Modeling Binary Systems That Survive Supernova Explosions and Give Rise to Gravitational Waves

J. Petrović[1], B. Arbutina[2], M. Jurkovic[1], A. Čeki[1] and G. Djurašević[1]

[1]Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia
[2] Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, 11000 Belgrade, Serbia

`jpetrovic@aob.rs`, `arbo@astro.edu.rs`

Abstract. The latest observations of gravitational waves by LIGO, Virgo and KAGRA scientific collaborations indicate that the observed gravitational wave emission originates in mergers of black holes with masses up to about 100 solar masses. The MOBY project (Modeling Binary Systems That End in Stellar Mergers and Give Rise to Gravitational Waves) aims at identifying and modeling the progenitors of such gravitational wave sources related to the massive stellar-mass binary black hole systems that can potentially survive two supernova explosions. Within the project evolutionary models of rotating close (Case A) massive binary systems will be calculated with the MESA (Modules for Experiments in Stellar Astrophysics) numerical code. Here we give some preliminary estimates of the masses of pre-supernova and ZAMS stars. The final goal is to produce an extensive grid of detailed evolutionary models of rotating massive binary systems with the initial masses of couple of hundreds solar masses or more, in order to reproduce observed binary black hole systems and constrain the initial and final physical parameters of their progenitors.

Mergers in double compact objects have been recently associated with the emission of gravitational waves (GWs) by the observations of the LIGO-Virgo-KAGRA collaboration (see e.g. Abbott et al. 2021, 2023). The merging objects are the end product of stellar evolution in close binary systems – the evolution that is significantly altered in comparison to the evolution of single stars by interactions that change the physical properties of both components and also affect the dynamics of the system. Although tidal forces in close binary systems, as well as GW emission lead to circularization of orbits, eccentricity can rise or the system can even be disrupted in supernova explosions. Assuming that explosion is instantaneous and ideally spherically symmetric, and that components after the explosion have the same velocity (plus an additional center of mass velocity), Verbunt (1993) finds:

$$e = \frac{\Delta M}{M_1' + M_2' - \Delta M}$$

One can see that the system will survive ($e < 1$) if the ejected mass is less than half the total mass before the explosion.

Unlike the case with neutron stars, ejecta mass in core-collapse (CC) supernovae (SNe) producing black holes (BHs) is likely to be rather small (failed SNe, i.e. direct collapse or fall-back). On the other hand, extremely massive stars at low metallicies are believed to end in pair-instability (PI) SNe that disrupt the whole star. The so-called pulsating pair-instability (PPI) SNe are on the other hand able to shed excess mass in a series of pulses, allowing them to survive complete disruption and end in core collapse. If we, very simplistically, assume that the first pulse expels the majority of mass and treat it as supernova explosion, since it needs to be $e < 1$, then

$$M_2 > M_1' - 2M_1$$

$$\vee$$

$$M_2 > \frac{1}{2}M_1' - \frac{1}{2}M_1$$

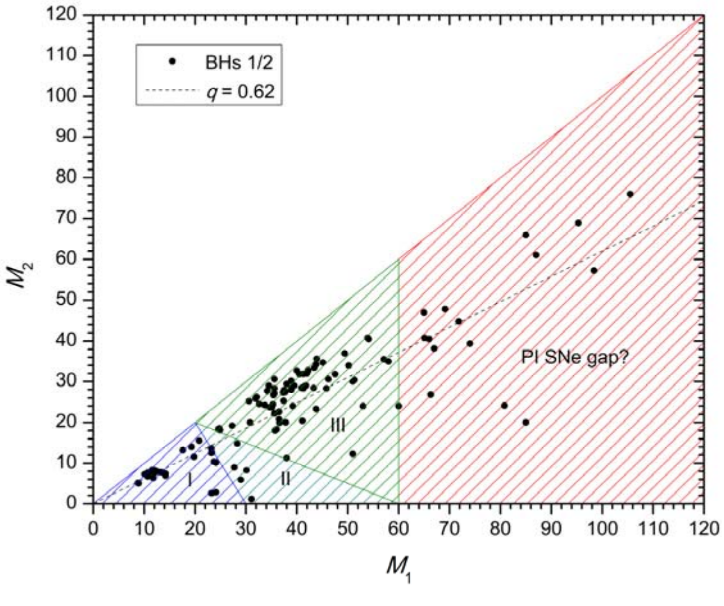

Figure 1. LIGO–Virgo–KAGRA BHs (see Abbott et al. 2021, 2023).

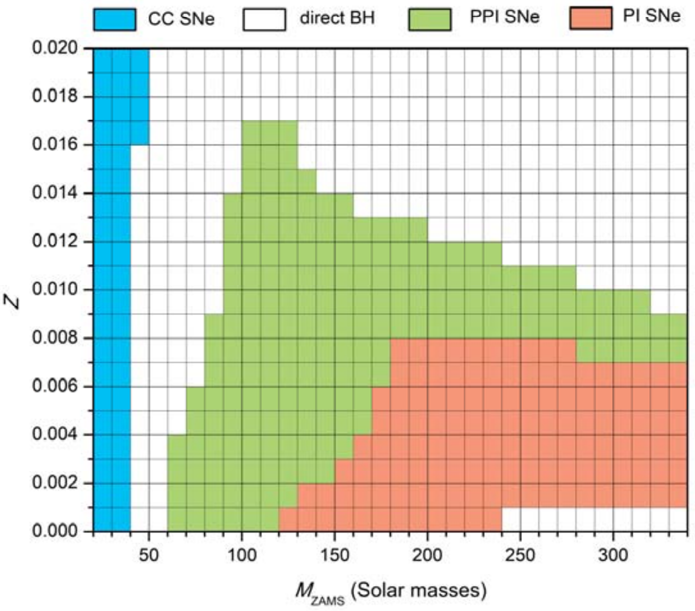

Figure 2. ZAMS masses versus metallicity (adapted from Spera & Mapelli 2017).

The system would almost certainly survive the first SN i.e. black hole formation, so we analyze here the second SN in which either, less massive or more massive, BH could form. M_1' and M_2' are masses of pre-supernova stars, for which we can roughly assume that they pile-up at ~ 60 solar masses in the case of PPI SN (otherwise $M_1' \approx M_1$, $M_2' \approx M_2$) (Farmer et al. 2019). This assumption is what separates regions I, II and III in Fig. 1. BHs in the region I are unlikely to have PPI SN origin, not only due to the mass function, but the system may not survive the second explosion/pulse. In the region II, this applies to the secondary. In the region III, both M_1 and M_2 could, in principle, come from direct CC, as well as from PPI channel. The region $60 < M_{1,2}/Mo < 120$ is the traditional PI SNe gap, although its boundaries remain uncertain. BHs could still populate this region (and they do) by invoking hierarchical mergers, stellar collisions, nuclear physics adaptations, H-rich progenitors (blue supergiants) (Abbott et al. 2024, Winch et al. 2024). LIGO-Virgo-KAGRA BHs follow roughly a linear trend, larger the primary larger is the secondary mass, with an average mass ratio $q = 0.62$.

To estimate initial masses for the observed BHs is even more difficult. In Fig 2. we plotted ZAMS masses versus metallicity, after Spera & Mapelli (2017). Our goal is to produce an extensive grid of detailed evolutionary models of rotating massive binary systems with the ZAMS masses up to couple of hundreds solar masses for higher and moderate metallicities, and perhaps with even higher masses for extremely low metallicity, to avoid PI SNe.

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References

Abbott, R. et al.: 2021, *Phys. Rev. X*, **11**, 021053.
Abbott, R. et al.: 2023, *Phys. Rev. X*, **13**, 041039.
Abbott, R. et al.: 2024, *Phys. Rev. D*, **109**, 022001.
Farmer R. et al.: 2019, *Astrophys. J.*, **887**, 53.
Spera, M., Mapelli, M.: 2017, *Mon. Not. R. Astron. Soc.*, **470**, 4739
Verbunt, F.: 1993, *Annu. Rev. Astron. Astrophys.*, **31**, 93.
Winch, E.R.J. et al.: 2024, *Mon. Not. R. Astron. Soc.*, **529**, 2980.