Helioseismology of a sunspot:
Confronting simulations with observations

Robert Cameron, Laurent Gizon

Max Planck Institute for Solar System Research, 37191 Katlenburg-Lindau, Germany

1. Waves through sunspots

SUNSPOTS appear on the solar surface as large dark regions, where strong magnetic fields constrict the outward flow of energy. Their structure below the solar surface is unknown to determine: possibly they are monolithic structures extending to the base of the convection zone, or perhaps they are shallow features and break up into spaghetti like strands just below the solar surface. Helioseismology is our best hope for "seeing" what actually lies beneath the surface.
To solve this problem it is necessary to consider the effects of the magnetic fields on the seismic waves, and the fact that the perturbations introduced by the sunspot are large compared to the background. These considerations lead us to a numerical treatment, for which purpose we developed the SLiM (Semi-spectral Linear MHD) code. Details of the basic code are given in Cameron, Gizon and Daiffallah (2007). This is the first time such simulations have been performed in three dimensions allowing a direct comparison with observations.

2. The Sunspot: AR9787

This active region contains a sunspot which is almost ideal for this study: it is long-lived, relatively isolated, almost circular and large. Figure 1 shows MDI/SOHO observations of the spot as it crossed the disk.

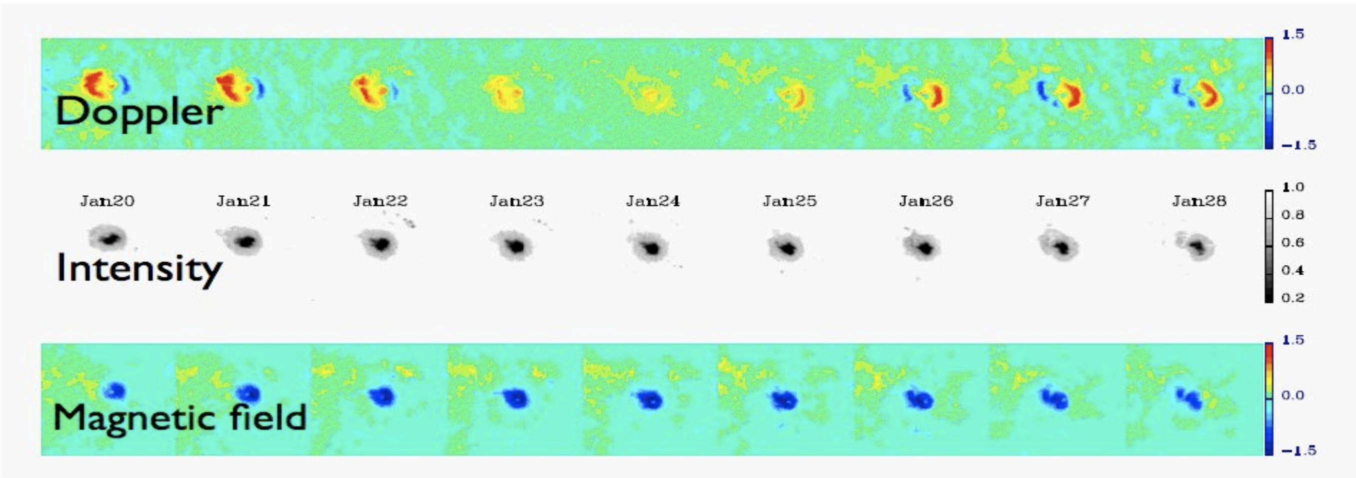

Figure 1: The sunspot during the 9 days analyzed here.

3. The observed signature

The basic data for helioseismology are 1 minute cadence maps of the line-of-sight Doppler velocity, $\phi(x, y, t)$. We use time-distance helioseismology and the SOHO/MDI data to study the interaction of the solar waves with the sunspot. We construct the temporal cross-covariance between ϕ averaged over the line $x = 0$, $\overline{\phi}(y, t)$, and $\phi(x, y, t)$. In other words, we form $C(x, y, t) = \int \overline{\phi}(y, t')\phi(x, y, t' + t)dt'$. This cross-covariance is a representation of a plane wave packet propagating in the $\pm x$ directions. It is shown for time lag t=0 and t=120 min in figure 2.

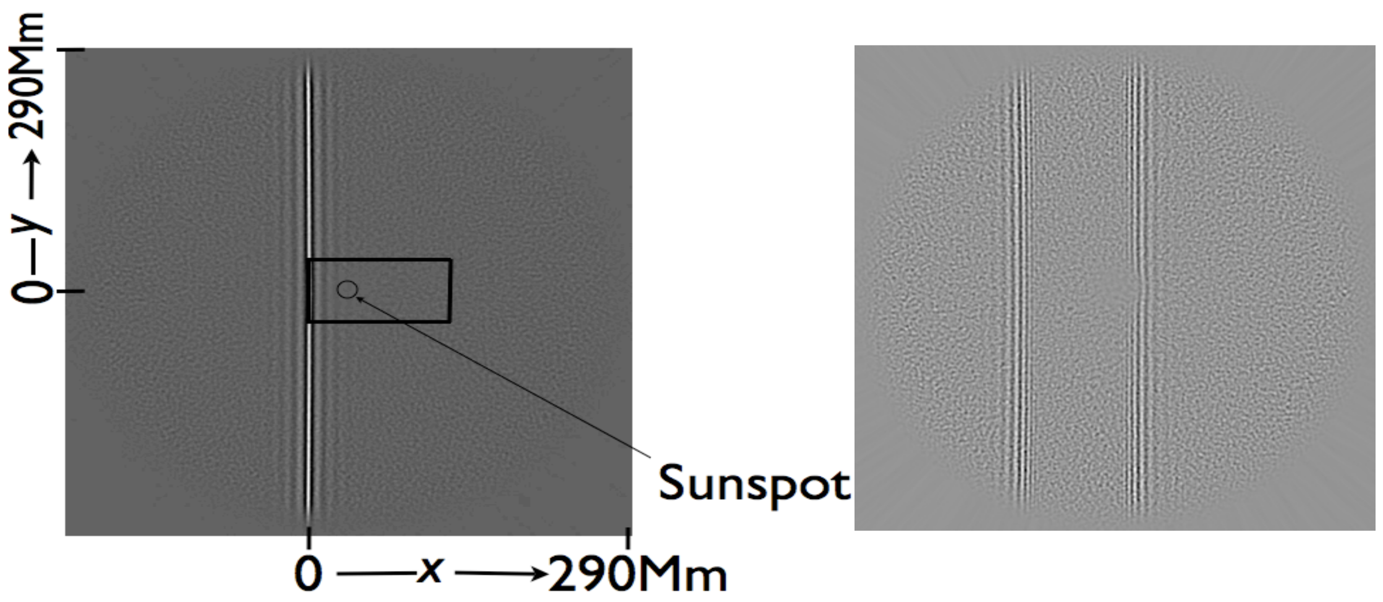

Figure 2: The cross-covariance at time lag $t = 0$ and t =120 min. The sunspot phase changes and absorption due to the spot can be seen.

4. The simulation

We have propagated waves through a model sunspot using a modified version of the SLiM code. The initial condition consists of an f-mode wave packet designed to be compatible with the observations (with power concentrated in a 1mHz band around 3mHz). The sunspot model is a monolithic magnetohydrostatic similarity solution, similar to Schlüter & Temesvary (1958, IAU Symp. 6 p623). We have assumed the vertical component of the field is given by $B_z(r, z) = B_0 \exp^{-z/\alpha} \exp^{-[(r/(\exp^{-z/\alpha})]^2/\sigma}$, where B_0 is the axial magnetic field at the solar surface (z=0), α determines the degree to which the field spreads with height, σ was chosen so that the horizontal half-width of B_z is 10Mm at the surface, and where r is the horizontal distance from the sunspot axis.

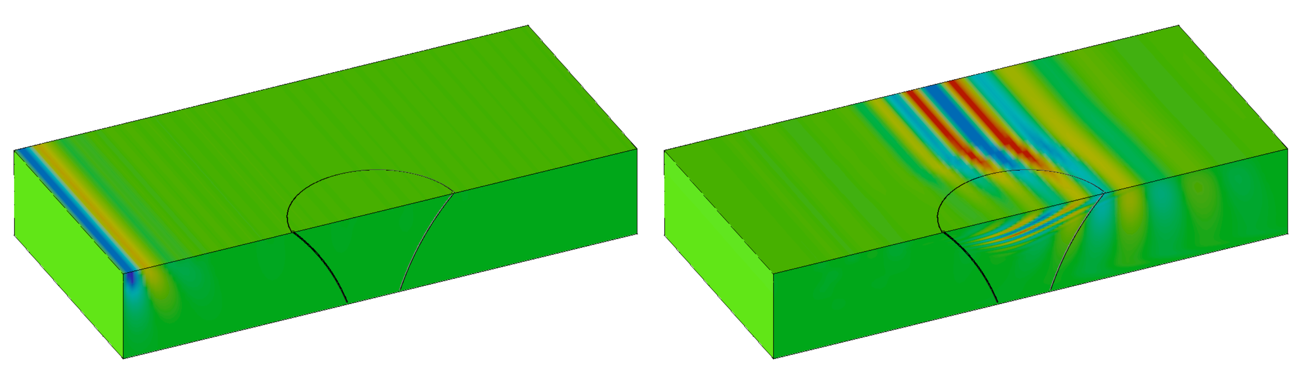

Figure 3: Shown is part the simulation box, with the sunspot. The left frame shows the initial condition, the right shows a later time. This segment of the box is 80Mm in the x-direction, 36Mm in the y and 14Mm in z. The full box is 145Mm in x, 72.5Mm in y and 14Mm in z.

5. Results for the f-mode

How well do we do?
Well. The top row of figure 4 shows the passage of the mode packet through the quiet sun (30 Mm away from the spot), in both the simulations and observations: the match is very good for B_0=3kG. The bottom row shows a comparison of the wave-forms before and after they have passed through the spot. Again the match is very good and the differences are mainly the signature of the moat flow which we have yet to model.

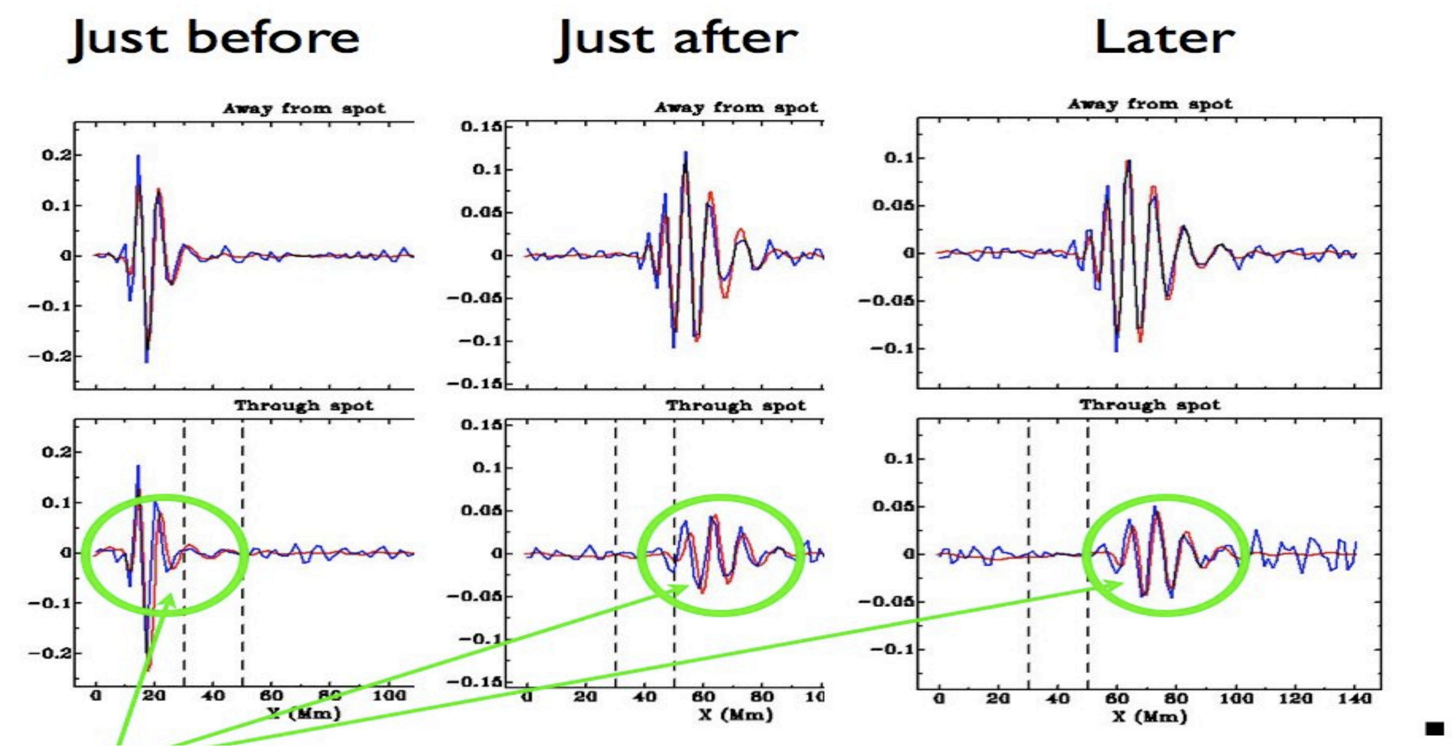

Figure 4: The simulation (red) and the observations (blue)are in very good agreement. The differences which are there are thought to be real: they can be used to constrain the sunspots structure, eg the the as yet not modeled moat flow.

Can we measure the magnetic field with helioseismology?
Yes. The phase mismatch between the simulations and the cross-covariance is a strong function of B_0. We find the best match is for B_0 around 3000G. This is the first seismic determination of solar-magnetic fields.

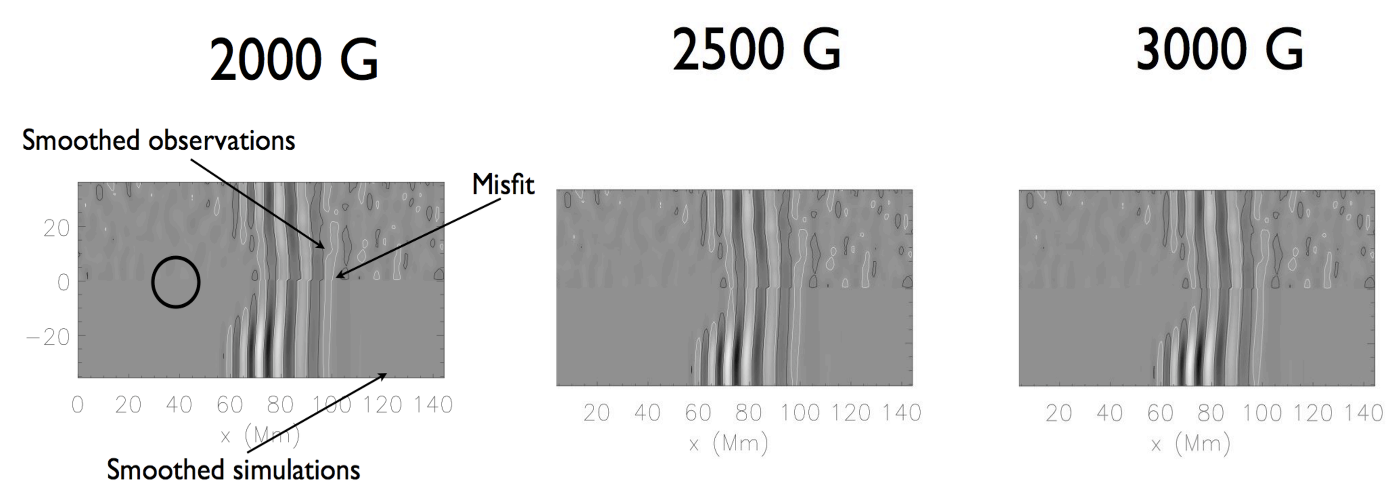

Figure 5: Different field strengths => Different seismic signatures.

Are the direct effects of the magnetic field, or the sunspot's sound speed and density changes important?
We performed a set of numerical experiments in order to answer this question
The effect from the Lorentz force is dominant. .

6. Summary

- We have developed a 3-D wave code for arbitrary backgrounds, including the effects of magnetic fields.
- We have processed the observations so that the effect of the sunspot can be clearly seen.
- We have compared the simulations and observations: the match is very good. The differences are real seismic signatures (eg of the moat flow).
- We can determine solar magnetic fields using helioseismology.
- The direct magnetic effects are large and cannot be ignored.