Stellar black hole binary mergers in open clusters

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We study the evolution of a massive primordial hard black hole binary (BHB) in small- and intermediate-size isolated star clusters, modelled as proxies of galactic open clusters (OCs), by means of direct N-body simulations. Some of our models show a significant hardening of the BHB in a relatively short time. Some of them merge within the cluster. The perturbation of stars around BHB systems is key to induce their coalescence. Under our assumptions, we estimate a BHB merger rate of $R_{\rm mrg} \sim 2$ yr^{-1} Gpc^{-3}. In some cases the BHB triggers tidal disruption events which, however, are not linked to the GW emission.

Keywords: Galaxy: open clusters and associations: general – stars: black holes stars: kinematics and dynamics – gravitational waves.

1. Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo have detected five sources of GWs[1–4] corresponding to a system of BHB.

BHBs, can form either (i) in the field in isolation and via stellar evolution of a binary of two extended stars[5] (ii) or via dynamical interactions in a dense stellar system[6,7] Here we focus on the evolution of primordial stellar BHBs in low-mass star clusters. In such models the impulsive effect produced by the stochastic, large, fluctuations of the field felt by stars, whose amplitude over the mean field is of order $\sqrt{N}/N$, can significantly affect the BHB dynamical evolution. This effect is also reflected in the two-body relaxation time scale which is short in such systems if compared for example to globular clusters. In addition, the relatively low number of stars of OCs gives the possibility to integrate the system upon a long evolution time without needing a rescaling of the results.

We shortly resume as follows the methods and results of the recent paper by Rastello et al. (2019).[8]

2. Method and Models

To study the BHB evolution inside its parent cluster, we used `NBODY7`,[9] a direct summation N-body code that integrates in a reliable way the motion of stars in stellar systems, with a careful treatment of strong gravitational encounters, taking also into account stellar evolution. We created four sets of simulations representing OC models at varying initial number of stars (Table 1, column 1). Each cluster is modelled assuming a Kroupa IMF and a Plummer density profile at virial equilibrium with a core radius $r_c = 1$ pc, and solar metallicity ($Z_\odot$). The OCs have masses in the range 300 $M_\odot$ − 3000 $M_\odot$ (Table 1, column 2). For simplicity, we do not take into account primordial binaries. Then we assumed that each cluster host a primordial hard massive BHB composed by two BH of mass $M_{BH} = 30\ M_\odot$ each) that is initially placed in the OC centre. The initial BHB semi major axis is 0.01 pc and we considered two initial eccentricities, $e = 0$ and $e = 0.5$ (Table 1, columns 3 and 4). To give statistical significance to the results we generated 150 different realizations of every model, which are denoted with names A00, A05, B00, B05, C00, C05, D00 and D05, where the letter refers to increasing N and the digits to the initial BHB orbital eccentricity. All models were evolved up to 3 Gyr, which is about 3 times the simulated OC relaxation time.

Table 1. Model main parameters.

N_{cl}	M_{cl} ($M_\odot$)	a(pc)	e	name
512	3.2×10^2	0.01	0.0	A00
			0.5	A05
1024	7.1×10^2	0.01	0.0	B00
			0.5	B05
2048	1.4×10^3	0.01	0.0	C00
			0.5	C05
4096	2.7×10^3	0.01	0.0	D00
			0.5	D05

3. Dynamics of the black hole binary

3.1. *General evolution*

Our simulations show the existence of three main evolutionary scenarios for the fate of the BHB because of the gravitational interactions (Table 2): (i) the binary shrinks, becoming harder; (ii) the BHB gains energy, increasing its semi-major axis and, finally, (iii) the BHB can be disrupted.

We can see that, typically, about 90% of all binaries shrink their semi-major axis as they evolve (Fig. 1), as one can expect upon the so-called *Heggie's law* (softer binaries get softer while hard binaries get harder). In few of the studied cases, typically those of very low dense clusters (model A and B), the BHB becomes wider. Because of the initial choice of the BHB semi-major axis, gravitational encounters with other stars rarely *ionise* it, although we observe a few such events, typically below 7%.[8] This ionisations happen in the interval between ∼ 5Myr and ∼ 100Myr, usually driven by the encounter of the BHB with a massive star ($\gtrsim 10\ M_\odot$).[8]

4. Sources of gravitational waves

4.1. *Relativistic binaries*

The fraction of BHB coalescences in our simulations is ∼ 3%. In particular, in low density clusters, model A and B, the percentage of mergers is quite low,

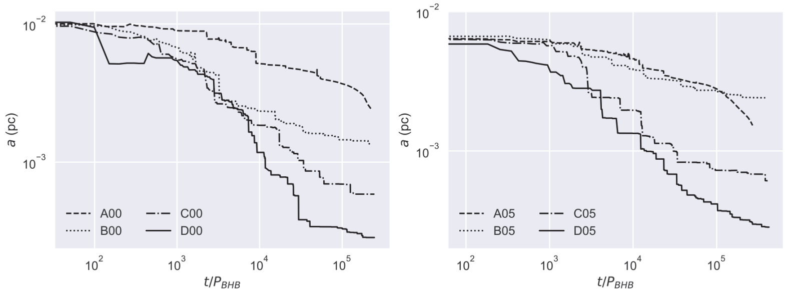

Fig. 1. Semi-major axis evolution in four of our simulations for initially circular and eccentric binaries.

Table 2. Percentage of BHBs (i) getting harder (col. 2); (ii) getting wider (col. 3) or (iii) break up (col. 4).

Model	% Harder	% Wider	% Break up
A00	89.1	7.9	2.9
A05	97.1	2.1	0.7
B00	92.5	2.7	4.8
B05	94.0	2.0	4.0
C00	93.6	0	6.4
C05	96.5	0	3.5
D00	94.2	0	5.8
D05	97.1	0	2.8

around 0.7%. As the mass (and the density) of the cluster increases, the number of relativistic mergers found is larger: 2.1% in model C00, 4.3% in C05 7.1% in D00 and 5.7% in D05. The majority of mergers occur in a time range between 5 Myr and 1.5 Gyr. As shown in Fig. 2, it is remarkable that the pericentre distances drop down to $7-8$ orders of magnitude with respect to the initial value. The eccentricities fluctuate significantly, episodically reaching values very close to unity. We found that about 50% of the mergers are mediated by a three body encounter with a perturber star which is thus a fundamental ingredient for BHB coalescence in low dense star clusters. An example of such mechanism is discussed as follows.

4.1.1. *A detailed example of a merger event*

In order to check with accuracy the process of BHB coalescence upon perturbation, we followed the evolution of one of the allegedly merging BHB by mean of the few-body integrator `ARGdf`.[7] Based on the `ARCHAIN` code,[10] `ARGdf` includes a treatment of dynamical friction effect in the algorithmic regularization scheme, which models at high precision strong gravitational encounters also in a post-Newtonian scheme with terms up to the 2.5 order. We chose, at random, one of our simulations of the D00 sample to set initial conditions for the high precision evolution of a "pre merger" BHB considering its interaction with the closest 50 neighbours, number that we checked as sufficient to give accurate predictions at this regard.

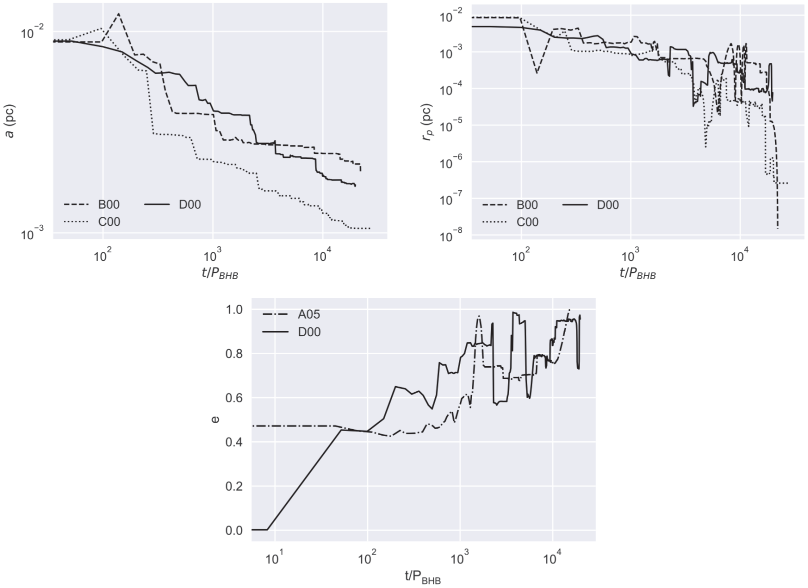

Fig. 2. Time evolution of the BHB semi major axis, pericentric distance, and eccentricity (from left to right, respectively) of some representative coalescence cases.

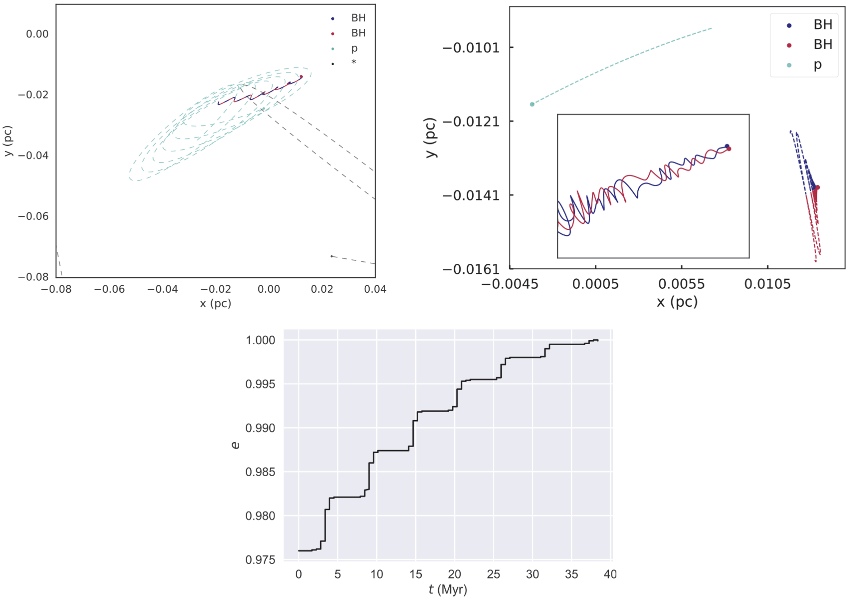

Fig. 3. *Left panel*: triple formation, *right panel*: zoom of the three body interaction, *bottom panel*: BHB eccentricity evolution.

This integration is a clear example of the relevance of dynamical interactions with other stars. Fig. 3 (*left panel*) is a snapshot of the BHB evolution and the formation of a triple system with a perturber star.[a] The BHB shrinks by interacting with such perturber, of mass 3.4 $M_\odot$, which is on a retrograde respect to the inner binary and with an inclination of 105° inducing an eccentric Kozai-Lidov mechanism. We note also a flyby star of mass 0.5 $M_\odot$ which interacts with the triple system (BHB & perturber). In Fig. 3 (*bottom panel*) we display the step-like increase of the BHB eccentricity, which is marked by the repeated interactions with the outer star. At any revolution of the perturber around the BHB we observe a step increasing of the eccentricity. On the contrary, this flyby is not sufficient to make a significant perturbation on the eccentricity evolution. Fig. 3 (*right panel*) sketches the evolution of the BHB latest orbits before the coalescence event. The plot in the rectangle is a zoom of the final part of the BHB trajectory (at its right side), spanning a length $\sim 10^{-7}$ pc. Therefore, in this particular case the triple system built up is the main ingredient that drives the BHB coalescence. A similar result is derived by Ref. 11 for low dense star clusters.

4.2. *Gravitational Waves*

In Fig. 4 we show the amplitude vs frequency of emitted gravitational waves for the case described in. 4.1.1 Using the last orbital parameters of the binary which correspond to the last integration made with `ARGdf`, we derive a coalescence time $T_{\rm mrg} \cong 7\,$yrs. We have set the luminosity distance to that of the first source detected by LIGO,[1] which corresponds to a redshift of about $z = 0.11$. As described by the work of Chen & Amaro-Seoane (2017),[12] only circular sources are audible by LISA, which is "deaf" to eccentric binaries of stellar-mass black holes that emit their maximum power at frequencies farther away from LISA. Hence, this particular source would only enter the Advanced LIGO detection band.

4.3. *Merger Rate*

We estimate the merger rate following the prescription in Rastello et al., 2019[8], Sec. 4.5, Eq. (3) and Eq. (4). Assuming the total number of OCs in our Galaxy and the number of Milky way-like galaxies within redshift z = 1, we obtain a merger rate $\mathcal{R}_{\rm mrg} \approx 2{\rm Gpc}^{-3}\,{\rm yr}^{-1}$.

This estimate is however derived under the most favourable conditions, and thus represents the highest merger rate expected from low-mass OCs. Note that the BHB merger rate inferred from the first LIGO observations (GW150914) is in the range 2 - 600 $\rm Gpc^{-3}\ yr^{-1}$.[13] Our BHB merger rate is consistent with those found in Refs. 11, 14, 15 for BHB mergers in Young Massive Star Clusters. Although BHB mergers originating in open clusters-like systems might be less numerous than those

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[a] An animation of the triple orbit and the eccentricity evolution is available at `https://youtu.be/zk8waNtubLk`.

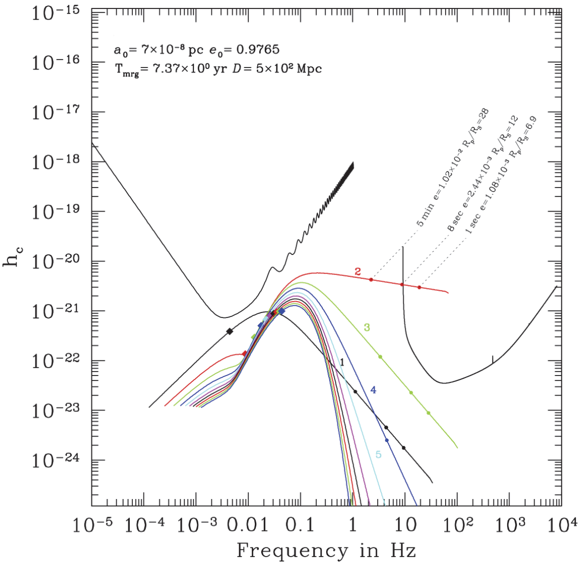

Fig. 4. Characteristic amplitude h_c of the first most important harmonics for the model of described in Sec. 4.1.1 at a luminosity distance of $D = 500$ Mpc.

produced in massive star clusters, they would add a comparable amount to the BHB merger rate in the Universe because of their larger abundance.[11,15,16]

4.4. *Tidal Disruption Events*

As a serendipity outcome in our simulations, we found that in a few cases, the BHB disruption is mediated by a star, which binds to one of the two BHB former components.[8] The newly formed BH-star pair is characterized by a high eccentricity ($e > 0.9$) and a pericentre sufficiently small to rip the star apart and give rise to a tidal disruption event (TDE). Such events are however not linked to the BHB coalescence. In our models, TDEs involve either main sequence stars (MS), stars in the core He burning phase (HB) or in the early asymptotic giant branch (AGB) phase. Indeed, a component swap occurs in 28.5% of the cases, with the new companion star being swallowed by the heavier BH. Our findings suggest that X-ray or UV emission from OCs can be the signature of the presence of BHs with masses as high as 20 – 30 M_⊙. Following the indications in Ref. 8 we found a TDE rate of $\Gamma_{\rm TDE} = 0.3 - 3.07 \times 10^{-6}{\rm yr}^{-1}$ per MW-like galaxies in the local Universe.

5. Conclusions

We studied the evolution of a primordial massive black hole binary in low density star clusters, and we derived that: (i) in $\sim$ 95% of the simulations performed, the BHB hardens (its semi-major axis reduces by 2 to 4 orders of magnitude) due to the repeated scatterings with flyby stars, while its eccentricity increases significantly. This process takes place on a relatively short time-scale, ~ 1 Gyr; (ii) in $\sim 1.2\%$ of the cases, instead, the perturbations induced by massive stars that occasionally approach the BHB make it wider; (iii) in the remaining $\sim 4.8\%$ cases, the interactions with OC stars are sufficiently strong to break up the BHB.

In $\sim 3\%$ of the models, the star-BHB interactions are sufficiently effective to drive the BHB coalescence within a Hubble time. We find that a crucial ingredient to induce the BHB to merge is the interaction with a perturbing star, whose individual action considerably shortens the merger time. In our simulations, we see mergers take place in a time ranging from 5 Myr to 2.9 Gyr. In a few cases, the merging binaries emit GWs from the 10^{-3} to the 10 Hz frequency band. This suggests that merging BHBs in OCs can, potentially, be seen both by LISA, ~ 200 yr before the merger, and LIGO, during the last phase preceding the merger.

Extrapolating our results to the typical population of OCs in MW-like galaxies in the local Universe, we found that the most optimistic merger rate for this type of BHB mergers in low-mass stellar systems is $\mathcal{R}_{\rm mrg} \sim 2\ {\rm yr}^{-1}\ {\rm Gpc}^{-3}$, a value compatible with the rate expected for galactic nuclei, but smaller than that inferred for globular clusters and young massive clusters.

Finally, we found that tidal disruption events in OCs would occur at a rate $\Gamma_{\rm TDE} = 3.08 \times 10^{-6}\ {\rm yr}^{-1}$ per MW-like galaxies in the local Universe.[8]

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