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The Seismic Effects of a Sunspot

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We simulate the helioseismic wave field by using the three-dimensional Semi-spectral Linear MHD (SLiM) code and exciting small-amplitude waves by sources distributed in the near-surface layers of a model solar atmosphere.Our model atmosphere is realistic in the sense that it has a standard sound-speed profile. Our source function is a realization drawn from a random process specified by a statistical description of solar convection. We obtain a quiet-Sun power spectrum of wave motions, which is consistent with Doppler observations. In order to study wave propagation through sunspots, we derive a simplified monolithic model sunspot embedded in the quiet-Sun model atmosphere. The corresponding wave field computed with SLiM is then compared with MDI observations of f- and p-mode scattering by magnetic region AR9787. The comparison is encouraging as the numerical simulation is able to reproduce wave absorption and scattering phase shifts. As part of our analysis, we show the advantage of computing a reference quiet-Sun wave field using the same realization of the sources for the purpose of comparisons and noise reduction.

The seismic effect of a sunspot

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Abstract

We simulate the helioseismic wave field by using the three-dimensional Semi-spectral Linear MHD (SLiM) code and exciting small amplitude waves by sources distributed in the near-surface layers of a model solar atmosphere. Our model atmosphere is realistic in the sense that it has a standard sound-speed profile. Our source function is a realization drawn from a random process. We obtain a quiet-Sun power spectrum of wave motions, which is consistent with Doppler observations. In order to study wave propagation through sunspots, we derive a simplified monolithic model sunspot embedded in the quiet-Sun model atmosphere. The corresponding wave field computed with SLiM is then compared with MDI observations of f-mode scattering by magnetic region AR9787. The comparison is encouraging as the numerical simulation is able to reproduce wave absorption and scattering phase shifts.

SLiM

•The SLiM code [1,2] uses the ideal linear MHD equations in an arbitrary background. for which the displacement, ξ, is solved,

$$\rho_0 \frac{\partial^2 \boldsymbol{\xi}}{\partial t^2} = -\nabla P' + \rho' g \hat{\mathbf{z}} + \frac{1}{4\pi}(\mathbf{J}' \times \mathbf{B}_0 + \mathbf{J}_0 \times \mathbf{B}') + \mathbf{F} \quad (1)$$

$$\begin{aligned} \rho' &= -\nabla \cdot (\rho_0 \boldsymbol{\xi}), \\ P' &= c_0^2(\rho' + \boldsymbol{\xi} \cdot \nabla \rho_0) - \boldsymbol{\xi} \cdot \nabla P_0, \\ \mathbf{B}' &= \nabla \times (\boldsymbol{\xi} \times \mathbf{B}_0), \\ \mathbf{J}' &= \nabla \times \mathbf{B}', \end{aligned} \quad (2)$$

where the primed quantities are the perturbations to the background pressure, P, density, ρ, magnetic field, $\mathbf{B}$, and current, $\mathbf{J}$.

•The forcing function is,

$$\mathbf{F} = f(\mathbf{k}_i, \omega_j) e^{\frac{-(z-z_0)^2}{2d^2}} \quad (3)$$

where f is an independent realisation of a complex random process with a variance of $(1+(\omega_j T)^2)^{-1}$ where T=400 seconds is a typical lifetime of granulation. The function is uniform in $\mathbf{k}$, meaning that the sources are spatially uncorrelated. The sources are inserted just below the surface at z_0 with a depth profile given by d.

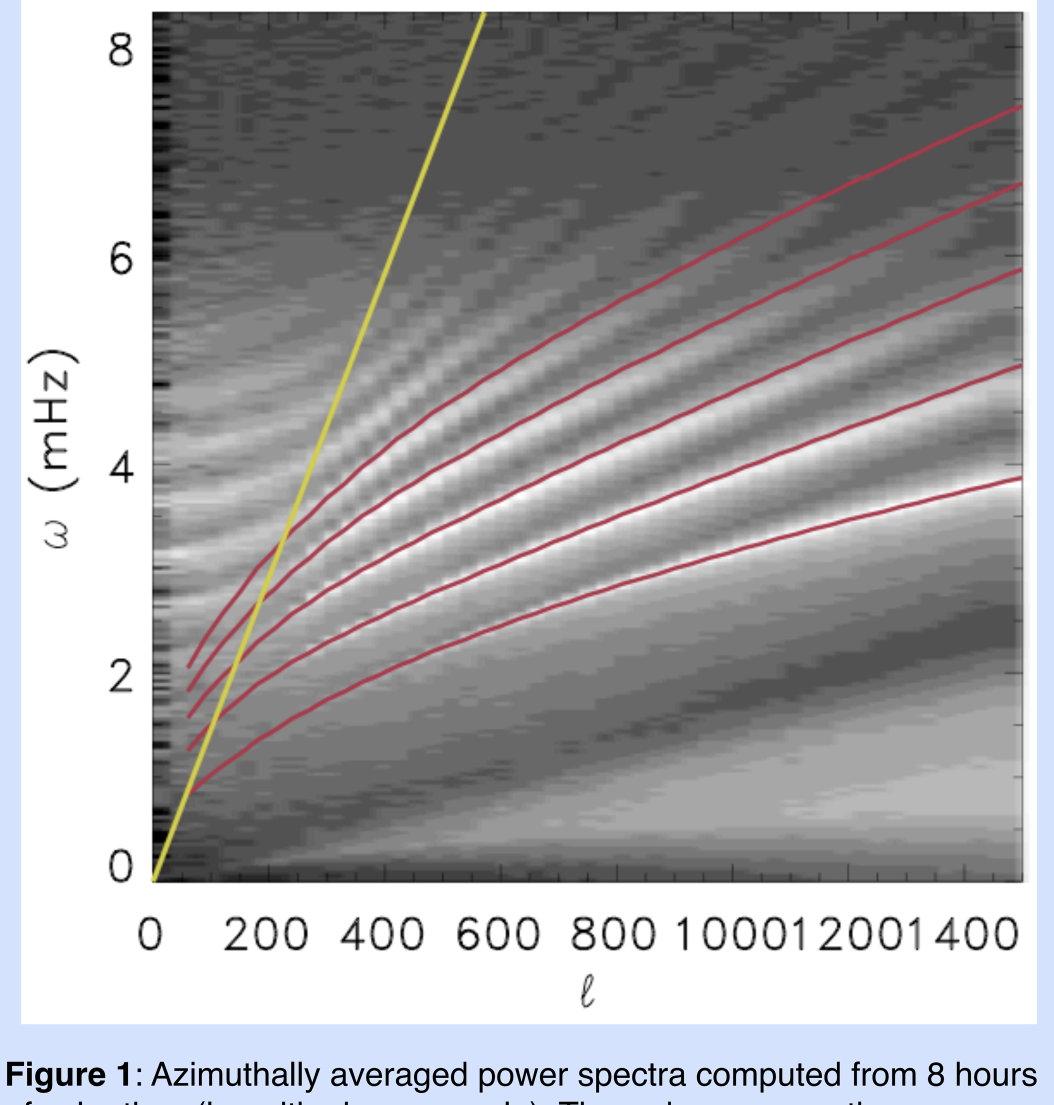


Figure 1: Azimuthally averaged power spectra computed from 8 hours of solar time (logarithmic grey-scale). The red curves are the eigenfrequencies from Model S. The yellow line is the phase speed at the bottom of the box.

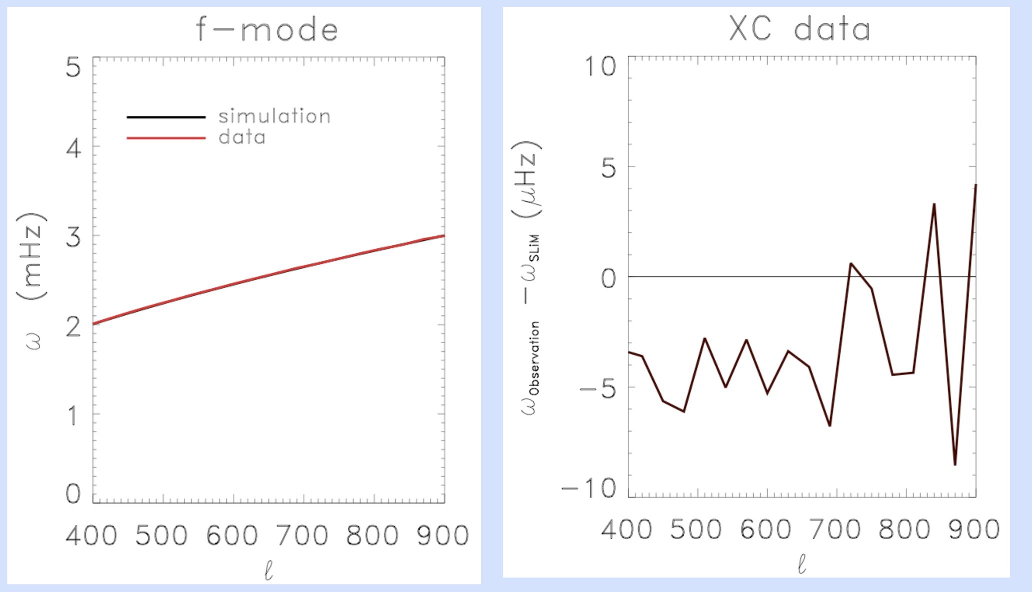


Figure 2
Left: the location of the f-mode ridge of the simulation (black) and observations (red) in spectral space. On the right we show the difference between the two spectral f-mode ridges. The difference is on the order of a fraction of a percent.

•The background is Model S [3] atmosphere stabilised by altering the pressure a few percent to ensure have stable modes.

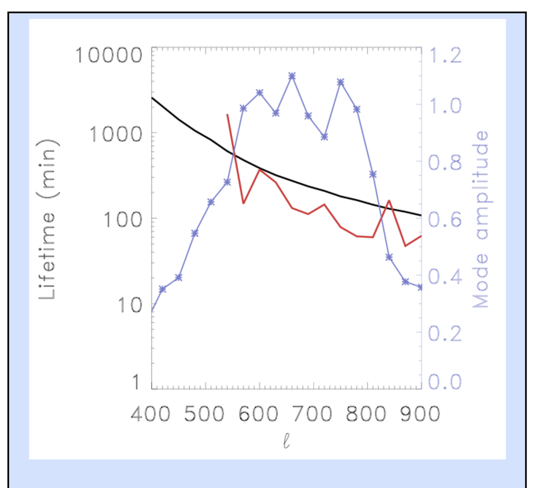


Figure 3 Lifetimes of the simulation (black) and the observations (red) in addition to the power distribution of the observed f-mode.

•To match wave speeds in the observations, the sound speed must also be modified by a few percent.

•The field of computation is a box of 27 Mm depth (25 Mm below the photosphere) and 145 Mm^2 horizontally.

•Sponge layers at the top and bottom boundaries prevent reflection.

•The equations are solved horizontally in Fourier space, finite difference in depth and by a Lax-Wendroff scheme in time.

•The atmosphere has been finely tuned to mimic the behaviour of the observed solar acoustics including the power distribution, the lifetimes of the modes and the location of the power ridges

The Atmosphere

•Figure 1 shows the azimuthally averaged power spectra of approximately 8 solar hours of a quiet Sun simulation. The red lines are eigenfrequencies of Model S. The yellow line is the phase speed at the bottom of the box.

•Figure 3 shows the lifetime of the f-mode from both the simulation (black) and the observation (red) against the power distribution of the f-mode from observations. Again, we are matching the observations.

•Figure 4 shows that a uniform field affects the location of the ridges.

•The p1-mode has also been measured and the location of the ridge and the lifetimes also agree. Qualitatively the other modes (up to p4) are also solar like, however further quantitative analysis is being done.

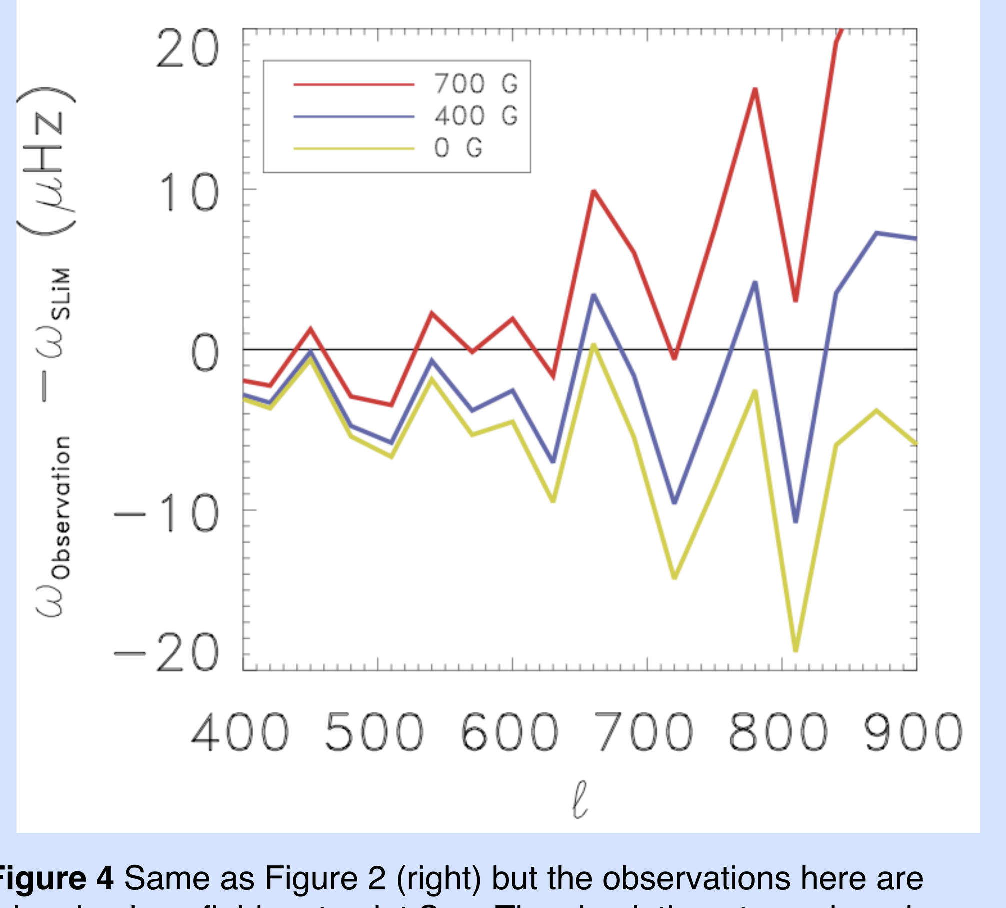


Figure 4 Same as Figure 2 (right) but the observations here are taken in plage field, not quiet Sun. The simulation atmosphere has different strength fields. The best match is for a 400 G field (blue curve).

Sunspot

The cross-covariance of a line is computed for the MDI Dopplergram observations of AR9787 [2]. This is then compared with the propagation of an f-mode plane wave through the SLiM atmosphere containing a sunspot with properties shown in Figure 4.

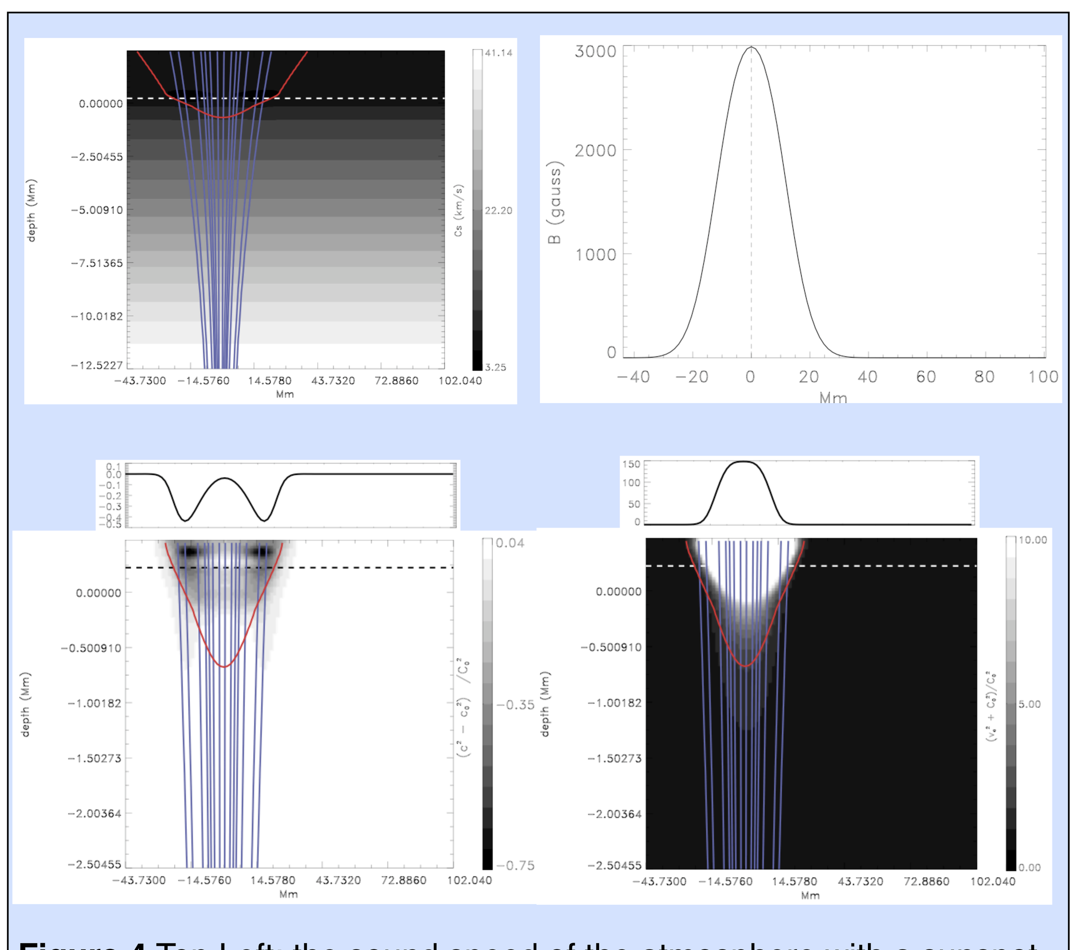


Figure 4 Top Left: the sound speed of the atmosphere with a sunspot Top right: field strength at the surface. Bottom Left: δc^2
Bottom right: fast mode speed saturated at 40 due to the large drop in density above the surface.
The contours of constant magnetic field are shown in blue, the 'surface' by the dashed line where the line plots are taken and $c_s = v_a$ surface is shown in red.

•Figure 5 shows the surface wave field after passing through the sunspot. In both, the energy of the waves has decreased and the propagation speed has increased.

•The propagation of the f-mode in the far-field is a good approximation to the observations.

•This is currently being calculated for the p-modes (up to p4).

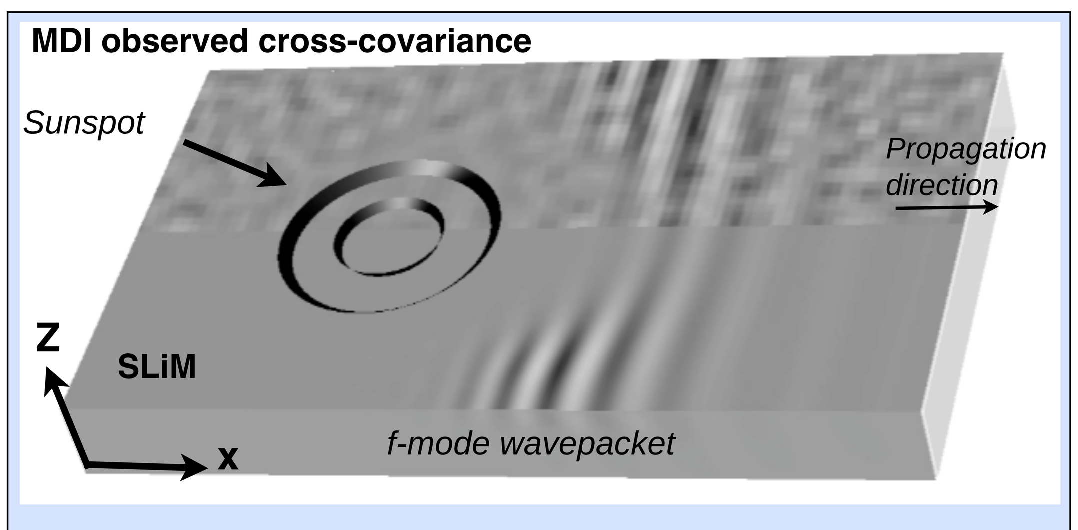
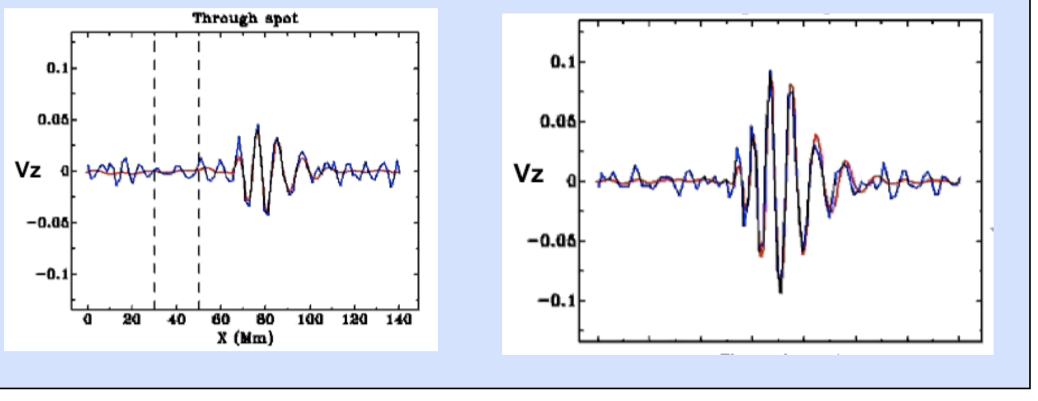


Figure 5 Above: Side-by-side comparison of the vertical velocity component of a plane f-mode propagating through the atmosphere with a simple sunspot model (3kG, r=10 Mm) and the cross-covariance of a line from MDI Doppler observations [1], [2]. Below: vertical velocity through the centre of the sunspot and some distance away from the sunspot (quiet Sun). The blue curve is the observations and the red curve is the simulation. The sunspot location is approximated by the



Summary

We have performed three-dimensional MHD simulations of waves propagating through sunspot models. The computations are set up in such a way as to allow comparing observed cross-covariances. We have shown that the full-waveform modeling of sunspots is feasible.

References

1. Cameron, Gizon & Daiffallah, 2007, *Astronomische Nachrichten*, **328**, 313
2. Cameron, Gizon & Duvall, 2008, *Solar Physics*, **online first**
3. Christensen-Dalsgaard *et al*, 1996, *Science*, **272**, *1286*

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