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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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Introduction

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 hydrodynamical simulations with the smoothed particle hydrodynamics (SPH) code STARSMASHER (Gaburov et al. 2010b) and detailed stellar evolutionary models with PARSEC (Bressan et al. 2012; Costa et al. 2019) and MESA (Paxton et al. 2019). In this work we simulated and analyzed the collision between a core helium burning star of about 58 $M_\odot$ and a main-sequence star of about 42 $M_\odot$.

Collision: SPH simulation

We create the 1D profiles of these two stars using PARSEC. Stellar profiles are shown in Figure 1. STARSMASHER re-samples these profiles with particles distributed in the 3D space, by keeping the number density of particles uniform. The CHeB and MS star are sampled with 8×10^5 and 9×10^4 particles, respectively. Then, we put the two stars on a hyperbolic radial orbit, with velocity at infinity 10 km s^{-1} and initial separation 110 $R_\odot$. We simulate an head-on collision to probe the most extreme case in terms of kinetic energy and to obtain an upper limit to the mass loss. Figure 2 shows the evolution of the collision at the beginning of the simulation, during and after the collision. As the MS star plunges in the atmosphere of the CHeB star, its outer layers form a strong shock in the frontal side of the collision, while they lead to a cometary tail in the back side. Then, the MS star is tidally disrupted by the core of the CHeB star. During the 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 $M_\odot$. We also traced the chemical composition of the post-collision star, and Figure 3 shows the reconstructed 1D post-collision stellar profiles.

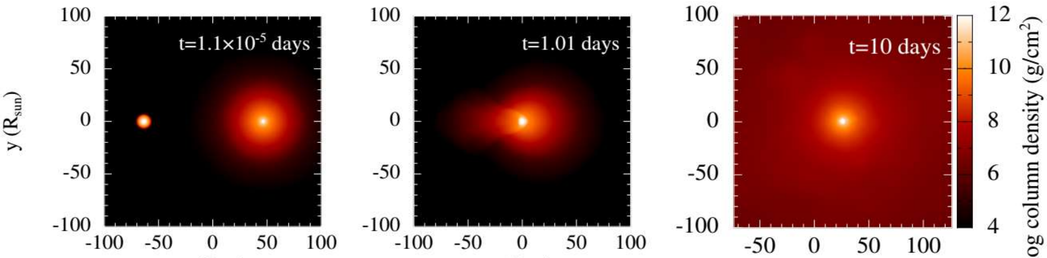

Figure 2: SPH collision snap-shot at the beginning, during and at the end of the simulation, from left to right.

Initial conditions

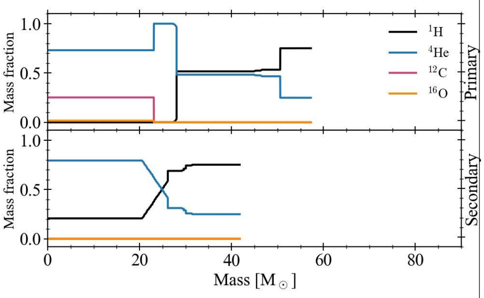

Figure 1: Chemical profiles of the primary and the secondary stars.

Post-collision profiles

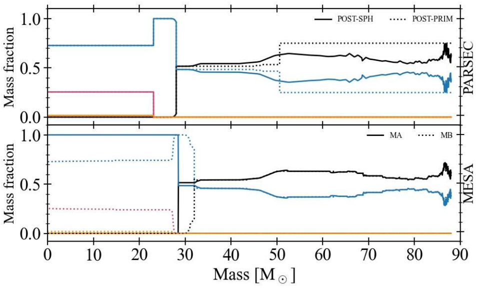

Figure 3: Chemical profiles of the post-collision PARSEC and MESA stellar models.

Post – Collision evolution

We use the outputs of the SPH simulation to study the evolution of the collision product with PARSEC and MESA. We build the post-collision star in two steps. Starting from the primary model, we accrete mass until its total mass becomes 88 $M_\odot$. During accretion, we take into account the heat injected by the accreting material (Kunitomo et al., 2017), which leads the star to inflate and become a RSG. Then, we create two post-collision models. In the first model (POST-PRIM) we maintain the pristine chemical composition of the envelope, while in the second model (POST-SPH) we change the chemical composition of the envelope to match the SPH simulation. In a similar manner, we build the post-collision MESA stellar tracks. The model MA is built with the primary in the terminal age main sequence phase. While the MB model is built with the primary in the CHeB phase.

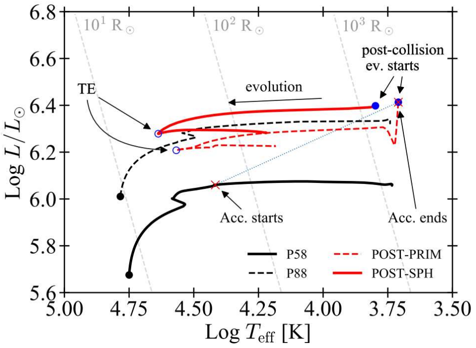

Figure 4: HR diagram of PARSEC stellar tracks.

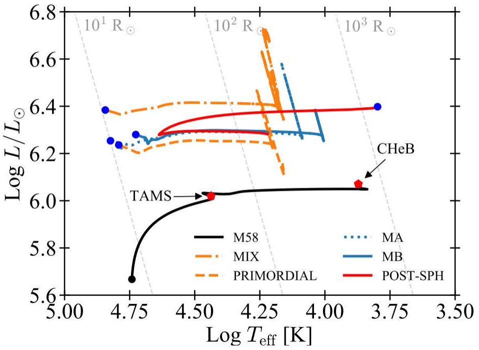

Figure 5: HR diagram of MESA stellar tracks.

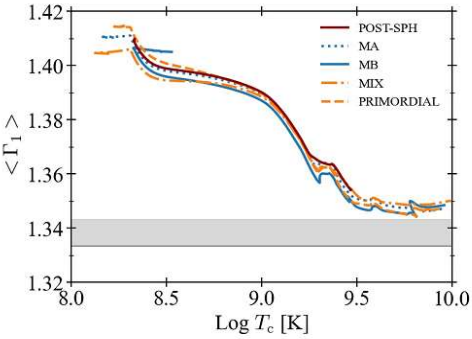

Figure 6: Evolution of the first adiabatic exponent weighted average versus the central temperature of all tracks.

Final Masses and Conclusions

We find that the stellar tracks computed for the post-collision stars avoid PI and evolve until the final CC (Figure 6). Remarkably, the PARSEC and MESA stellar models evolve in a very similar way, ending their life as BSG stars. We estimate the final BH mass by taking into account the possible **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 ($\xi_{\rm env} = 0.2 - 0.5$). Thus, **we expect that all our models produce BHs with mass ≈ 87 $M_\odot$, within the PI mass gap.**

Papers references

https://arxiv.org/abs/2204.03493 & https://arxiv.org/abs/2204.03492

End of core oxygen burning

Model	$M_*/M_\odot$	$M_{\rm He}/M_\odot$	$M_{\rm CO}/M_\odot$	$\xi_{2.5}$	$\xi_{\rm env}$	$M_{\rm ej}$	$M_{\rm BH}$
POST-PRIM	87.9	28	23.3	0.250	0.479	0.04 – 0.28	87.3
POST-SPH	87.8	28	24.5	0.279	0.525	0.03 – 0.26	87.3
MIX	98.5	29.1	25.4	0.293	0.367	-	-
PRIMORDIAL	98.9	28.9	25.8	0.273	0.528	-	-
MA	87.6	28.5	25	0.277	0.291	-	-
MB	87.7	31	27.5	0.281	0.201	-	-

Onset of core collapse

Model	$M_*/M_\odot$	$M_{\rm He}/M_\odot$	$M_{\rm CO}/M_\odot$	$\xi_{2.5}$	$\xi_{\rm env}$	$M_{\rm ej}$	$M_{\rm BH}$
MIX	98.5	29.1	25.4	0.51	0.362	0.03 - 0.27	97
PRIMORDIAL	98.9	28.9	26	0.561	0.523	0.03 – 0.22	97.3
MA	87.6	28.5	25	0.591	0.289	0.04 – 0.36	87
MB	87.7	31	27.5	0.541	0.20	0.06 – 0.43	87