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3D MHD modelling of a chromosphere above the sun's convective zone

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Abstract. We report on the extension of the ASH code to include an atmospheric stable layer (*i.e* not convective). This layer is meant to model the sun's chromosphere within the anelastic approximation limits while coping with the wide range of densities, time and spatial scales between $r = 0.7\ R_\odot$ and $r = 1.03\ R_\odot$. Convective overshoot into the stable atmospheric layer is observed in a region $\sim 0.01\ R_\odot$ thick, exciting waves which propagate upwards into the atmosphere.

1. Introduction

The physical connections between the sun's convection zone (CZ) and the atmospheric layers are reputedly a hard problem to study. The chromosphere separates plasma of very different length and time-scales, as well as of different MHD regimes (*e.g* $\beta < 1$ and $\beta > 1$). In consequence, most atmospheric and sub-photospheric phenomena are studied separately. The most remarkable exceptions are small-scale numerical investigations (typically, with $10 - 40$ Mm tall and wide domains) of the sub-photospheric and chromospheric layers (*e.g* Martínez-Sykora, *et al.* 2008). We perform global-scale 3D simulations including the CZ and the sun's chromosphere. Our goal is to study flux emergence issues consistently and without treating the photosphere as an impenetrable boundary (or any type of boundary condition whatsoever). This is a necessary condition to correctly capture the dynamics of the transition between the CZ and the chromosphere, together with the MHD transport processes taking place there. Our study differs from the *small-scale* simulations cited above in that it aims at capturing the physics of *global* phenomena such as sunspot origin and evolution, magnetic transport between loop footpoints (Grappin, *et al.* 2008), large-scale flows.

2. Numerical model and results

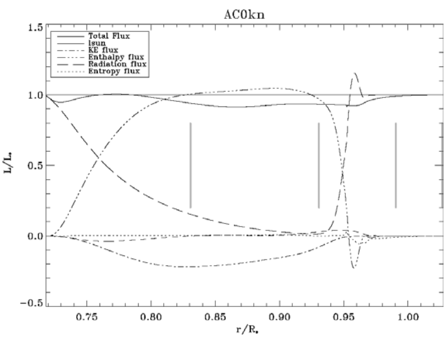

Figure 1. Energy flux balance in the radial direction in "units of solar luminosity". Note the layer of negative enthalpy flux ($0.95 - 0.96\ R_\odot$), which indicates convective overshoot into the photosphere. Note also that all the star's luminosity is transported radiatively at the top. The vertical grey bars indicate the positions of the spherical shells in Fig. 2.

We use the ASH 3D MHD anelastic stellar code (Clune *et al.* 1999; Brun *et al.* 2004). The initial state was built from a CESAM solar profile of the CZ (Morel, 1997; Brun,

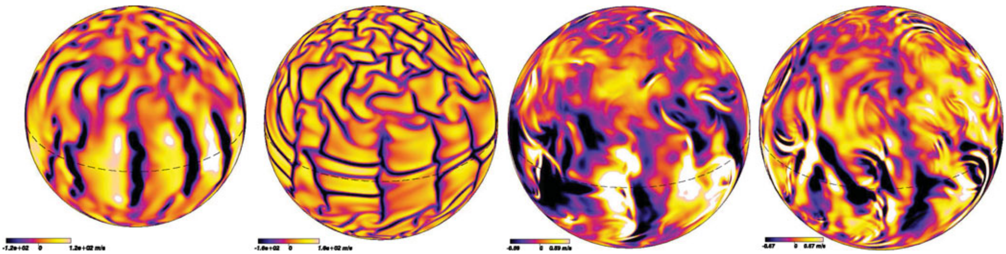

Figure 2. Radial velocity V_r at spherical surfaces with different radii. From left to right, top to bottom: $r = 0.83,\ 0.93,\ 0.99,\ 1.03\ R_\odot$ (*cf.* Fig. 1).

et al. 2002) with a transition to a nearly isothermal chromosphere in hydrostatic equilibrium. The chromospheric temperature is explicitly set to $\sim 4\times$ the standard 6000 K for numerical stability. We do not include a coronal *Transition Region* (TR), but rather extend our chromosphere up to 1.03 $R_\odot$. The minimum of H_ρ is 10 Mm. Before considering any magnetic effects, we let the convection settle in a purely hydrodynamical CZ and waited until the whole system relaxed. At this point, the system reaches a steady state (in a statistical sense; the main properties remain unchanged despite any local fluctuations). The conditions for the goodness of the anelastic approximation are verified at all times. The transition from the CZ to the chromosphere is clearly visible in fig. 1, which shows the radial energy flux balance (averaged over θ and ϕ) in the relaxed state. The enthalpy flux vanishes there, and becomes negative in the overshoot layer. The radiative flux assumes all the energy transport afterwards (in the convectively stable atmosphere). Fig. 2 shows the radial velocity V_r over spherical cuts taken at different radii (signalled by the vertical grey lines in Fig. 1). The first spherical shell sits well within the CZ, the second one corresponds to a layer just below the photosphere and the two remaining ones are chromospheric layers. Convective overshoot excite waves which propagate into the chromosphere, while any traces of the underlying granular motions fade away. The atmospheric layer shows a prograde differential rotation, but rotating slower and more uniformly than the CZ/photosphere. We added at this point a global magnetic field and let it evolve in the CZ. The issues concerning its evolution (*e.g* ohmic diffusion, advection into the atmosphere, back-reaction on the flows) will be addressed in a forthcoming paper.

3. Conclusions

We developed a 3D model of the CZ and solar chromosphere using the ASH code. Some simplifications were made in order to achieve both physical correctness (from the anelastic approximation point of view) and numerical stability. In particular, the chromosphere is warmer than the solar one and it is rooted at a lower radius. The coronal TR was not included in the model, and the chromosphere was extend up to 1.03 $R_\odot$. We judge this as an essential step for the comprehension of flux emergence scenarios (*cf.* Jouve &Brun, 2009), before any finer modelling becomes feasible. These issues will be discussed in a future paper.

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