What do the Observations Tell Us About the Excitation of Solar Oscillation Modes?

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ABSTRACT. Present theories suggest two different classes of excitation mechanisms which may be responsible for the observed amplitudes of solar p-mode oscillations—self-excitation of the modes (*e.g.* the κ mechanism), and stochastic excitation by turbulent convection. I discuss here the agreement and disagreement between the predictions of these two mechanisms and the observed mode amplitudes and linewidths.

Introduction. To date most of the effort put into helioseismology has been concerned with the comparison between measured and calculated frequencies of solar oscillation modes, for the purpose of determining the structure of the solar interior. Because calculations of the mode frequencies always use the linearized equations of motion, they can say nothing about another fundamental aspect of the physics of solar oscillations, namely how the mode amplitudes are excited to their observed amplitudes.

While the mode frequencies depend on the structure of the sun, the amplitudes depend on the dynamical processes taking place inside the sun; for this reason we might expect to further our knowledge of solar heat transport and convection by studying the mode excitation question. Furthermore a better understanding of the excitation processes is an important input for the field of asteroseismology, since one would like to know which stars are expected to be oscillating at observable amplitudes.

Two classes of excitation models have been discussed in the literature, one which describes the modes as being overstable and therefore self-excited[1], and another which proposes that the modes are stable but driven by turbulence in the sun's convection zone[2,3].

Overstability models list several possible driving forces for the modes, including the κ- and γ-mechanisms[4], and the radiative and convective Cowling mechanisms[5]. The theoretical problem of determining the stability of oscillation modes in the sun is made difficult by our lack of an adequate theory of turbulent convection, and by the fact that the sun's hydrogen ionization zone lies inside the convection zone. As a result some growth-rate calculations show that the modes are overstable[1,5], while others show they are stably damped[2,6]. Without a better theory describing the contribution from turbulent viscocity, the theoretical question of whether the modes are overstable or not will be difficult to resolve. Nevertheless it is worth noting that no overstability calculation predicts overstable f-modes, and yet these modes are observed on the sun.

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If one goes ahead and assumes that the modes *are* overstable, then the question shifts to what sort of higher-order damping mechanism is responsible for limiting the oscillation velocity of a single mode to $\lesssim$ 20 cm/sec in the photosphere (Mach number $\lesssim 2 \times 10^{-5}$), as is observed. Non-linear effects should still be very small with such a low Mach number, making it hard to understand why the mode amplitudes do not grow larger.

The second class of models for exciting the oscillation modes assumes that they are driven by convective turbulence, which introduces acoustic noise into the resonating solar cavity. Goldreich and Keeley[2,3] first showed that this idea is plausible, but calculated oscillation amplitudes that were $\sim$ 30 times smaller than observed. However Goldreich and Kumar[7] recently showed that there was an error in the earlier work, in which the modes exchanged energy with convection via quadrupole acoustic radiation only, and in fact the modes can be excited by dipole radiation while being damped via quadrupole radiation. This increases the predicted mode amplitudes to where the agreement with observations is quite good.

Observations. Two measurable aspects of the solar oscillations are especially relevant for comparison with theories of mode excitation, the mode linewidths and mode amplitudes. The first of these has been measured at low l as a function of frequency by Libbrecht and Zirin[8] and by Isaak[9], and recently as a function of l up to $l = 100$ by Duvall and Harvey[10]. The measurements show that the linewidth is strongly dependent on frequency, increasing rapidly from $\lesssim 1\,\mu$Hz below $\nu = 3$ mHz to greater than 5 μHz at $\nu = 4$ mHz. The l-dependence is not as pronounced, with a slow increase in the linewidth with increasing l.

Mode amplitudes as a function of l, m, and ν have been measured by Libbrecht *et al.*[11]. As a function of l the mode velocity power increases slowly with l for $l \leq 200$, then decreases with higher l. At Big Bear Solar Observatory we are currently in the process of determining how much of the decrease can be attributed to atmospheric seeing. The discrepancy between these results and the l-dependence in the amplitudes measured by Kuhn and O'Hanlon[12] was recently resolved when Kuhn[13] discovered a systematic error in his earlier measurements.

The velocity power as a function of frequency is shown in Figure 1, which is similar to that in Ref. 11. Note the shape of the 'noise' power curve, $P_{noise}(\nu)$, which is a measure of the oscillation power between the mode peaks and their $\pm 11.6\,\mu$Hz sidelobes. For frequencies near the power maximum, $P_{noise}(\nu)$ is approximately equal to 1/5 the actual mode power curve $P_v(\nu)$. This appears to be due to overlaps in the Y_l^m fits for different l, caused by the fact that only one hemisphere of the sun can be observed. At high frequencies the linewidths are very large, so $P_{noise}(\nu)$ is in fact coming from the wings of the true oscillation peaks.

Using mode eigenfunctions generated by a solar model[11], the corrected velocity power data can be cast into the form of an energy per oscillation mode, shown in Figure 2. The energy presented here is lower than in Ref. 11, owing to the correction made here for the noise power. The total power in all the oscillation modes is $\sim 10^{33}$-10^{34} ergs.

Discussion. With the data in hand—linewidth and energy per mode as functions of l and ν—one would then like to try to distinguish between the two proposed excitation mechanisms.

Most overstability calculations do not at present include estimates of non-linear damping terms, so it is difficult to compare the observed mode amplitudes with theory. Nevertheless if the non-linear damping depended on mode velocity, rather than mode energy, then one would expect to see the high-mass modes having greater energy than lower mass, which is inconistent with the data (see also Ref. 11). Also no calculation predicts that f-modes, which have very

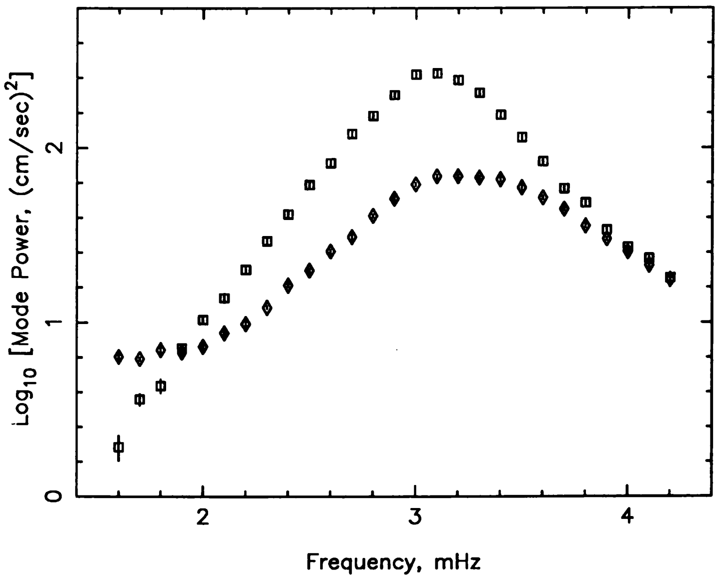

Figure 1. Squares: mode velocity power P_v as a function of frequency, for modes with $5 \leq l \leq 20$, corrected for the noise power; Diamonds: noise power P_{noise} measured between the mode peaks.

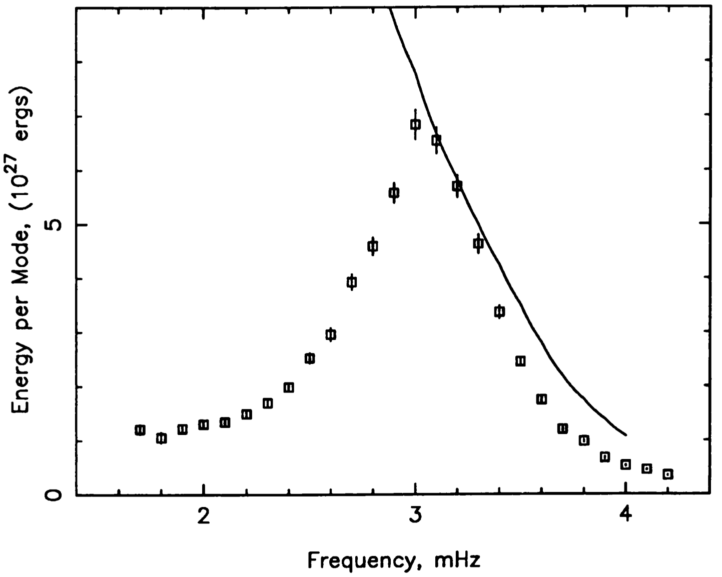

Figure 2. Energy per oscillation mode as a function of mode frequency, averaged over modes with $5 \leq l \leq 20$. The solid line shows $7/L$, where $L(\nu)$ is the mode linewidth in μHz.

little compression, are overstable. Finally if all modes were excited independently with no mode coupling, then modes with the same l and n but different m would all be excited to the same

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time-independent amplitude. The data are more consistent with a Boltzmann-type distribution of energies.

Thus the data seem to rule out self-excitation models where the modes are *independently* excited and damped. However if the modes were strongly coupled, they would share their energy, which could account for the near-energy-equipartition observed at low frequencies. If the modes were strongly coupled they could be damped collectively by non-linear effects at the sun's surface, where the total oscillation velocity of all the modes combined is roughly one-tenth the speed of sound, and also energy coupled into high frequency modes would be lost to radiative damping. Qualitatively the models could then fit the data, but a quantitative comparison cannot be made without a detailed theoretical model of the mode coupling.

The stochastic excitation model is better in that it gives definite predictions for the mode amplitudes. According to the recent theory by Goldreich and Kumar[7], the energy per mode should be the same as the mass of one resonant turbulent eddy times the speed of sound squared, or $E = Mc^2$. Thus the observed near-energy-equipartition is predicted by the theory, with nearly the correct absolute value of the energy. The energy per mode as a function of l is also predicted to be roughly constant, as is observed[11]. However the large energy peak at 3 mHz has yet to be explained by the model.

In summary, self-excitation models cannot be compared with the data until the theory is better developed, while the turbulent excitation model gives about the right energy per mode, but with some of the details still missing. Although the issue is certainly not settled, the turbulent excitation model is more likely the correct one, since it produces the correct mode amplitudes in a natural way. Also, preliminary calculations have shown that direct mode couplings are probably too small to efficiently exchange energy between modes[7].

If this is the case, then it is likely that further development of the theory, and computer models of the energy exchange between convection and oscillation modes, should provide valuable new insights into the workings of the solar convection zone.

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