MONASH University

Science

MHD WAVES AND DIRECTIONAL EFFECTS IN SUNSPOTS

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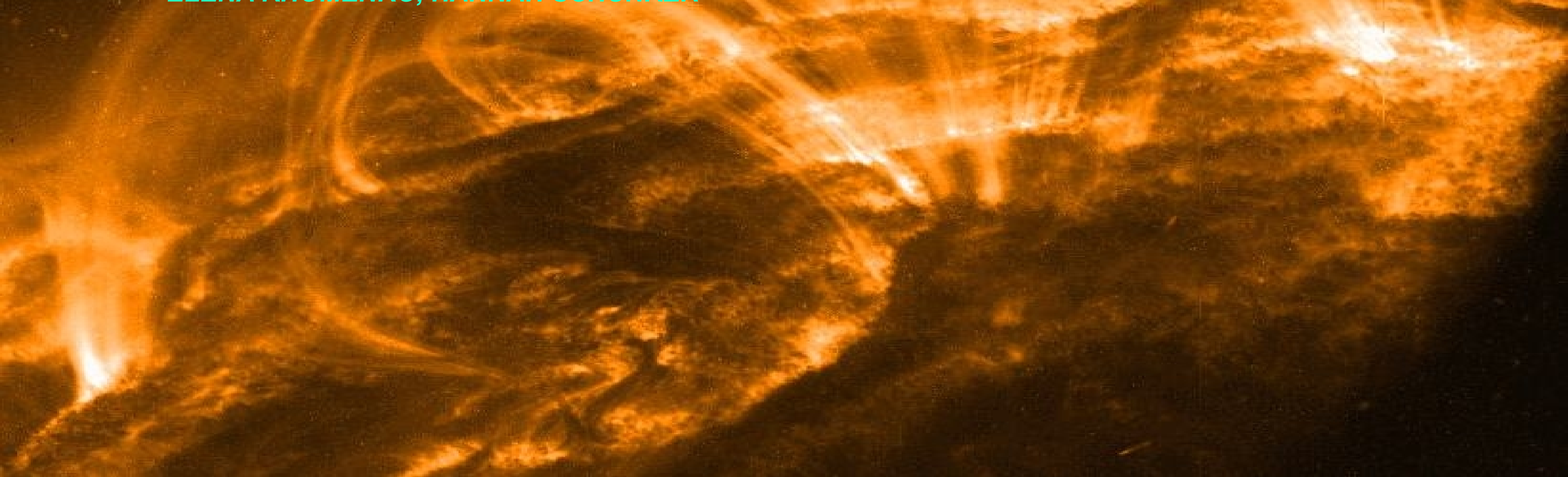

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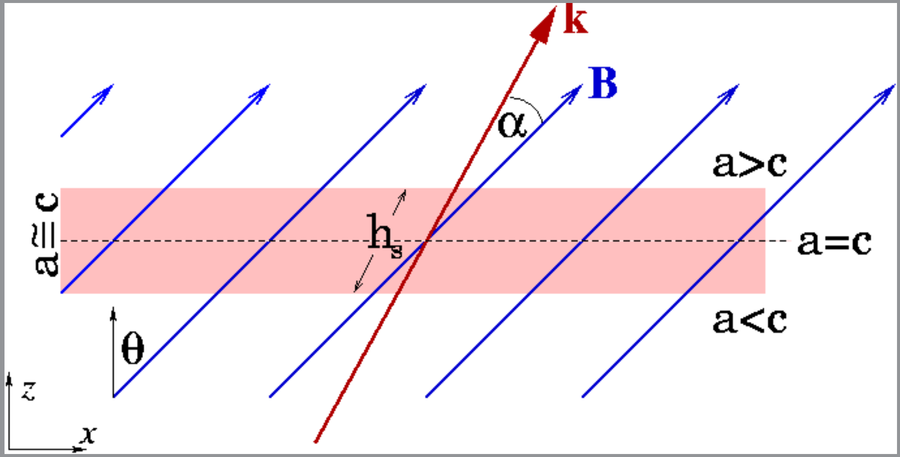
Section 1 Directional Basics



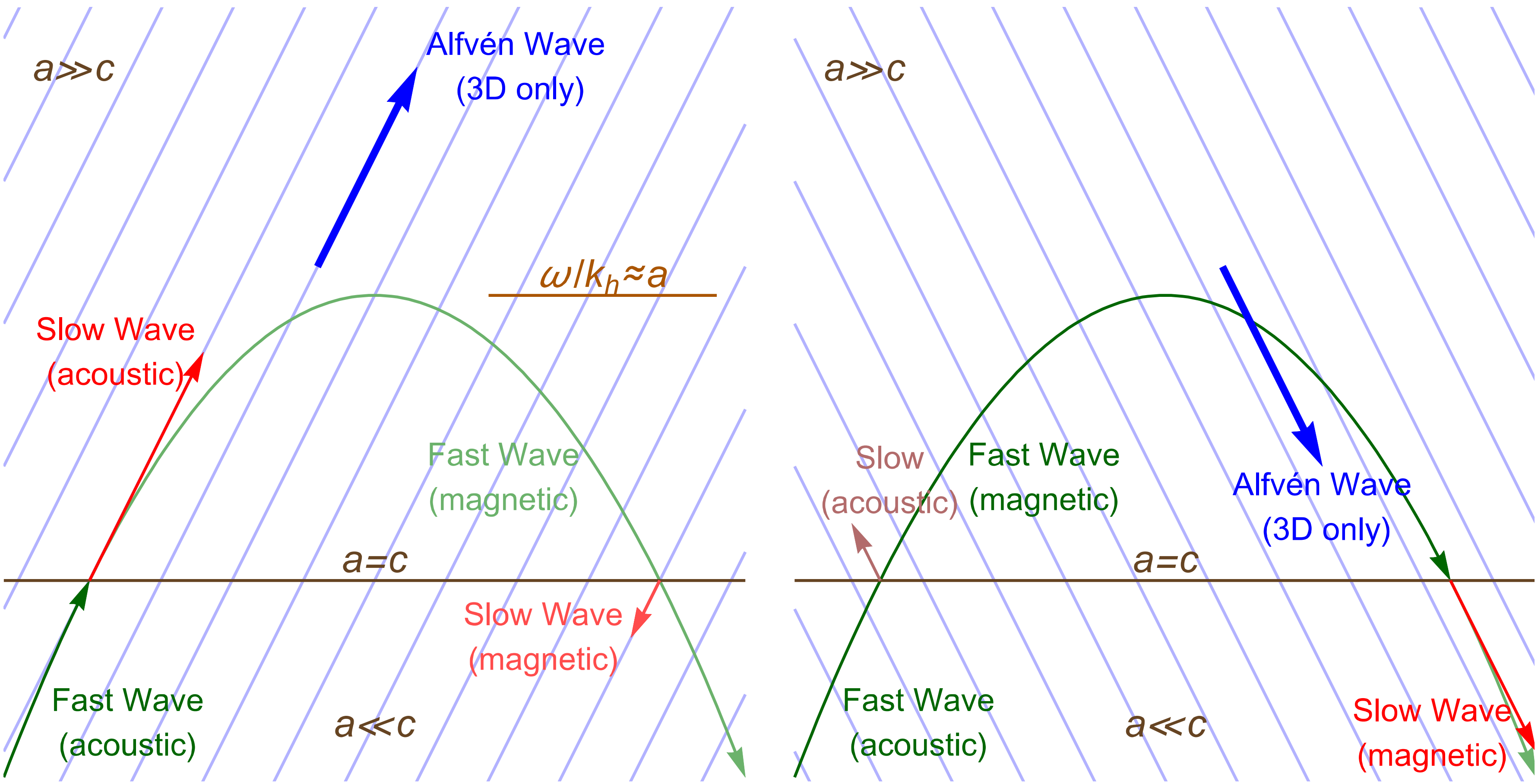
Fast-to-slow transmission/conversion

$$T = \exp\left[-\pi |\mathbf{k}| h_s \sin^2 \alpha\right]_{a=c}$$

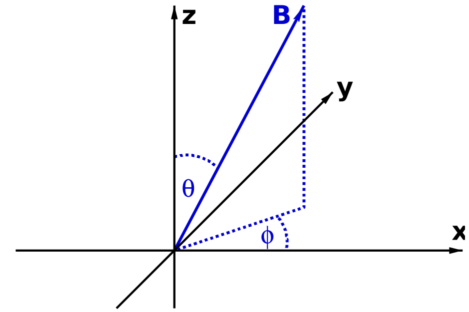
Transmission (acoustic-to-acoustic; simplified)

See e.g., Schunker & Cally 2006)

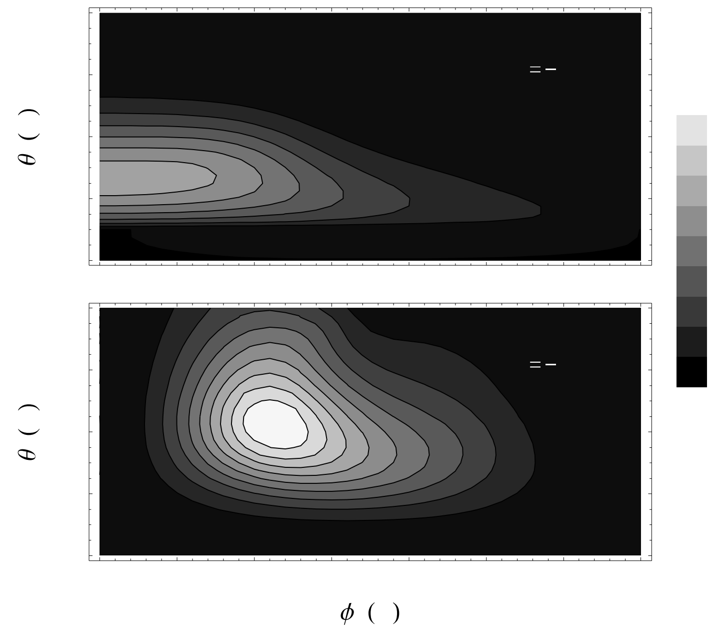
Schematic of Conversion/Transmission/Reflection



Acoustic and Magnetic Losses



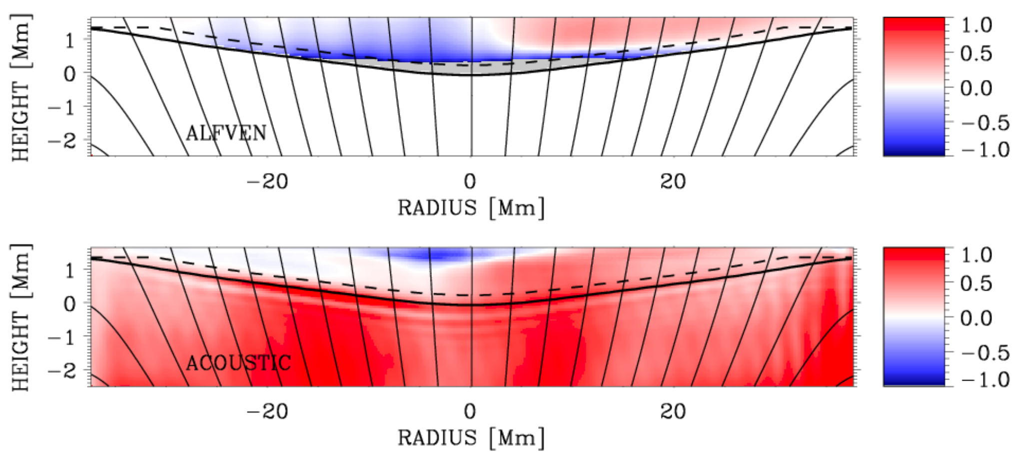
- Cally & Goossens (2008)
  - Uniform inclined field 2kG
  - Model S + isothermal "chromosphere"
  - Acoustic driver at -5 Mm
  - k_x = 1.37 rad Mm^{-1}
  - Calculate wave energy flux escaping at top
  - Strong dependence on direction θ, ϕ



Sunspot model

- Application to “realistic” sunspot models confirms Alfvén conversion
  - Khomenko & Cally (2012) – 2.5D
  - Felipe (2012) – 3D

- 5 mHz k_x=1.37 rad Mm^{-1} seismic wave
- Converts to fast at a=c (full line)
- Reflects beyond ω/k_x=a
- Alfvén wave flux shows expected directionality dependent on field inclination



K & C (2012): 5 mHz

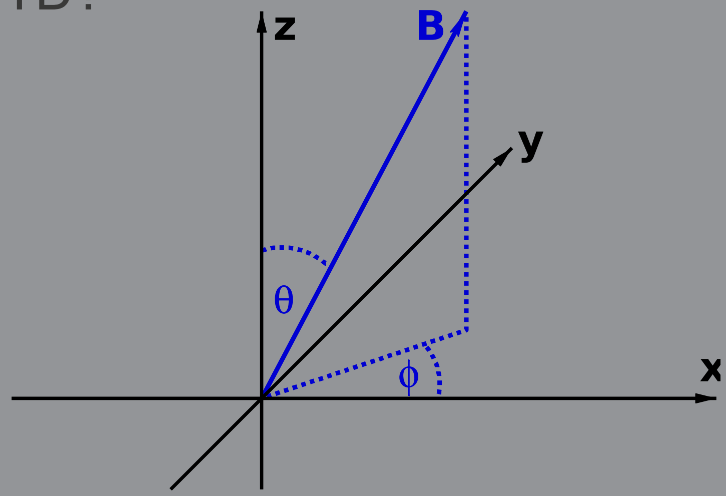
Note distorted aspect ratio

But does any of this affect the internal seismology of the Sun?

SECTION 2 CONSEQUENCES FOR SEISMOLOGY

Simple Model

- Model solar atmosphere with uniform inclined field
- Inclination θ from vertical
- Oriented ϕ out of plane of wave propagation (*x*-*z*)
- Effects on
  - Magnetic and acoustic wave flux escaping at top?
  - Travel times as measured by TD?

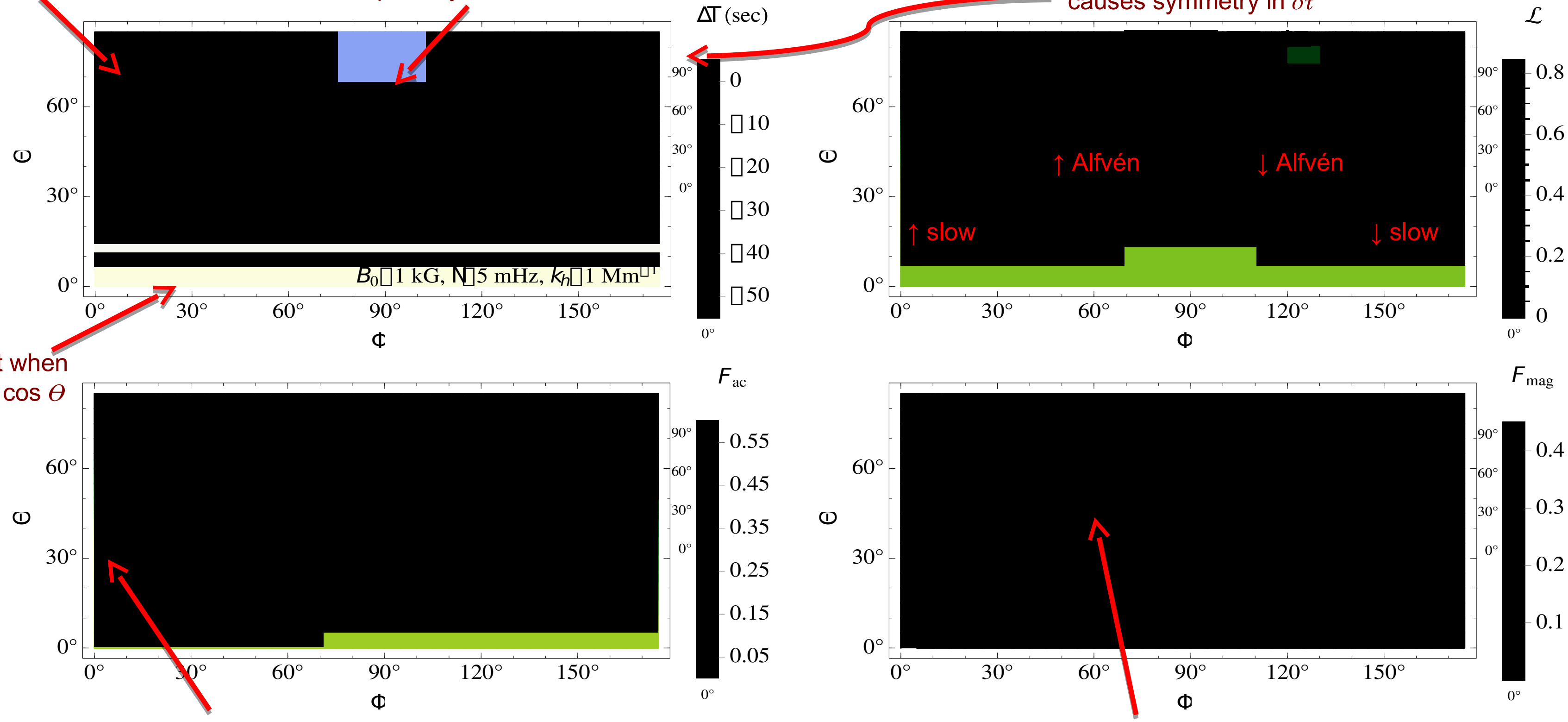


Travel Time and Energy Losses

Fast-slow conversion causes negative travel time shift

Fast-Alfvén conversion causes positive shift that partially cancels f-s

Total losses essentially symmetric about ϕ=90º; causes symmetry in $\delta\tau$



No shift when $\omega < \omega_c \cos\theta$

Upward acoustic transmission T greatest at small attack angle α

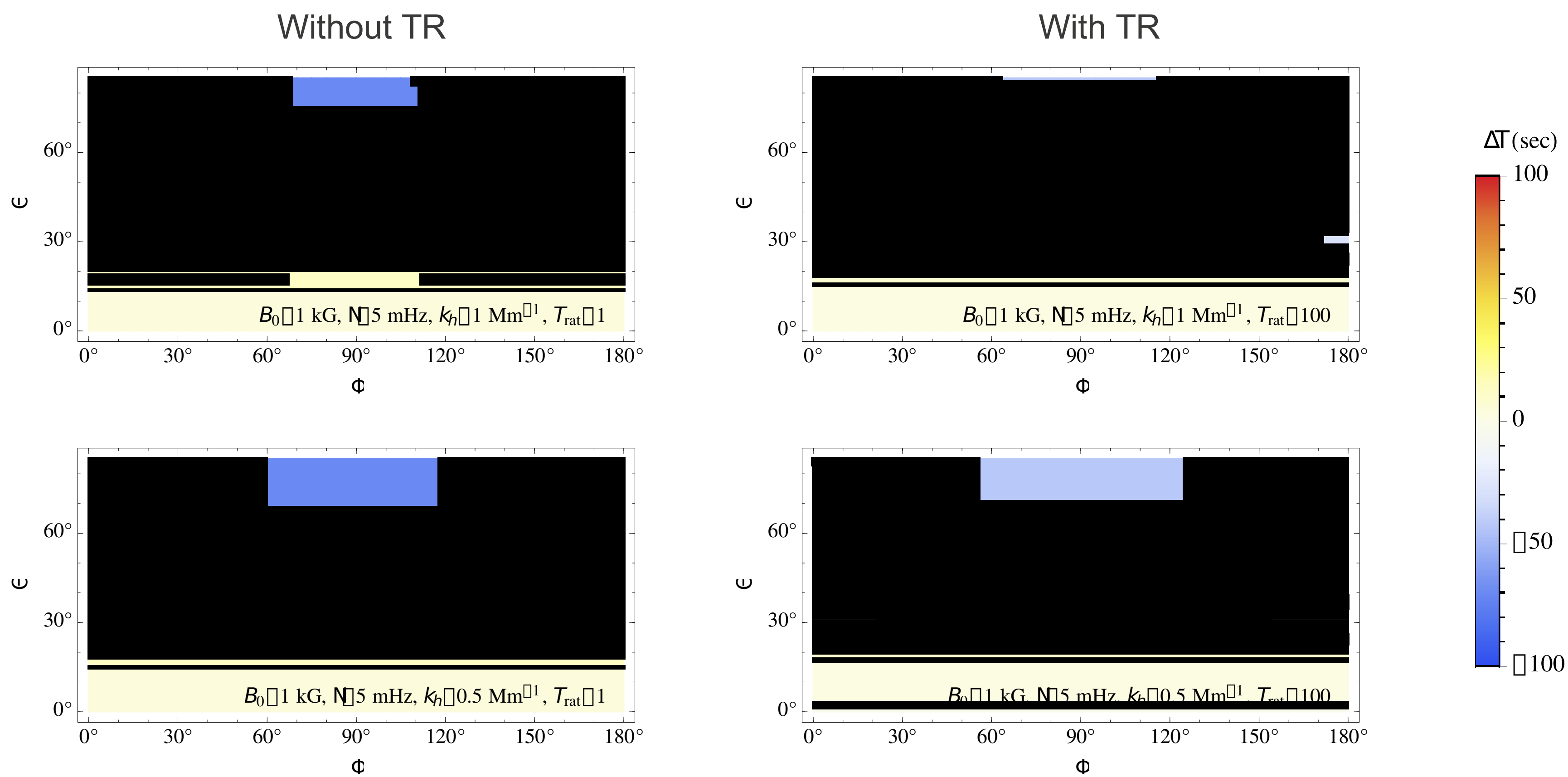
Upward Alfvén losses enhanced for ϕ<90º

$$T = \exp\left[-\pi |\mathbf{k}| h_s \sin^2\alpha\right]_{a=c}$$

Moradi & Cally, *Seismology of the wounded sun*, MNRAS 2013

With and without Transition Region

Hansen & Cally (2014)

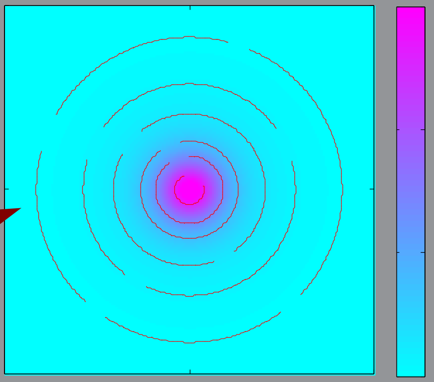


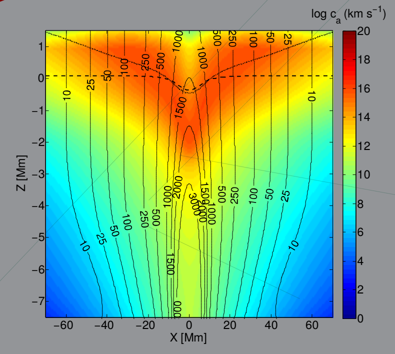
How are TD results along different travel paths affected by field direction?

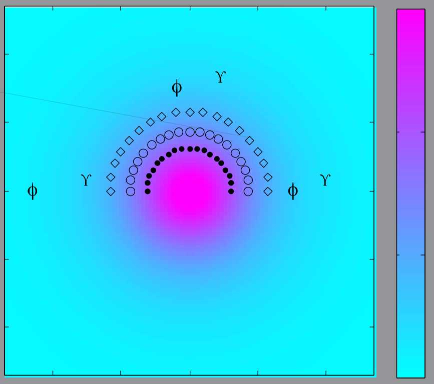
SECTION 3 DIRECTIONAL TIME-DISTANCE NEAR MODEL SUNSPOT

Directional TD

- Moradi, Cally, Przybylski & Shelyag 2015 (2015, accepted)
- Axially symmetric model spot (Khomenko & Collados prescription)
- SPARC wave simulation
- Broad spectrum about 3.3 mHz
- Single compact acoustic source 650 km beneath surface at various radii/field inclinations (x in top panel)
- Filter out *f*-modes
- Frequency filter for 3 mHz and 5 mHz bands
- Receivers placed at 10° intervals from field direction and at distances Δ=6.2 Mm (v_{ph}=12.2 km/s), 8.7 Mm (14.1 km/s), and 11.6 Mm (16.4 km/s)
- Measure phase travel time perturbations using Gabor wavelet fits

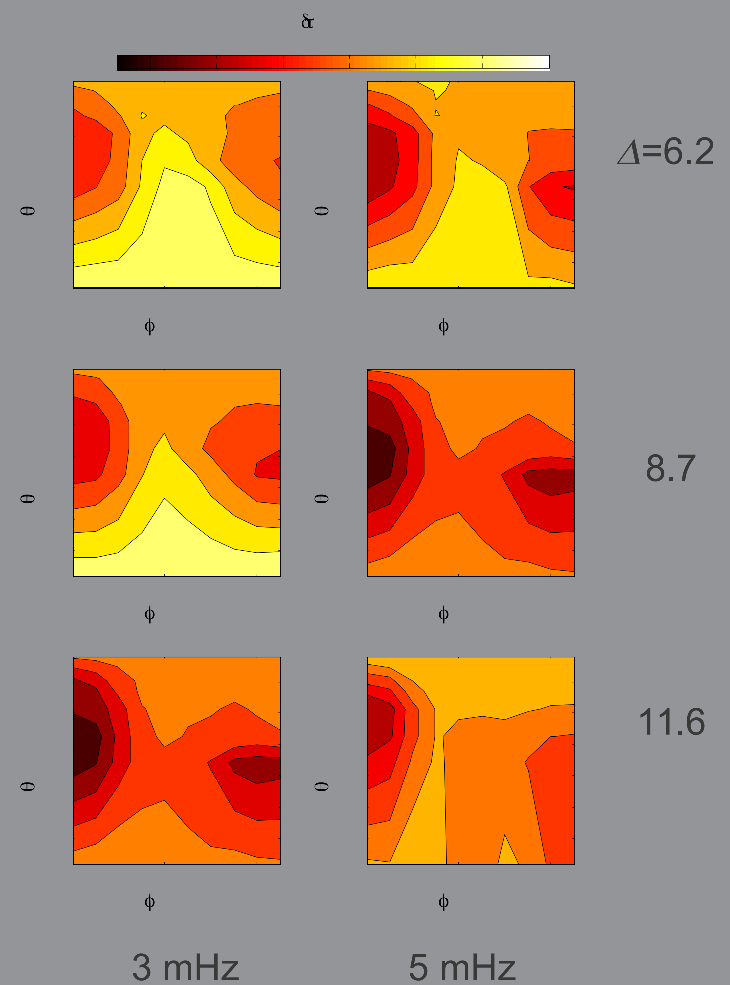






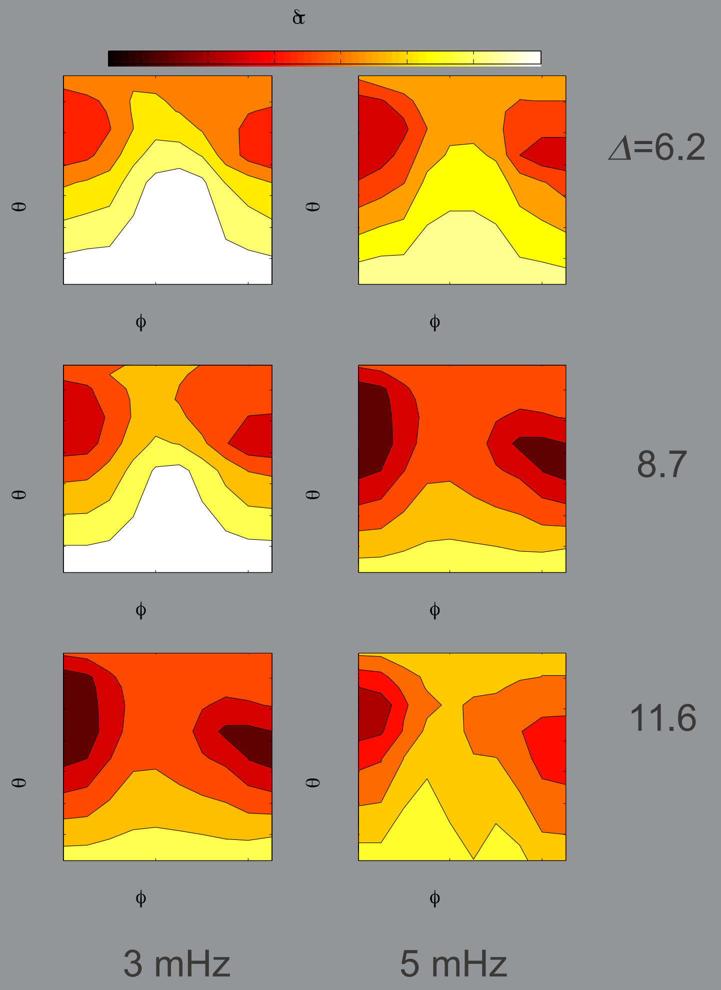
1.5 kG Spot

- Axisymmetric spot, Wilson Depression = 400 km
- Very similar to uniform inclined field calculations
- Largest negative $\delta\tau$ for ϕ=0° or 180°
- Near transverse direction produces Alfvén conversion and partially reverses travel time shift
- Note acoustic cutoff effect: larger “buffer” at bottom for 3 mHz
- Ramp effect: acoustic propagation iff $\omega > \omega_c \cos\theta$



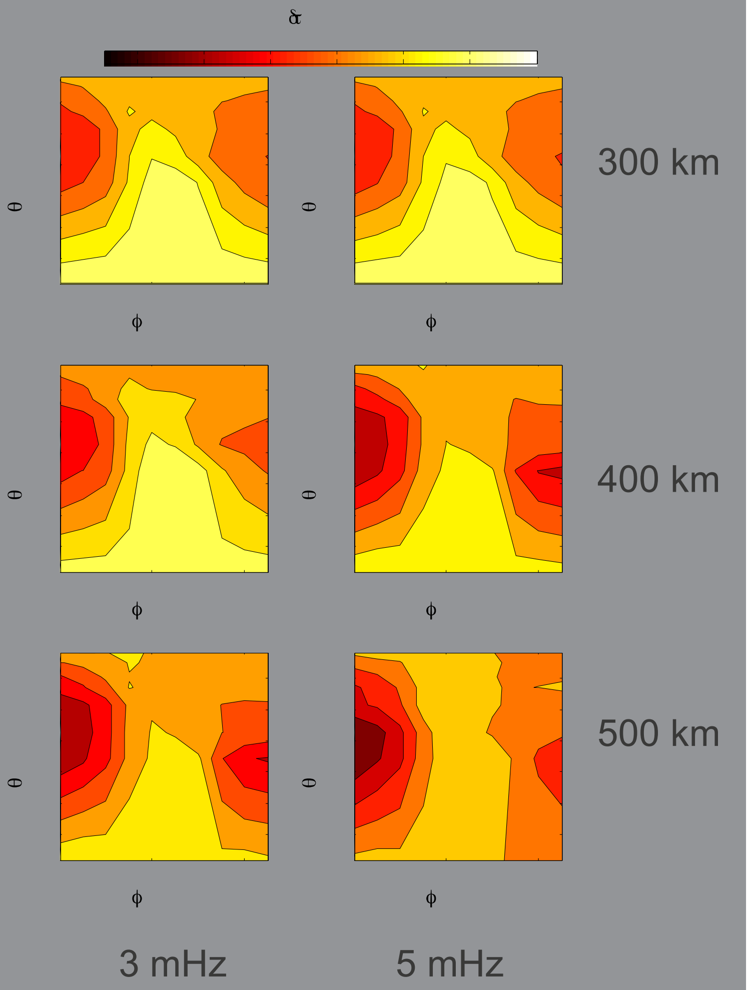
2.5 kG Spot

- Similar



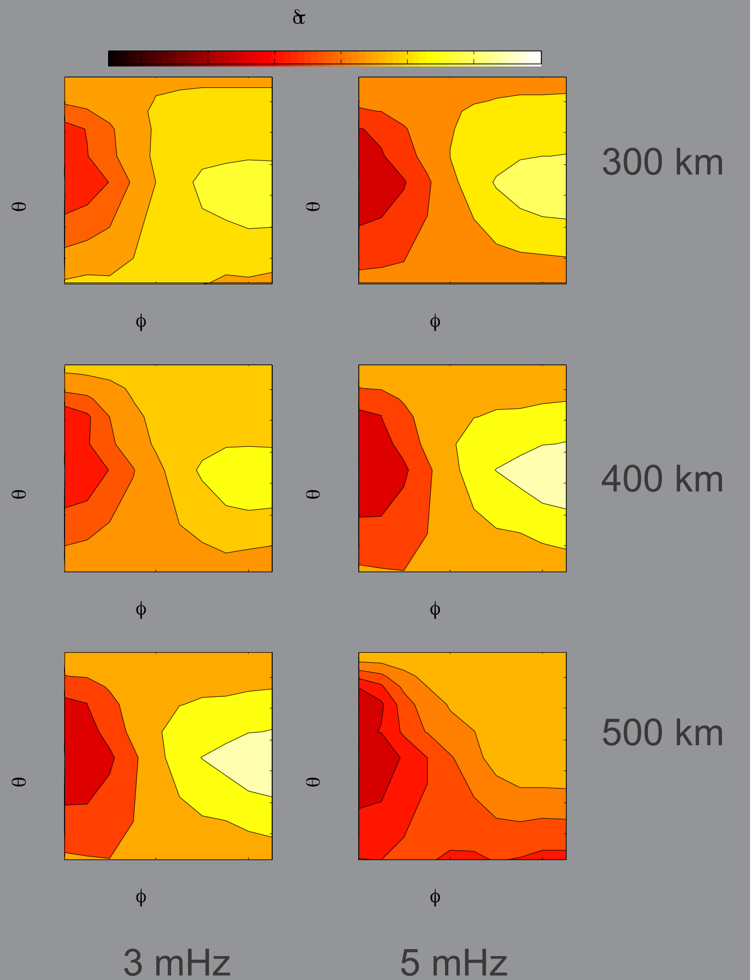
Effect of Wilson Depression

- Δ = 6.2 Mm
- Various Wilson Depression depths
- Changes in detail, as expected (path length changes)



Thermal Effect Only

- Δ = 6.2 Mm
- Wilson Depression = 400 km
- Turn off magnetic field and leave only thermal "spot"
- Very different!



It depends on your point of view

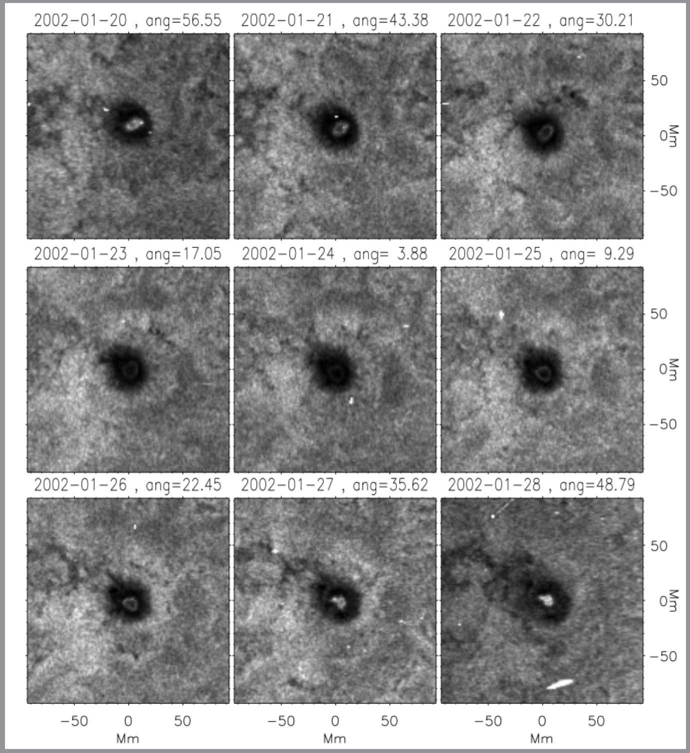
SECTION 4 DIRECTIONALLY DEPENDENT OBSERVATION IN THE SOLAR ATMOSPHERE

(DAMIEN PRZYBYLSKI, SERGIY SHELYAG & PAUL CALLY, 2015 IN REVIEW)

Acoustic Power Maps with Angle

MDI Acoustic Power AR9787
(6 mHz):

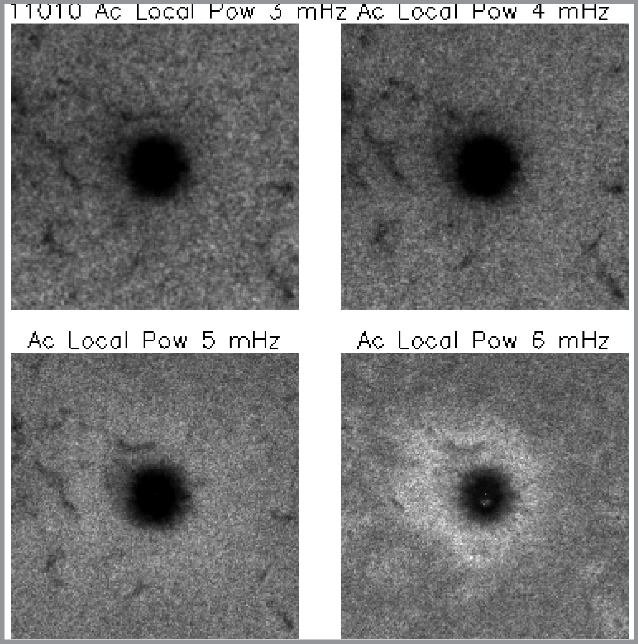
Zharkov et al 2013



Note difference in halo and belly button.

Why?

With Frequency:



See halo poster of Thaler, Vigeesh & Roth

in coffee area

Spectral Synthesis

Przybylski, Shelyag & Cally (2015, in review)

Determine the output radiation spectrum of a simulation cube.

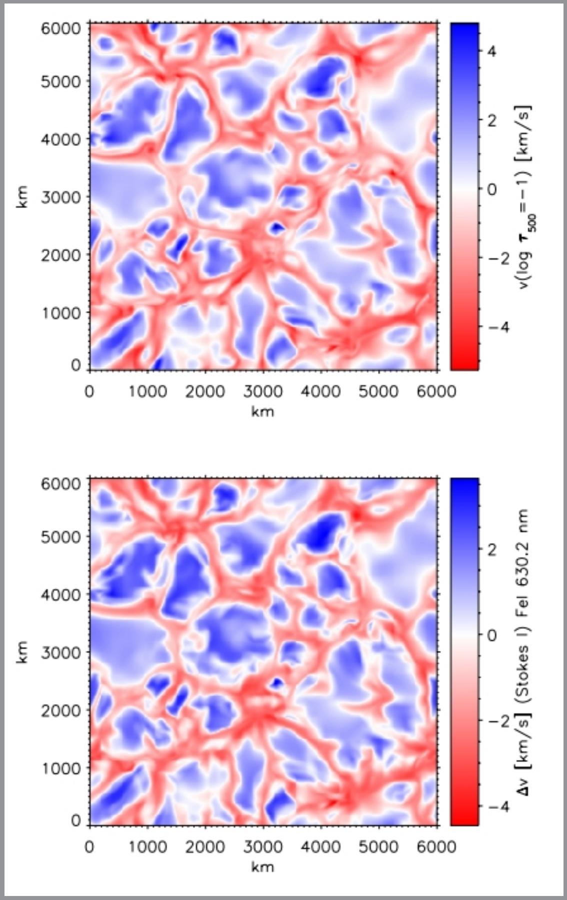
We require a variety of wavelengths for investigation of the solar surface and atmosphere.

The Radiative Transfer Equation must be solved for the Stokes vector **I**.

$$\frac{d\mathbf{I}}{dz} = -\mathbf{K}\mathbf{I} + \mathbf{j}$$

K is the absorption matrix and **j** is the emission vector.

Dependence on thermal effects.

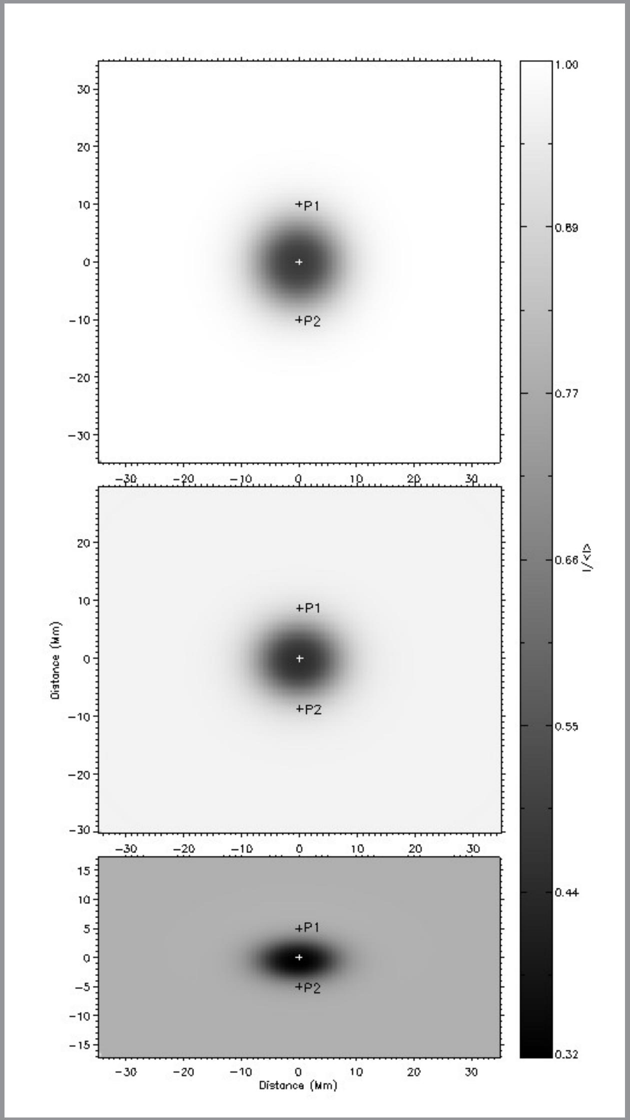


Velocity determined from (Shelyag et al. 2007):

1) MuRAM velocity output

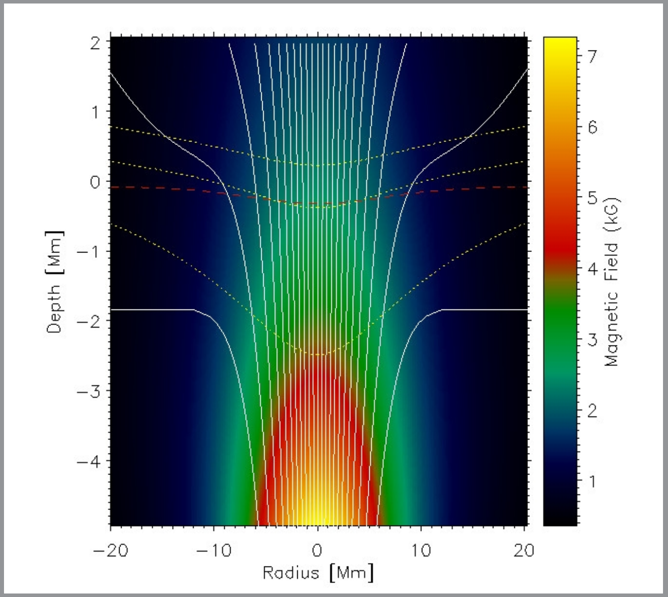
2) Doppler velocities calculated from synthesised Fe 6302 Å spectrum

Modelling a Sunspot



6173 Å continuum from 0°, 30°, 60°

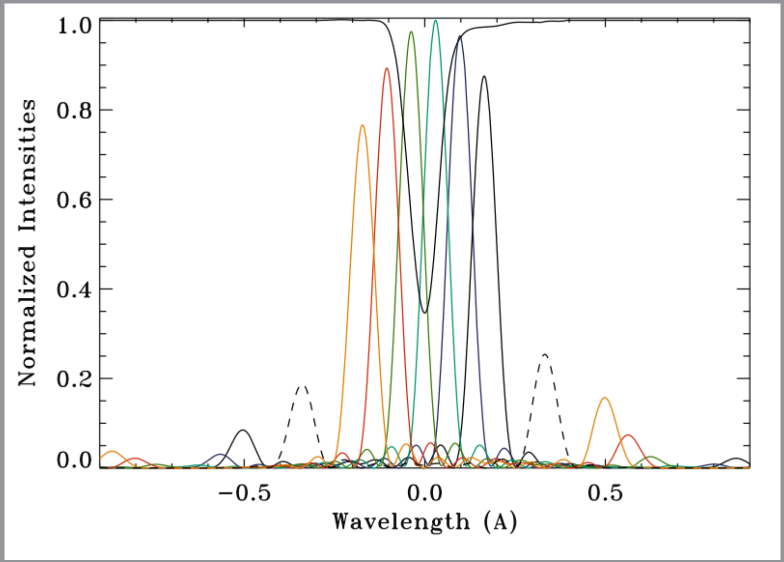
(normalized to quiet sun at 0°)

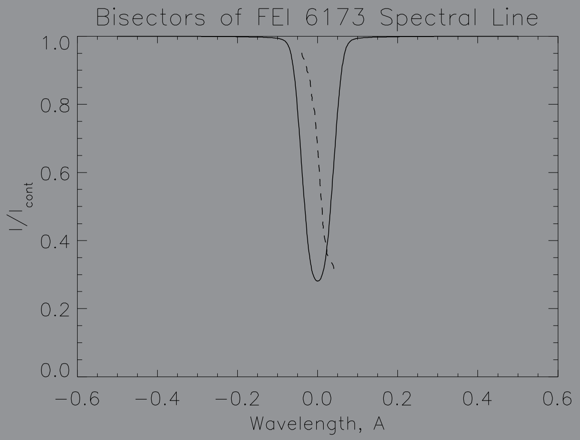


Model spot

Formation of Spectral Lines

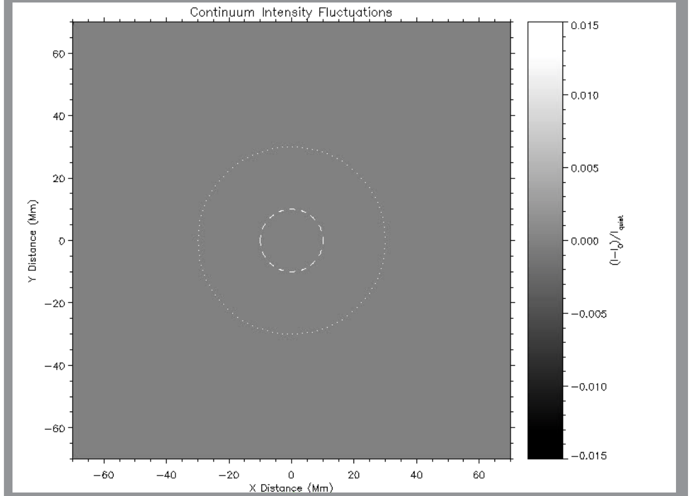
- The height dependency of the line contribution function complicates measurement of wave-behaviour.
- It also gives us an opportunity to investigate multi-height measurement with one spectral line.
- How can we emulate this in modelled Spectra:
- - Bisector method.
- - Direct approximation using the HMI filter-gram pipeline.
- Acoustic power is calculated from these measurements by taking the FFT of a long time-series.

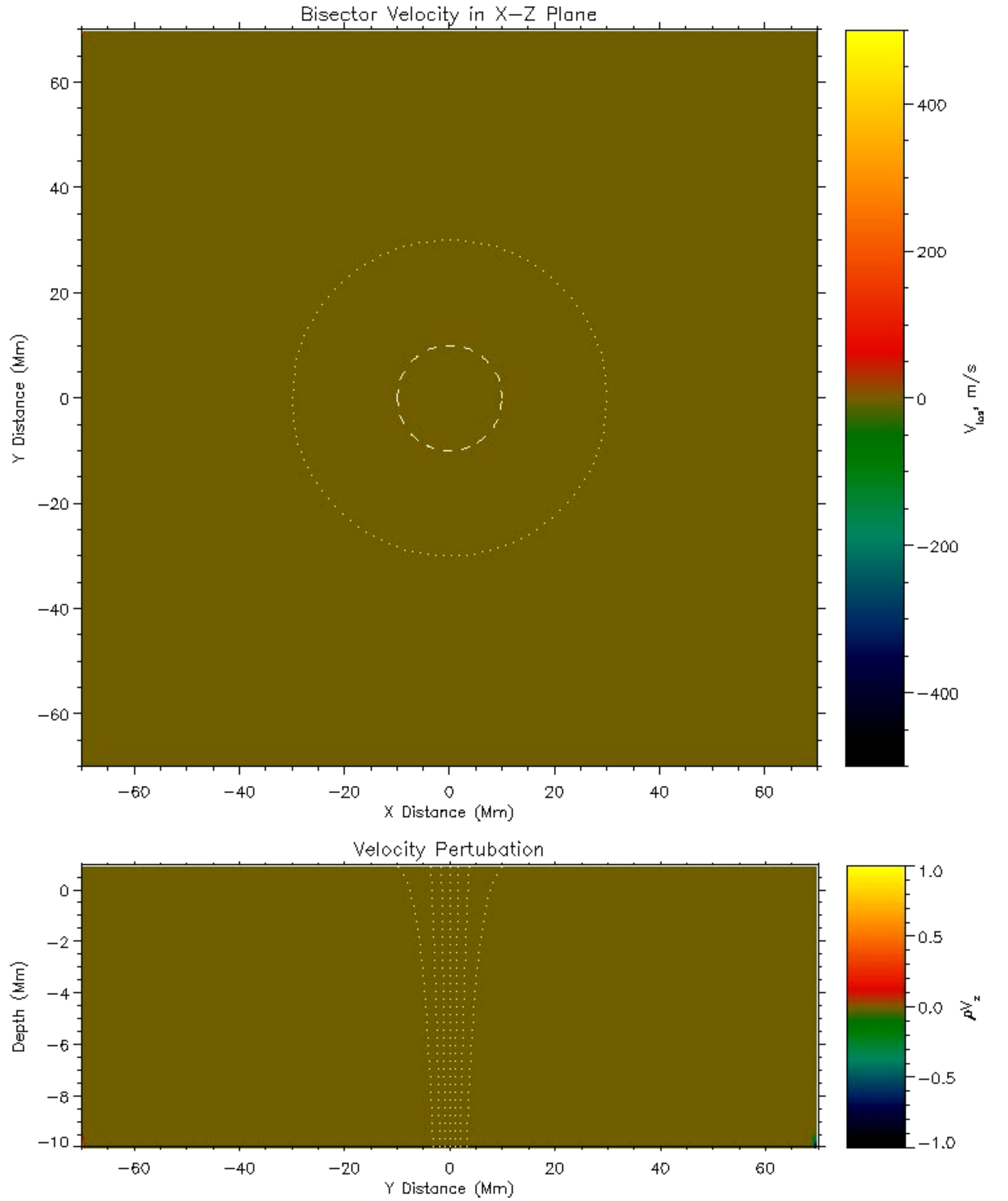




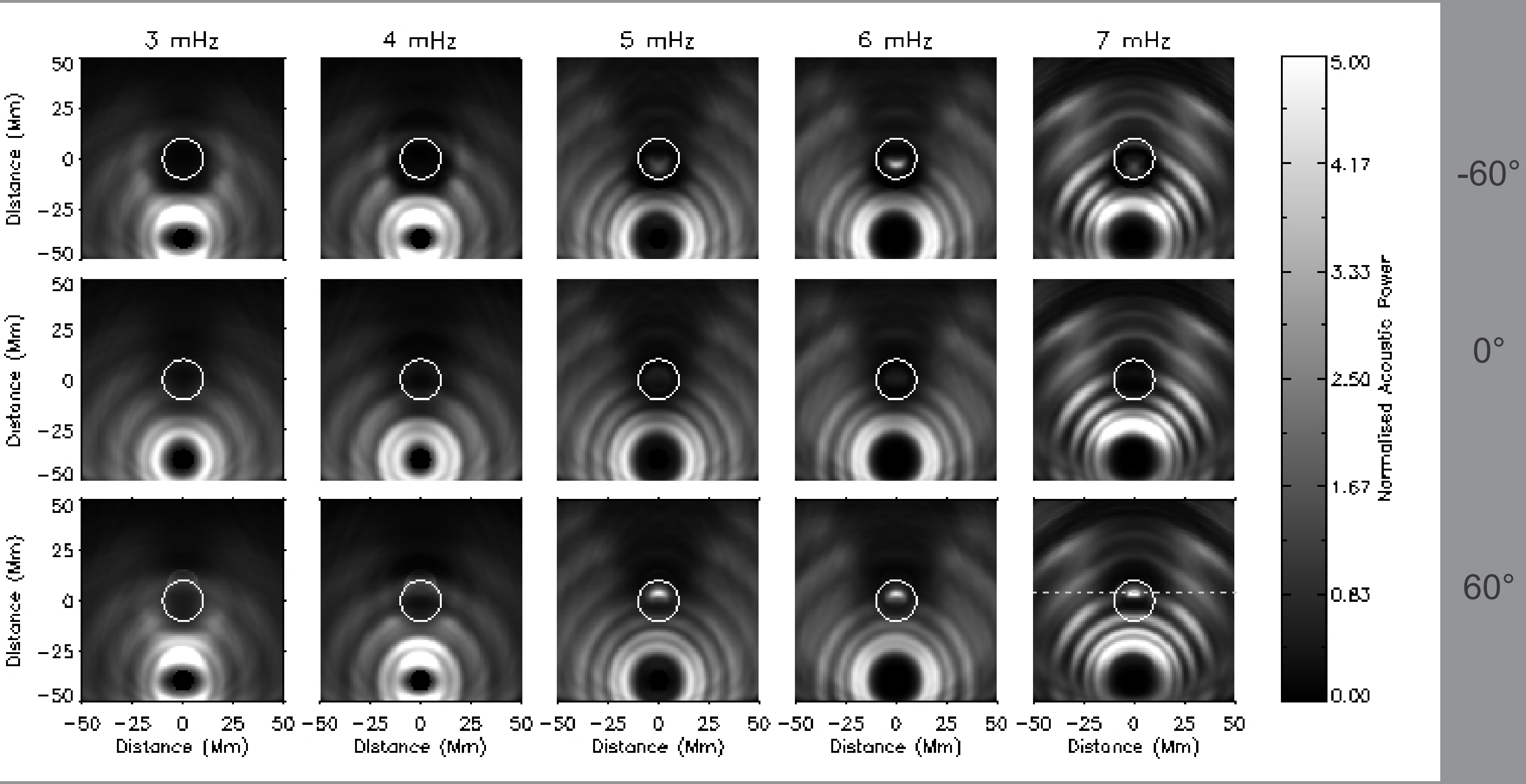
Simulation

SPARC simulation with short-lived compact source outside spot

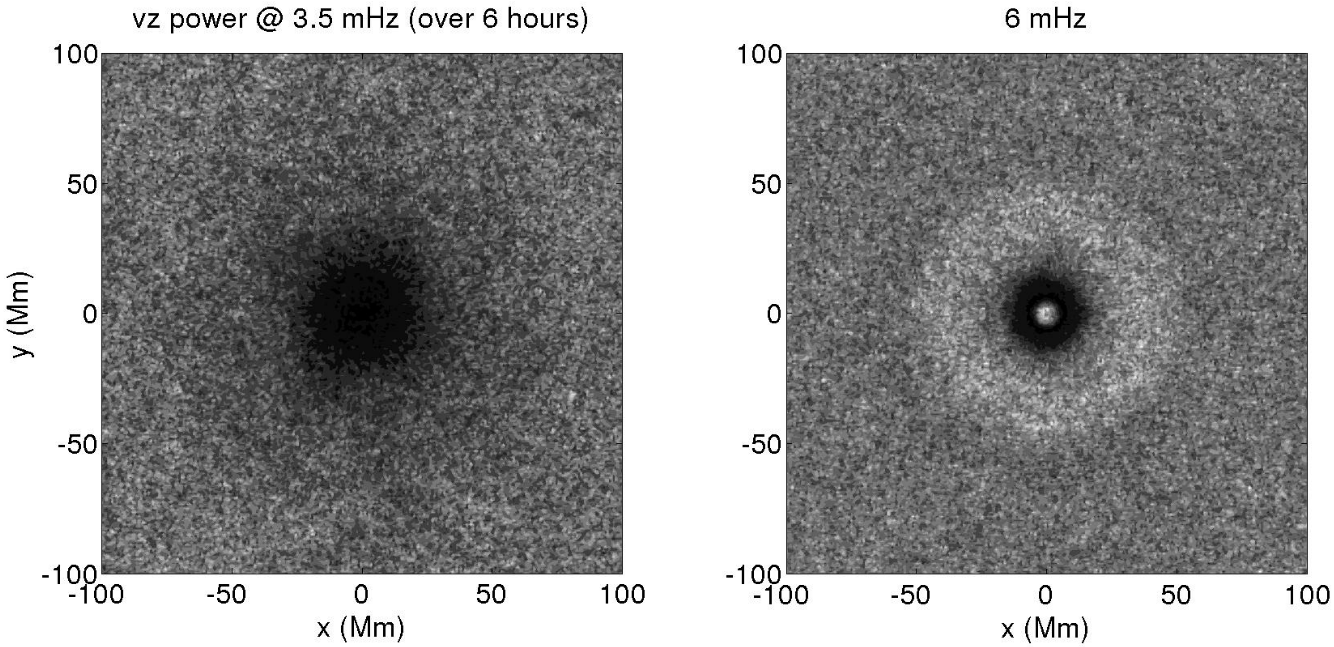




Acoustic Power Maps: Line Core



Acoustic power map calculated from the shifts in the bisector of the Fe I 6173 Å line. Przybylski et al 2015.



Simulations with Distributed sources (Rijs)

- Disk centre, ~140 km constant geometrical height
- Halo clearly visible
- Bellybutton seen in vertical velocity!
- But if we calculate the signal in Fe6173 line, which follows the Wilson depression, we pass underneath the bellybutton and see nothing.
- Indication of mode changing character from transverse to longitudinal with height.

Section 4 Summary

- Directional dependence of MHD wave observations
- Caused by wave polarization, and to a lesser extent optical depth
- Belly button shows up in observations and simulations
  - Not light scattering in telescope
    - Confirmed by Shelyag (Venus transit test)

Conclusions

- Magnetic field direction has measureable effects on observed oscillations
  - Affects fast-slow and fast-Alfvén mode conversion
  - Affects TD seismic “travel times”
  - “Directional TD” feasible (tested only in simulations, not observations)
  - Directional variation of sunspot halos and umbral belly buttons
- Progress of (fast) waves through active region atmospheres has large affect on “internal” seismology results!
- Active regions are open windows from the interior to atmosphere; everything is connected
  - The “Wounded Sun” (Cally & Moradi 2013)