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3D hydrodynamical CO5BOLD simulations of a chromosphere of a red giant

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Abstract. We present the results of a 3D hydrodynamical simulation of a cool red giant star with a chromosphere. The simulation was performed using a 3D hydrodynamic CO5BOLD model atmosphere ($T_{\rm eff}$ = 4000 K, $\log g$ = 1.5 [cgs], [M/H] = 0.0 [dex]), which was extended outwards to include chromospheric layers. We synthesized the spectral energy distribution of a model atmosphere including chromosphere and compare it to the spectral energy distribution of a model atmosphere without the chromosphere. We find that adding a model chromosphere leads to a significant increase of the radiative flux at wavelengths smaller than 300 nm. The increase in the UV flux is attributed to the presence of shock waves, which provide additional heating in the chromosphere.

Key words. Stars: atmospheres – Stars: chromospheres – Stars: late-type – Line: profiles – Convection – Hydrodynamics

1. Introduction

The structure of red giant chromospheres is poorly known. From the modelling point of view, attempts were made to construct semi-empirical 1D hydrostatic chromosphere models by adjusting their temperature profiles to reproduce the strengths of spectral lines that form in the chromosphere (e.g., McMurry 1999). Nevertheless, the existing chromosphere models of red giant stars suffer from numerous shortcomings. For example, they are unable to simultaneously account for the UV pumping of CO resonance lines and for the cool excitation temperatures of these lines in the chromosphere of Aldebaran (McMurry & Jordan 2000).

In case of the Sun, Wedemeyer et al. (2004) have used 3D hydrodynamical model atmospheres with a chromosphere, which they calculated with the radiation (magneto-)hydrodynamics code CO5BOLD (Freytag et al. 2012), to show that the chromospheric structure of the Sun can exhibit both cool and hot features needed to explain the observed spectral line profiles. Unfortunately, to our knowledge no 3D hydrodynamical models of red giants star chromospheres have been produced yet.

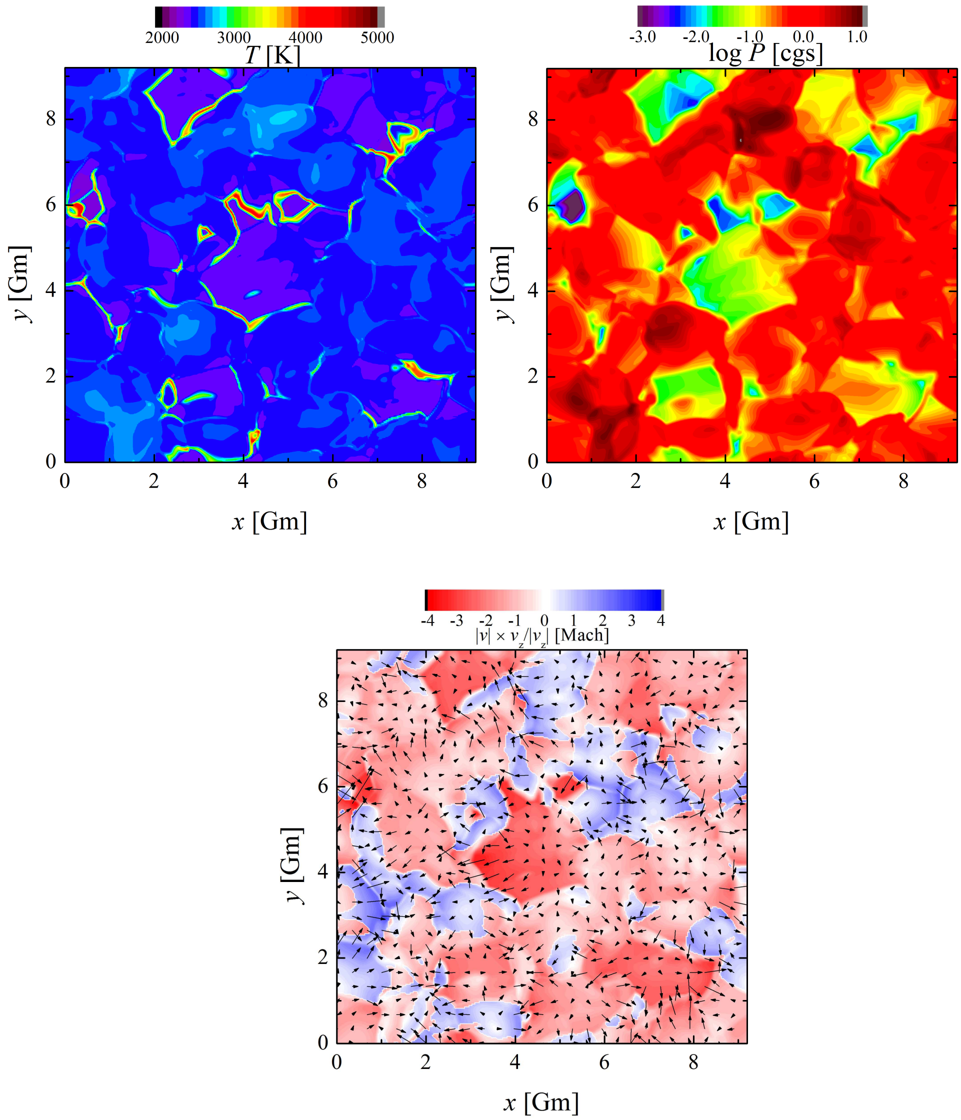

Fig. 1. Gas temperature (a), logarithm of gas pressure (b), and the product of the absolute velocity and the sign of the vertical velocity component (c) in the 3D hydrodynamical model atmosphere of a red giant as seen at one particular moment in time at $\log \tau_{\rm Ross} \approx -6$. The streamlines in the right panel show the direction and strength of the horizontal velocity field.

In this work, we present some early results of 3D radiation hydrodynamical simulations with `CO5BOLD` for a red giant model with a chromosphere. In particular, we aim to understand how the presence of the chromosphere alters observable properties of the star, such as its radiative flux at different wavelengths.

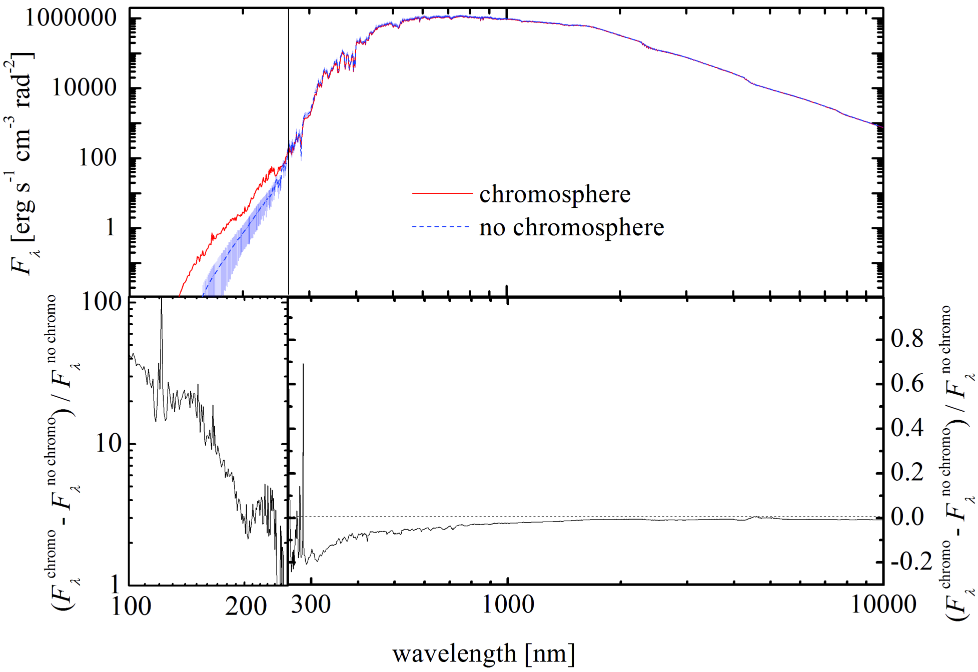

Fig. 2. Top: spectral energy distributions of model atmospheres with (red line) and without (blue line) chromosphere. The shaded area marks the standard deviation of the flux variations between the model structures computed at different instants in time (of the model atmosphere without a chromosphere). **Bottom:** relative flux difference between the model atmospheres with and without chromosphere (note that the vertical scale is different in the wavelength region < 300 nm).

2. Setup of the model atmospheres and spectrum synthesis

The 3D hydrodynamical `CO5BOLD` model atmosphere (Freytag et al. 2012) used in this work has atmospheric parameters ($T_{\rm eff} = 4000$ K, $\log g = 1.5$ [cgs], [M/H] = 0.0 [dex]) similar to those of Aldebaran (α Tau). The model atmosphere was computed using MARCS opacities (Gustafsson et al. 2008) grouped into 5 opacity bins. The initial computational box size containing atmospheric layers in a "box-in-a-star" setup $x \times y \times z$ was $140 \times 140 \times 150$ ($4.6 \times 4.6 \times 2.8$ Gm^3). The computational box was subsequently doubled in each horizontal direction and extended to the outer layers by 130 grid points (1.3 Gm). The new model atmosphere therefore consisted of 280×280×280 gridpoints ($9.2 \times 9.2 \times 4.1$ Gm^3) and extended to $\log \tau_{\rm Ross} \approx -8$. After the model has relaxed to its equilibrium state, the entropy flux at the bottom of the model box was adjusted to ensure that the new model has the same total emergent flux (and thus, the same effective temperature) as the starting model without the chromosphere.

The emergent radiative flux of this model atmosphere was computed in the 100 – 10000 nm wavelength range using the `NLTE3D` radiative transfer code. For this purpose, we used `ATLAS9` LITTLE opacity distribution functions (ODFs) taken from Castelli & Kurucz (2003).

3. Results and discussion

As in the case of the Sun, the thermal structure of the red giant chromosphere is strongly influenced by shock waves (cf. Wedemeyer et al. 2004). In the shock fronts the temperatures may reach 5000 K (Fig. 1). The moving shock waves leave behind relatively cool regions with temperatures down to 2000 K. The size of these cool regions is comparable to those of granules seen at the optical surface. However, smaller structures form in regions where several shock waves collide and impede each other's flow. Typical shock wave velocities in the red giant chromosphere are 10 km/s (∼ 2 Mach), with the fastest shock waves accelerating to 20 km/s (∼ 4 Mach). Aside from shock-wave-to-shock-wave collisions, it is worth noting that shock waves collide with downfalling material accelerated under the force of gravity to velocities comparable to those of the fastest shock waves. The addition of a chromosphere results in a significantly larger radiative flux (Fig. 2) in the UV range (< 300 nm). This increase is caused by the shock waves propagating in the chromosphere. At other wavelengths, the addition of the chromosphere does not change the radiative flux much. In case of the model with chromosphere, there is less flux in the 300 − 10000 nm wavelength range. The difference, however, is small and does not exceed a few percent at ≥ 450 nm.

It is important to note that magnetic fields, dynamical hydrogen ionization, and line cooling that occurs under the conditions of non-local thermodynamic equilibrium were not considered in the present study although their influence may be important in defining the structure of the outer photosphere and chromosphere.

4. Conclusions

We have presented some of the early results of modelling the chromospheric structure of a red giant with the 3D hydrodynamical `CO5BOLD` model atmosphere code. The chromospheric structure of the red giant is inhomogeneous and governed by propagating shock waves. These hot shock waves significantly contribute to the increase of radiative flux at < 300 nm.

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