Massive Stars Across Redshifts in the Era of JWST and Large Surveys
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Including realistic atmospheres in massive stars evolution models

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Abstract. Realistic model atmospheres have progressively been included through various methods in state-of-the-art low- and intermediate-mass stars evolution calculations. At the same time model atmospheres for massive stars have become increasingly realistic over the last 50 years, with the progressive inclusion of non-LTE and non-gray effects, wind extension, and line-blanketing. However all these improvements have never been included in massive star evolution calculation, which in their vast majority still use the Eddington gray approximation. We describe here a method to include realistic model atmospheres in the evolution calculations of massive stars. We present preliminary results of the application of this method to a $60M_{\odot}$ star at solar metallicity. These results show that for these mass and metallicity the Eddington gray approximation is valid for the main-sequence evolution.

Keywords. stars: evolution, stars: massive, stars: atmospheres

1. Introduction

Ideally we would want to model stars from their center to their outermost regions using one unified model. However as different physical processes become dominant in the atmosphere of stars and in their center this unification is in practice numerically unfeasible. There is thus a decoupling in the way we model stars. On one hand we use stellar evolution codes, which compute the evolution of the internal structure of stars and produce evolutionary tracks. On the other hand we use stellar atmosphere codes, which perform detailed radiative transfer simulations in order to determine the structure of the atmosphere of stars and to compute synthetic spectra.

Stellar evolution codes need boundary conditions at their surface in order to close the set of stellar structure and evolution (SSE) equations, which form a coupled differential equation system. These boundary conditions must come from a model atmosphere. However it is too time-consuming to compute a realistic model atmosphere at each timestep of an evolution model. Thus the Eddington gray approximation, a very simplified model atmosphere, is generally used to provide the boundary conditions needed for the evolution computations to be performed. The Eddington gray approximation is analytic and therefore easy to implement.

There have been attempts to include realistic model atmospheres in massive star evolution computations in the past. This can be done for instance in post-processing. The idea is to first compute an Eddington gray evolution model. Then for several points of the resulting evolutionary track a model atmosphere is computed using as an input the stellar parameters coming from the evolutionary track. Then a new value of the photospheric radius is extracted from this model atmosphere and is used to recompute the effective temperature. The new effective temperature is then substituted into the Eddington gray one. The main drawback from this method is that there is no feedback from the model

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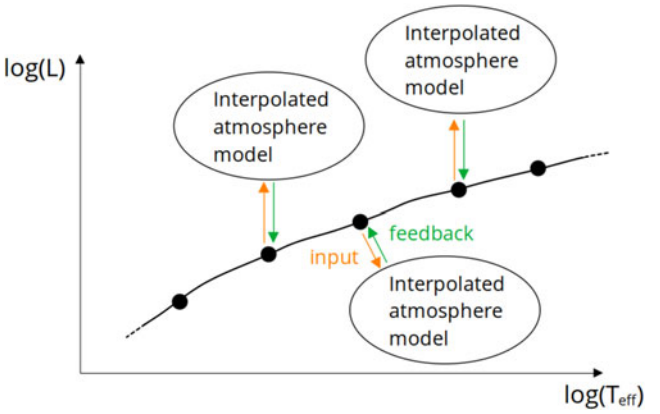


Figure 1. Schematic representation of our self-consistent method to include realistic atmospheres in massive stars evolution computation.

atmosphere onto the evolution model through the boundary conditions. Post-processing was notably used by Groh et al. (2014) on the evolutionary track of a $60M_{\odot}$ star at solar metallicity. This study showed that the recomputed effective temperatures are close to the Eddington gray ones for the main sequence evolution. However for the later stages of the evolution the effective temperatures derived from realistic model atmospheres are significantly lower than the Eddington gray ones.

Another method is direct code-coupling, which was done by Schaerer et al. (1996). The concept is to directly include a radiative transfer simulation inside an evolution code. At each iteration and for each time-step a model atmosphere is computed using the stellar parameters from the evolution model as an input. This model atmosphere is then used to compute the radius and the effective temperature of the star, and to provide boundary conditions to the evolution model. There is an iterative process so that both the internal and atmospheric structure converge. The main drawback of this method is that for it to be feasible in a acceptable computing time the model atmosphere needs to be very simplified compared to what is done in state-of-the-art atmosphere codes. In their study Schaerer et al. (1996) used this method to compute the main sequence evolution of a $60M_{\odot}$ star at solar metallicity, finding almost no differences compared to an Eddington gray track.

However including realistic model atmospheres in massive stars evolution computations has never been done in a self-consistent way. This is the purpose of this study.

2. Methods

We rely on the method presented by Schaerer et al. (1996) to include realistic model atmospheres. A schematic representation of the method we developed is shown in Figure 1. This method can be summarized as follows. We first compute an Eddington gray evolution model. We then compute a grid of realistic model atmospheres which encompass the Eddington gray evolutionary track. We then compute an evolution model taking into account realistic atmospheres. At each iteration of each time-step we interpolate a model atmosphere within our grid. This model is used to compute the effective temperature of the stellar model and to provide the boundary conditions on temperature and density which are necessary for the evolution model. This method is applied routinely in low-mass stars evolution model (see for example Chabrier and Baraffe 1997;

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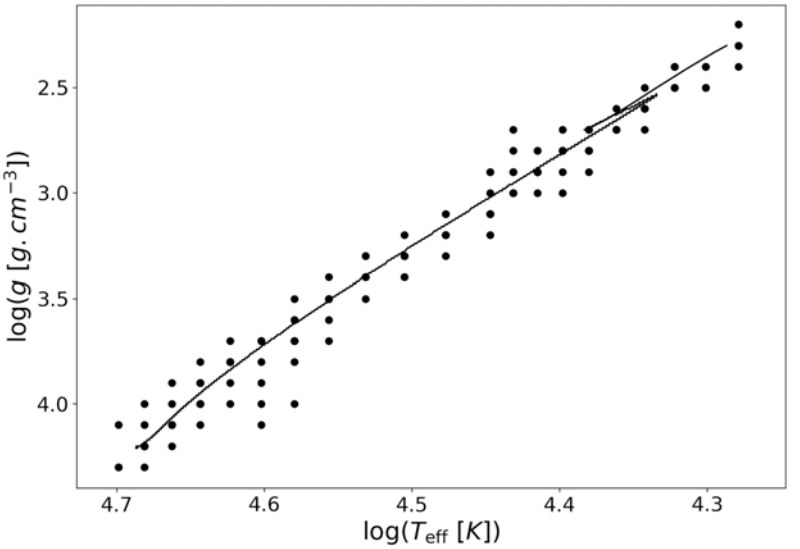


Figure 2. Representation of our grid in the Kiel diagram for the main sequence evolution along with an Eddington gray evolutionary track.

Chen et al. 2014; Baraffe et al. 2015; Mosumgaard et al. 2018; Amard et al. 2019). This method has a very limited computational cost compared to the "on-the-fly" coupling to a radiative transfer code, and makes possible the inclusion of realistic model atmospheres in massive stars evolution computations.

We use the stellar evolution code STAREVOL (Amard et al. 2019), which solves the SSE equations using the Henyey scheme (Henyey et al. 1964). To compute our model atmospheres we use the atmosphere code CMFGEN (Hillier and Miller 1998). CMFGEN is a state of the art non-Local Thermodynamic Equilibrium atmosphere code which takes into account sphericity, wind extension and line-blanketing.

We apply our method to a $60 M_{\odot}$ single stellar model at solar metallicity and without rotation. This choice was made in order to compare our results with those of the previous studies of Groh et al. (2014) and Schaerer et al. (1996). We represent our model atmosphere grid in the Kiel diagram along with an Eddington gray model for the main sequence evolution in Figure 2. As we can see the grid encompasses the evolutionary track.

The interpolation is performed in the parameter space $(T(\tau_{\rm match}), \log(g), \log(\dot{M}))$, where :

- $T(\tau_{\rm match})$ is the temperature of the evolution model at an optical depth $\tau_{\rm match}$ which is a fixed parameter chosen to be located where the diffusion approximation is valid. This choice is based on the fact that in the diffusion approximation the model atmosphere's temperature structure is supposed to be the same as the evolution model's. For the models we present here we used $\tau_{\rm match} = 25$.
- $g = GM_*/R_*^2$ is the gravity at the photosphere.
- $\dot{M}$ is the mass-loss rate, which is computed in the evolution model.

We interpolate a temperature, a density and a radius profile. We use the temperature and density profiles to apply boundary conditions at the numerical surface of the evolution model. This numerical surface is located at a fixed optical depth $\tau_0 = 10$, where again the diffusion approximation holds. For optical depths $\tau < \tau_0$ we patch the interpolated atmosphere structure. We assume the luminosity L_*, the mass M_* and the chemical

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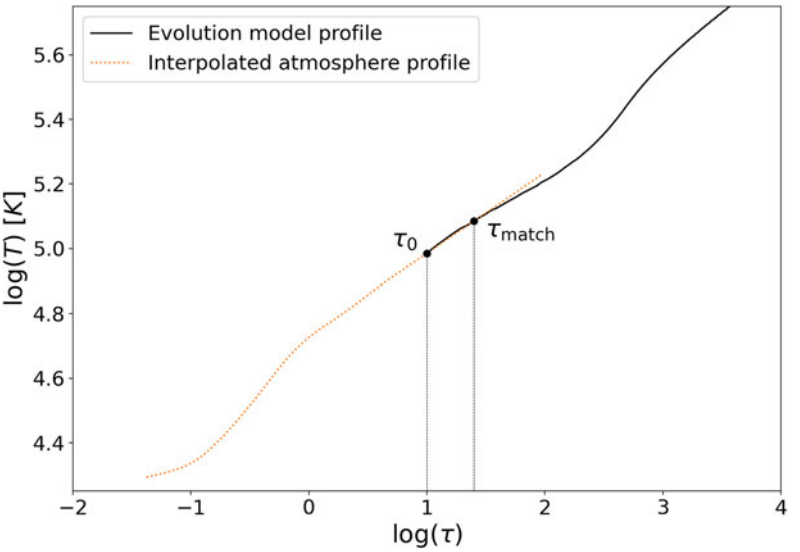


Figure 3. Evolution (in black) and model atmospheres (in orange) temperature profiles a functions of the Rosseland optical depth.

composition to be constant in this region (their values being taken from the evolution model at the numerical surface). We show in Figure 3 the temperature profile of the evolution model at a given time-step along with the interpolated atmosphere profile. We also highlight the positions of τ_0 and $\tau_{\rm match}$.

The photospheric radius R_* is read from the radius atmosphere profile at an optical depth $\tau = 2/3$. This choice to define the photosphere at $\tau = 2/3$ is made in order to assure consistency with the Eddington gray evolution models. We then compute the effective temperature $T_{\rm eff} = L_*/(4\pi\sigma R_*^2)$ and the gravity at the photosphere g.

3. Results

We plot the results obtained with our self-consistent method on the main sequence in Figure 4 along with an Eddington gray model. We find that the inclusion of realistic atmospheres does not modify the main sequence evolutionary track for a $60M_\odot$ star at solar metallicity. This result is consistent with the previous findings of Groh et al. (2014) and Schaerer et al. (1996). We also verified this finding using another method based on the Hopf function (Hubeny Mihalas 2014).

We performed a post-processing test similar to the one of Groh et al. (2014) on the main-sequence Eddington gray model. For each time-step of the evolution we interpolated model atmospheres using the method described above. We then used these models to recompute the effective temperature of the evolution model. As this is post-processing, the recomputed effective temperature is not used during the evolution computation, and we use the Eddington gray boundary conditions to close the SSE equations system. Using this method we find almost no differences between the Eddington gray effective temperature and the one recomputed using realistic model atmospheres. This confirms that the Eddington gray approximation is valid for the main sequence evolution of a $60M_\odot$ star at solar metallicity.

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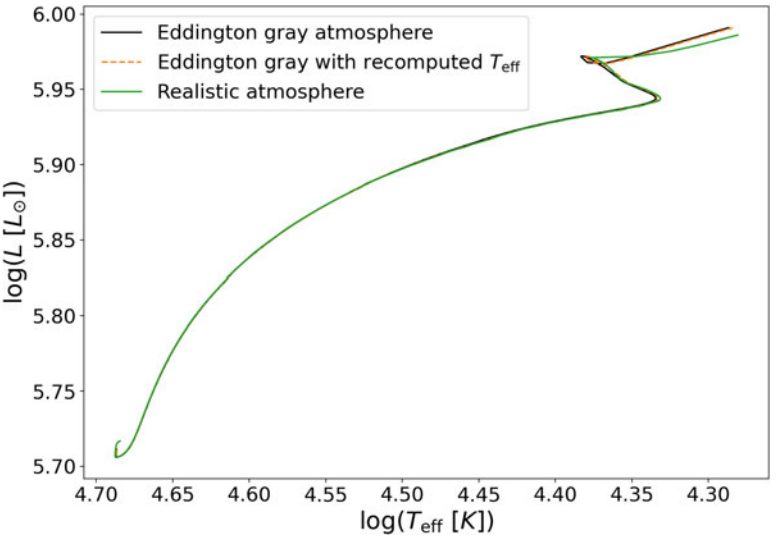


Figure 4. Hertzsprung-Russell diagram showing an evolutionary track including realistic atmospheres with our self-consistent method (in green) compared with one including realistic atmospheres in post-processing (in orange) and an Eddington gray computation (in black) for the main sequence evolution.

4. Conclusion

We implemented a method to perform massive stars evolution computations including realistic model atmospheres and we tested it on a $60 M_\odot$ stellar model at solar metallicity. We confirm that the Eddington gray approximation is valid on the main sequence evolution.

References

Hillier, D. J. and Miller, D. L. 1998, *ApJ*, 496, 407
Amard, L. and Palacios, A. and Charbonnel, C. *et al.* 2019, *A&A*, 631, A77
Groh, J. H. and Meynet, G. and Ekström, S. and Georgy, C. 2014, *A&A*, 564, 30
Schaerer, D. and de Koter, A. and Schmutz, W. and Maeder, A. 1996, *A&A*, 310, 837
Henyey, L. G. and Forbes, J. E. and Gould, N. L. 1964, *ApJ*, 139, 306
Chabrier, G. and Baraffe, I. 1997, *A&A*, 327, 1039
Chen, Y. and Girardi, L. and Bressan, A. *et al.* 2014, *MNRAS*, 444, 2525
Baraffe, I. and Homeier, D. and Allard, F. and Chabrier, G. 2015, *A&A*, 577, A42
Mosumgaard, J. R. and Ball, W. H. and Silva Aguirre, V. *et al.* 2018, *MNRAS*, 478, 5650
Hubeny, Ivan and Mihalas, Dimitri 2014, *Theory of Stellar Atmospheres*

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