Massive Stars Near and Far
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Evolution and final fate of massive post-common-envelope binaries

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Abstract. Mergers of neutron stars and black holes are nowadays observed routinely thanks to gravitational-wave astronomy. In the isolated, binary-evolution channel, a common-envelope phase of a red supergiant and a compact object is crucial to sufficiently shrink the orbit and thereby enable a merger via gravitational-wave emission. Here, we use the outcome of three-dimensional hydrodynamic common-envelope simulations of a 9.4 solar mass red supergiant and a 5 solar mass black-hole to explore the further evolution and final fate of the remnant binary. The binary system undergoes another phase of mass transfer during which it is visible as an X-ray binary. We find that the donor star does not explode as an ultra-stripped supernova because of the large remaining envelope mass, but as a Type Ib/c supernova. Supernova kicks are actually required to sufficiently perturb the orbit and thus facilitate a merger within a Hubble time via gravitational-wave emission.

1. Introduction

In the isolated binary-evolution channel, a common-envelope(CE) phase of a red supergiant (RSG) and a compact object is crucial to sufficiently shrink the orbit of the binary, and thereby enable a merger via gravitational-wave emission. Here, we use the outcome of three-dimensional hydrodynamic CE (3D-CE) simulations of a $9.4\,M_\odot$ RSG and a $5\,M_\odot$ black-hole (BH) to explore the further evolution and final fate of the remnant binary.

2. Results and Conclusions

We use the MESA stellar evolution code (Paxton et al. 2018) to let the same RSG star, as employed in a complex 3D-CE simulation from Moreno et al. (2022), lose most of its envelope quickly to get a remnant RSG core, mimicking a 3D-CE event. A BH companion of $5.0\,M_\odot$ orbits this remnant core as a post-CE binary in our MESA model. We simulate the binary with the original parameters from the outcome of the 3D-CE model. However, the remnant RSG core with $2.97\,M_\odot$ in our model expands during the CE envelope removal such that it does not fit into the Roche lobe of the post-CE binary orbit as suggested by the 3D-CE simulation. Further envelope removal ($\sim 0.17\,M_\odot$) is required and was applied. Therefore, we get a remnant RSG core of $2.8\,M_\odot$. The orbital period of this post-CE binary is 3.53 days, determined at the point where the available

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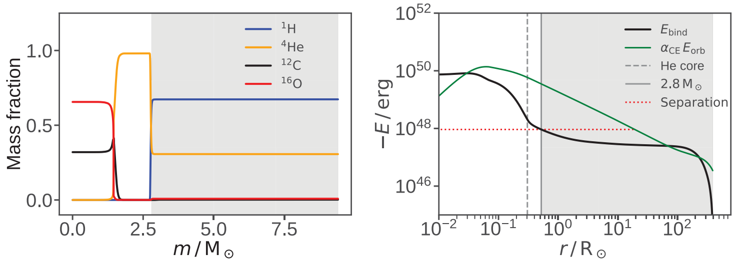

Figure 1. Chemical composition of the RSG donor with $9.4\,M_{\odot}$ in the left panel. The gray shaded area indicates the envelope lost in the CE event. The right panel shows binding energy ($E_{\rm bind}$) of the RSG donor and the available orbital energy ($\alpha_{\rm CE}E_{\rm orb}, \alpha_{\rm CE} = 0.69$) of the binary with a $5.0\,M_{\odot}$ BH companion.

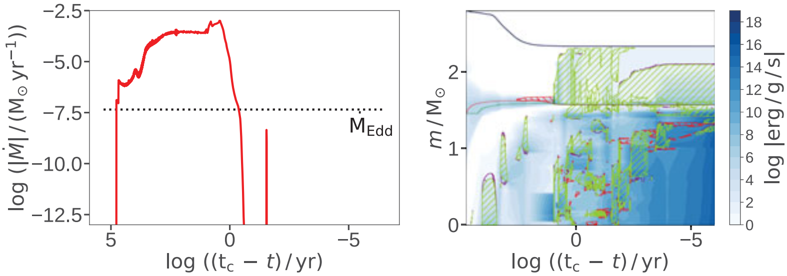

Figure 2. Mass-transfer rate and Kippenhahn diagram of the remnant RSG core, as a function of the remaining stellar age of the remnant RSG core ($t_c - t$) until core collapse.

orbital energy ($\alpha_{\rm CE}\, E_{\rm orb}$) equals the binding energy ($E_{\rm bind}$) of the donor star (see the right panel in Fig. 1). The envelope-ejection efficiency $\alpha_{\rm CE} = 0.69$ (Moreno et al. 2022).

The post-CE binary initiates a mass-transfer (MT) phase, and is fully computed until core-collapse (see Fig. 2). After the MT phase, the mass of the remnant RSG core decreases to $\sim 2.3\,M_{\odot}$, but only quite few material ($\sim 0.002\,M_{\odot}$) is accreted by the BH companion due to Eddington-limited accretion of $4.42 \times 10^{-8}\,M_{\odot}\,{\rm yr}^{-1}$. The remaining helium-rich envelope of the remnant RSG core is $\sim 0.7\,M_{\odot}$. It will not explode as an ultra-stripped SN. The final orbital configuration is too wide (5.16 days) to get a merger within a Hubble time without a SN kick. However, it is possible that roughly 5% of the post-CE binary merge within a Hubble time if the SN kick is favorable (Moreno et al. 2022). The mass of the remnant RSG core is changed during the MT phase, which affects the possibility of a SN explosion. It can also end its life as an electron-capture SN or an oxygen-neon-magnesium white dwarf, in other slightly different binary configurations.

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