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Three-dimensional numerical simulation of wave propagation through a model sunspot

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Abstract

The interaction of waves with sunspots is being studied using numerical simulations. The code we have developed follows the linearized evolution of wave perturbations through an inhomogeneous (solar) atmosphere, including magnetic fields. The simulations are fully 3-D. We have used the model sunspot of Schüssler and Rempel (2005). Several possible applications in the context of local helioseismology will be discussed.

Wave Propagation

The solar atmosphere is, on the length-scales of interest to local helioseismology, far from horizontally uniform. Sunspots and granulation are but two examples of large amplitude inhomogeneities. Theory and simulations have both been used to study how these inhomogeneities affect wave propagation (see for example Cally and Bogdan, 1997) -eg scattering, refraction, reflection and dispersion. We have developed a numerical code which treats the 3-D linearized initial value problem for a wide range of background states. The idea is to consider the evolution of small perturbations (eg an f-mode wave packet) superimposed on a sunspot/non magnetic background.

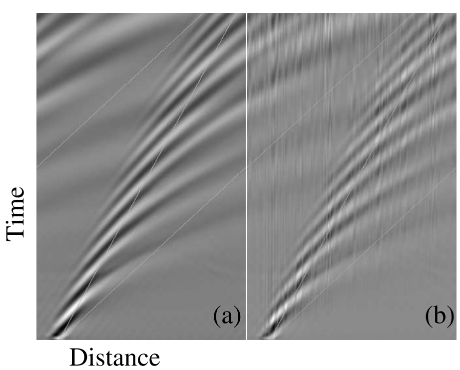

Fig. 1: Propagation of an f-mode wave packet through a 2-D unperturbed atmosphere (right) and an atmosphere with the density and temperature perturbations from a realistic photospheric simulation (see eg Voegler et al for details of the code used to generate the background). In both cases the atmosphere has been modified to have neutral stability.

For simplicity we currently assume the waves are adiabatic, and the wave propagation is ideal. A complication necessarily arises because the background stratification is unstable (it is after all the convection zone) and perturbations grow exponentially. As we are not interested in these modes we have adjusted the stratification to make the background neutrally stable. Whilst this is not desirable it appears to be unavoidable and should not greatly affect the propagating modes we are interested in. We have so far tested this idea in a non magnetic two dimensional atmosphere, with preliminary results shown if Figure 1.

We only intend to simulate small regions of the solar surface and so have used a box-geometry and used a spectral treatment in the horizontal directions and finite difference for the vertical.

The sunspot models

The 2-D example above is the start of a study on the effect of granulation on linear wave propagation. We now turn to the study of wave propagation through sunspots.

Monolithic static sunspot models have existed since Deinzer (1965). The main assumptions of this type of model are that the radial dependence at all heights are similar, eg $B_z(r,z) = B_0(z) f(r\sqrt{B_0(z)})$, and that the temperature profile is fixed. The magnetohydrostatic equations are then solved to determine $r_0(z)$. The essential feature of monolithic models is that the flux tube becomes increasingly narrow with depth.

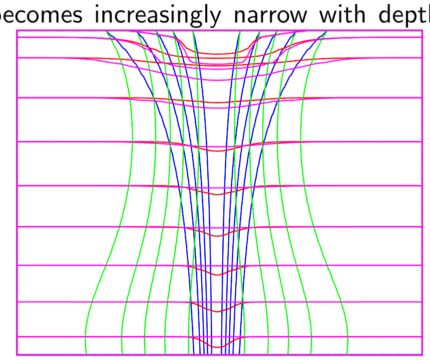

Fig. 2: A vertical cut through the monolithic and "jelly-fish" sunspots. The top of this box is just above the photosphere. Whilst our simulations extend much deeper, this box is stretched vertically and cut off at 6Mm. The horizontal extent is ...... The blue and green lines are magnetic field lines of the two sunspot models, the red and purple lines are temperature isolines. The field distribution near the photosphere is similar in both cases.

Recently Schüssler and Rempel (2005) have relaxed the assumption of a fixed thermal stratification and have considered evolutionary behavior. They begin with a monolithic sunspot. Photospheric cooling produces a sunspot a cooling front inside the sunspot. This cooling front propagates into the spot, weakening the field until the sunspot "disconnects" from its roots. The monolithic sunspot in Figure 2 is taken slightly after the simulation begins. The evolved fieldline structure is shown in green in figure 2. The field lines spread out with depth: the spot is no longer monolithic. We intend to investigate the helioseismic signatures of various spots using a fully-3D simulation. Figure 3 shows a snapshot taken from a preliminary test run.

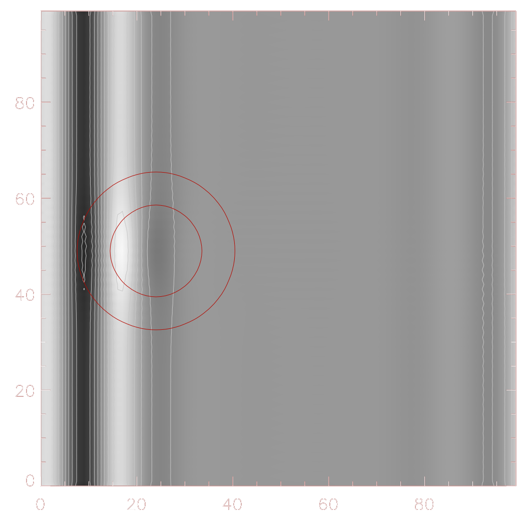

Fig. 3: Preliminary example of an f-mode wave packet passing through a sunspot. Shown is a horizontal slice from a 3-D simulation. The slice is from near the surface, and the vertical component of the velocity during the passage through the spot is shown.

References

Parker, E. N., 1979 ApJ, 230, 905
Deinzer, W., 1965 ApJ, 141, 548
Schüssler, M. and Rempel, M., 2005 A&A, 441, 337 Cally, P. and Bogdan, T. J., 1997 ApJL, 486, L67 Vögler, A. et al, 2005 A&A 429, 335

Acknowledgments

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