Studying p-mode damping and the surface effect with hydrodynamical simulations

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Hydrodynamical simulations can be used as a complementary tool to observations for the study of the damping of p-modes and the so-called surface effect in solar-like oscillators. Here, we present the state-of-the-art in this research. Examples of applications include our Sun and the CoRoT target stars HD 49385 and HD 49933.

1 Introduction

Once helioseismological measurements had become accurate enough to determine the depth of the solar convection zone (Christensen-Dalsgaard et al., 1991), it became quickly evident that there was a systematic difference between observed and computed p-mode oscillation frequencies which increased as a function of frequency up to the acoustic cut-off value. The modelling of convection in standard solar structure calculations was quickly identified to be responsible for this discrepancy (Christensen-Dalsgaard & Thompson, 1997). Some of the first attempts to remedy the problem of too high pulsation frequencies predicted by the solar structure models (Baturin & Mironova, 1995) suggested to replace the classical mixing length theory of convection in the form suggested by Böhm-Vitense (1958) with an alternative model of convection proposed by Canuto & Mazzitelli (1991). This model predicted a steeper temperature gradient in the superadiabatic layer of the solar convection zone which in turn consists of the bottom region of the solar photosphere and the uppermost layers inside the Sun. An alternative explanation was found when averages from a 3D hydrodynamical simulation of solar granulation (encompassing roughly the first 4 Mm in depth and assuming horizontally periodic boundary conditions for a simulation box 6 Mm wide) were used to replace the surface layers of the standard 1D mixing length model (Rosenthal et al., 1999). This model also reduced frequency differences to almost one tenth of its original value, but for other reasons: in this case the increase of the size of the resonance cavity was due to turbulent pressure and the effects of horizontal inhomogeneity of the fluid in the numerical simulation on the radiative transfer. The large amount of observational data which this type of simulations can simultaneously explain without readjusting numerical parameters to "optimize" the predictions (Nordlund et al., 2009) has lead to the general acceptance of this explanation as major contribution to the *near surface effects*, with the detailed modelling of the surface layers being key to correct frequency predictions for the higher part of the pulsation frequency spectrum (Houdek & Dupret, 2015).

Sonoi et al. (2015) have investigated the systematic dependence of the magnitude of this effect as a function of effective temperature and surface gravity by numerical simulations with the CO^{5}BOLD code followed by a similar study of Ball et al. (2016) with the MuRAM code and devoted to main sequence stars. However, a direct comparison with seismic observations from a star other than the Sun has not been made thus far. Magic & Weiss (2016) repeated the comparison made by Rosenthal et al. (1999) for the solar case with an up-to-date version of the same code (now known under the name of STAGGER) and also accounted for the effect of a magnetic field. But to account for non-adiabaticity is important, too, since these corrections can be large (see Sect. 5 in Houdek & Dupret 2015).

While the near-surface-effect results from *convection changing the mean structure of the near surface layers of the star*, a sufficiently high frequency resolution also allows studying *mode damping* of the stochastically excited p-modes found for the Sun and other stars with surface convection zones ranging deep into the stellar envelope. Stein & Nordlund (2001) demonstrated that numerical simulations similar to those made to study the near surface effect could also be used to study mode driving and suggested the study of mode damping as a next step. This requires simulations over a long time interval to resolve the lines in Fourier space and obtain a high enough signal to noise ratio in the physical quantities analysed this way.

Here, we report on numerical simulations performed with the ANTARES code (Muthsam et al., 2010) to compute the near surface effect for the CoRoT target stars HD 49385 and HD 49933. These calculations have been made with the intention of a direct comparison to observational data and we summarize some first results on that work in Sect. 3. In addition, we report on long-term numerical simulations with ANTARES performed for the solar case in an effort to study the damping of its p-modes and provide some first results in Sect. 4. Before presenting our results we briefly describe the ANTARES code in Sect. 2 and we comment on the interpretation of data on solar-like p-mode oscillations for red giants collected by the BRITE Constellation satellites in Sect. 5.

2 ANTARES

ANTARES is a general purpose hydrodynamical simulation code developed with both mathematical and astrophysical requirements on such a tool in mind (Muthsam et al., 2010). Among others it features numerical schemes for high resolution and shock capturing, local grid refinement (even recursively), subgrid scale models to deal with unresolved flow features, highly flexible simulation geometries (Cartesian grids, polar co-moving grids, and mapped grids for complex geometries — this allows for both box-in-a-star and box-adapted-to-star geometries). Simulations can be done with one, two, or three spatial dimensions for dynamical equations based on either the Euler or Navier-Stokes equations with various explicit and semi-implicit time integration schemes. Optionally, magnetic fields can be considered in the magneto-hydrodynamic case and the stationary radiative transfer equation can be solved for both the grey and the non-grey case. Various microphysical setups can be considered (realistic, idealized) and simulations can be made also for two-component fluids and either for the fully compressible case or in the Boussinesq approximation. The code is fully MPI parallelized.

For the present simulations the setup and especially the initial and boundary conditions are described in Grimm-Strele et al. (2015). Thus, we are dealing with

3D box-in-a-star simulations in Cartesian geometry for the fully compressible Navier-Stokes equations (with viscosity chiefly due to the numerical scheme and subgrid scale modelling), without grid refinement, with fully explicit time integration, and non-grey radiative transfer based on an opacity binning method (as described in Muthsam et al. 2010). A single component fluid with realistic microphysics is considered while magnetic fields are neglected for the present case (Grimm-Strele et al., 2015).

3 Near surface effect for HD 49385 and HD 49933

We consider the question if current 3D hydrodynamical simulations can successfully explain the near surface effect as observed for target objects of the CoRoT satellite. To this end non-grey simulations for HD 49385 and HD 49933 have been made with the ANTARES code. The boundary conditions were thus horizontally periodic and vertically open as for the case BC3b from Table 1 of Grimm-Strele et al. (2015).

For HD 49385, a G0 subgiant, a simulation box with a Cartesian grid of 12.44 Mm vertical and 19.1 Mm horizontal extent has been considered and discretized by 313 grid points in vertical direction and 179 points horizontally. Subtracting boundaries this results in a simulation domain of 304 cells vertically and 170 cells per horizontal direction. The grid spacings are thus about 41 km vertically and 112 km horizontally. The simulations were performed on 144 CPU cores on VSC-2 for a relaxation phase of just over 25 sound crossing times (the latter referring to the time a sound wave needs to cross the vertical extent of the simulation box). Data was then collected for a period of just over 10 sound crossing times (or about 2 hours and 37 minutes of stellar time) with a total of 207 (roughly equispaced) snapshots. The starting model, chemical composition, and the surface gravity were taken from the analysis of Deheuvels et al. (2010) and Deheuvels & Michel (2010, 2011).

For HD 49933, a mid F-type main sequence star, the simulation box had correspondingly smaller dimensions of 7.9 Mm vertically and 11.7 Mm horizontally, since the expected size of granules relative to the solar case varies proportional to effective temperature and inversely proportional to surface gravity and mean molecular weight. The horizontal number of grid size was identical to that one for HD 49385, while vertically 323 points with effectively 314 layers for the interior of the simulation domain were used. This corresponds to a vertical resolution of about 25 km and a horizontal one of 68 km. The simulation was mostly performed on the Stampede Computer at TACC on 64 CPU cores and the relaxation phase required 29 sound crossing times followed by data being collected over about 16 sound crossing times (or about 2 hours and 23 minutes) with a total of 301 (again roughly equispaced) snapshots. In the case of HD 49933, the starting model, chemical composition, and the surface gravity were taken from the analysis of Gillon & Magain (2006), Michel et al. (2008), and Bruntt (2009).

For HD 49385 the main result is that the near surface effect, in the range of 3 to 9 μHz, less than one half of the values found for the solar case (Houdek & Dupret, 2015), can be explained with the 3D simulation to a level of less than 2 μHz. Compared to the standard seismic solution the only major discrepancy is a somewhat lower age (by about 8%, which, however, is still within mission requirements of PLATO 2.0).

For HD 49933, the near surface effect could not be explained to the same level. The reason appears to be the very high sensitivity to the value of surface gravity, $\log g$, which in analyses is also sensitive to the rather uncertain helium abundance. A solution to this problem would be to either rescale mode frequencies such that they

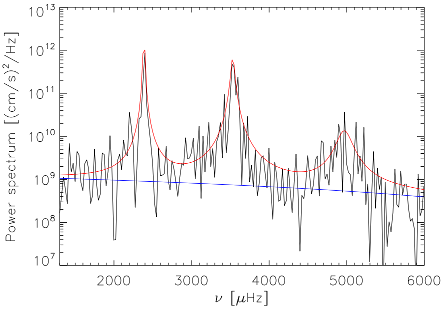

Fig. 1: Power spectrum of vertical velocity as function of frequency (black line). Lorentzian profiles for the three modes (red line) and a linear background (blue line) are shown for comparison.

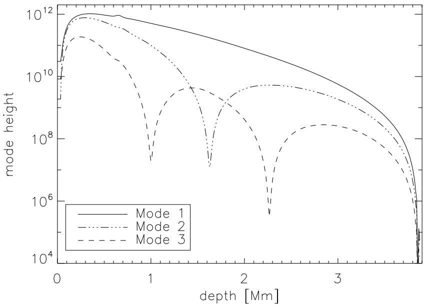

Fig. 2: Mode height as a function of the depth for the three radial modes found in the simulation (no, one, and two nodes in the interior) visualized in the frequency spectrum in Fig. 1.

are not sensitive to $\log g$ or to recompute the hydrodynamical simulation with a more precise value of this parameter (the difference is an increase by ~ 0.025 dex).

4 Damping of p-modes and solar granulation simulations

For the Sun, a Cartesian grid was again considered for a simulation box 3.88 Mm deep and 6 Mm wide and discretized by 359 points vertically and once more 179 points in each horizontal direction. Information on 350 layers in vertical direction with 170 cells horizontally is thus available and the grid spacings are hence about 11 km vertically and 35 km horizontally. The simulation has been run on 144 CPU cores on the VSC-2 and after a relaxation period of about 19 soundcrossing times, data were sampled during 11 hours of solar time for 2527 snapshots with a spacing of about 15.84 sec. This simulation has a $T_{\rm eff} \approx 5750$ K, a solar $\log g$ of 4.4377 and the chemical composition is $(X, Y, Z) = (0.7373, 0.2427, 0.0200)$ with a metallicity distribution as in Grevesse & Noels (1993). This simulation reveals three well defined, normal, radial p-modes which corresponds to solar p-modes of radial orders $n = 16$, $n = 24$, and $n = 33$ (see Fig. 1 and Fig. 2). The first one has a ν_0 of ~ 2.39795 mHz which is below the power maximum at $\nu_{\rm max}$. The second one has a ν_0 of ~ 3.54041 mHz and hence $\nu_0 > \nu_{\rm max}$. For a solar model to which the averaged 3D mean structure is patched similar to the description in Rosenthal et al. (1999) these two modes have their first (for $n = 16$) and second node (for $n = 24$) close to the bottom of the simulation box. This simplifies a direct evaluation of work done by the modes when using the simulation data. The third mode is close, although still below, the acoustic cut-off frequency. Since it has its first node in the simulation box interior just underneath the superadiabatic layer, this mode is very strongly influenced by the surface layers and the signal it yields is much noisier than that of the others. A more detailed analysis of the radial modes found in this simulation is currently under investigation and will be published elsewhere.

5 Studying p-modes and BRITE Constellation data

As has been demonstrated by the presentations of D. Huber and T. Kallinger at this conference, even for red giants the measurements of solar-like p-mode oscillations are challenging for the BRITE Constellation satellites. It has been possible to identify about five of the target objects as pulsating and in one case the large frequency separation has clearly been measured. However, the small frequency separation appears to be beyond reach. On the other hand, it was also suggested by J. Matthews to proceed similarly as has been done for data obtained from the MOST satellite and, motivated by the stochastic nature of the mode driving, concatenate the data from different runs to obtain a time series as long as possible and this way improve the signal-to-noise ratio. Whether this might be precise enough to study the near surface effect in red giants, which is also accessible to numerical simulations (cf. Sonoi et al. 2015), remains yet to be shown. The study of p-mode damping, however, requires both a very high frequency resolution and low noise and appears thus unsuitable for study with BRITE. We thus have to rely on data from CoRoT and Kepler/K2 and future missions such as TESS and PLATO 2.0 for this purpose to gain new insights into the physics of p-modes and how it relates to scaling relations and other tools used in stellar parameter determinations with asteroseismology.

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