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Introduction

Massive stars interact with their surroundings by emitting winds and ionizing photons. Here, we simulate the evolution of the circumstellar medium around stars of $12 M_{\odot}$, from their birth up to the supernova stage. These stars are expected to expand at least twice into red supergiants (RSGs), with intermediate hot stages where fast winds are emitted. We utilize the stellar parameters as function of time from detailed stellar evolution calculations as input for our hydrodynamic models.



Figure 1. HST image of NGC 7635 (Bubble Nebula), showing the wind driven shell expanding into a photoionized region.

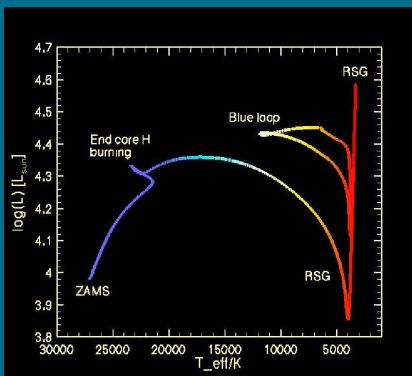


Figure 2. Evolution of a $12 M_{\odot}$ star in the Hertzsprung-Russell diagram; see [1].

Stellar evolution

A $12 M_{\odot}$ star, after its main-sequence evolution, becomes a red supergiant (RSG) when it starts core He burning. During core helium burning, as consequence of a variation of the hydrogen shell burning efficiency, the star undergoes a so called “blue loop”, i.e. it evolves into a blue supergiant (BSG) stage, where it finishes core helium burning and

becomes a RSG again, before exploding as a supernova (cf. Fig. 2).

Mass loss history

Throughout its life, a $12 M_{\odot}$ star emits a wind. However, mass loss rate and wind velocity vary with time. While the mass loss rate increases in the post-main sequence phases, the wind velocity scales with the escape velocity from the stellar surface, and is thus large, when the star is hot and compact and small, in the RSG stage. The interaction of a fast wind with a slow preceding wind, but also that of a slow wind with the hot bubble created by a fast preceding wind, give rise to the formation of circumstellar shells. By following the detailed time evolution of the stellar winds with a hydrodynamic code (ZEUS-3D; see [4]), we follow the formation and evolution of the various wind bubbles and shells during the life of the star until its pre-supernova stage.

Presupernova stage

The evolution of the circumstellar medium at the presupernova stage ends with a RSG shell close to the central star (~ 3 pc). The previous shells have collided and are dispersed within the hot bubble.

Conclusions and future work

The evolution of the circumstellar medium around massive stars, in this case a $12 M_{\odot}$ star, produces various distinct features, and is determined by the evolution of the central star itself. During the first RSG stage, the wind creates a shell at the location where the RSG wind ram pressure equals the hot bubble pressure created by the main sequence wind. During the blue loop, the fast BSG wind forms a shell by sweeping up the remaining RSG wind, which then violently collides with the RSG shell (Fig. 4), producing knots and filaments which later on get scattered inside the hot bubble. The final RSG stage of the star leads to a RSG shell forming very close to the star, at about 3 pc. This shell will start to interact with the fast supernova ejecta about 30 yr after the explosion. Stellar wind anisotropies, expected during the blue loop will give rise to a latitudinal dependence of the shell structures

[3], perhaps as observed in Sher 25 and in SN 1987A. A continuation of the calculations through the stage of SNR formation will allow a comparison with observations of late stages of supernovae and with young SNRs.

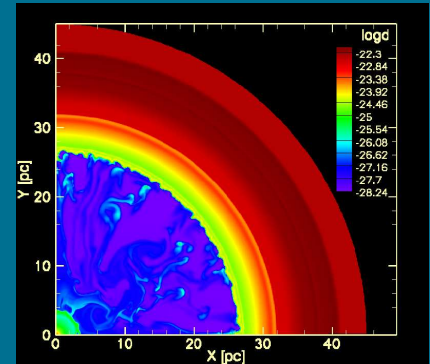


Figure 3. Pre-supernova circumstellar medium density structure around a $12 M_{\odot}$ star as the result of our 2D simulations. The clumps inside the low-density hot bubble are the remainder of the interaction of the BSG wind with the first RSG shell (cf. Fig. 4). In the central part, a second RSG shell has formed ($r \approx 3.5$ pc), a blow-up of which can be seen in the last segment of Fig. 4.

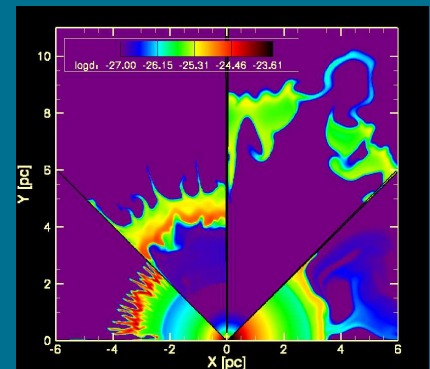


Figure 4. Four snapshots of a 2D simulation of the circumstellar medium evolution around a $12 M_{\odot}$ star: The first three snapshots illustrate the collision of the BSG wind shell with the first RSG shell; the last snapshot depicts the pre-supernova situation (cf. Fig. 3).

References

- [1] Heger A., Langer N., 1998, A & A 334, 210
- [2] Heger A., Langer N., Woosley S.E., 2000, ApJ, 528, 368
- [3] Langer, N., García-Segura, G. & Mac Low, M.M. 1999, ApJ, 520L, 49L
- [4] Stone, J.M. & Norman, M.L. 1992, ApJS, 80, 753