Massive Stars Near and Far
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The evolution of binary-stripped stars: consequences for supernovae and black hole formation

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Abstract. Gravitational-wave (GW) observations are revealing the population of compact objects from a new angle. Yet their stellar progenitors remain uncertain because few observational clues on their progenitors exist. Theoretical models typically assume that the progenitor evolution can be approximated with single-star models. We explore how binary evolution affects the pre-supernova (SN) structure of stars, and the resulting distribution of compact object remnants. We focus on the differences in the core properties of single stars and of donor stars that transfer their outer layers in binary systems and become binary-stripped. We show that the final structures of binary-stripped stars that lose their outer layers before the end of core helium burning are systematically different compared to single stars. As a result, we find that binary-stripped stars tend to explode more easily than single stars and preferentially produce neutron stars and fewer black holes, with consequences for GW progenitors.

Keywords. stars: evolution, stars: binaries, stars: interiors, supernovae: general black hole physics

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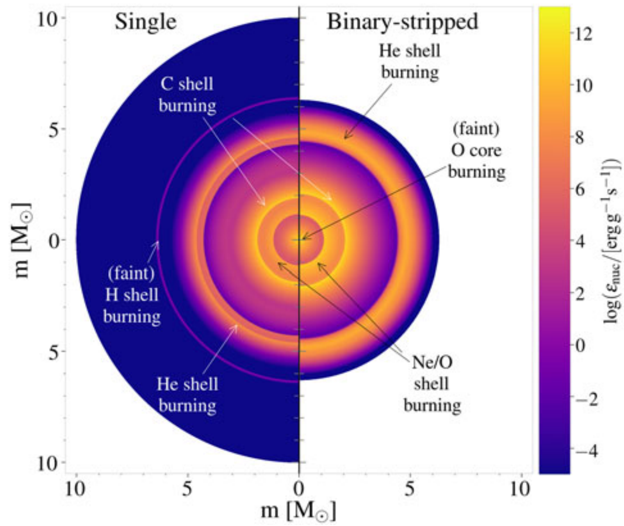

Figure 1. Core structure and nuclear energy generation rate of a single (left half-circle) and binary-stripped (right half-circle) star with the same reference helium core mass, shown at the end of core carbon burning (see also Laplace et al. 2021). Even for the same core mass, the location and strength of the nuclear burning shells is different, ultimately leading to changes in the chemical composition and final fate. The diagram was created with the TULIPS software (Laplace 2022).

1. Introduction

Understanding the final fate of massive stars is a pressing question in the era of GW sources. GW detectors have now detected almost a hundred compact objects, and yet their stellar progenitors remain uncertain (LIGO Scientific Collaboration and Virgo Collaboration et al. 2019). It is now established that most massive stars live in close multiple systems, with short enough separations to interact during their lifetime (Sana et al. 2012). Isolated binary systems are promising candidates for the progenitors of GW sources. Here, we investigate the impact of binary mass transfer on the final fate of massive stars and on the resulting population of compact objects.

2. Methods

We compute one-dimensional single and binary evolutionary models at solar metallicity using the MESA stellar evolution code (Paxton et al. 2011; 2013; 2015; 2018; 2019). In the calculations presented in Laplace et al. (2021) we focus on post main sequence mass transfer (case B) from primary stars with initial masses between 11 and 21 $M_\odot$, following a similar approach as Laplace et al. (2020). In (Vartanyan et al. 2021), the supernova explosion of these models is simulated self-consistently with the two-dimensional FORNAX code. To understand the effects of binary stripping on a stellar population, Schneider et al. (2021) explores a larger range of periods and initial masses and simulates the outcome of neutrino-driven supernova explosions of these progenitors based on an improved version of the parametric supernova code by Müller et al. (2016).

3. Results

As illustrated in Fig. 1, we find that binary-stripped stars that lose their outer layers before the end of core helium burning develop systematically different core structures compared to single stars, even for similar core masses (Laplace et al. 2021,

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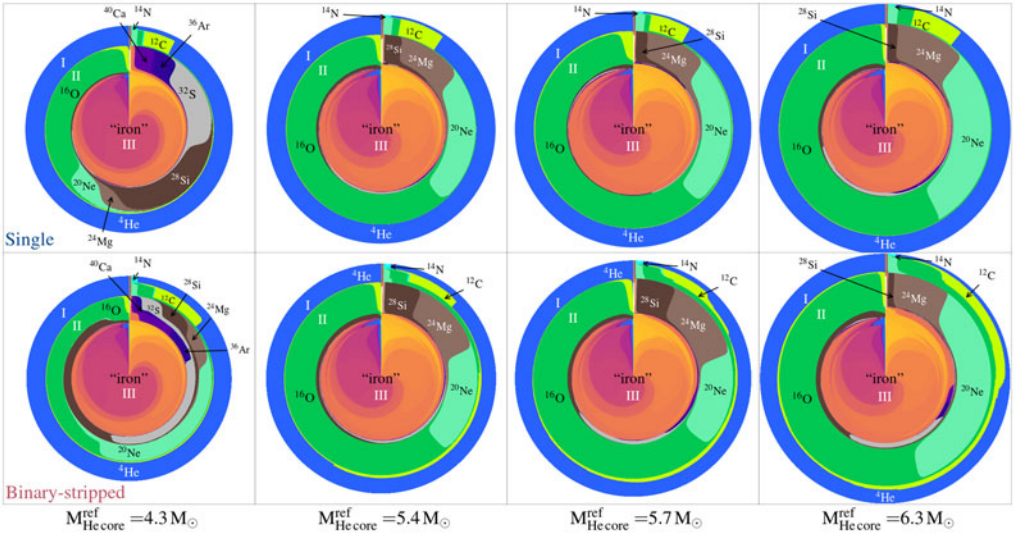

Figure 2. Chemical composition of the inner helium core of single and binary-stripped stars with the same reference helium core mass at the onset of core collapse (Laplace et al. 2021). Every isotope is represented by a different color. The radial direction is proportional to the square-root of the mass coordinate. Consequently, the surface area covered by each color is proportional to the mass of the corresponding isotope. Binary-stripped stars contain a gradient of carbon, oxygen, and neon around the helium-depleted core (region II), that is not present in single stars. The diagrams were created with the TULIPS software (Laplace 2022).

Schneider et al. 2021), in agreement with previous studies. Due to mass loss, the helium core shrinks during core helium burning, leading to a different chemical composition and density structure. From self-consistent simulations of the supernova explosions, we find that, for the same initial mass, binary-stripped stars tend to explode preferentially compared to single stars (Vartanyan et al. 2021). We also show that binary-stripped stars can populate the "mass gap" that may exist between the highest-mass neutron star (NS) and the lowest-mass black hole (BH) through fallback accretion. This could explain the recent report of a GW source containing a compact object within this gap (The LIGO Scientific Collaboration et al. 2020).

As shown in Fig. 2, the chemical composition of single stars and binary stripped stars is different, even for the same core mass. The most prominent difference is the presence of a layer above the helium-depleted core that contains a gradient of carbon, oxygen, and neon, and is not present in single stars. In Farmer et al. (2021), we show that this difference in chemical structure has also large consequences for the nucleosynthesis expected from single and binary-stripped stars. In particular, the binary-stripped stars we model are twice as efficient at producing ^{12}C compared to single stars.

In Fig. 3, we present the distribution of compact objects expected from a population of binary-stripped and single stars (Schneider et al. 2021). Binary-stripped stars create neutron stars for a larger range of initial masses than single stars, and for lower initial masses. In addition, they only create BHs for initial mass larger than 70 $M_\odot$ and for an "island of BH formation" at an approximate initial mass of 32 $M_\odot$. As a result, the number of gravitational-wave mergers from isolated binary evolution is expected to be significantly smaller than typically assumed in population synthesis calculations (Schneider et al. 2021). Based on a 1D parametric supernova code, we find that a number of models may experience fallback accretion and populate the NS-BH mass gap, in agreement with our expectations from 2D supernova simulations (Vartanyan et al. 2021).

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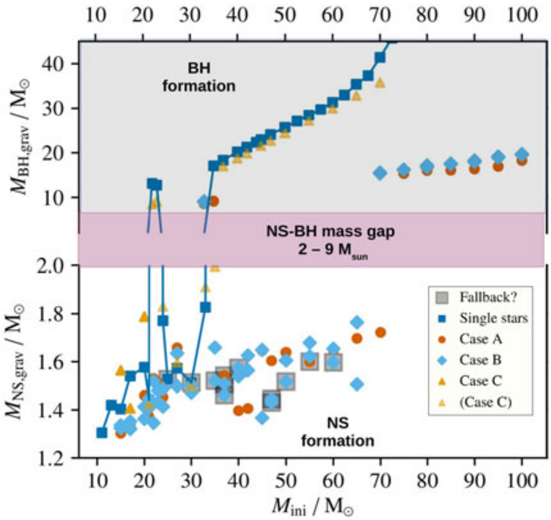

Figure 3. Compact remnants from single and binary-stripped stars (adapted from Schneider et al. 2021). Binary-stripped stars produce neutron stars for a much larger range of initial masses (up to 70 M$_\odot$) and black holes for a much smaller range (mainly for initial masses above 70 M$_\odot$).

4. Conclusions

We conclude that taking binary evolution into account is crucial to understand the formation of compact objects, and for interpreting the population of GW sources. Binary stripping is particularly important because it typically affects the deep interiors of stars, as well as their outer layers. This shifts the distribution of the compact objects to lower masses, leads to preferential explosion compared to single stars, and to differences in the nucleosynthesis. To obtain a full picture of the effect of binary interactions on the final fate of stars, other binary processes, such as accretion and merging, need to be investigated in the future.

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Discussion

Bersten: I wonder how how we can use your results to analyze the SNe observable (LC and spectra). Because, you find differences on the chemical patron and density structure between single and binary but you are using some specific path of binary calculation. Is this path representative for what we expected for stripped star?

Laplace: Very good point. We focused on the most common channel that creates binary-stripped stars due to stable mass transfer, case B mass transfer. This means we expect most stripped stars (at solar metallicity) to come from this channel and our models to be representative of a large fraction of stripped SNe progenitors.

Sander: Since you mentioned that you use a large network, are you distinguishing between ^{20}Ne and ^{22}Ne? If so, could you make any predictions about Ne surface abundances that could help to identify the different scenarios for H-depleted stars?

Laplace: Yes we can distinguish between ^{20}Ne and ^{22}Ne. The issue is that to save computational cost we switched to the larger network at the end of core oxygen burning. Before, we used a network of 21 isotopes. This means the core chemical structure is very well resolved, but we may miss differences in the chemical composition of the outer layers from earlier phases of the evolution.

Negueruela: When you consider the difference between a stripped star and a single star, do you mean a fully stripped star (i.e. without any mantle, as your diagrams seem to imply)? Do your models produce stars that are partially stripped?

Laplace: These models are computed at solar metallicity. Due to wind mass loss, the binary-stripped stars lose all their hydrogen-rich envelope at the end of core helium burning. This means they may be partially stripped right after mass transfer, but at the end of their lives, they do not have a hydrogen-rich envelope any longer.

Roberti: I have a question about the explodability: do you evaluate it by using only the compactness or do you also consider other parameters?

Laplace: We compute the collapse self-consistently in 2D with the FORNAX code and identify explosion as the shock reaching runaway expansion at the end of the simulation (1s post bounce). Interestingly, we found that the compactness is not a sufficient diagnostic for successful explosion. For some models, we also need to look at the critical curve, so the interplay between the competing but coupled effects of accretion and neutrino luminosity in driving the explosion.

Moriya: Do you find significant differences in explosion energies and ^{56}Ni masses from the explosions of single and binary progenitors? I especially wonder if you find significant differences in the progenitors with the similar core mass or compactness.

Laplace: For progenitors with the same initial mass, we found that for the duration of the simulation (up to one second post bounce) binary-stripped star models have higher net explosion energies than their single-star counterpart. However, the energy growth of the single stars models is higher than for the binary-stripped models (probably because of a larger accreting mass), suggesting that when integrated over the full time of the explosion, the single star models should have larger explosion energies. We would need 3D models to be certain about this. Unfortunately, this trend is less clear for progenitors with the same helium core mass. We did not compute the ^{56}Ni masses but we are planning to compute supernova nucleosynthesis abundances, including ^{56}Ni, in future work led by Rob Farmer.

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