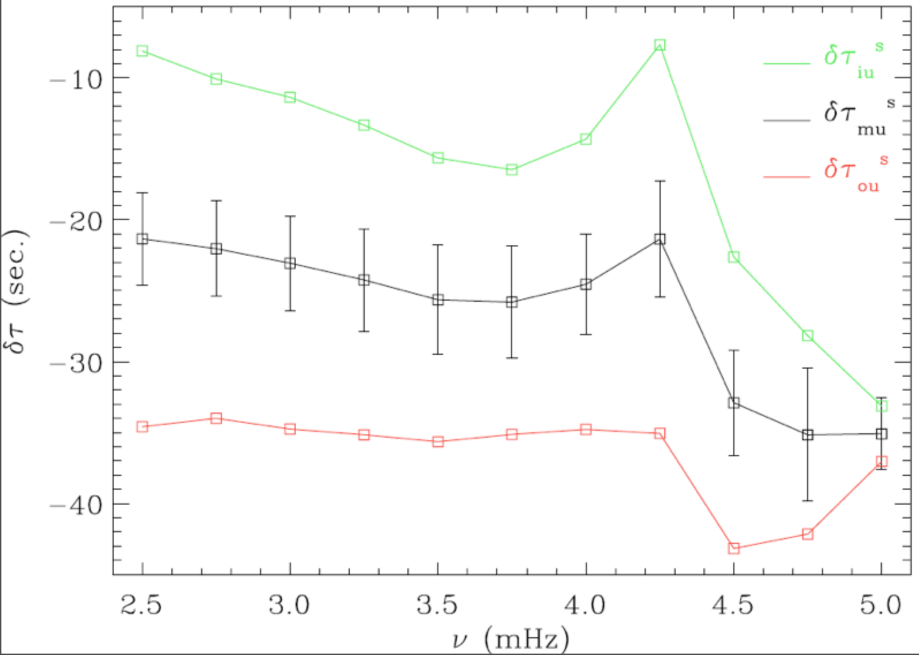


Can acoustic sources beneath umbral photospheres explain the travel time asymmetries and frequency dependences?

Claerbout's Conjecture:

"In the presence of a homogeneous distribution of stochastic wave-field, cross-correlation of signals from two spatially separated points corresponds to a source-receiver correlation".

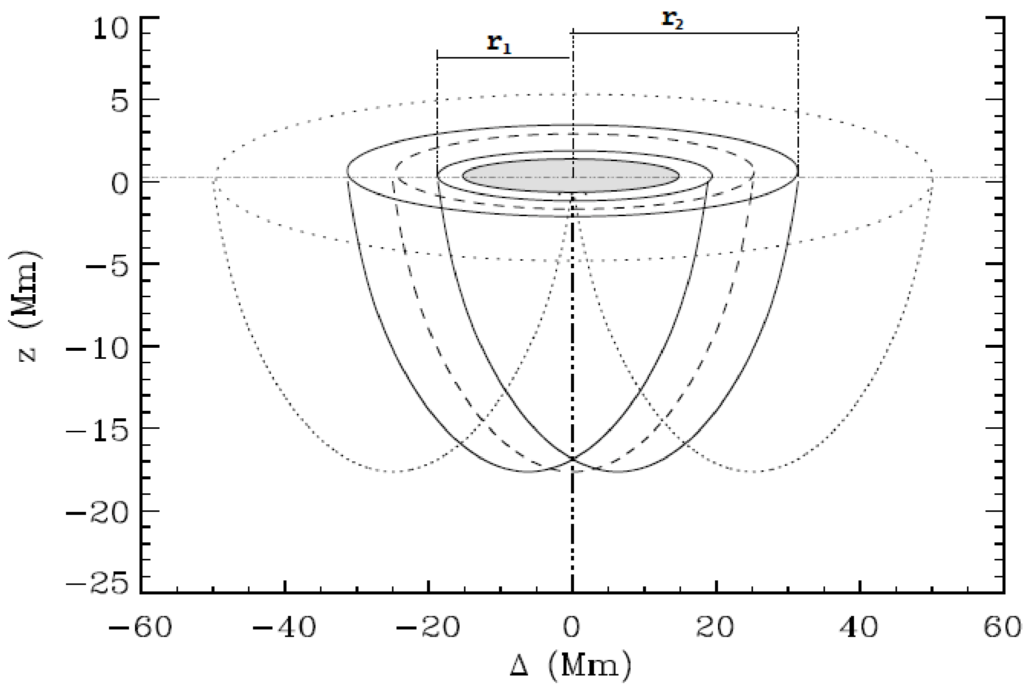




Deep focus and double-skip geometries

- measurements designed to avoid using oscillations observed within sunspots.
- deep focus geometry
- more appropriate characterization of ‘surface magnetic contributions’

Ref.: Rajaguru, S.P., 2008 ApJL (under review)



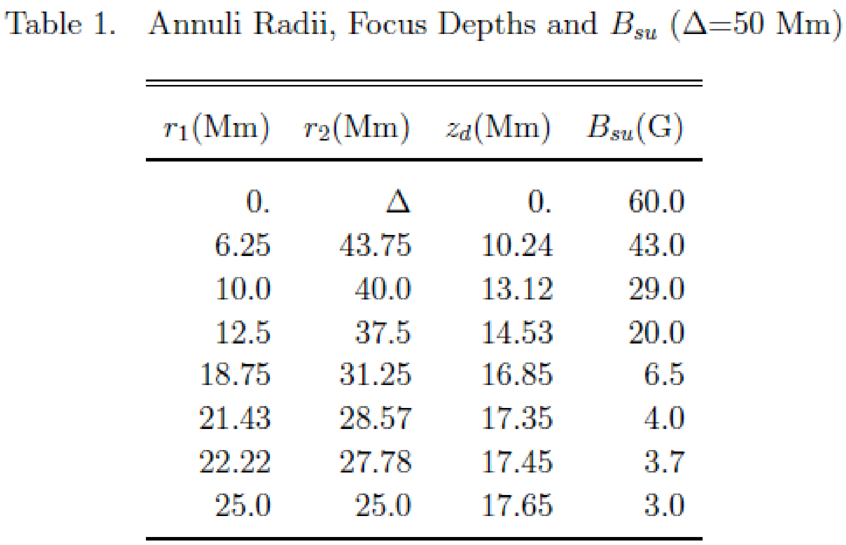
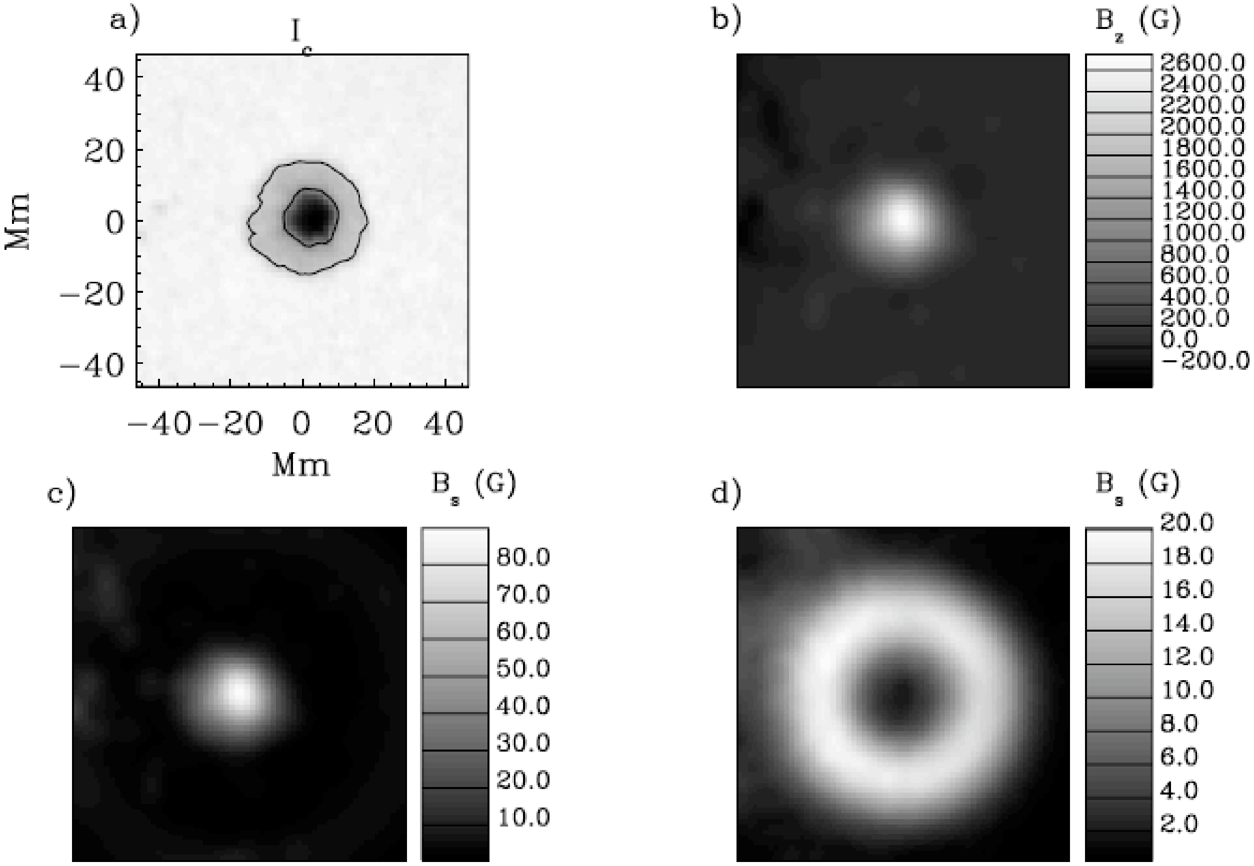


Table 1. Annuli Radii, Focus Depths and B_{su} (Δ=50 Mm)

r_1(Mm)	r_2(Mm)	z_d(Mm)	B_{su}(G)
0.	Δ	0.	60.0
6.25	43.75	10.24	43.0
10.0	40.0	13.12	29.0
12.5	37.5	14.53	20.0
18.75	31.25	16.85	6.5
21.43	28.57	17.35	4.0
22.22	27.78	17.45	3.7
25.0	25.0	17.65	3.0

Fig. 1.— Ray-path diagram depicting the surface- and deep-focus measurement geometries: the ray paths correspond to model S of Christensen-Dalsgaard et al. (1996). Dotted lines correspond to the well-known center-annulus geometry, and solid and dashed lines correspond to annulus-annulus deep focus geometry with q=0.6 and 1 (focus at the lower turning point), respectively



A new surface magnetic proxy, which is a weighted convolution of B over measurement pixels,

$$B_s(x,y) = \int a(x-x', y-y') B(x', y') w(r) dx' dy'$$

Variation of travel times against surface magnetic proxy

Signatures of a deep seated, increased sound speed region?

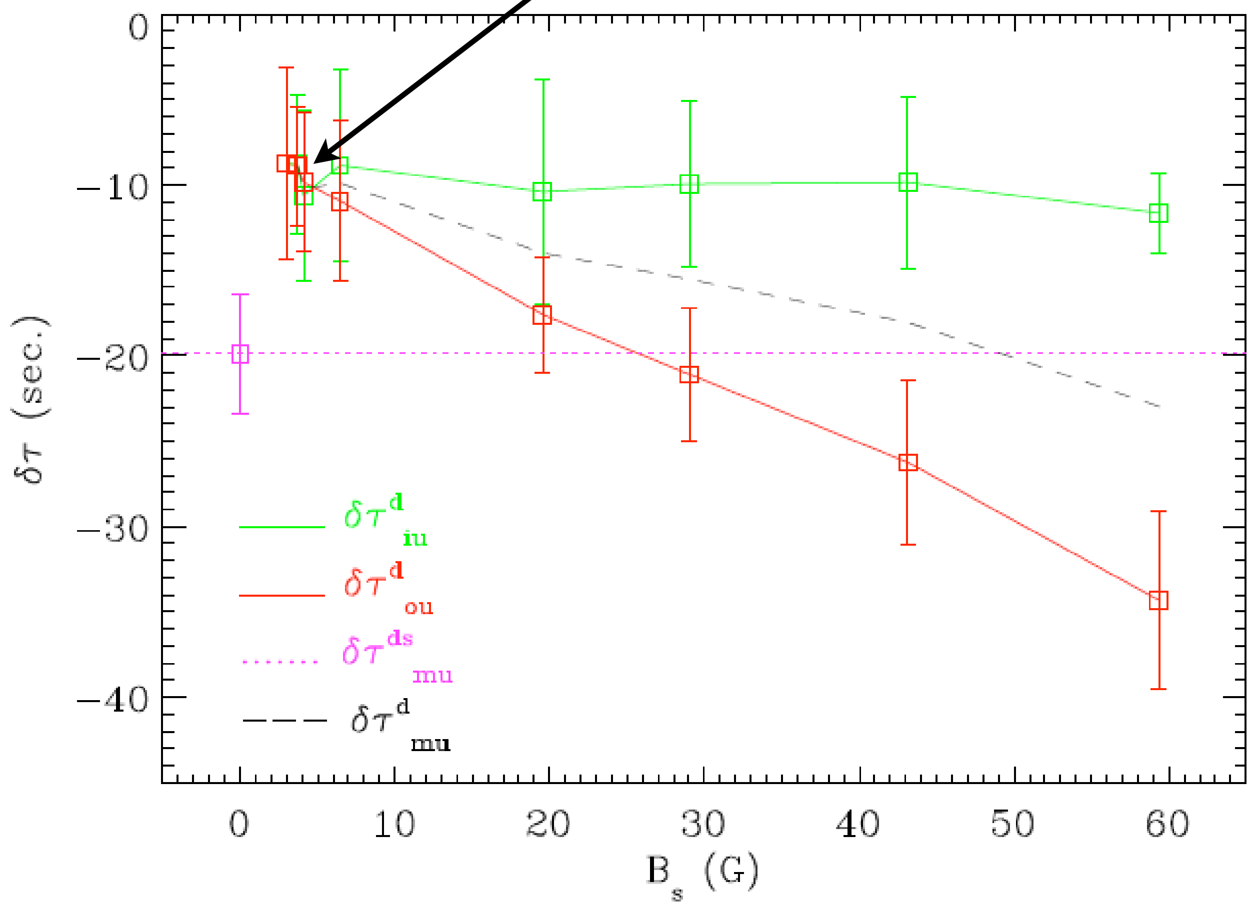
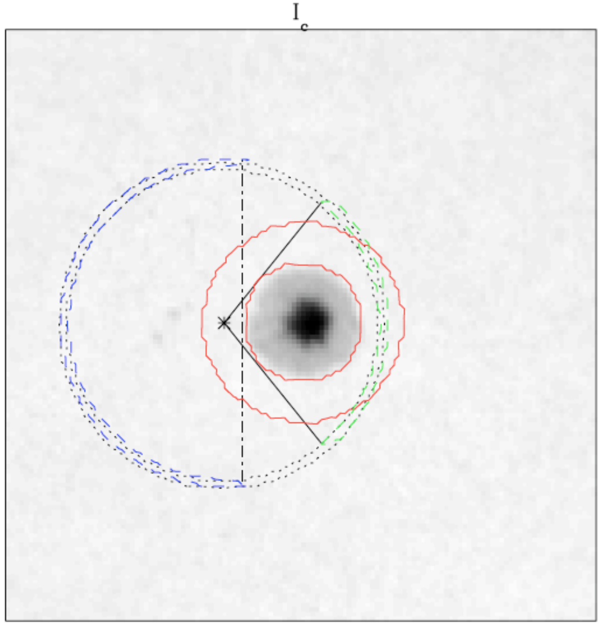
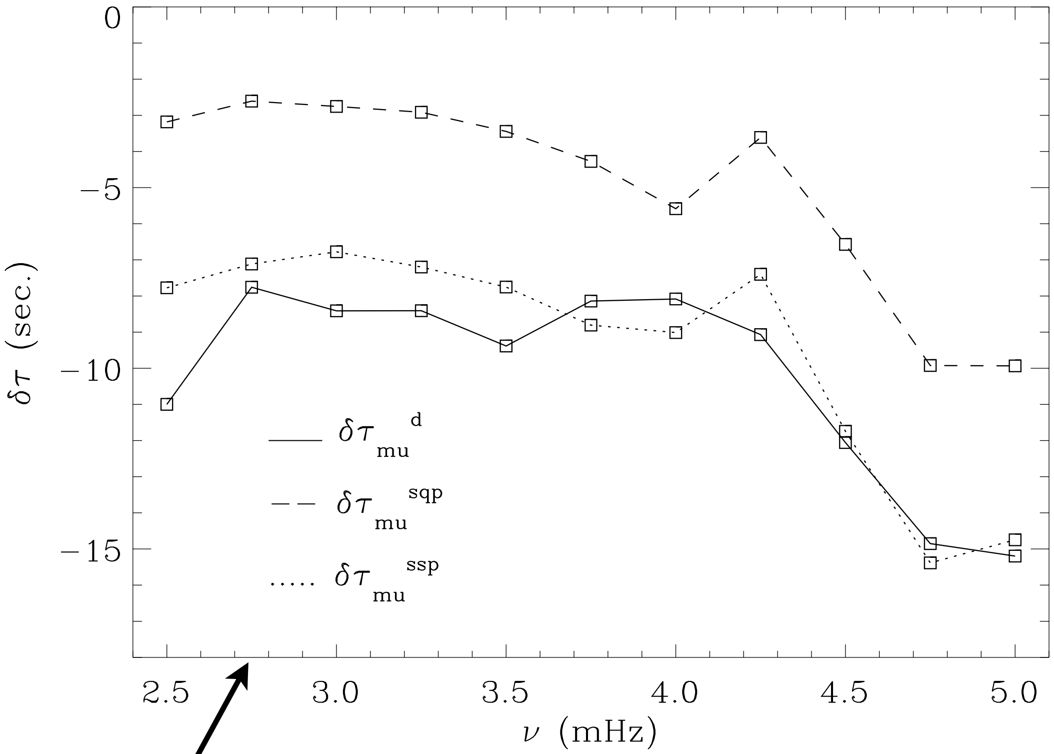
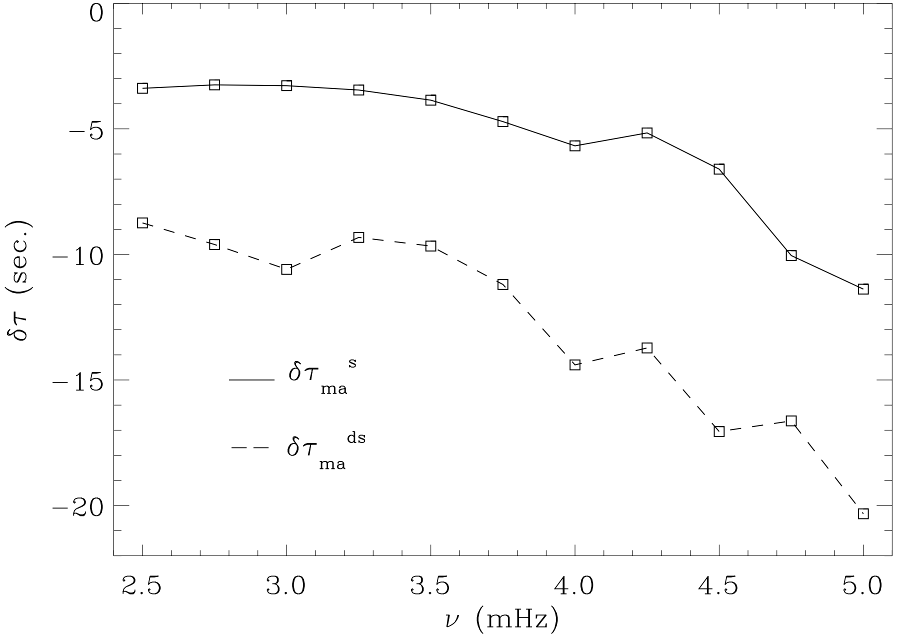


Fig. 3.— Variation of umbral area averaged one way and mean travel times against B_{su} for surface- and deep-focus geometries; see text for details.

A closer scrutiny: some more tests of surface and deep contributions (prompted by ApJL Referee's comments)







Give more credence to a presence of deep-seated increased wave speed region.

Various measurement techniques have been stretched to their limits, and limitations in observations and measurements require cross-checks and validations by means of detailed forward numerical calculations and simulations of wave propagation.

Way Forward:

- Direct Numerical Simulation
  - Realistic simulations of fully-compressible non-linear convection and magneto-convection (e.g., Stein, Nordlund & Benson 2006).
  - Generate artificial data through wave propagation simulations that mimic the generation of waves by convection (e.g., Hanasoge et al. 2006, 2007; Cameron, Gizon & Duvall 2007).

Discussions

In the absence of reliable model for sunspot - p mode interactions, an useful procedure would be to avoid oscillations observed within sunspots and try to measure possible signatures of any sub-surface perturbations beneath sunspots.

We have just attempted that and have detected significant mean travel time perturbations indicating faster wave propagation extending down to atleast about 10 - 11 Mm (with a location uncertainty of about 7.5 Mm). Control experiments using oscillation signals well outside of a sunspot add further credence to the above inferences.

However, the detected signals are weak, and possibly reflect competing influences of near-surface effects and depth gradients.

Thank You.

Analysis of the inferred sound speed changes

$\delta c/c \sim B^2/8\pi p$ for B effects, and $\delta c/c \sim 2\,\delta T/T$ for temperature changes

If only T causes all the changes in c, then a 2% change in c at 7 Mm depth would correspond to ~ 1800 K perturbation.

⇨ this magnitude in δT is too large to maintain over areas that show the inferred δc

If all the changes are due to only the magnetic field, then 2% change in c at a depth of ~ 7 Mm will correspond to a B of ~ 30 kG.

From the inferred results, we see that the positive changes in c are over an area, at any depth > 5 Mm, substantially larger than the surface area of the spot.

⇨ magnetic flux conservation does not allow that unless unemerged B ~ 30 kG are at that depth, which is again very difficult as such fields are bouyant.

⇨ however, if the B field is in the form separated thin strong fibrils spread out over the inferred areas, then they could account for inferred changes in c.