Massive Stars Near and Far
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Formation of black holes in the pair-instability mass gap: Hydrodynamical simulation of a massive star collision & evolution of a post-collision star

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Abstract. In this work, we study in detail the collision formation scenario of black holes (BHs) which lie in the pair-instability (PI) mass gap. We study the collision scenario of two massive stars by means of a smoothed-particle hydrodynamics (SPH) simulation and the post-collision evolution with detailed stellar evolutionary codes. We find that the stellar collision scenario is a suitable formation channel to populate the BHs' PI mass gap.

Keywords. stars: evolution, hydrodynamics, black hole physics

1. Introduction and SPH collision simulation

The detection of GW190521 by the LIGO-Virgo collaboration revealed the existence of black holes (BHs) in the pair-instability (PI) mass gap. Here, we investigate the formation of BHs in the PI mass gap via star-star collisions in young stellar clusters. To avoid PI, the stellar collision product must have a relatively small core and a massive envelope. We investigated this issue by means of the SPH code STARSMASHER (Gaburov et al. 2010) and detailed stellar evolutionary models with PARSEC (Costa et al. 2019) and MESA (Paxton et al. 2019). In this work, we simulated the collision of a core helium burning (CHeB) star of $\sim 58\ M_{\odot}$ with a main-sequence (MS) star of $\sim 42\ M_{\odot}$.

In Ballone et al. (2022), we created the initial condition of the two stars using PARSEC. Then, STARSMASHER re-samples these profiles with particles distributed in the 3D space. The CHeB and MS stars are sampled with 8×10^5 and 9×10^4 particles, respectively. Then we put the two stars on a hyperbolic radial orbit with a velocity at infinity of 10 km s^{-1} and an initial separation of 110 $R_{\odot}$. We simulate a head-on collision to probe the most extreme case in terms of kinetic energy and to obtain an upper limit to the mass lost in the collision. As the MS star plunges into the atmosphere of the CHeB star, its outer layers form a strong shock on the frontal side of the collision, while they lead to a cometary tail on the back side. Then, the MS star is tidally disrupted by the core of

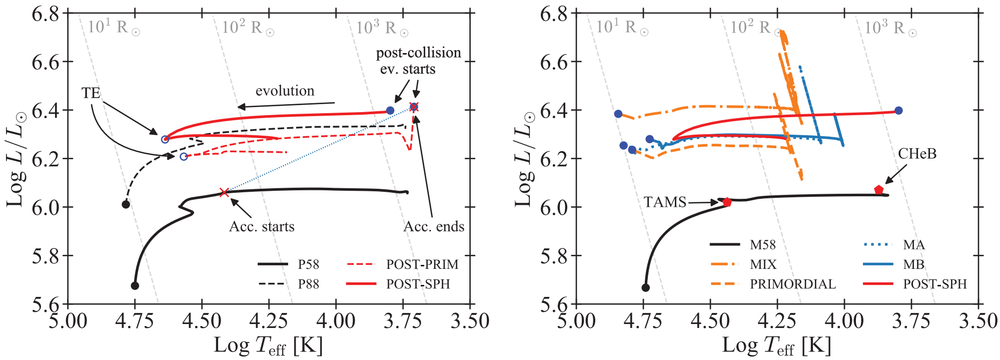

Figure 1. HR diagram of post-collision PARSEC (MESA) tracks in the left (right) panel. Solid black lines indicate the primary star P58 (M58) for PARSEC (MESA). The dashed black line on the left panel shows the 'standard' PARSEC track with 88 $M_\odot$. The red crosses mark the starting and ending points of the accretion. The blue points (empty circles) indicate the post-collision evolution starting (thermal equilibrium, TE) points. Details on the text.

the CHeB star. During collision, up to 12% of the total mass is lost. At the end of the simulation, the post-collision star has a mass of 88 $M_\odot$ and a helium core of 28 $M_\odot$.

2. Post-Collision evolution and Final masses

In Costa et al. (2022), we used the output of the SPH simulation to study the evolution of the collision product with PARSEC and MESA. We build the PARSEC model POST-PRIM by accreting mass on the primary CHeB star until its total mass is 88 $M_\odot$. In this model, we maintain the pristine chemical composition of the envelope. Starting from the POST-PRIM model, we build the POST-SPH model by changing the chemical composition of the envelope to match that of the SPH simulation. Both post-collision stars start their evolution as red supergiants and evolve to become blue supergiants (BSG). After reaching thermal equilibrium (TE), they evolve toward the red part of the HR diagram until they explode (Figure 1). Similarly, we build the post-collision MESA stellar tracks, accreting mass and matching the SPH simulation envelope composition. The model MA is built with the primary in the terminal age main sequence phase (TAMS). The MB model is built with the primary in the CHeB phase. Remarkably, the PARSEC and MESA stellar models evolve in a very similar way after TE, and finish their lives as BSGs (Figure 1). All of them avoid PI and evolve until the final core collapse. We estimate the final BHs masses taking into account the mass ejected during the final collapse, due to shocks induced by neutrino loss; we find that all our models lose less than 0.5 $M_\odot$ during the final collapse because of the relatively high compactness of the stellar envelope. Therefore, we expect that all our models produce BHs with mass $\sim 87\ M_\odot$, within the PI mass gap.

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Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1743921322002903.

References

Ballone, A., Costa, G., Mapelli, M., & MacLeod, M. 2022, arXiv e-prints, arXiv:2204.03493
Costa, G., Ballone, A., Mapelli, M., & Bressan, A. 2022, arXiv e-prints, arXiv:2204.03492
Costa, G., et al. 2019, A&A, 631, A128
Gaburov, E., Lombardi, James C., J., & Portegies Zwart, S. 2010, MNRAS, 402, 105
Paxton, B., et al. 2019, ApJS, 243, 10