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On long-duration 3D simulations of stellar convection using *ANTARES*

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Abstract. We present initial results from three-dimensional (3-D) radiation hydrodynamical simulations for the Sun and targeted Sun-like stars. We plan to extend these simulations up to several stellar days to study p-mode excitation and damping processes. The level of variation of irradiance on the time scales spanned by our 3-D simulations will be studied too. Here we show results from a first analysis of the computational data we produced so far.

Keywords. Convection, hydrodynamics, radiative transfer; Sun: oscillations; stars: oscillations

1. Tools and simulation setup

We performed 3-D simulations of solar and stellar convection in a Cartesian box ranging ≈ 3.61 Mm vertically and ≈ 5.88 Mm horizontally with the *ANTARES ("Advanced Numerical Tool for Astrophysical RESearch")* Fortran90 code (Muthsam *et al.* 2010). Most post-processing has been done with our own Fortran90 analysis tool *statistics*. The output of *ANTARES* and *statistics* has been visualized with *Paraview* and *gnuplot*, respectively. Additionally, we used these tools to produce figures.

2. Results

2.1. *Snapshots of solar convection*

Starting from a mean stratification given by a 1-D stellar structure model with a small perturbation to initiate a flow, the 3D simulation with *ANTARES* rapidly recovers the usual granulation pattern of solar convection, as we show in Fig. 1 with a snapshot from our latest solar simulation ("SLOPMD1", covering $\sim$ 1 solar day of relaxed state).

2.2. *Power spectrum*

We aim at a careful study of power spectra and line asymmetries for helio- and asteroseismology applications (see, e.g., Benomar *et al.* 2018). In Fig. 2 we show the power spectrum of vertical velocity some 600 km from the top of the simulation box, i.e., where $< T > \approx T_{\rm eff}$, as obtained from two of our solar granulation simulations. Two power peaks are clearly visible, the first around 2.7 mHz and the second around 3.5 mHz, corresponding respectively to oscillations with periods of ~ 6.2 and ~ 4.8 min. The first peak has become better defined in our recent, longer-duration simulation, since we are getting closer to resolve it in frequency space. The second peak is already resolved in the shorter

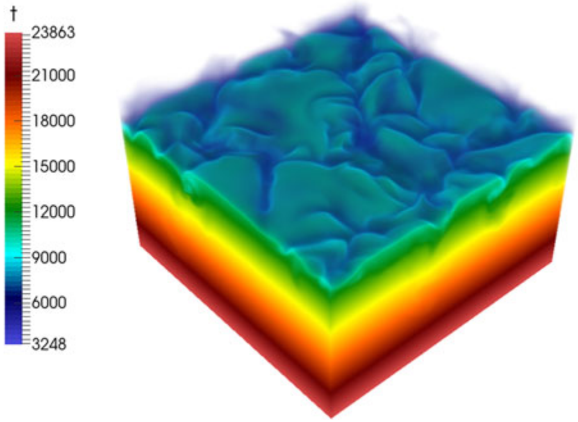

Figure 1. The imprint of granules on temperature (in units of K) at around 6 solar hours of time evolution within the relaxed part of the simulation.

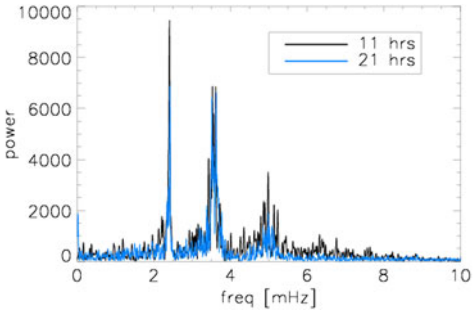

Figure 2. The vertical velocity power spectrum as function of frequency for a height where $<T>\approx T_{\rm eff}$, obtained from two of our solar granulation simulations: a run of 11 solar hours length (Kupka *et al.* 2017) and a new one of above 21 solar hours of relaxed state (black and blue line, respectively). The power spectrum shows, in both cases, three radial p-modes, of which the first two are clearly above the convective background.

simulation. A third peak close to 5.0 mHz (equivalent to a period of ~ 3.3 min) turns out to have significantly-reduced power in our longer-duration simulation, to a level not clearly distinguishable from the convective background, a further confirmation of the importance of performing simulations with sufficiently long duration (ideally, several solar/stellar days).

3. *ANTARES* code improvements

3.1. *Input data*

We developed the possibility of using 1-D models from YREC (the *Yale Rotating Stellar Evolution Code*, see Spada *et al.* 2013) as input for *ANTARES*. The input models from the stellar structure code can then be patched with 1-D atmospheric models available from the literature to provide better initial conditions for the outer layers. For compatibility with the setup used to produce the 1-D models, we are also updating the equation of state and opacity input tables for arbitrary metal abundances, based on the solar chemical mixture in Grevesse & Sauval (1998).

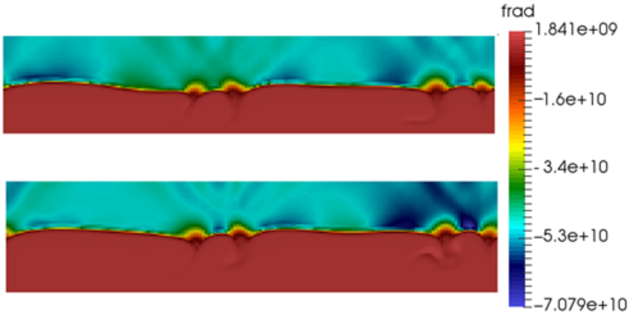

Figure 3. Radiative flux (in units of erg $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) in the outer layers of the simulation box, for our new radiative transfer scheme (upper panel) and for the short-characteristics method (lower panel). Due to the coordinate system, outwards directed flux is negative and $F_{\mathrm{rad}} \approx -6.3 \cdot 10^{10}$ for solar $\mathrm{T}_{\mathrm{eff}}$ at the very top after relaxation.

3.2. *Improved radiative transfer*

So far ANTARES uses the short characteristics method for the calculation of intensity as the default radiative transfer (RT) method, the trapezoidal rule for calculating optical depth, and weighted parabolas (or the monotonic method of Steffen 1990) for interpolation. But overshooting of parabolas can lead to unphysical results which required introducing limiters and which can cause artifacts along the calculated rays. A new scheme, which prevents overshooting, is implemented. It is based on quadratic, monotonic Bezier-like splines (see de la Cruz Rodríguez & Piskunov 2013). The 3-D implementation of this scheme is done as in Ibgui *et al.* (2013). Fig. 3 shows how artifacts are reduced by the new RT implementation. Due to improved RT boundary conditions in the vertical direction the new method achieves a significantly-improved stability, too.

3.3. *Possibility of using the Eddington approximation*

To achieve faster calculations with only a limited increase in error we are implementing the non-grey Eddington approximation avoiding the expensive angular integration for radiative transfer. We calculate the mean intensity J_ν from

$$-\nabla \cdot \left(\frac{1}{3\kappa_\nu \rho} \nabla J_\nu \right) + \kappa_\nu \rho J_\nu = \kappa_\nu \rho B_\nu .$$

This can speed up calculations by a factor of 10−100.

4. Outlook

We are developing long-duration 3D simulations for the study of the interaction between convection and oscillations for several stellar targets of interest, including the Sun and planet-hosting stars (e.g., Kepler-409), with a focus on helio- and asteroseismology.

5. Acknowledgements

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