Solar-Stellar Dynamos as Revealed by Helio- and Asteroseismology
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Numerical Simulations of Quiet Sun Oscillations

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Abstract. We develop a quiet Sun background model to be used for the numerical simulation of solar oscillations and explore the properties of this model using the three-dimensional Semi-spectral Linear MHD (SLiM) code. We first suggest criteria for defining a convectively stable, but solar-like, background model. A first step in the development of such a solar-like model is presented and we demonstrate that it meets the first of the criteria by comparing the power spectrum of the simulation with *SOHO*/MDI observations.

1 Introduction

The interpretation of helioseismic observations in the presence of large amplitude inhomogeneities, such as sunspots, is not trivial (see e.g. Gizon et al. 2008). Numerical simulations of wave propagation in the Sun are expected to be useful in understanding and interpreting the observations. Success requires the simulations and observations to be directly compared. The purpose of this paper is first to outline criteria that can be used to determine how comparable to observations a model is. Secondly, we present an initial effort aimed towards producing a solar-like simulation of oscillations in the quiet Sun.

There are two ways to develop solar-like models. One is to compute realistic numerical simulations that include all the physics and in which the waves are naturally excited by turbulent convection (e.g. Stein & Nordlund 2000). The second is to compute the linear response of a prescribed background solar model to sources of wave excitation (e.g. Cameron, Gizon & Daiffallah 2007; Cameron, Gizon & Duvall 2008; Hanasoge 2008; Khomenko & Collados 2006). While the first is the more direct way to proceed, it has the disadvantage of requiring enormous computational power. Here we consider the second approach, which is less computationally intensive, but requires a background solar model that is stable under convection. Unless the model is stabilised, the solution is quickly dominated by the exponentially growing convective modes. The general practice to overcome this is to modify the model to make it stable against convection. Most, though not all, of these stabilised models begin with Model S (Christensen-Dalsgaard et al. 1996). However, there are countless ways to achieve stabilisation.

In Section 2, we discuss the properties that a background model would ideally have in order to support solar-like quiet Sun oscillations. In Section 3 we describe a particular stabilised background solar model that has some of the desired properties. In Section 4, we prescribe the source of excitation for the waves that is meant to model the driving effects of solar granulation. In particular, we use a stationary spatially-homogeneous random process to drive the waves

(Gizon & Birch 2004). In Section 5 we use SLiM (Cameron, Gizon & Daiffallah 2007) to numerically explore the response of the model to the imposed excitation. The resulting power spectrum is compared with a power spectrum calculated from full-disk Doppler observations from the Michelson Doppler Imager (MDI) aboard the *Solar and Heliospheric Observatory* (*SOHO*). We conclude in Section 6 with a short summary and future work to be done creating a sufficiently solar-like model.

We emphasise that the current work is a first step towards numerically modeling wave propagation in the quiet Sun. This is a prerequisite to gaining a full understanding of wave propagation through more complex inhomogeneities.

2 Criteria Defining a Stabilised Solar-Like Model

What does it mean for a model to be solar-like in the context of oscillations? Optimally, the waves of the model should have the same properties as the waves in the Sun: this includes the sources (in a statistical sense) as well as the subsequent direct and scattered wave fields. This is a broadly stated goal, and to use it in any particular instance requires us to choose a specific set of properties of the waves which should be reproduced. We explicitly do not aim to reproduce instabilities, and exclude these from the above goal.

In the current context, we suggest that the model should minimally have (1) eigenfrequencies, (2) eigenfunctions, and (3) responses to inhomogeneities that are similar to those of the Sun. The eigenfrequencies of the Sun can be directly calculated from observations. Since we can only observe the Sun's surface, there exists the problem that there is no direct way of observing eigenfunctions or responses in the solar interior to make comparisons for the second and third criteria. This can, however, be side-stepped by making a comparison against the eigenfunctions of Model S and a comparison of subsurface responses against that of Model S and the Born approximation (for weak inhomogeneities only) instead.

It is not clear how well these criteria can be satisfied. In this paper, we take a first step towards satisfying these criteria, restricting ourselves to considering only the eigenfrequencies.

3 A Stabilised Quiet Sun Model

We model a small volume near the solar surface which extends 25 Mm below the surface, 2.5 Mm above the surface and 145.77 Mm over 100 grid points in each of the horizontal directions, x and y. The grid point size in the vertical direction along z is 25 km and there are 1098 uniformly spaced grid points. The surface is defined as in Model S at $z = 0$. There are two sponge layers reducing the energy of the waves and preventing them reflecting back into the box. One is in the top 1.8 Mm of the box and one in the bottom 5 Mm of the box, where $z_{\rm b} = -20$ Mm is the height of the top surface of the bottom sponge layer and $z_{\rm t} = 0.7$ Mm is the height of the bottom surface of the top sponge layer, such that the physical domain is between $z_{\rm b} = -20$ Mm and $z_{\rm t} = 0.7$. We account for the effects of sphericity under the assumption that the horizontal extent of the box is small, and use the depth dependent gravitational acceleration prescribed by Model S.

Here we will discuss one possible candidate for a solar-like quiet Sun background, but this is not the only viable one as will be discussed in forthcoming papers. We begin with the Model S (Christensen-Dalsgaard et al. 1996) solar model. In order to achieve stability, we choose to adjust the pressure (Cameron, Gizon & Duvall 2008) while keeping it as solar-like as possible. Stability requires that a vertically displaced fluid element is not buoyant. We have found that the degree of stabilisation can be less severe than previously used in Cameron, Gizon & Duvall (2008), so that we take the gradient of the stabilised pressure to be

$$\frac{\partial P_0}{\partial z} = \max\left\{0.95\, c_{\mathrm{S}}^2\, \frac{\partial \rho_{\mathrm{S}}}{\partial z}, \frac{\partial P_{\mathrm{S}}}{\partial z}\right\}, \quad (1)$$

where the subscript ‘0’ refers to the stabilised model and the subscript ‘S’ refers to Model S.

In altering the pressure gradient we find that this increases the eigenfrequencies. To counter this we reduce the sound speed close to the surface according to

$$c_0(z) = c_{\mathrm{S}}(z)\left[1 - 0.06\, e^{-(z/10\ \mathrm{Mm})^2}\right]. \quad (2)$$

We again note that this is not the only way to stabilise the model. Furthermore, these modifications are likely to introduce changes to the acoustic cut-off (and other properties) that we have not as yet explicitly taken into account. This issue will be addressed in future papers.

We note that this is not the only way to stabilise the model, and probably not the best, since these changes are likely to introduce changes to the acoustic cut-off. Other possibilities will be addressed in a future paper.

Figure 1 shows the relative difference between our model and Model S of the pressure gradient, $(\partial_z P_0 - \partial_z P_{\mathrm{S}})/\partial_z P_{\mathrm{S}}$, and the sound speed, $(c_0 - c_{\mathrm{S}})/c_{\mathrm{S}}$. The relative difference is greatest close to the surface.

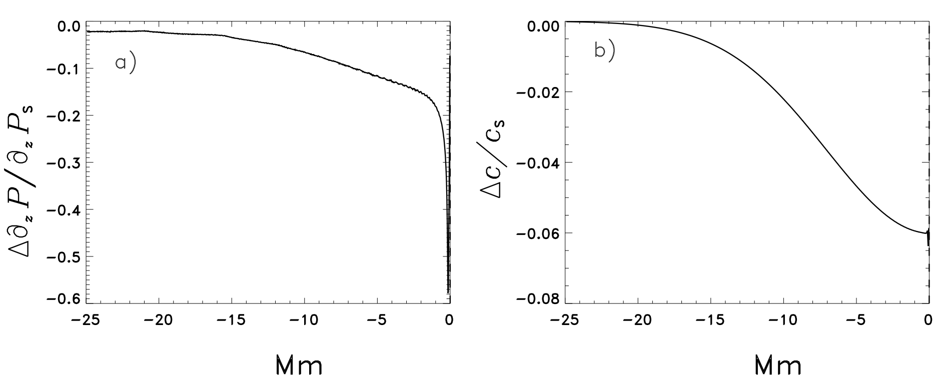

Figure 1. The relative difference between our stabilised model and Model S of (a) the pressure gradient and (b) the sound speed.

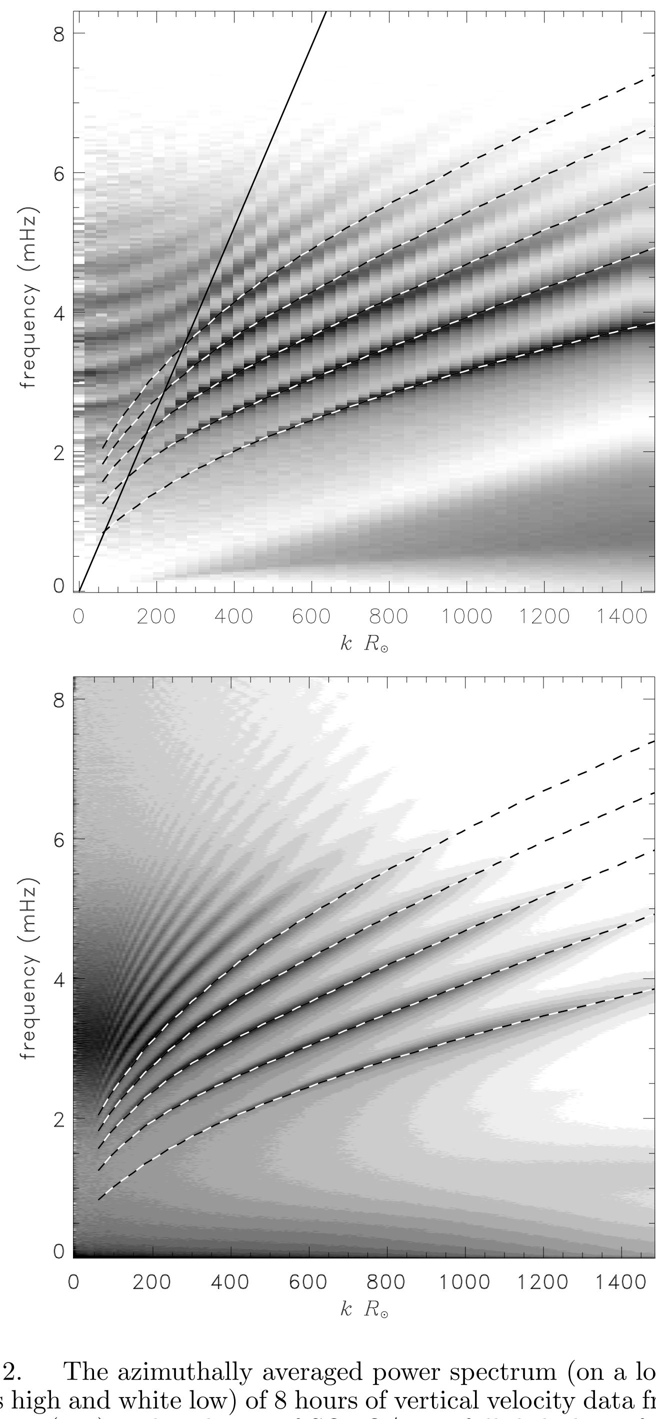

Figure 2. The azimuthally averaged power spectrum (on a log scale where black is high and white low) of 8 hours of vertical velocity data from the SLiM simulation (top) and 24 hours of SOHO/MDI full-disk, line-of-sight Doppler observations (bottom). The eigenfrequencies of Model S are overplotted as dashed lines. Modes with a horizontal phase speed ω/k greater than $c(z_b)/(1+z_b/R_\odot)$ (solid line in top panel) encounter the bottom sponge layer before reaching their lower turning point.

4 Forcing Function

The generation of acoustic waves in the Sun is due to stochastic excitation from convective turbulence. We model this by imposing an additional force, corresponding to a vertical acceleration a_z. Following Gizon & Birch (2004), in Fourier space we take the form of the acceleration to be

$$a_z(\mathbf{k}_i, \omega_j) = G_{ij} e^{-(z-z_\mathrm{s})^2/d^2}, \tag{3}$$

where $\mathbf{k}_i$ is a horizontal wavevector, ω_j is an angular frequency, and G_{ij} is an independent realisation of a complex Gaussian random variable with zero mean and variance given by $E[|G_{ij}|^2] = 1/[1 + (\omega_j \tau)^2]$ with $\tau = 400$ s. The height of the sources is at $z_\mathrm{s} = -100$ km, which is close to the highly superadiabatic layer where solar waves are strongly excited (Elliott & Kosovichev 1996), and $d = 75$ km. The waves' attenuation is a function of wavenumber only and modelled in the same way as in Cameron, Gizon & Duvall (2008).

5 The Numerical Simulation and Comparison with Observations

From the full simulations we use horizontal slices of vertical velocity taken 200 km above the surface every 60 seconds. Figure 2 (top) shows the power spectra from a simulation of 8 hours. The dashed curves are the eigenfrequencies calculated from Model S. Modes with a horizontal phase speed ω/k greater than $c(z_b)/(1+z_b/R_\odot)$ encounter the bottom of the computational domain before reaching their lower turning point, and thus are not properly modelled. These are all the waves with phase speeds higher than the solid line in the figure. For comparison we show the quiet Sun azimuthally averaged power spectrum from 24 hours of full-disk *SOHO*/MDI observations in the bottom panel of Figure 2. The ridges at higher wavenumbers in the observed power spectrum are not as pronounced as those in the simulations due to the modulation transfer function of the *SOHO*/MDI instrument (Rabello-Soares, Korzennik & Schou 2001) that reduces the contrast at high wavenumbers.

Figure 3 shows cuts through the azimuthally averaged power spectra for different values of $kR_\odot$ (300, 450 and 690). Each power curve from the simulation has been normalised by the integral of the observed power. The simulations reproduce the sign of the line asymmetries seen in the observations. The power profiles are quite similar, but get progressively worse at higher frequencies.

6 Summary and Future Work

We have set out criteria by which the solar-likeness of a quiet Sun model can be judged from the point of view of oscillations. In this paper we have taken a first step towards meeting these criteria by modifying Model S to create a convectively stable model of the quiet Sun. The model successfully meets the first criterion with eigenfrequencies similar to those observed on the Sun and it represents perhaps the best such model available. In the future we will build on this in an attempt to create a quiet Sun model that satisfies, as best we can manage, all the criteria we have set out.

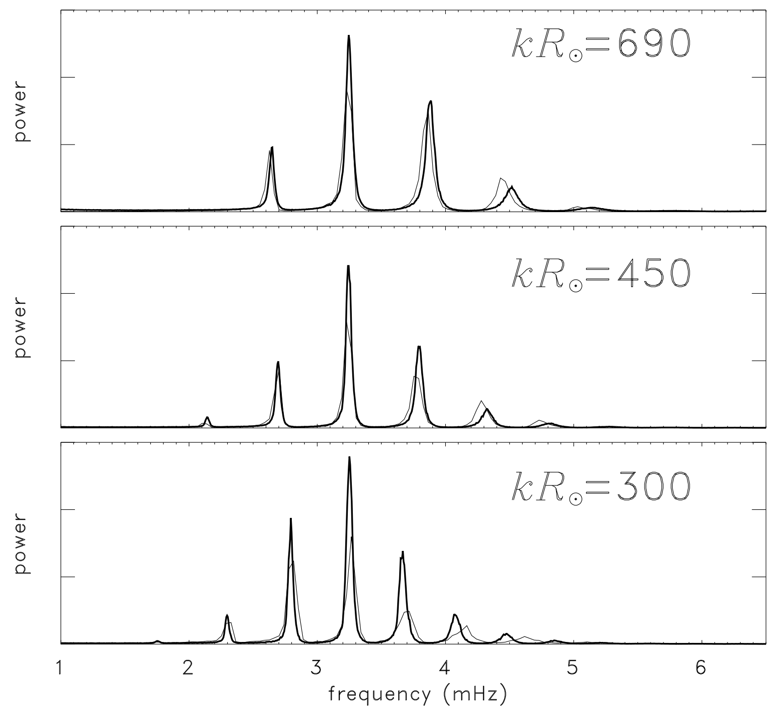

Figure 3. Cuts through the power spectrum at different wavenumbers, k, as indicated. The observational power spectrum (thick curve) is calculated from *SOHO*/MDI full-disk, 24 hour, quiet Sun data. The simulation (thin curve) and the observations are qualitatively similar.

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