Chapter 9

Exploratory attempt for non-grey treatment of opacities with RHD simulations

I have identified the grey treatment of the opacity as a major problem in the RHD simulation of RSGs (e.g., Sect. 4.4, 6.2.3, 6.2.4). The implementation of the non-grey treatment in RHD is an important task to be done in the near future.
In order to estimate the impact of the non-grey treatment on the simulations, I have tested the non-grey opacity tables described in Sect. 2.2.1 on a RSG global simulation (st35gm03n06 in Tab. 4.1).
These tables have not the extension needed to cover the temperature range of RSG simulations (they span values up to 30000 K, while in global models the maximum temperature is 300000 K, Fig.2.10, upper left panel).
This is a first exploratory attempt, further improvements on opacity tables for merging MARCS opacity (for the atmosphere) and OPAL opacity (for stellar interior) are on-going.

Since the computational time-scale roughly increases with the number of wavelength bins (see Sect. 2.3.4), the CPU time needed for computing one time-step of the simulation is five times (e.g., for five bins in the opacity table) as long as a single one bin (i.e., grey case). Thus, I chose to compute only a few time-steps ($\sim$115 days covered) because: (i) the opacity tables are not adapted to the RSG case but they have been built for Red Giant local models, (ii) I needed to compute the post-processing analysis on the same machine.
Fig. 9.1 shows the average over spherical shells of the enthalpy flux of the grey model (solid line) and the first subsequent snapshot switched to non-grey (dashed line). The maximum enthalpy flux of the grey model is significantly smaller than the non-grey one in the stellar interior where the grey treatment of opacity is a good approximation. In the outer layers the enthalpy flux is similar.

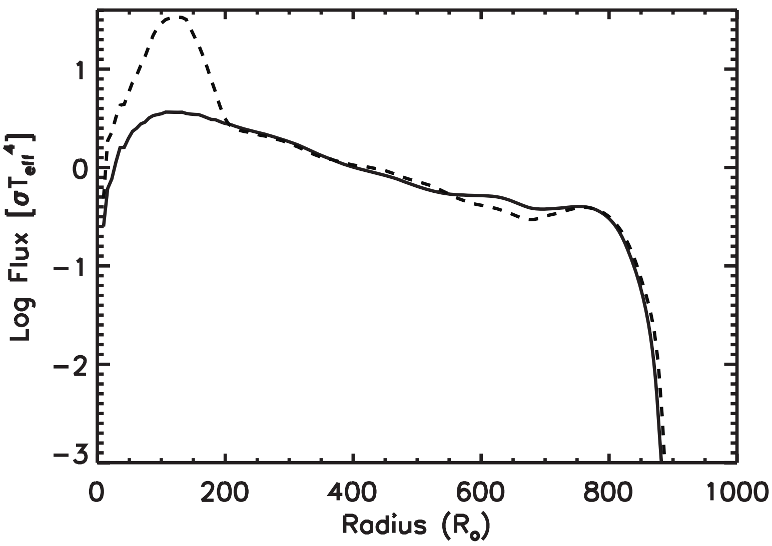

Figure 9.1: Average enthalpy flux over spherical shells of the grey model (solid line) and of the same snapshot switched to non-grey (dashed line). The effective temperature of this snapshot is 3370K.

Fig. 9.2 shows the effects of the altered radiative transfer on the average over spherical shells temperature (top and central rows) and on the spectra (bottom row). The black line always refers to the grey model, the red line to the following snapshot switched to non-grey and the green one to a snapshot ∼115 days later (switched to non-grey).
At around $\tau = 1$ (top left panel), the non-grey temperature gradient is steeper than in the grey case. The radiative flux is partially blocked in the non-grey model so that a steeper temperature gradient is necessary to transport the same radiative flux as in the grey model. At the same time, an increased temperature gradient implies an enhanced convective flux that is indeed small in the outer layers (Fig. 9.1).
Central row of Fig. 9.2 shows the temperature profiles as a function of the stellar radius: in the outer layers, the absolute temperature differs by ∼ 500 K. On the other hand, the deeper layers of the atmosphere are warmer because the frequency band available in the continuum is decreased by the presence of the lines; therefore the flux per unit frequency interval must increase. Since the basic requirement is that the same total flux must escape from the star, it is evident that the flux in the continuum between the lines must be higher (*backwarming*).
Ludwig et al. (1994) found for local RHD simulations that frequency dependent radiative transfer causes an intensified heat exchange of a fluid element with its environment tending to reduce the temperature differences. Consequently, the temperature fluctuations in the non-grey local models are smaller than in the grey case. This is also expectable for a "relaxed" RSG global models where the temperature fluctuations, in the grey case, are about 60%. Also the intensity maps can be affected because the temperature contrast should decrease and therefore also the visibility fluctuations.
Bottom left panel of Fig. 9.2 shows three synthetic spectra of the grey model (black), the

following snapshot switched to non-grey (red) and the non-grey snapshot ∼115 days later (green). The continuum intensity is moving up because the average temperature at τ=1 increase (central left panel): 4200K for the grey model (black), 4500K for the non-grey red curve and 5100K for the more advanced non-grey snapshot (green). The contrast between the continuum and the absorption lines do not change so much or becomes even weaker (bottom right panel). The temperature gradient is still not steep enough to increase the contrast. However, this simulation is not "relaxed" because too few snapshots have been computed. The temperature gradient can change affecting the resulting synthetic spectra.

Non-grey radiation transfer is expected to cause a closer coupling to the radiative equilibrium temperature stratification and strongly influences the evolution of the flow features. In fact, the gas motions overshooting from the convective envelope into the stably stratified layers of a stellar atmosphere try to establish a temperature profile close to adiabatic. The radiation tries to keep the thermal structure close to radiative equilibrium conditions. The balance between these two controlling processes affect the resulting temperature (see e.g., Stein & Nordlund 1998 and Ludwig et al. 1994).
Convective overshoots could cool the higher photospheric layers ($\tau_{Rosseland} \lesssim 0.1$) below the temperature at the radiative equilibrium, increasing the temperature gradient in the RHD simulation and maybe changing also the dynamics of the atmosphere.

This exploratory model is not enough to establish the effects of the non-grey treatment of opacities. More snapshots and the complete (merging the opacities up to 300000K, the inner temperature of the global simulation) opacity tables are necessary. The switch to non-grey is indeed necessary in order to obtain realistic atmospheric temperatures.

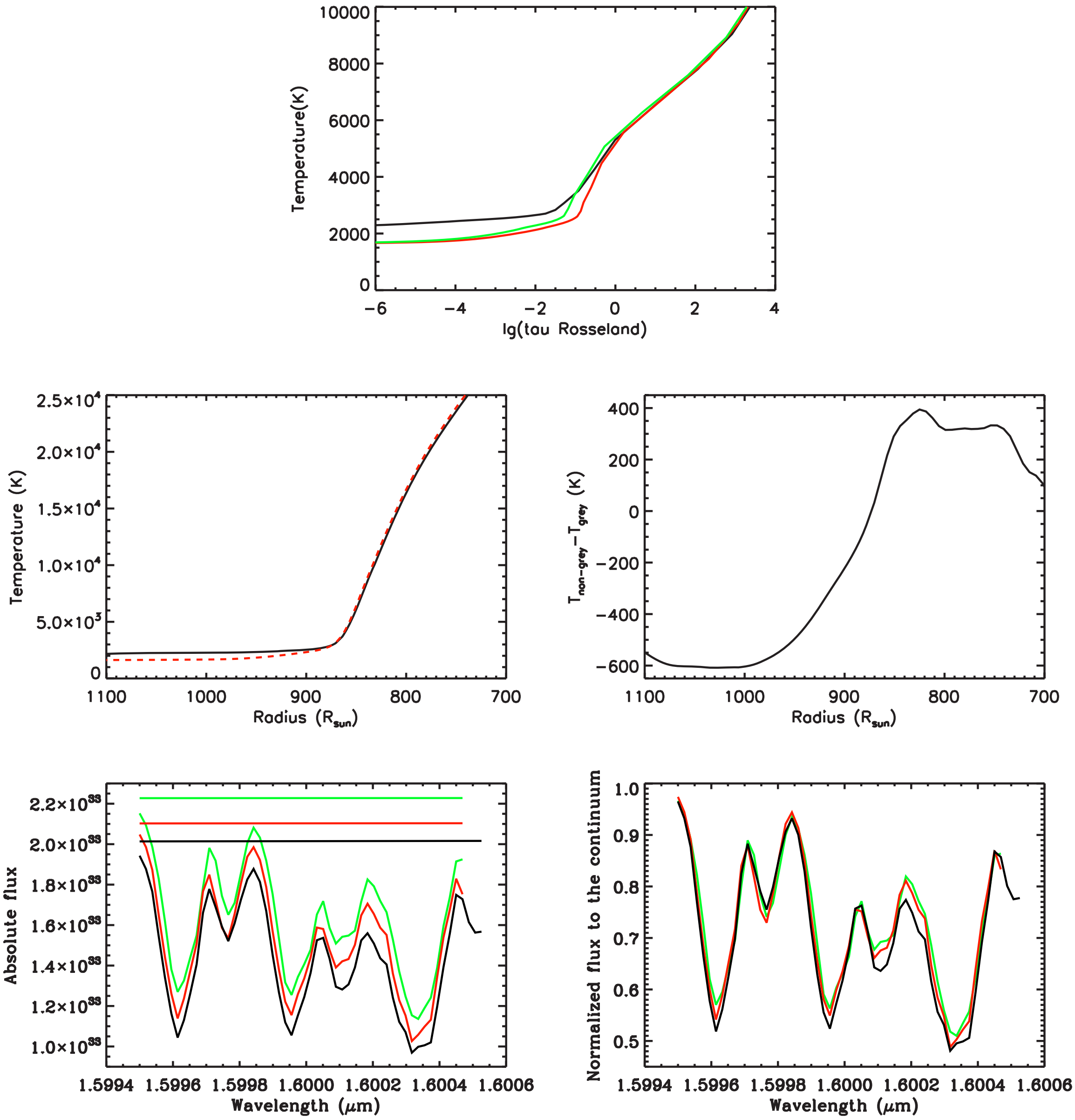

Figure 9.2: *Top panel:* average over spherical shells temperature profile of the grey model (black curve) and non-grey model (red curve, following snapshot) as a function of the Rosseland optical depth scale. The green curve is a non-grey model snapshot $\sim$ 115 days later. *Central left panel:* average temperature profile of the grey model (black curve) and non-grey model (red curve, subsequent snapshot) as a function of the stellar radius. *Central right panel:* difference between the average temperature profiles. *Bottom left panel:* spectra computed from one snapshot of the grey model (black), the subsequent snapshot switched to non-grey (red) and $\sim$115 days later (green). The continuum is also plotted. *Bottom right panel:* Spectra normalized to the continuum, the colors have the same meaning as in bottom left panel.