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Black Hole dynamics in Young Star Clusters

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Abstract. Young star clusters are a promising environment for forming binary black holes. Such binaries may form dynamically or via binary star evolution or through the interplay of these two channels. To study these formation pathways, we have performed high precision direct N-body simulations of low-mass ($M < 1000\ M_\odot$) young star clusters. The simulations were carried out with the code `Nbody6++GPU` coupled with the population synthesis code `MOBSE`. Our results highlight the importance of dynamics to form massive black hole binaries even in low-mass young star clusters.

Keywords. black hole physics - gravitational waves - methods: numerical - galaxies: star clusters: general - stars: kinematics and dynamics - binaries: general

1. Introduction

One of the main open questions of gravitational wave (GW) astronomy is to understand the formation channels of merging black holes (BHs), observed for the first time by the LIGO-Virgo collaboration (LVC, Abbott *et al.* 2016a,b; Abbott *et al.* 2018). Merging black hole binaries (BHBs) may result from the evolution of isolated binaries (e.g. Belczynski *et al.* 2016, Giacobbo *et al.* 2018a,b; Mapelli & Giacobbo 2018 and references therein). Alternatively, a BHB may form through dynamical interactions in a dense stellar system (e.g. Portegies Zwart & McMillan 2000; Banerjee *et al.* 2010; Rodriguez *et al.* 2016; Askar *et al.* 2017; Arca-Sedda *et al.* 2018 and references therein). Here we study the formation and evolution of BHBs in young star clusters (YSCs). YSCs are the nursery of massive stars (which are thought to be the progenitors of BHs and neutron stars). Thus, it is reasonable to expect that BHs participate in the dynamical life of their parent YSCs, at least for few Myr. Despite such promising features, only few studies investigates BHBs in YSCs (Ziosi *et al.* 2014; Mapelli 2016; Banerjee 2017, 2018; Rastello *et al.* 2019; Di Carlo *et al.* 2019), because modelling YSCs is a computational challenge: they are clumpy and asymmetric stellar systems and host a high fraction of binaries. Hence, YSCs cannot be modelled with Monte Carlo codes but they require expensive direct N-body simulations. In addition, since stellar evolution plays a fundamental role in YSCs, influencing their lifetime and global evolution, population synthesis codes are necessary to properly study these systems. Here, we discuss a novel set of 30000 direct N-body simulations of YSCs, including a high binary fraction ($f_b = 0.4$) and clumpy initial conditions.

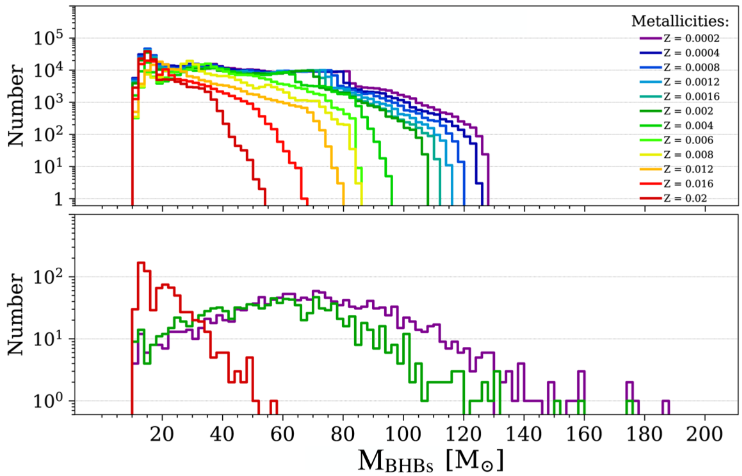

Figure 1. Total mass of BHBs formed from isolated binary simulations (Giacobbo *et al.* 2018a, *top panel*) and from direct N-body simulations (*bottom panel*). Different colors refer to different progenitor's metallicity.

2. Method and Models

We generate each YSC model with fractal initial conditions ($D = 1.6$, Küpper *et al.* 2011), to mimic clumpiness of star forming regions. YSC masses are sampled from a power-law distribution following Lada & Lada (2003), in the range $300 < M < 1000\ M_{\odot}$. The masses of single stars are extracted from a Kroupa IMF with $0.1 < M < 150\ M_{\odot}$. The orbital parameters of binaries are generated following Sana *et al.* (2012). We simulate YSCs with 3 different metallicities: $Z = 0.02$, 0.002 and 0.0002. The simulations were carried out with the code `Nbody6++GPU` (Wang *et al.* 2015), coupled with the population synthesis code `MOBSE` (Giacobbo *et al.* 2018a,b). `MOBSE` is a vigorous upgrade of BSE (Hurley *et al.* 2002), including up−to−date metallicity−dependent prescriptions for stellar winds. We evolve each simulations for 100 Myr (which is approximately the lifetime of small YSCs) including a Solar neighbourhood-like static tidal field. In addition, we simulate a comparison sample of isolated binaries with the stand-alone version of `MOBSE`. See Di Carlo *et al.* (2019) for more details on the simulation codes.

3. Results

Here we discuss the evolution of BHBs in the simulated YSCs and we compare them with the sample of isolated binaries.

BHB population: global evolution

Metal-poor YSCs ($Z = 0.0002$) produce a larger number of BHBs. At $Z = 0.0002$, $\sim$63 % of BHBs form trough dynamical exchanges, while at solar metallicity only $\sim$50 % of BHBs form dynamically. This happens because BHs formed from metal-poor stars can be significantly more massive than BHs originating from metal-rich progenitors, and more massive BHs are more efficient in acquiring companions through dynamical exchanges. We also notice that there is no correlation between the mass of BHBs and the the mass of the host YSC.

BHB population: isolated binaries vs. dynamics

In Fig. 1, we compare the total masses of BHBs formed in YSCs and isolated binaries. Dynamically formed BHBs can have total masses up to $180 - 190\ M_{\odot}$ in metal-poor YSCs, significantly higher than the maximum mass of isolated BHBs ($\sim$130 $M_{\odot}$). This

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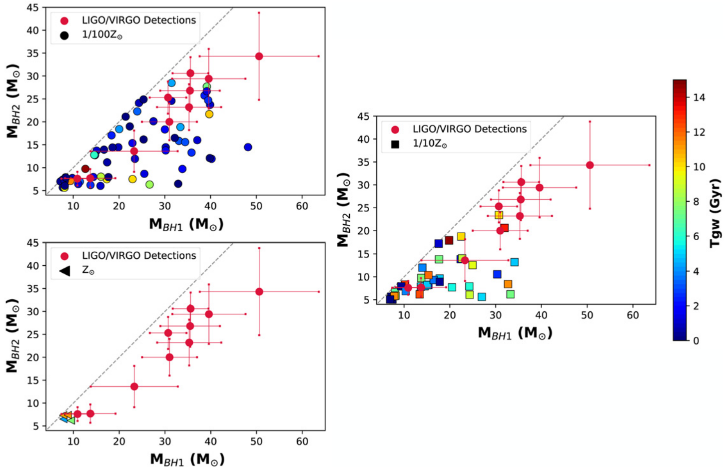

Figure 2. Secondary mass versus primary mass of coalescing BHBs for different progenitor's metallicity. The color-map indicates the delay time (in Gyr) elapsed from the beginning of the simulation to the BHB merger. The red symbols show merging BHBs from the LVC collaboration (Abbott *et al.* 2018) with 90 % credible intervals.

results from the interplay between stellar winds and dynamics: in metal-poor YSCs, where stellar winds are inefficient, dynamical processes can lead to the formation of very massive BHs through multiple stellar collisions and dynamical exchanges allow such massive BHs to pair with other BHs. In contrast, stellar winds are efficient at $Z_\odot$, preventing the formation of massive BHs even in YSCs (Mapelli 2016; Di Carlo *et al.* 2019). In addition, we notice that dynamics suppresses the formation of light BHBs ($M_{\rm BHBs} \lesssim 40$ M$_\odot$) in metal-poor YSCs.

Coalescing BHBs

Fig. 2 focuses on those BHBs that form in YSCs and merge within a Hubble time† At low metallicity coalescing BHBs are significantly more massive (up to ~ 60 M$_\odot$) and tend to merge in a time shorter than 1 Gyr. Metal-rich YSCs produce less (and less massive) merging BHBs than metal-poor YSCs. The average mass ratio of BHBs merging in our N-body simulations is $q \sim 0.7$. Overall, the masses of our simulated BHB mergers match the BHB population observed by the LVC (except for GW170729).

We stress here that these are still preliminary results, based on a fraction of the set of N-body simulations we plan to run (Rastello *et al.*, in preparation). However, our results confirm (Di Carlo *et al.* 2019) that BHBs formed in YSCs are more massive with respect to BHBs formed from isolated binaries.

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† When a BHB escapes from the YSC, we estimate the merger time following Peters (1964).

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