Massive Stars Near and Far
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PION: Simulating bow shocks and circumstellar nebulae around massive stars

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Abstract. Expanding nebulae are produced by mass loss from stars, especially during late stages of evolution. We describe the algorithms and methods implemented in the radiation-magnetohydrodynamics (MHD) code PION for highly scalable simulations using static mesh-refinement. We present results from 3D MHD simulations of bow shocks around runaway massive stars, and of the expansion of a fast wind from a Wolf-Rayet star into the slow wind from a previous red supergiant phase of evolution. PION is free software that can be downloaded from https://www.pion.ie/

Keywords. Hydrodynamics - methods: numerical - ISM: bubbles - Stars: winds, outflows

1. Introduction

Massive stars have a strong effect on their surroundings through their intense radiation (especially extreme-UV, ionizing radiation), strong winds, eruptive explosions and supernova explosions at the end of their lives. Understanding these effects is important for understanding the dynamical and chemical evolution of galaxies, and also the structure and dynamics of the interstellar gas in our own Galaxy. In some cases it is also possible to infer the evolutionary history of a specific star by studying and modelling the nebula surrounding it.

In Mackey et al. (2021) we presented a public release of PION, a software package for simulating nebulae around massive stars. The source code and tutorials for PION v2.0 are available at https://www.pion.ie. PION is a grid-based code that solves the Euler or ideal-magnetohydrodynamics (MHD) equations on a uniform or statically refined mesh. The default integration scheme is second-order accurate in time and space, a finite-volume scheme using a Riemann solver to calculate fluxes between grid cells. Green et al. (2022) used PION to make 3D MHD simulations of the bow shock around the nearby O star, ζ Ophiuchi, and more details of the algorithms and post-processing methods can be found there.

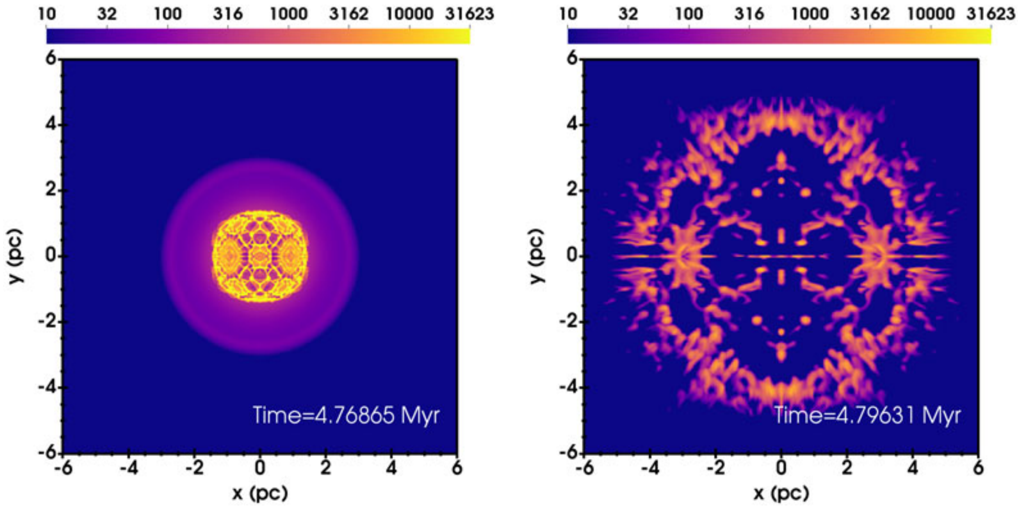

Figure 1. Emission measure (EM) from the expanding nebula 14 000 years (left) and 42 000 years (right) after the RSG→WR transition. The EM is shown with a logarithmic scale (units cm^{-6} pc). Time is shown since the beginning of the stellar evolution calculation; the RSG phase ended at $t \approx 4.755$ Myr.

2. Wolf-Rayet Nebulae

Nebulae around Wolf-Rayet (WR) stars are bright and short-lived ($\sim 10^5$ years) expanding nebulae, as the fast wind and hot radiation from the stellar core sweeps through the extended stellar envelope. The envelope was ejected either through a slow stellar wind from a previous evolutionary phase as red supergiant (RSG), or through binary stripping. A beautiful example is the nebula M1-67 around WR 124 (see poster by Jiménez Hernández in this Volume). Using a stellar evolution calculation for a 35 $M_\odot$ star from García-Segura et al. (1996), we made a 3D radiation-hydrodynamical calculation of the expanding Wolf-Rayet nebula with resolution 256^3 cells on each level and with 4 levels of refinement (see Mackey et al. 2021 for more details).

Fig. 1 shows synthetic observations of the simulation, calculating the projected Emission Measure (EM) and using a raytracing method that neglects internal absorption. In the left panel, about 14 000 years after the transition from RSG to WR, the cool and dense RSG wind is being slowly eroded from the inside by the hot and fast WR wind. The bright inner sphere is the swept-up material in a thin shell. The right panel shows the situation 28 000 years later, when the shock driven by the WR wind has broken out of the RSG wind into the relic hot-wind bubble from the even earlier main-sequence phase. In future work we will develop these simulations and compare quantitatively with observed nebulae.

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Supplementary material

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