EFFECT OF SUPPRESSED EXCITATION ON THE AMPLITUDE DISTRIBUTION OF 5 MINUTE OSCILLATIONS IN SUNSPOTS

K. V. Parchevsky and A. G. Kosovichev
W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305
Received 2006 June 23; accepted 2007 July 13; published 2007 August 21

ABSTRACT

Five minute oscillations on the Sun (acoustic and surface gravity waves) are excited by subsurface turbulent convection. However, in sunspots the excitation is suppressed because a strong magnetic field inhibits convection. We use three-dimensional simulations to investigate how the suppression of excitation sources affects the distribution of the oscillation power in sunspot regions. The amplitude of random acoustic sources was reduced in circular-shaped regions to simulate the suppression in sunspots. The simulation results show that the amplitude of the oscillations can be approximately 2–4 times lower in the sunspot regions in comparison to the quiet Sun, just because of the suppressed sources. Using SOHO MDI data we measured the amplitude ratio for the same frequency bands outside and inside sunspots and found that this ratio is approximately 3–4. Hence, the absence of excitation sources inside sunspots makes a significant contribution (about 50% or higher) to the observed amplitude ratio and must be taken into account in sunspot seismology.

Subject headings: Sun: oscillations — sunspots

1. INTRODUCTION

It has long been known that 5 minute solar oscillations have significantly lower amplitude (by a factor of 2–5) in sunspots and plages than in the quiet Sun (e.g., Woods & Cram 1981; Thomas et al. 1982; Title et al. 1992). Hindman (1997) enumerated four possible mechanisms to explain the observed power suppression: (1) reduction of excitation of p-modes inside sunspots, (2) absorption of p-modes inside sunspots (e.g., Cally 1995), (3) the different height of spectral line formation due to the Wilson depression, and (4) altering of p-mode eigenfunctions by the magnetic field. The precise contribution of these effects to the observed amplitude reduction is still unknown. In this Letter we study the first effect: changes in the oscillation amplitude due to suppression of acoustic sources by using three-dimensional numerical simulation of solar acoustic waves, which are important for solar seismology studies. Inside sunspots, a strong magnetic field inhibits the turbulent convective motions that are the source of the 5 minute solar oscillations. Therefore, the waves in the 5 minute period (3 mHz frequency) range, observed in sunspots, mostly come from the outside regions, and thus their amplitude is reduced in comparison to the quiet Sun. Our goal was to estimate the significance of this effect by modeling wave fields in horizontally uniform background solar models with regions of reduced excitation. The main result is that the suppression of oscillation sources inside sunspots can make substantial (about 50% or greater) contribution to the reduction of amplitude inside sunspots and thus must be taken into account in sunspot seismology.

2. METHOD

Wave propagation on the Sun (in absence of magnetic field and flows) can be described by the following system of linearized Euler equations:

\[ \frac{\partial \rho'}{\partial t} + \nabla \cdot (\rho' \mathbf{u}') = 0, \]

\[ \frac{\partial}{\partial t} (\rho' \mathbf{u}') + \nabla p' = g_0 \rho' + f(x, y, z, t), \tag{1} \]

where \( u', v', w' \) are the perturbations of \( x, y, z \) velocity components, \( \rho' \) and \( p' \) are the density and pressure perturbations respectively, and \( f(x, y, z, t) \) is the function describing the acoustic sources. The pressure \( p_0 \), density \( \rho_0 \), and gravitational accelerations \( g_0 \) of the background reference model depend only on depth \( z \). We used the adiabatic relation \( \delta p/\rho_0 = 1/\Gamma_1 \delta p/\rho_0 \) between Lagrangian variations of pressure \( \delta p \) and density \( \delta \rho \). The adiabatic exponent \( \Gamma_1 \) was calculated from an OPAL equation of state (Rogers et al. 1996).

The numerical method is based on a high-order finite difference scheme, developed by Tam & Webb (1993) and described in details by Parchevsky & Kosovichev (2006). The coefficients of this finite difference scheme are chosen to minimize the error of the Fourier transform of numerical derivatives. Such a scheme preserves the dispersion relations of the continuous case for shorter wavelengths. At the top and bottom boundaries we used the high-order stable boundary closures developed by Carpenter et al. (1993). A third-order strong stability preserving Runge-Kutta method (Shu 2002) was used for time integration.

The standard solar model (Christensen-Dalsgaard et al. 1996) with a smoothly joined chromospheric model of Vernazza et al. (1976) was used as the background state. The model was corrected in the near-surface layers to prevent development of convective instability in the superadiabatic layer by replacing large negative values of the Brunt-Väisälä frequency by zero (or small positive) values and recalculating the hydrostatic equilibrium (Parchevsky & Kosovichev 2006). This is a necessary modification for all linear simulations of this type. It suppresses rapidly growing, convectively unstable modes but does not affect essential properties of acoustic wave propagation in the Sun.

To prevent reflection of acoustic waves from the boundaries of the computational domain, we follow the perfectly matching layer (PML) method of Hu (1996). We set the top nonreflecting boundary condition above the temperature minimum. This simulates a realistic case in which the waves are only partially reflected by the photosphere. The waves with frequencies higher than acoustic cutoff frequency \( \nu_c \sim 5 \text{ mHz} \) pass through the photosphere and are absorbed by the PML. For frequencies below \( \nu_c \), the top boundary does not affect the reflection be-
Fig. 1.—Power spectrum of the vertical component of velocity obtained from the (a) simulations and (b) high-resolution SOHO MDI data (Scherrer et al. 1995). The acoustic spectral density depicted by the gray scale is given in arbitrary units. The white curves show observed \( f_p \) and \( p_1 \) mode ridges; \( l \) is the angular degree.

cause the acoustic waves are mostly reflected by the photosphere and become evanescent in the chromosphere.

The damping mechanism of solar modes below the acoustic cutoff frequency is not yet completely understood. It can be due to wave scattering on turbulence in subsurface layers (e.g., Murawski 2003) and also due to partial escape of waves and radiative losses (Christensen-Dalsgaard & Frandsen 1983). We have investigated both of these mechanisms. The atmospheric damping was modeled by imposing the upper absorbing boundary at different levels and choosing the height of this boundary in such a way (about 500 km above the photosphere) that the observed line widths in the oscillation power spectrum are well reproduced. To model the subsurface (turbulent) damping we followed Gizon & Birch (2002) and added a friction-type term \(-\sigma(z)v_r\) to the vertical component of momentum equation, where the damping coefficient \( \sigma(z) \) is constant above the photosphere and smoothly decreases to zero at a depth of ~500 km. For this case, the upper boundary was placed at the chromosphere-corona transition layer (about 1750 km above the photosphere), and the value of \( \sigma(z) \) was adjusted to match the observed line widths and relative amplitude of the peaks in the acoustic spectrum. The lateral boundary conditions are periodic. Duration of simulations was 4.5 hr of solar time. We compared results with longer runs and checked that the rms oscillation amplitude reaches an equilibrium state, and also that the simulated acoustic spectra are close to the observed power spectrum.

The question of the depth of the acoustic sources on the Sun is also still open. Numerical simulations of solar convection (Stein & Nordlund 2001) show that in the region around 3–4 mHz the most driving occurs between the photosphere and subsurface layer 500 km deep, with a maximum driving at 200–300 km below the surface. Accordingly, the sources were randomly distributed in time and on a horizontal plane 350 km below the photosphere. We also considered the case of shallow (100 km deep) sources, as suggested by Nigam & Kosovichev (1999) and Kumar & Basu (2000). The sources were modeled by spherically symmetric Gaussian shape vertical force perturbations with FWHM of 300 km and random amplitudes and frequencies. The time dependence was either a one-period sin function, \( \sin[\omega(t - t_0)] \), \( t_0 \leq t \leq t_0 + 2\pi/\omega \), or Ricker’s wavelet, \((1 - 2x^2)e^{-x^2}, \) where \( x = [\omega(t - t_0)/2 - \pi], t_0 \leq t \leq t_0 + 4\pi/\omega \). The frequency distribution of acoustic sources was uniform in the range of 2–8 mHz. The simulations were carried out in the rectangular domain of size 122 × 122 × 30 Mm³ using a uniform 816 × 816 × 630 grid. The simulated and observed power spectra are shown in Figure 1.

3. RESULTS

Using this method we simulated the distribution of oscillation power for sunspots of various size, acoustic source models, and compared with observations. Observations for sunspots in active regions AR 10373 (panels a, b, and c) and AR 8243 (panels d, e, and f) obtained by SOHO MDI are shown in Figure 2. Panels a and d represent maps of the line-of-sight magnetic field from high-resolution MDI data. Panels b and e show the corresponding vertical velocity oscillation amplitude maps, averaged in the frequency interval \( \Delta \nu = 1.2 \) mHz with central frequency \( \nu = \)
3.65 mHz. The azimuthally averaged profiles of the oscillation amplitude (thick solid curves for observations and dashed curves for simulations) and the profile of the source strength (thin solid curves) are shown in panels c and f.

We simulated the suppression of the acoustic sources (changes in acoustic emissivity) due to magnetic field in sunspots by zeroing the source amplitude at the center of sunspot umbra and smoothly increasing the source strength in the penumbra toward a constant value outside the sunspots (source masking). Numerical experiments with different profiles of the source strength show in all cases that the simulated wave field profile has the shape similar to the profile of the acoustic source strength (this was not a priori obvious). Thus, we use a horizontal profile of the observed wave field (shifted and scaled to be in the range [0, 1]) as an acoustic source strength profile. In reality, the strength of acoustic sources depends on magnetic field strength. The actual dependence is unknown, however; the distribution of acoustic sources calculated from the wave field is similar to the inverse profile of the sunspot magnetic field (Fig. 3).

The simulation results (Figs. 2c and 2f) show that the waves propagate into the region of reduced excitation, but oscillation amplitude is substantially decreased. However, it still does not match the observed values at sunspot center. This means that the suppression of acoustic sources is obviously a very important effect in sunspot seismology. However, other factors can be evidence that the depth of the acoustic sources is between 100 and 350 km, if the absence of acoustic sources inside the sunspot, and the results are not overly sensitive to the mechanism of wave damping. Our numerical experiments showed that amplitude ratio \( V_{\text{out}} / V_{\text{in}} \) is insensitive to the detailed shape of the profile of the acoustic source strength. However, it is important that the FWHM of the source strength is close to the FWHM of the averaged horizontal amplitude profile of the observed wave field. We found that the amplitude ratio increases for smaller depth \( h_{\text{src}} \) of the acoustic sources and equals 5.5 ± 1.7 for \( h_{\text{src}} = 100 \) km below the photosphere (low top absorbing boundary without explicit damping). This can be evidence that the depth of the acoustic sources is between 100 and 350 km, if the absence of acoustic sources is a dominating mechanism of the amplitude suppression in sunspots.

We have carried such simulations for several other sunspots and obtained similar results. The comparison between simulations and observations for sunspots of different sizes is shown in Figure 5a. The ratio \( V_{\text{out}} / V_{\text{in}} \) as a function of umbra diameter is plotted. The open circles represent observations, and the stars represent simulations. Both the simulations and the observations show the same trend: the amplitude suppression increases with the size of sunspots. On average, the amplitude ratio is about half of the observed one for the sources at depth.
350 km, and higher for shallower sources. Frequency dependence of the amplitude ratio for AR 8243 is shown in Figure 5b. The frequency shift between the simulations and observations in Figure 5b can be evidence that the acoustic cutoff frequency inside sunspots is much lower than that in the quiet Sun, but this requires further investigation. This may be one of the additional factors that affects the oscillation amplitude in sunspots.

4. DISCUSSION

We have carried out numerical simulations of the effect of reduced excitation of solar oscillation in sunspot regions. The oscillations are excited by random sources and modeled as vertical momentum and pressure perturbations (in reality caused by turbulent convection). In sunspot regions, the wave sources are weaker because the magnetic field of sunspots inhibits convective motions. The results of simulations show that for a wide range of sunspot diameters, more than half of the suppression of oscillation amplitude can be explained by the absence of acoustic sources in sunspots.

Our simulations also showed that the oscillation amplitude in regions of suppressed excitation only weakly depends on the wave damping mechanism in the upper convection zone and atmosphere as long as the line widths in the simulated power spectrum are close to the observed ones. We modeled wave damping by two methods: introducing a friction-type term into the z-component of the momentum equation and putting the wave absorbing boundary at various heights in the chromosphere. In both cases we get the similar ratios of oscillation amplitudes. If the acoustic cutoff frequency in sunspots is reduced, this will increase the damping and may lead to an even stronger reduction of the wave amplitude compared to the quiet Sun.

We thank P. Scherrer for fruitful discussions.

REFERENCES

Cally, P. S. 1995, ApJ, 451, 372
Carpenter, M. H., Gottlieb, D., & Abarbanel, S. 1993, J. Comput. Phys., 108, 272
Christensen-Dalsgaard, J., & Frandsen, S. 1983, Sol. Phys., 82, 165
Christensen-Dalsgaard, J., et al. 1996, Science, 272, 1286
Gizon, L., & Birch, A. C. 2002, ApJ, 571, 966
Hindman, B. W. 1997, ApJ, 476, 392
Hu, F. Q. 1996, J. Comput. Phys., 129, 201
Jones, H. P. 1989, Sol. Phys., 120, 211
Kumar, P., & Basu, S. 2000, ApJ, 545, L65
Murawski, K. 2003, in Turbulence, Waves and Instabilities in the Solar Plasma, ed. R. Erdélyi, E. Forgács-Dajka, & K. Petrovay (Dordrecht: Kluwer), 61
Nigam, R., & Kosovichev, A. G. 1999, ApJ, 514, L53
Parchevsky, K. V., & Kosovichev, A. G. 2007, ApJ, 666, 547
Rogers, F. J., Swenson, F. J., & Iglesias, C. A. 1996, ApJ, 456, 902
Scherrer, P. H., et al. 1995, Sol. Phys., 162, 129
Shu, C. W. 2002, in Collected Lectures on the Preservation of Stability under Discretization, ed. D. Estep & S. Tavener (Proc. Appl. Math 109; Philadelphia: SIAM), 51
Stein, R. F., & Nordlund, . 2001, ApJ, 546, 585˚A
Tam, C., & Webb, J. 1993, J. Comput. Phys., 107, 262
Title, A. M., et al. 1992, ApJ, 393, 782
Vernazza, J. E., Avrett, E. H., & Loeser, R. 1976, ApJS, 30, 1
Woods, D. T., & Cram, L. E. 1981, Sol. Phys., 69, 233