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Theoretical amplitudes of solar-like oscillations in classical pulsators

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Abstract

Seismology based on oscillation mode amplitudes allows a different probing of turbulent convection zones than usual seismology based on frequencies as shown, for instance, by Belkacem et al. (2006) for the Sun. Going a step further, we now turn to investigations of stochastic excitation of solar-like oscillations in superficial convective layers as well as in convective cores of stars more massive than the Sun. Issues are the frequency domain where solar-like oscillations can be excited, the expected magnitude of these oscillation amplitudes, and whether these amplitudes are detectable with the CoRoT mission. This is an important task since the detection of solar-like oscillations will provide strong seismic constraints on the dynamical properties of the convective layers. The detection of solar-like oscillations in stars such as β Cephei or SPB stars will also help to determine their fundamental stellar parameters.

Introduction

Every turbulent convective region is theoretically able to excite modes through the Reynolds stresses. One issue therefore is to determine the amplitudes of damped modes excited by turbulent convection in main sequence classical pulsators. Hybrid pulsators are already known to exist, some stars present both γ Doradus and δ-Scuti type oscillations (e.g., Rowe et al. 2006) or β Cephei and *SPB* type oscillations (e.g., Jerzykiewicz et al. 2005). In particular, stars oscillating with both types of unstable and stable (stochastically excited) *p* modes would probe the uppermost region of the stars and would provide additional seismic contraints.

For instance, the knowledge of a large frequency separation would help identify unstable modes and would be a powerful tool to get more insight into the convective turbulent region through the study of the driving mechanisms.

With its high quality data (Michel et al. 2008b), CoRoT is the only available photometric mission able to detect stochastically excited modes that have very low amplitudes compared to unstable ones. Hence the objective of this paper is to provide some theoretical estimations of the amplitudes for damped stochastically excited modes for main sequence classical pulsators such as *SPB* and β Cephei stars.

Computation of amplitudes

The mean square amplitude ($\langle |A|^2 \rangle$) of a stochastically excited mode at the surface of a star is given by:

$$\langle |A|^2 \rangle = \frac{P}{2\,\eta\, I \omega_0^2} \tag{1}$$

where P is the excitation rate, η the damping rate, ω_0 the mode frequency, and the mode inertia (I) is defined by

$$I = \int_0^R \vec{\xi}^* \cdot \vec{\xi}\, r^2 \rho \,\mathrm{d}r \tag{2}$$

where $\vec{\xi}$ is the mode displacement, R the star radius and ρ the density.

From Eq. (1), the computation of mode amplitudes then needs the determination of both the excitation rates and damping rates. These are calculated using the non-radial nonadiabatic code developed by Dupret (2002), while the excitation rates are computed according to the formalism developed by Belkacem et al. (2008).

The typical convective length-scales are poorly known for main sequence massive stars. Hence, the classical mixing-length theory is used to get the injection length-scale (*i.e.* the scale at which the turbulent kinetic energy spectrum is maximum) and a parameter β is introduced (see also Balmforth 1992) such that the associated wavenumber is $k_0 = 2\pi/\beta\,\Lambda$, where Λ is the mixing-length. Note that in the Sun, Samadi et al. (2003) have shown that $\beta \approx 5$ using 3D numerical simulations. The sensitivity of the results to the parameter β is presented in the following sections. Apart from the length-scale, one also has to specify the way the turbulent eddies are time-correlated by defining an eddy-time correlation function. A Lorentzian function had successfully been used, in the solar case (Belkacem et al. 2006) as well as for the star α Cen A (Samadi et al. 2008) and reproduces the observational data. Consequently, such a modeling will be used in the following.

Slowly Pulsating B-stars

The problem of the theoretical determination of solar-like oscillations for in δ-Scuti stars has already been addressed by Samadi et al. (2002). Here, we then focus on more massive stars on the main sequence, *i.e.* Slowly Pulsating B-stars (SPB).

Driving regions

In such stars, one can distinguish three convective regions; the convective core and the superficial regions associated with He II and He I opacity bumps (at $T \approx 40\,000K$ and $T \approx 20\,000K$, respectively). The more favorable in terms of available turbulent kinetic energy flux is the convective core due to its high density. The less favorable is the He I convective zone located in the uppermost layers. Nevertheless, the matching between convective time-scales and mode periods plays an important role for determining the efficiency of the excitation. Convective turn-over time-scales, evaluated using the MLT, are found to be of several months in the core, several days in the He II region and several hours in the most superficial convective zone.

Hence, we find that acoustic modes are only weakly excited by turbulent convection, since in the region where there is a matching between the mode period and the convective time-scales, the He I region, the available turbulent kinetic energy is small due to low densities. The computation shows that the amplitudes of those modes are of the order of 0.1 ppm, that is lower than the CoRoT detection threshold (Lefèvre, 2008 same volume). Gravity modes of lower frequencies are found to be more efficiently excited by the convective core. The excitation rates increase with decreasing frequency, because of a better time-matching between mode periods and the convective core turn-over time-scale.

Amplitudes of stochastically excited gravity modes

Thus, we focus our attention to low-frequency gravity modes for which most of the supplied energy comes from the convective core. The damping rates are found to be of the order of $\eta \approx 10^{-5}\,\mu$Hz, the minimum is found near the instability strip and they increase with frequency. They are dominated by the radial part of the perturbation of the radiative flux in the radiative regions. Hence, following Eq. (1) the computed mode amplitudes are presented in Fig. 1.

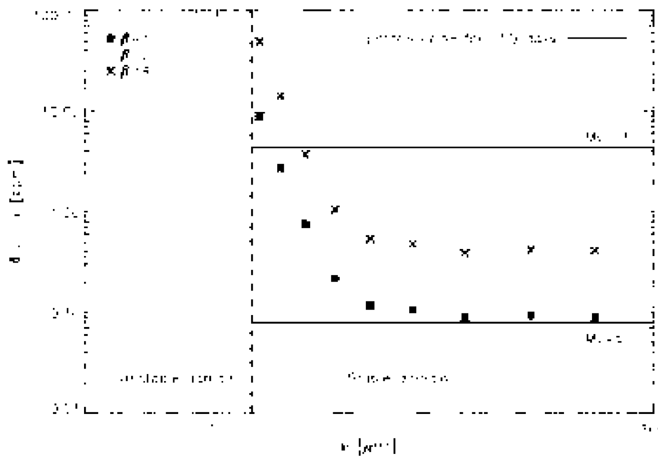

Figure 1: Relative amplitude in terms of luminosity as a function of frequency, for $\ell = 1$ g modes and three differents values of the parameter β. The dashed vertical line corresponds to the limit between the domain of unstable and stable modes while the black thick horizontal lines correspond to the photon noise for an observation of 150 days and for stars with a magnitude of $M_v = 10$ and $M_v = 5$. Those amplitudes are computed for a model of main sequence 5 $M_\odot$ star with a mixing-length parameter of $\alpha = 1$ using a Böhm-Vitense mixing-length formalism (see Samadi et al. 2006, for details) and a central hydrogen content of $X_c = 0.2$.

The maximum is found for high-order *i.e.* low-frequency gravity modes, near the instability frequency domain. This is the result, as explained above, of the excitation rates that increase for modes with periods closer to the core convective turn-over time-scale. The amplitude of those modes are of several *ppm* depending on the values of the parameter β. Such low amplitudes, even with a high value of β, are still close to the CoRoT detection threshold (around 1 *ppm*, Lefèvre, same volume). It then makes their detection a challenge. Note that for modes of higher angular degrees, i.e. $\ell > 1$, the damping rates increase, leading to smaller amplitudes thus making the detection even more difficult.

However, near the instability domain, theoretical amplitudes are found to be high enough to be detectable. Nevertheless, the line-width are of the order of 3×10^4 yrs, much longer than the observing time duration. Hence, they will appear in the Fourier spectrum as unresolved modes which will be difficult to discriminate from unstable modes.

β Cephei Stars

The next step consists in considering more massive main sequence stars such as β Cephei type stars. Their masses range between ≈ 9 and $\approx 25\,M_\odot$. The overstable modes are found in the vicinity of the fundamental radial one. They are excited[1] by the κ-mechanism due to the iron opacity bump that is even more developed than for *SPB* type stars, (see Pamyatnykh, 1999) and generates a convective region. The issue then is to determine whether or not such an unstably stratified region is efficient to excite stable modes to detectable levels.

Excitation by the iron convective region

Excitation of radial modes by the iron convective region is found to be efficient for two reasons; first, for a 10 $M_\odot$ model, the iron opacity bump is located deep into the star compared to the helium bump. Thus, the density is higher and the turbulent kinetic-energy flux which can be transferred to the modes is more important. Second, the efficiency of the excitation depends on the involved time-scales, *i.e.* the convective time-scale and the period of the mode. The period of radial modes is of several hours while, using mixing-length arguments, we find the convective time-scale to be also of several hours. Hence, excitation is nearly resonant. The damping rates are found to be dominated by the radial part of the radiative flux divergence, as for stable *SPB* modes.

The final result is presented in Fig. 2. The amplitudes, as shown in Fig. 2, are sensitive to the value adopted for β but are found to vary from several *ppm* to 20 *ppm*. These amplitudes lie well above the detection threshold of CoRoT for such stars, which is around one *ppm* (see Lefèvre same volume). The amplitude level indicates a quite efficient excitation process if one compares with the amplitudes for the Sun that are around 2.5 *ppm* (Michel et al. 2008a).

Fig. 2. also shows that the mode amplitudes oscillate with the frequency of the mode. This is mainly due to oscillations of the excitation rates. The reason is due to the dependence of P on the radial derivative of the radial component of the displacement eigenfunction. Hence depending on the location of the node (*i.e.* relatively to the iron convection zone) the derivative is more or less important explaining this oscillation. Such a behavior of the amplitude is of importance since it gives a possible diagnostic about the spatial extent of the iron convective region. In addition, the detection of such stable modes would give a signature of the driving region.

We find that along the main sequence in a Hersprung-Rüssell diagram, stars with masses around 10 $M_\odot$ are the most favorable candidates to present detectable solar-like oscillations. For lower masses, the convective region due to the iron opacity bump becomes too thin making the convection weak or inexistent. For higher masses, due to an increase of the effective temperature, the iron convective zone is located in layers with smaller densities. Then, the kinetic energy flux is smaller making the excitation less efficient, resulting in lower amplitudes.

Conclusion

To summarize, the purpose of this work was to investigate the possibility that stable (with respect to the κ-mechanism) modes can be stochastically excited by turbulence and in such a case to determine if those modes can be detected according to the CoRoT detection threshold. We find that detection of solar-like oscillations in *SPB* stars will be difficult since their theoretical amplitudes are expected below the *ppm*. In contrast, β Cephei stars are more promising. Theoretical computations for these stars yield amplitudes of radial *p* modes excited stochastically by the iron convective region well above the CoRoT detection threshold. The optimum mass is found to be around 10 $M_\odot$, as discussed above and near the *SPB* and β Cephei instability strip. Hence, the detection of a star simultaneously pulsating on *SPB*, β Cephei and solar-like oscillations would be the first *Chimeræ*[1] star.

[1] monstrous creature made of multiple parts of different animals. The denomination has been introduced by S. Talon.

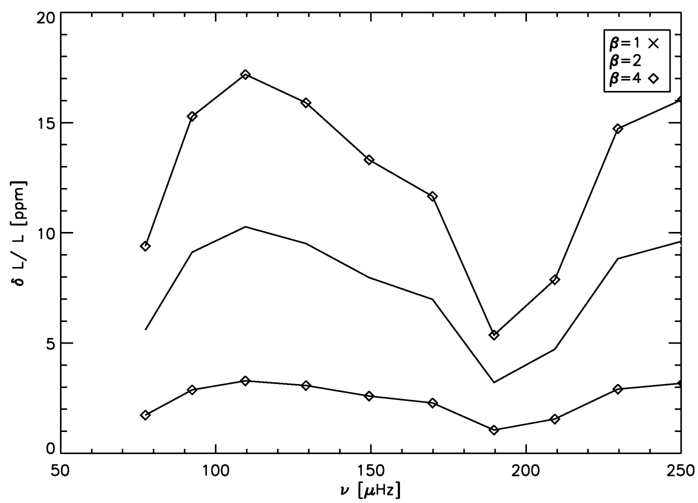

Figure 2: Relative amplitude in terms of luminosity as a function of frequency, for $\ell = 0$ p modes and three different values of the parameter β, for a 10 $M_\odot$ model on the main sequence.

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