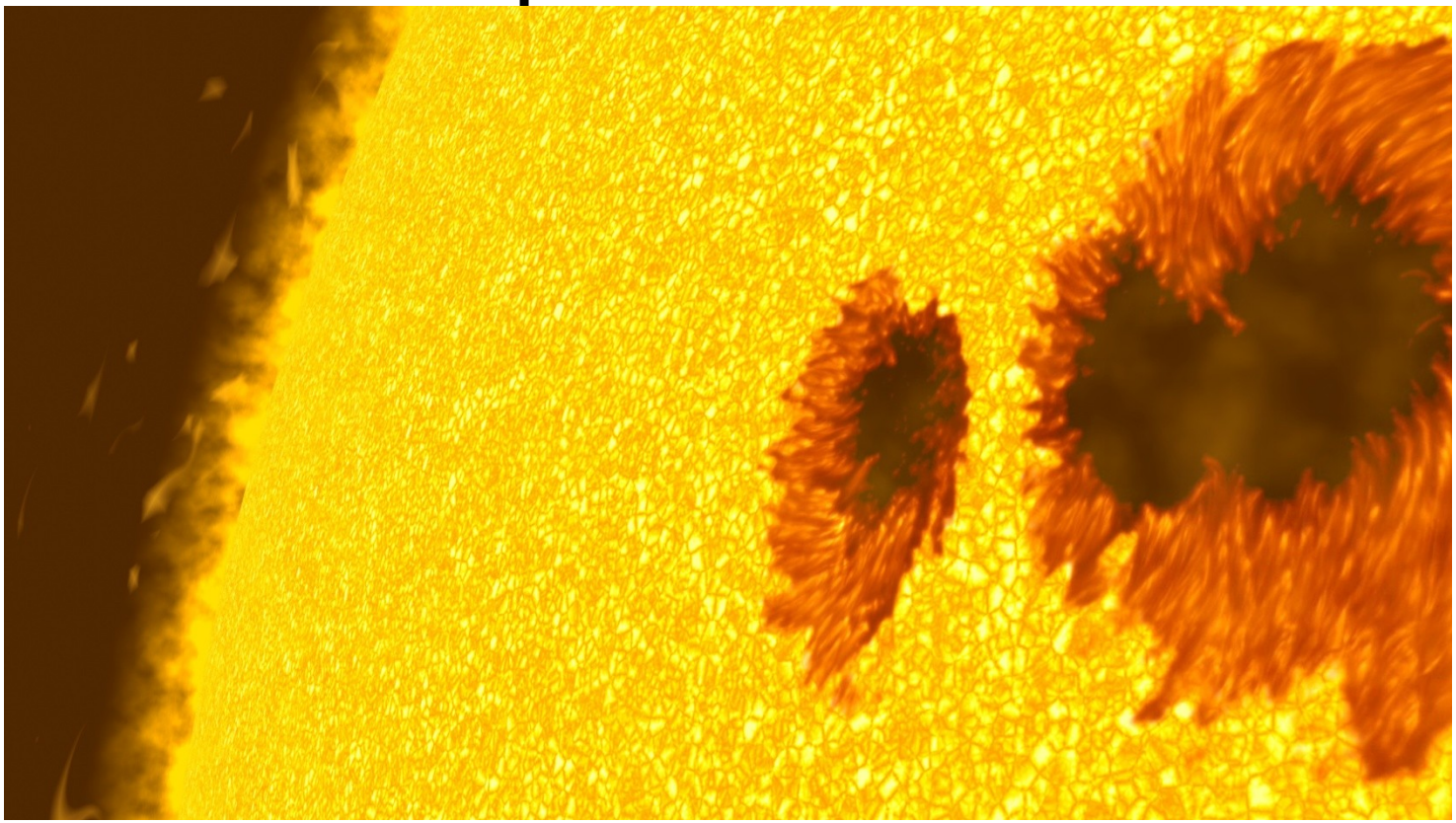
Signatures of mode conversion in a sunspot simulation



Work with Sergiy Shelyag & Paul Cally

The Astronomical Society of Australia

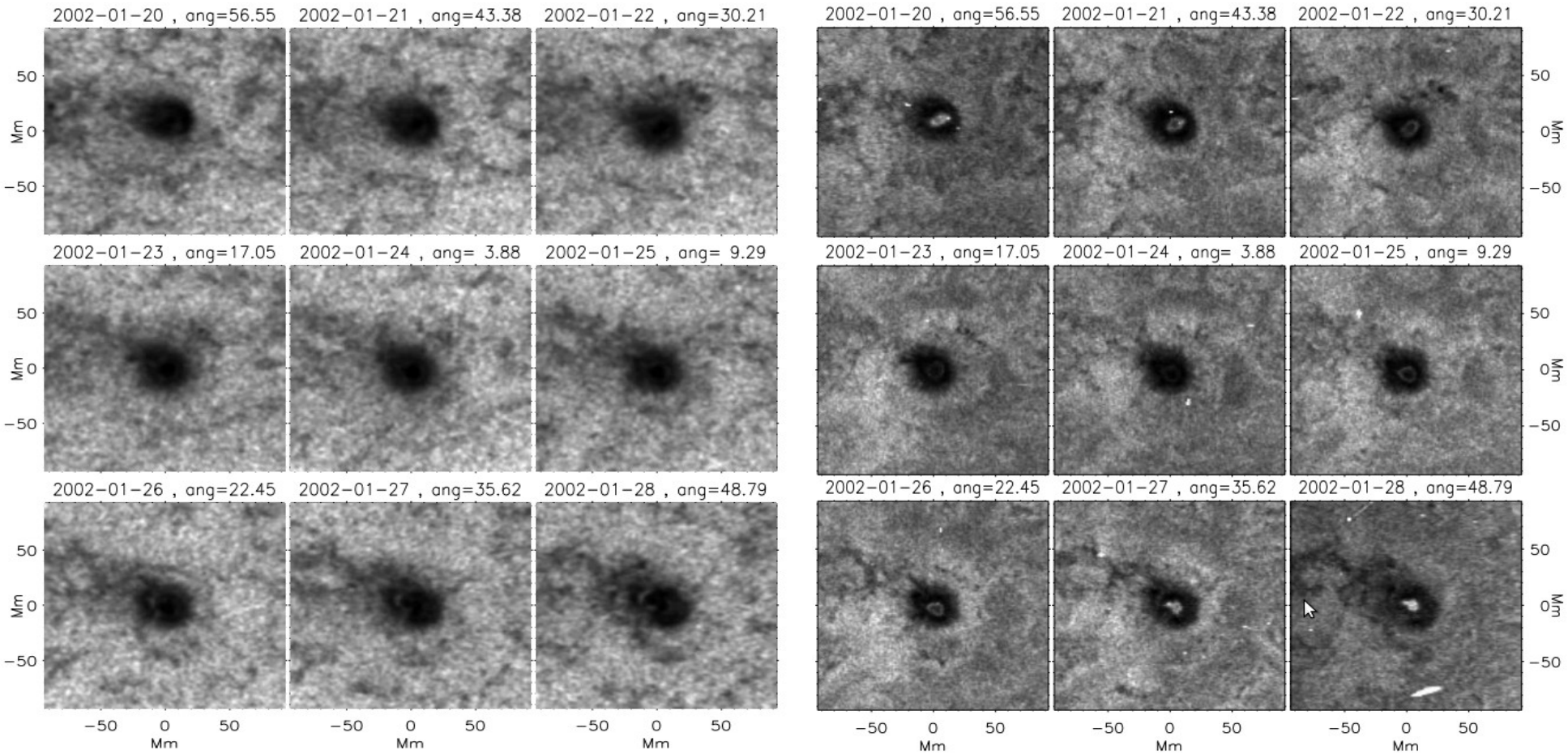
MONASH University Science

MoCA Monash Centre for Astrophysics

Outline

- Active region seismology requires a robust understanding of wave behaviour in sunspots.
- Forward Modelling: Three dimensional MHD simulations waves in sunspots.
- Large scale spectral synthesis of simulation outputs.
- What do we see in our simulations.
- Observation of mode-conversion will require measurement of non-vertical velocity components, Centre-to-limb observation.

Observations of a Sunspot:

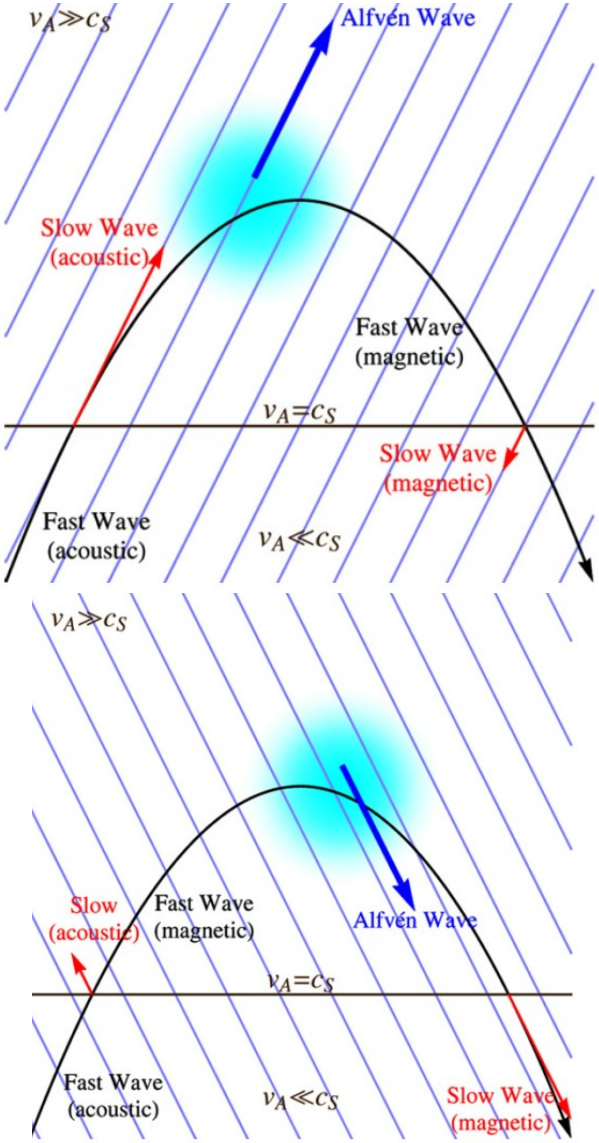


Acoustic power of AR9787 estimated from LOS data at various angles. Frequency filtered centred on 3 mHz (left), and 6 mHz (right).

Taken in the Ni-I 6776.772 A line by the Active Region Michelson Doppler Imager Instrument on the Solar and Heliospheric Observatory. (Zharkov et al., 2013)

Mode Conversion:

- Fast-slow mode conversion occurs at the equipartition (cs/va = 1) level.
- Varies with wave-number and therefore frequency.
- Conversion to Alfvén waves occurs around the fast wave turning point.



Right: Mode conversion as an acoustic wave travels above the equipartition layer. For a low (top) and high (bottom) angle of incidence. (Khomenko + Cally 2012)

Modelling a Sunspot:

- Stable for MHD simulations.

$$\nabla \times \mathbf{B} \times \mathbf{B} - \nabla \mathbf{p} - \rho \mathbf{g} = \mathbf{0}$$

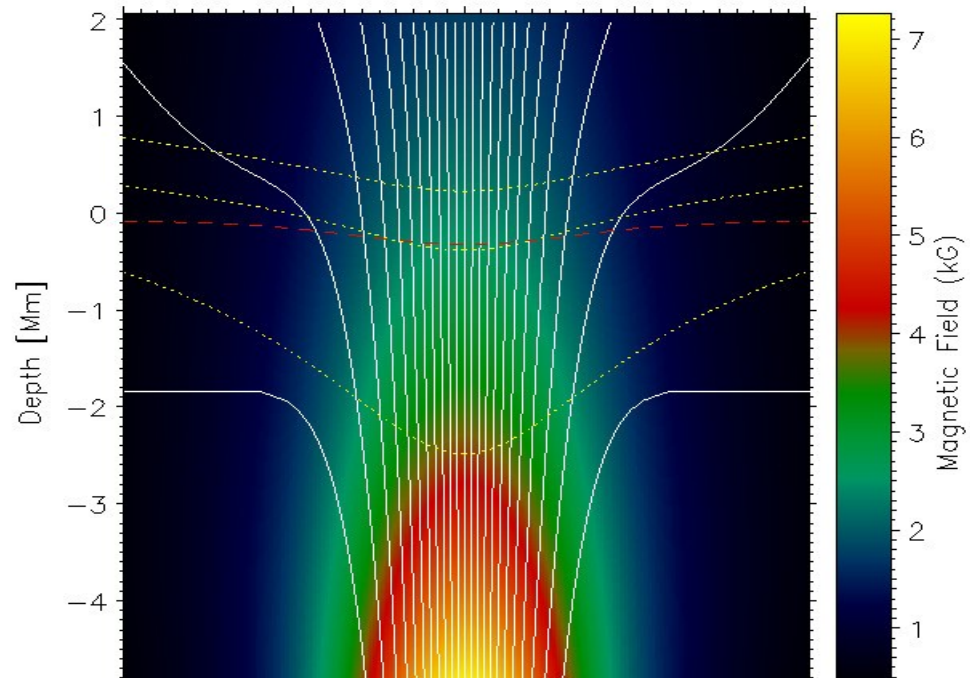
- Based on the Khomenko et al. (2009) Model:
- A self-similar solution in the lower layers:

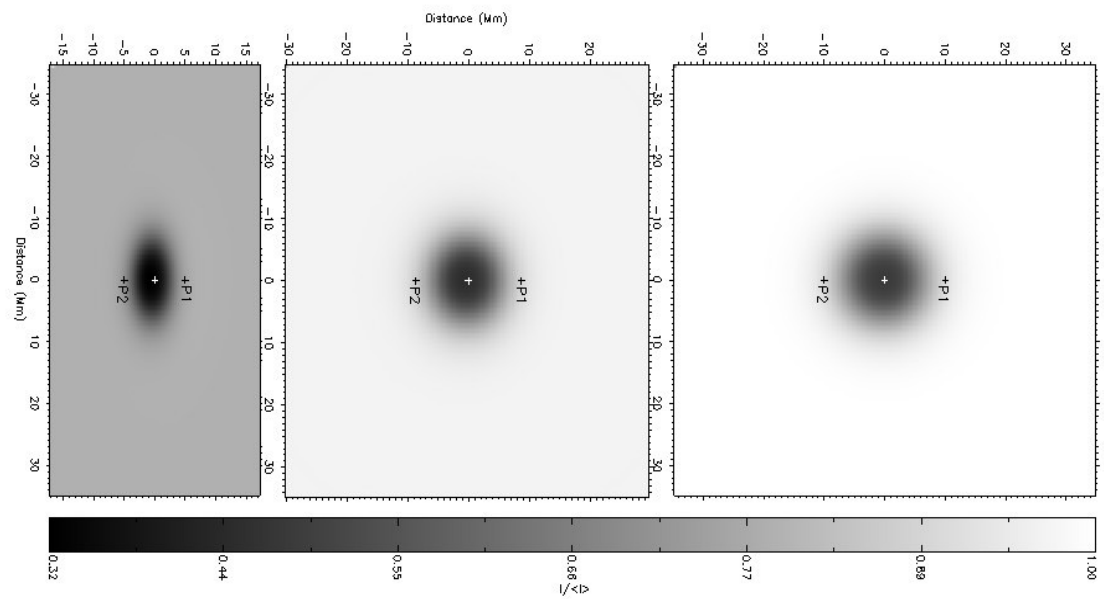
$$B_z = f(r\sqrt{B_{0z}})B_{0z}$$
$$B_r = -\frac{r}{2} f(r\sqrt{B_{0z}})\frac{dB_{0z}}{dz}$$

- A semi-empirical solution in the upper layers:

$$\frac{\partial^2 u}{\partial r^2} - \frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial z^2} = -4\pi r^2 \frac{\partial P(u,z)}{\partial u}$$

$$B_r = -\frac{1}{r}\frac{\partial u}{\partial z}, \qquad B_z = \frac{1}{r}\frac{\partial u}{\partial r}.$$



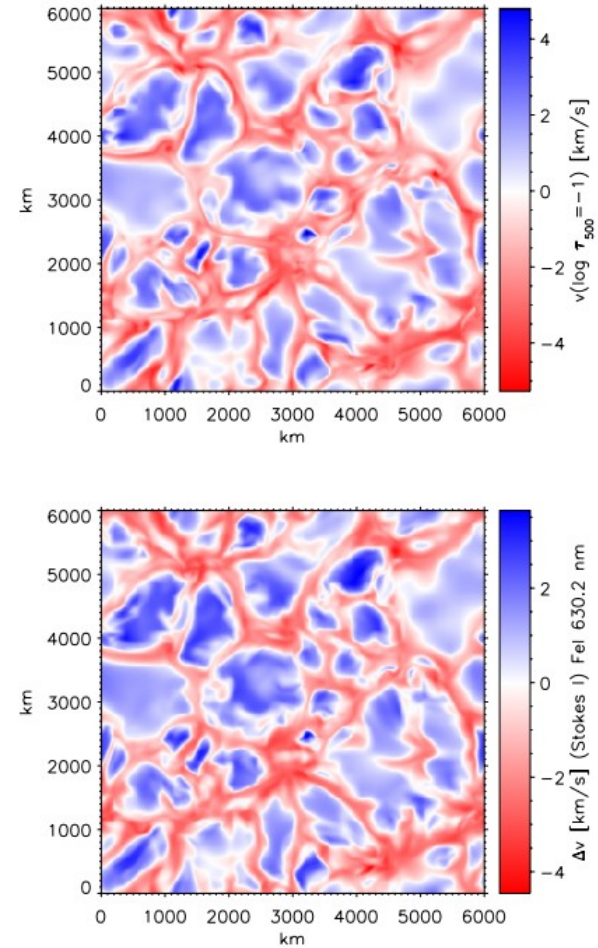


Spectral Synthesis

- Calculate output radiation spectrum of a simulation cube.
- The Radiative Transfer Equation must be solved $\frac{d\mathbf{I}}{dz} = -\mathbf{K}\mathbf{I} + \mathbf{j}$
- K is the absorption matrix and j is the emission vector.
- Codes available: SPINOR (Solanki) or NICOLE (Socas-Navarro) + more.

Absorption line	Lande g	Pre-filter width [Å]	Formation height [km]
Mg b2 5172	1.75	10	583±100
Fe I 5434	0	4.0	687 ±250
Fe I 5576	0	3.0	402±105
Na D2 5890	0	3.2	961±200
Na D1 5896	0	3.0	580±600
Fe I 6173	0	3.0	332±230
Fe I 6301	1.6	3.0	304±120
Fe I 6302	2.5	3.0	337±100
Hα 6563	0	6.0	1986(*)±150

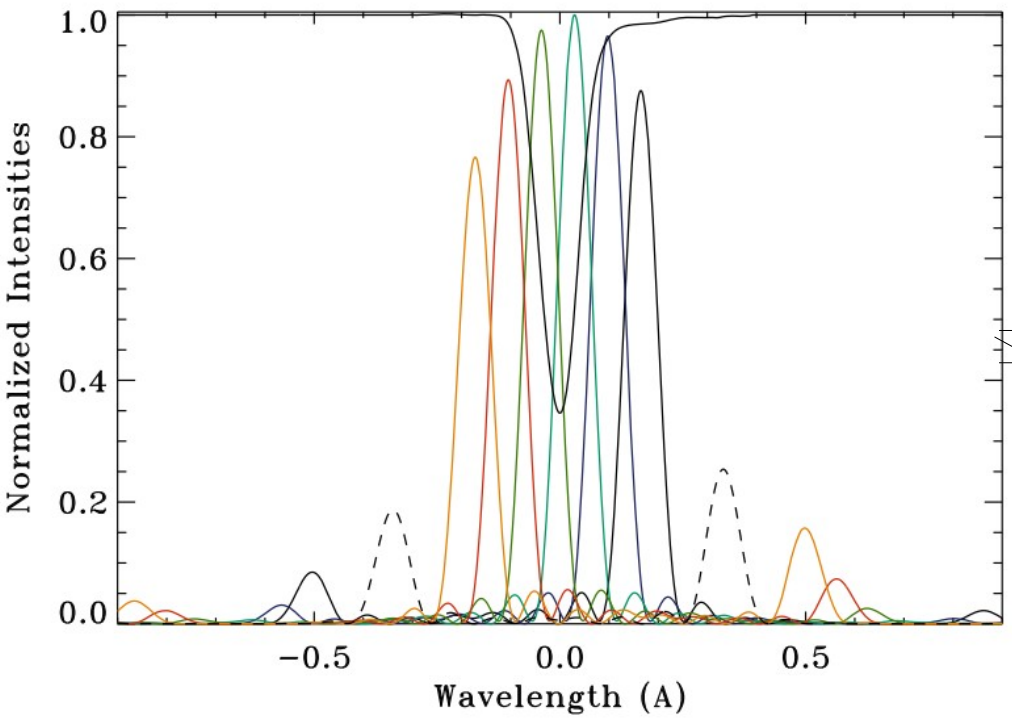
(*) intensity contribution function

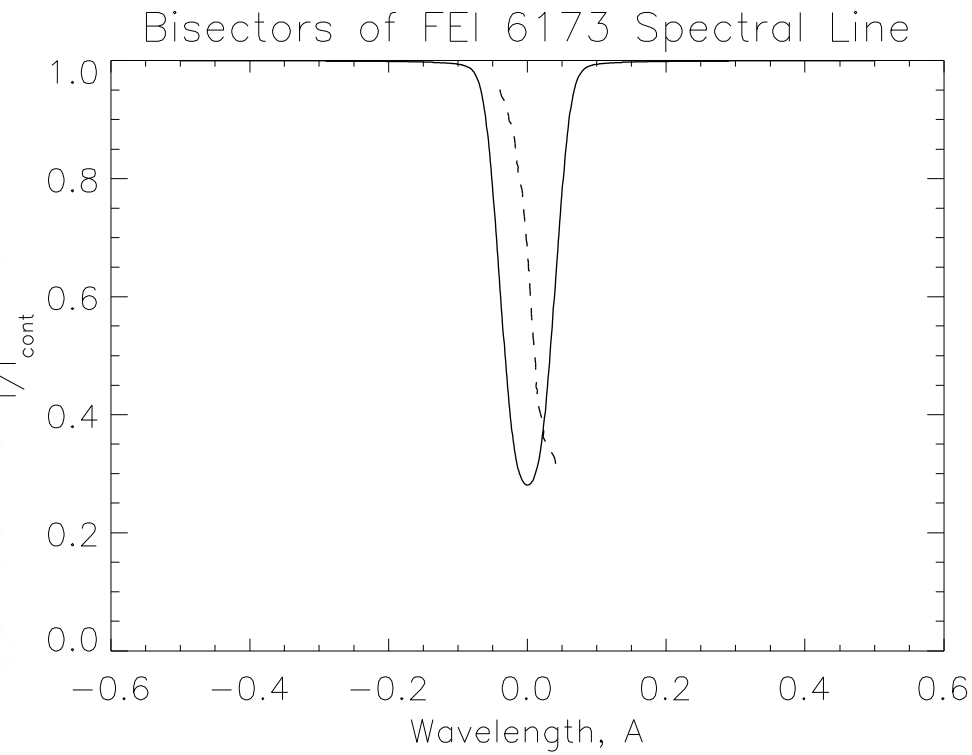


Velocity determined from:
1) MuRAM velocity output
2) Doppler velocities calculated from synthesised Fe 6302 A spectrum.
(Shelyag et al. 2007)

Observation: Spectral Lines

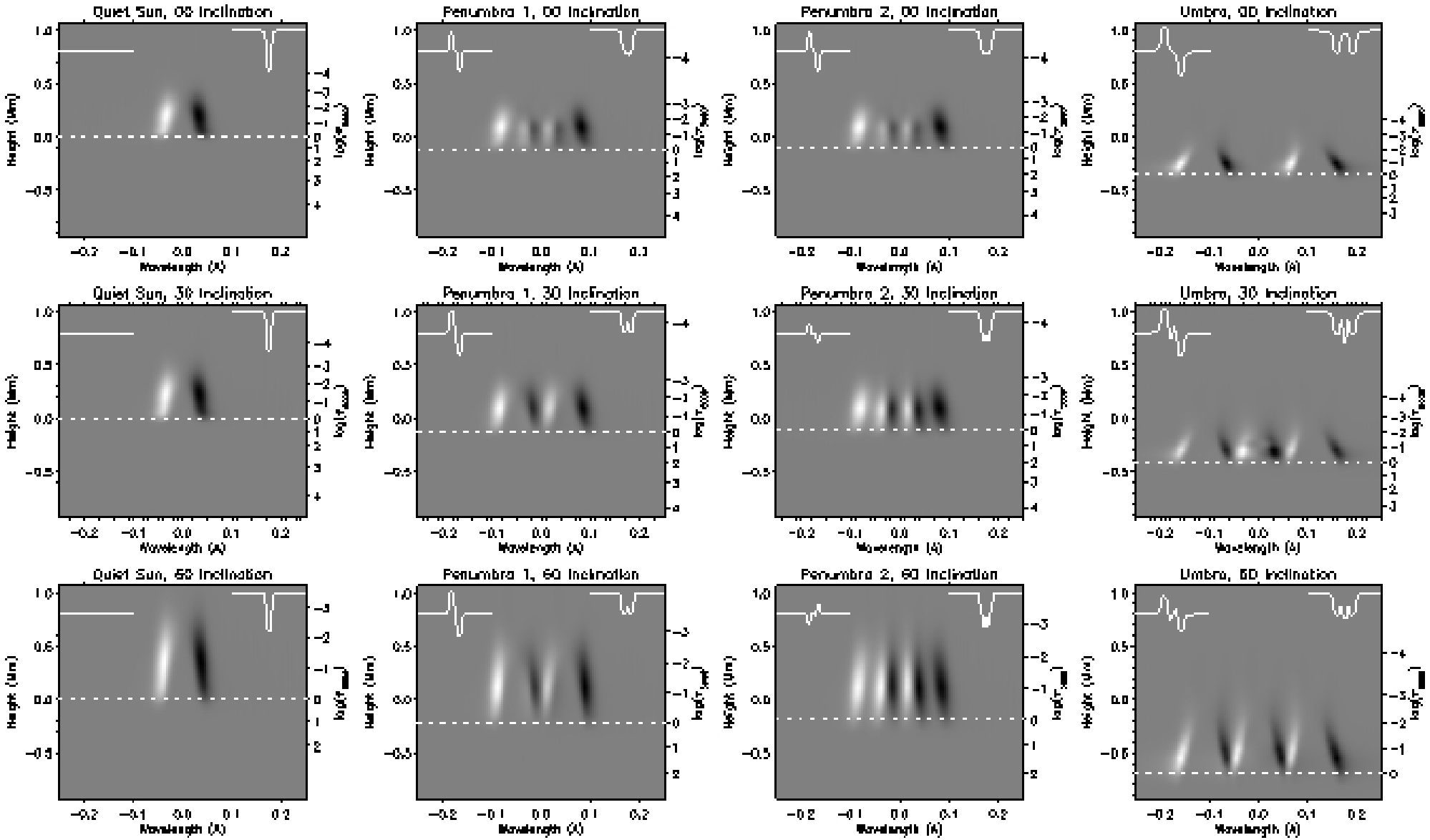
- Height dependency of the line contribution function.
- Spectral line bisector used to make multi-height measurements.
- A filter-gram approach (HMI).



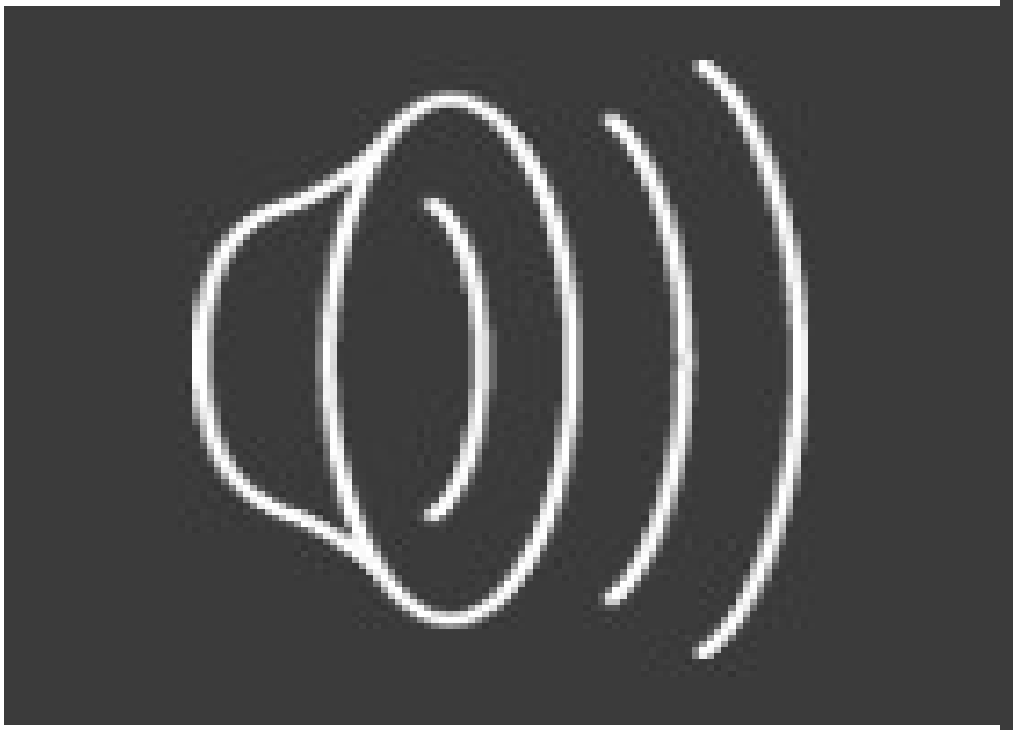


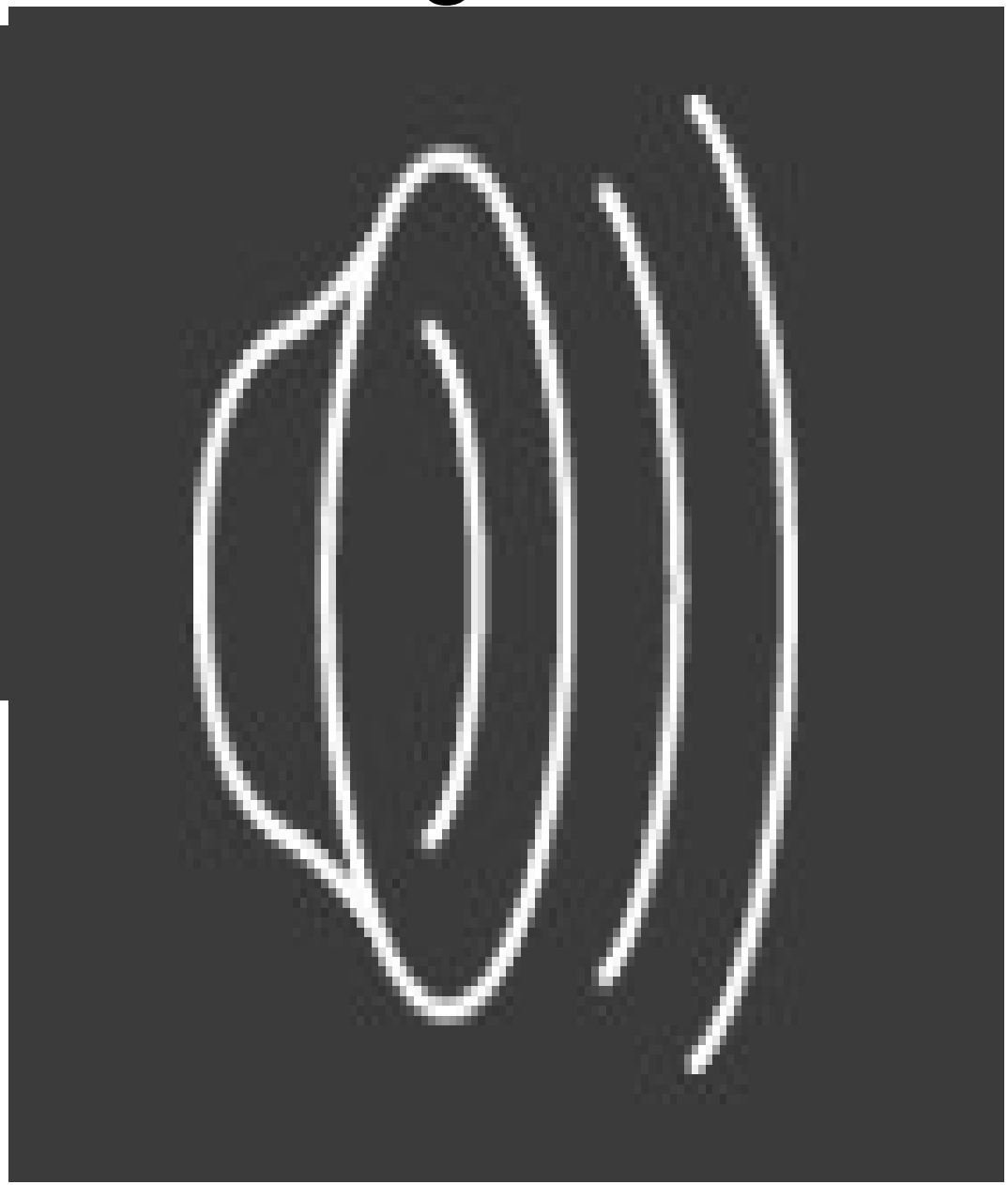
Left: Iron 6173 spectral line and overlaid filters (Couvidat et al. 2012).
Right: Spectral line with (exagerated) bisector-shape.

Centre-to-Limb Response:



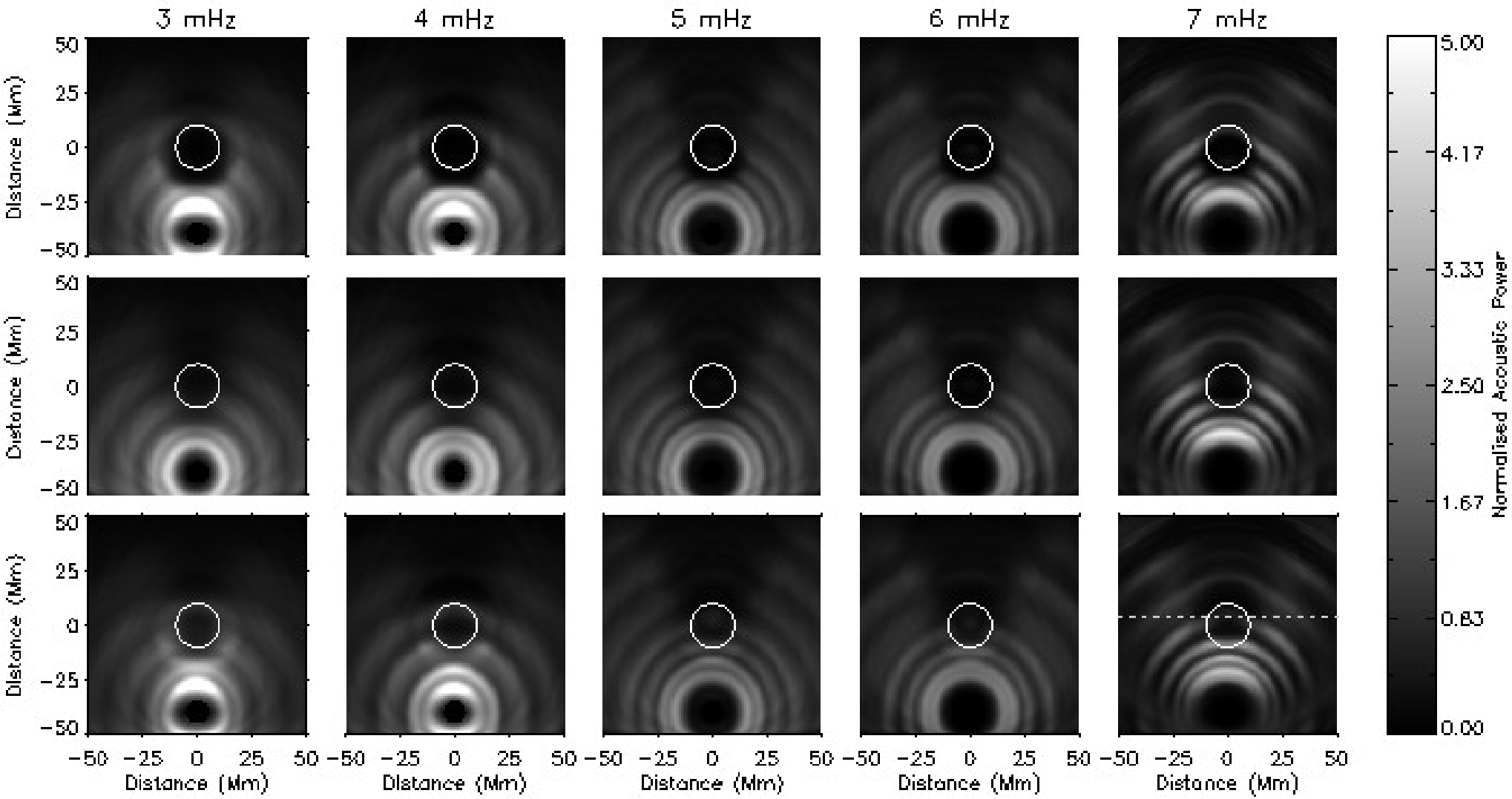
Forward Modeling



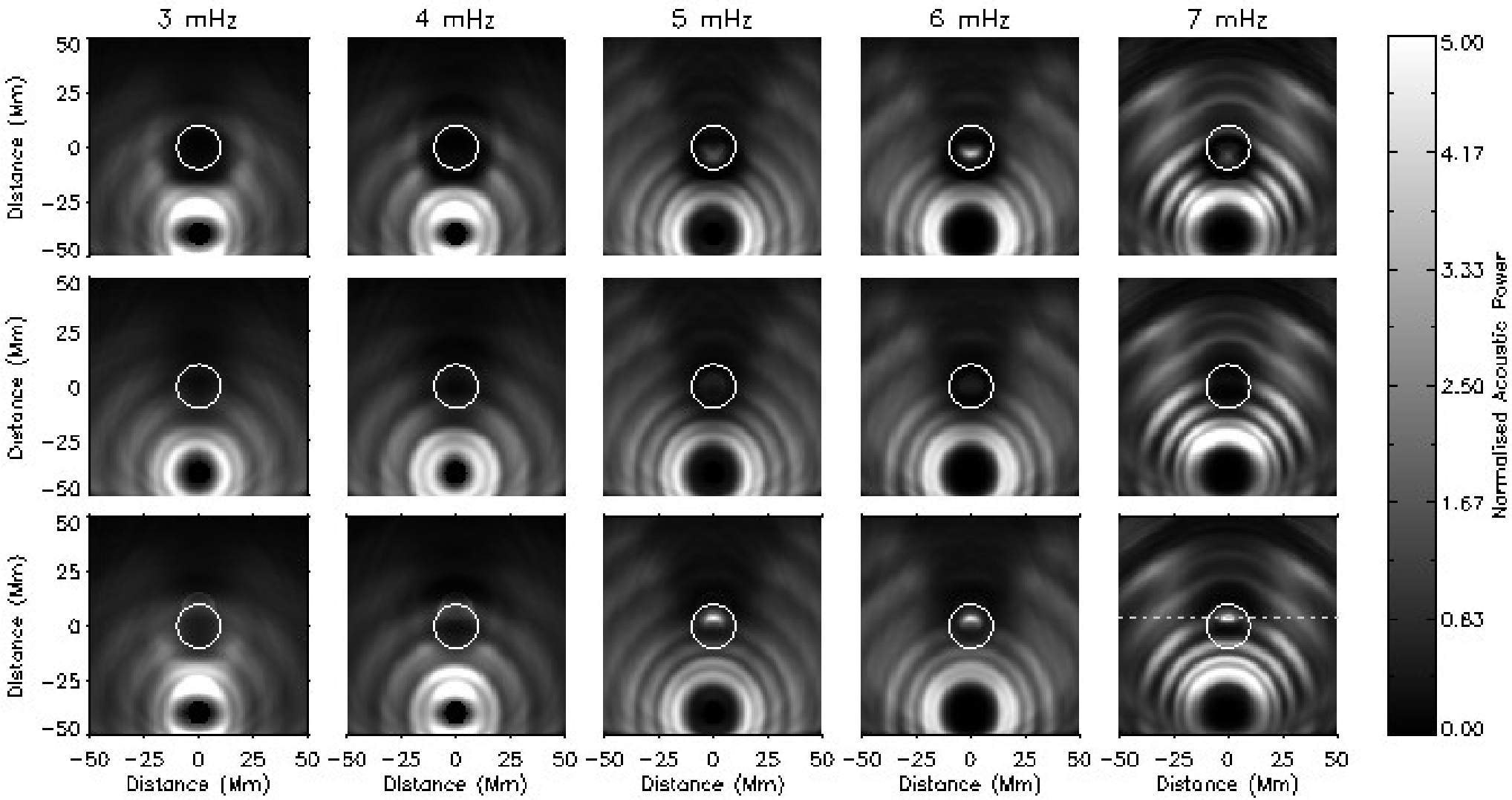


- Linear Simulations using SPARC code.
- Finite differences + Runge Kutta. Digital Filter.
- Lorentz force limiter.

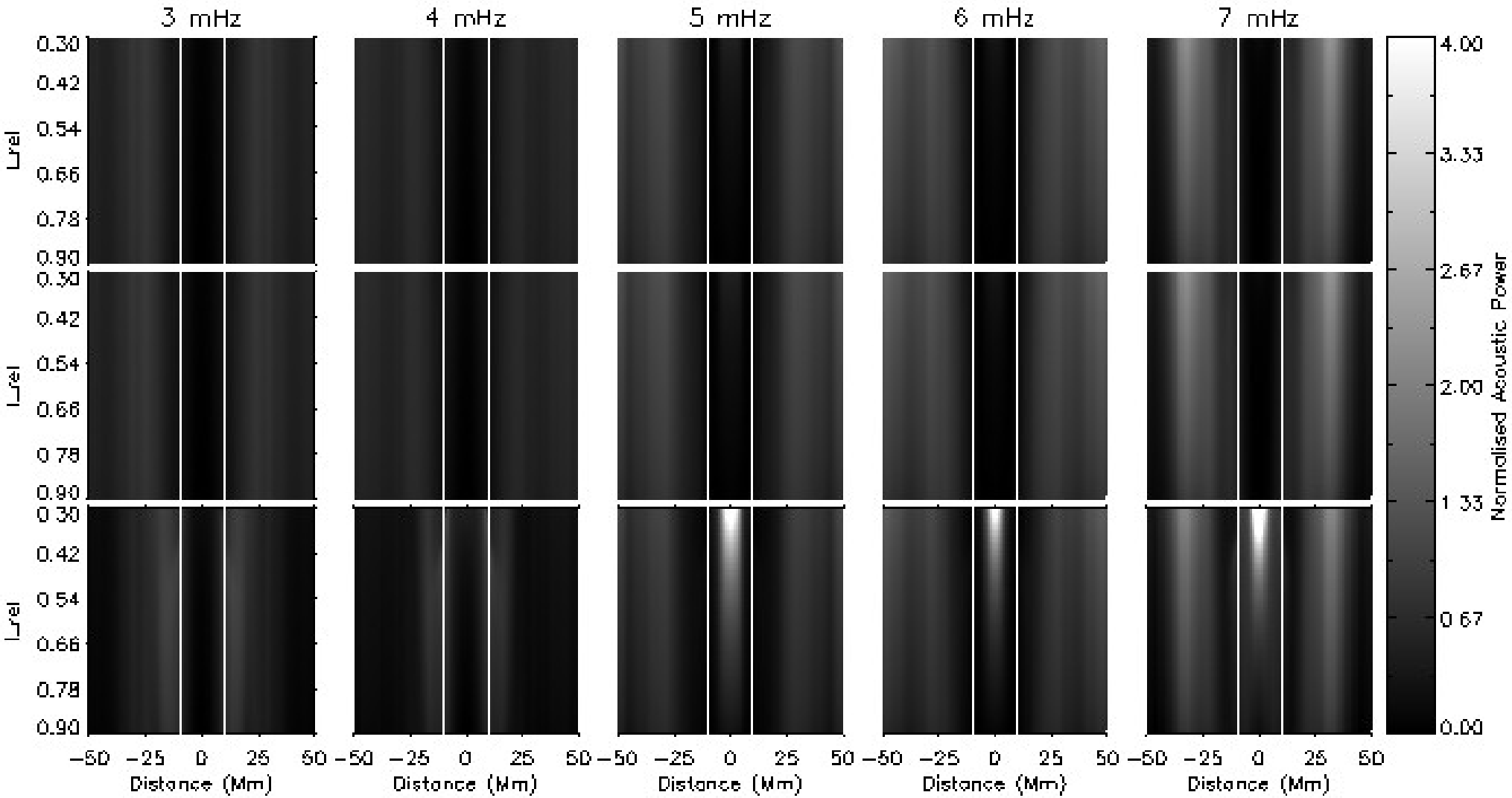
Acoustic Power Maps: Continuum Formation Height



Acoustic Power Maps: Line Core



Acoustic Power Maps: “In Height”



Conclusions

- Mode conversion in a sunspot umbra can be directly observed as a 'ring'.
- Locations of equipartition layer and observation height.
- Need to be aware of both the effects of the magnetic field and the radiative effects in sunspots.
- What's Next:
  - Multi-height observations w/ multiple spectral lines.
  - Sunspot Helioseismology; longer simulations needed.
- Thank you!