LINE ASYMMETRY OF SOLAR $p$-MODES: PROPERTIES OF ACOUSTIC SOURCES

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ABSTRACT

The observed solar $p$-mode velocity power spectra are compared with theoretically calculated power spectra over a range of mode degree and frequency. The shape of the theoretical power spectra depends on the depth of acoustic sources responsible for the excitation of $p$-modes and also on the multipole nature of the source. We vary the source depth to obtain the best fit to the observed spectra. We find that quadrupole acoustic sources provide a good fit to the observed spectra provided that the sources are located between 700 and 1050 km below the top of the convection zone. The dipole sources give a good fit for a significantly shallower source, with a source depth of between 120 and 350 km. The main uncertainty in the determination of depth arises because of poor knowledge of the nature of power leakages from modes with adjacent degrees and the background in the observed spectra.

Subject headings: convection — line: profiles — Sun: oscillations — turbulence

1. INTRODUCTION

The claim of Duvall et al. (1993) that solar $p$-mode line profiles are asymmetric is now well established from the data produced by the Global Oscillation Network Group (GONG) and the instruments aboard the Solar and Heliospheric Observatory (SOHO). The unambiguous establishment of the asymmetry is important, since fitting a symmetric profile to the asymmetric line in the power spectra can give erroneous results for the solar eigenfrequencies (see Nigam & Kosovichev 1998). In the last few years a number of different aspects of the line asymmetry problem have been explored, and there appears to be a general consensus that the degree of line asymmetry depends on the depth of acoustic sources responsible for exciting solar $p$-modes (see Duvall et al. 1993; Gabriel 1995; Abrams & Kumar 1996; Rosenthal 1998). We make use of the best available observed power spectra, for low-frequency $p$-modes, and the solar model to determine the location and nature of sources. One of the main differences between this work and others is that we determine the source depth using a realistic solar model and taking into account the fact that the observational profiles of a given degree have a substantial contribution of power from modes of neighboring degrees. The effect of $\ell$-leakage on the line asymmetry and on the background of the power spectra that affects the determination of source depth is considered in § 2. The main results are summarized in § 3.

2. THEORETICAL CALCULATION OF LINE ASYMMETRY

The calculation of power spectra is carried out using the method described in Abrams & Kumar (1996) and Kumar (1994). Briefly, we solve the coupled set of linearized mass, momentum, and entropy equations, with a source term, using the Green’s function method. We parameterize the source by two numbers—the depth where the source peaks and the radial extent (the radial profile is taken to be a Gaussian function), instead of taking the source as given by the mixing length theory of turbulent convection. Power spectra for different multipole sources are calculated using the following equation:

$$ P(\ell) = \left| \int dr S(r, \ell) \frac{d^2 G_{\ell\ell}}{dr^2} \right|^2, $$

where $n = 0$ for dipole and 1 for quadrupole sources and $G_{\ell\ell}$ is the Green’s function for the linearized set of nonadiabatic wave equations. Physically, dipole sources produce acoustic waves by applying a time-dependent force on the fluid, whereas only fluctuating internal stresses are associated with quadrupole sources, and there is no associated net momentum flux.

The power spectrum calculated using equation (1) is asymmetric, and the amount of asymmetry is a function of the source depth (see Abrams & Kumar 1996). Thus by matching the asymmetry of the theoretical spectrum to that of the observed, we can estimate the depth of the sources that excite solar $p$-modes.

Other than the source depth, for any given mode there are three free parameters in the fit—the amplitude, the line width, and the background. We normalize the observed and model amplitudes to unity. The background is assumed to be frequency independent over the narrow range of frequencies over which we carry out the fit.

The solar model used in this work is a standard model of the present Sun. It was constructed with OPAL opacities (Iglesias & Rogers 1996) supplemented by low-temperature opacities of Kurucz (1991), and the OPAL equation of state (Rogers, Swenson, & Iglesias 1996) was used. Convective flux is calculated using the formulation of Canuto & Mazzitelli (1991), and the photospheric structure is calculated using the empirical $T-\tau$ relation of Vernazza, Avrett, & Loeser (1981). To check model dependencies we have also used a similar model that uses the mixing-length formalism to calculate convective flux. We have also used model S of Christensen-Dalsgaard et al. (1996) and the old Christensen-Dalsgaard model used in Kumar (1994, 1997), which had earlier been used to determine the source depths.

The observed power spectra used in this work are the 144 day data from the Michelson Doppler Imager (MDI) of the Solar Oscillation Investigation (SOI) on board SOHO and the data obtained by GONG during months 4–10 of its operation.

2.1. The Source Depth without $\ell$-Leakage

The calculated power spectrum superposed on the observed spectrum is shown in Figure 1. The calculated spectrum in Figure 1 does not include power leakage from modes of adjacent degrees.
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Fig. 1.—Calculated line profile superposed on observed line profiles. The observed line profiles are shown by the thin continuous lines. They have been obtained by averaging the spectra of all azimuthal orders, $m$, of the given mode after frequency shifts to account for rotational splitting. The theoretical profiles obtained with a quadrupole source are shown as the heavy solid line, and that for the dipole source is shown by the heavy dashed line. The quadrupole source is at a depth of 1050 km and the dipole at depth of 350 km from the top of the convection zone. The data for the $l = 35$ mode are GONG data, while the $l = 60$ data are from MDI.

We define the goodness of fit by the merit function (see Anderson, Duvall, & Jeffries 1990)

$$F_m = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{O_i - M_i}{M_i} \right)^2,$$  

where the summation is over all data points, $O_i$ is the observed power, and $M_i$ the model power. The quadrupole and dipole sources give very similar line profiles. The figures of merit are also very similar: 0.0069 for quadrupole and 0.0073 for dipole sources for the fit to the $l = 35$ mode in the frequency range $\pm 6$ μHz from the peak. For the $l = 60$ mode, $F_m$ is 0.0053 for the quadrupole source and 0.0047 for the dipole.

However, the source depths obtained for the two types of sources are very different. For the same source depth, dipole and quadrupole sources give rise to different sense of line asymmetry. The source depth for the spectrum shown in Figure 1 is about 1050 km for the quadrupole source and 350 km for the dipole source. The depth required seems independent of the degree of the mode in the range where we attempted the fit ($l = 35$–$80$). However, there appears to be a small dependence on the frequency of the mode, with higher frequency modes, $\sim 3$ mHz, requiring slightly shallower sources. The difference is within the uncertainty.

Note that there is some difference between the observed and the theoretical spectra in the wings of the lines. We find that we cannot fit the line wings properly without taking $l$-leakage into account.

2.2. The Source Depth with $l$-Leakage

The observed spectra for modes of a desired degree contains leakage from neighboring $l$-modes as a result of partial observation of the solar surface.

A rough estimate for $l$-leakage can be obtained from the amplitudes of different $l$-peaks at low frequencies. Inclusion of $l$-leakage in the theoretical calculations decreases asymmetry of the model. This can be seen in Figure 2. Moreover, it can be seen that $l$-leakage contributes to the background of the spectra. This implies that the observed spectrum can be fitted with a theoretically calculated power spectrum with a shallower source depth and a significantly smaller background term than was used in § 2.1. As a result, the source depth determined in the previous section is just an upper limit to the depth.

In Figure 3 we show the fit to the observed spectrum of an $l = 35$ mode when $l$-leakage is taken into account while calculating the theoretical spectrum. The source depths needed are 950 km for a quadrupole source and 300 km for a dipole source. We have taken the leakage from the mode of degree ($l - 2$) to be 10% of its power, the $l - 1$ mode leaks 45% of its power, the $l + 1$ mode leaks 75% of its power, and the $l + 2$ mode leaks 25% of its power into the power spectrum of the mode under consideration. These
numbers were estimated from the observed power spectrum for the mode obtained by the GONG network. The best-fit theoretical curves, for both dipole and quadrupole sources, provide a much better match to the observed spectrum than the case where the leakage was ignored. The figures of merit are 0.0028 for the quadrupole source and 0.0025 for the dipole source. So, unfortunately, it is still not possible to say whether the excitation sources in the Sun are quadrupole or dipole based on the observed asymmetry of low-frequency $p$-modes.

To get a lower limit to the depth, we considered an extreme case where modes of $\ell = \pm 1$ and $\pm 2$ leak all their power into the mode under consideration and find that for quadrupole sources we require a source depth of 700 km, and for a dipole source a source depth of 120 km is needed.

3. DISCUSSION

The calculation of power spectra using the method described in Kumar (1994) has been shown previously to fit the high-frequency velocity power spectra (see Kumar 1997). In this paper we have shown that the same method can be used to calculate the power spectrum with observed line shapes for low- and intermediate-frequency modes as well. The variable parameter is the source depth. The depth required to fit the observed low-frequency $p$-mode spectra depends mainly on the nature of the sources; quadrupole
sources have to be very deep—between 700 and 1050 km—while dipole sources need to be relatively shallow—between 120 and 350 km. The main uncertainty in the source depths arises because of the lack of accurate knowledge of power leakages into the spectrum from modes of adjacent degrees. We find that using the low-frequency data it is not possible to say whether the sources that excite solar oscillations are dipole in nature or quadrupolar. The source depth can have some latitude dependence. However, the observed spectra are m-averaged to improve the signal, which precludes the determination of possible latitude dependence.

Acoustic waves of frequency 2.2 mHz are evanescent at depths less than approximately 900 km. So it appears, according to our best-fit model, that the source of excitation for low-frequency waves lies in the evanescent region of the convection zone.

The frequencies of peaks in the theoretically calculated power spectra are shifted with respect to the nonadiabatic eigenfrequencies of corresponding p-modes by approximately 0.1 μHz for modes of 2 mHz and 0.2 μHz at 3 mHz (35 ≤ f ≤ 80).

We have repeated some of the calculations with a model constructed with the conventional mixing-length theory and find that the source depth decreases by about 50 km, which is much smaller than the other uncertainties. We find the same using model S of Christensen-Dalsgaard et al. (1996). Since model S is also constructed using the mixing-length theory, the difference in source depth must be a result of the difference in surface structure because of the two different convection formalisms. It is known that models constructed with the Canuto-Mazzitelli formulation of convection have frequencies that are closer to solar frequencies than models constructed with the standard mixing-length formalism (Basu & Antia 1994).

The fit to the high-frequency part of the observed spectra, for peaks lying above the acoustic cutoff frequency of ~5.5 mHz, is provided by sources lying at somewhat shallower depth, although the GONG/MDI data we have used does not show peaks beyond ~7.5 mHz, and the signal-to-noise ratio is not very high, which precludes assigning a high significance to this result. Kumar (1994, 1997), using South Pole spectra that had clear peaks extending to 10 mHz, had found that quadrupole sources lying about 140 km below the photosphere provide a good fit to the entire high-frequency power spectra, but Kumar used an older solar model. With the model used by Kumar (1994, 1997), we find that the observed line profiles of low-frequency p-modes are well modeled when quadrupole sources are placed at a very shallow depth of order of 200 km. Thus we conclude that the source depth determination is quite sensitive to the inaccuracies of the solar model near the surface. Since the newer models are much better than the old ones, perhaps the source depth determination using the newer models has less systematic error.

In this paper we have concentrated on the velocity power spectra of solar oscillations. In a companion paper, we consider the question of reversal of asymmetry in the intensity power spectrum relative to the velocity power spectrum.

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