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Intermediate-Mass Black Holes in binary rich star clusters

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Abstract. Three-body interactions of stellar-mass binaries with intermediate mass black holes (IMBHs) in nuclei of globular clusters may produce specific features that may serve as an independent indicator of existence of the IMBHs. By means of direct N-body integrations we follow the dynamical evolution of globular clusters of moderate extension and mass with 50% binary population over a time span of $\approx 0.8\,\mathrm{Gyr}$ and compare the cases with and without the primordial binaries as well as with and without the IMBH. We show that (i) presence of the IMBH leads to rapid formation of a density cusp regardless of the initial binary fraction, (ii) binary rich clusters with the IMBH produce high velocity escapers at a rate of $\approx 0.1\,\mathrm{Myr}^{-1}$ and (iii) clusters hosting an IMBH together with high number of binaries form a denser halo of marginally unbound stars than clusters that lack either the IMBH or the binary population.

Keywords. stellar dynamics, globular clusters: general, binaries: general, methods: n-body simulations

1. Introduction

Intermediate-mass black holes represent an open question of contemporary astrophysics. While being assumed to reside in nuclei of (preferably globular) star clusters in various theoretical considerations, incontrovertable observational evidence for their existence is still missing. In this situation, theoretical predictions of possible indirect indicators of the presence of IMBHs in star clusters are of great value. This contribution aims to investigate how the putative IMBH would interact with the cluster binary population. In particular, we expect to see the process of tidal separation of binaries passing close to the IMBH in act. We refer to it as the Hills mechanism, as it was first investigated in detail by Hills (1988) and proposed as a source of hyper-velocity stars ejected from nuclei of galaxies due to the interaction of stellar binaries with a supermassive black hole. The typical outcome of such an interaction, which may be directly rescaled to the environment of nuclei of star cluster hosting an IMBH, is one component of the binary being ejected out of the cluster with velocities up to the order of $1000\,\mathrm{km\,s^{-1}}$ (in the case of the galactic nucleus) while the other star becomes tightly bound to the massive body (Šubr *et al.* 2019).

2. Numerical models

For the purpose of studying processes indicated above in a computationally manageable full N-body treatment, we constructed a reference model named BH-BIN with following key features:

• total mass of the cluster is $M_{\mathsf{c}} \approx 20000\,M_{\odot}$, initial half-mass radius $R_{\mathsf{h}} \approx 3\,\mathrm{pc}$ and its density follows the Plummer (1911) profile

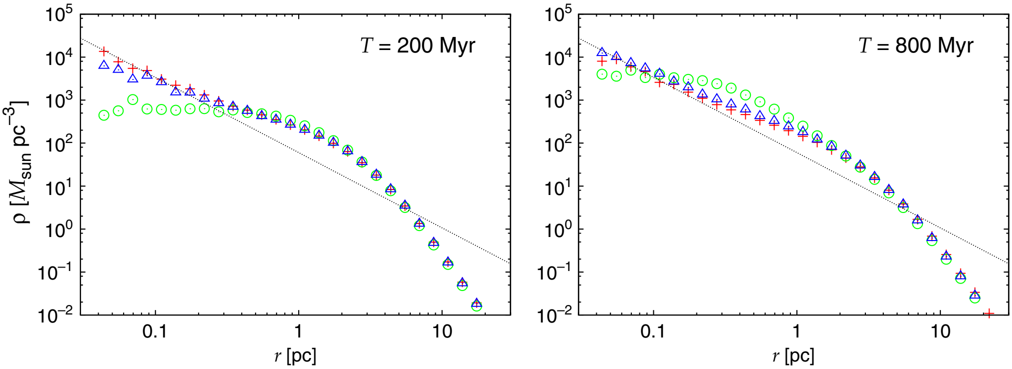

Figure 1. Radial density profiles of the three models of star clusters at two different stages of dynamical evolution. The red, blue and green symbols correspond to models BH-BIN, BH and BIN, respectively. The thin dotted line depicts the Bahcall & Wolf (1976) power-law profile. The initial state can be inferred from the profile of BIN at $T = 200$ Myr which is practically unevolved at that time.

• the major phase of stellar evolution is already over, i.e., the cluster consists of 44500 main sequence stars, $0.1\,M_\odot < M_\star < 1\,M_\odot$, following the Kroupa (2001) initial mass function, 5500 compact remnants (WD, NS, BH) all of them of mass $M_\star = 1\,M_\odot$ and a single IMBH of a mass of $M_{\rm IMBH} = 1000\,M_\odot$

• binary fraction is 50%; the period distribution of binaries is from Duquennoy & Mayor (1991)

In order to clearly distinguish the role of mutual interaction of stellar binaries with the IMBH on the cluster evolution, we further investigated two additional models: one named BH with zero initial binary fraction and another, named BIN, without the IMBH but with primordial binaries (except for the initial binary fraction and presence of the IMBH, all other properties are identical to that of the reference model).

For each model, we integrated seven realisations with different initial conditions, but with identical global parameters. The results presented below are based on averages of the seven integrations of each model that were carried out up to $T = 0.8$ Gyr. As a numerical integrator, we used NBODY6 code (Aarseth 2003).

3. Overall cluster evolution

Even though being placed at a random position initially, the IMBH sinks to the cluster centre on the crossing time-scale (which is of the order of 1 Myr). A power-law stellar cusp starts to build up immediately around it. Its density profile very soon approaches the Bahcall & Wolf (1976) solution, $\rho(r) \propto r^{-7/4}$ (Fig. 1). As time proceeds, the cusp slightly grows in extent. Nevertheless, no more than several tens of stars are on average within the sphere of influence of the IMBH even at the end of the integrations. The overall radial density profile as well as velocity distribution are practically the same for both models hosting the IMBH (BH-BIN and BH). This means that the binaries do not play an important role in the cluster overall evolution. Even the stars being captured on tightly bound orbits around the IMBH due to the Hills mechanism do not contribute significantly to the subsystem of tightly bound stars so that they can produce some characteristic pattern. Clusters without the IMBH (model BIN), evolve considerably slower. However, they also tend to develop a power-law density profile at larger scales and later times as they proceed towards core-collapse (see the right panel of Fig. 1).

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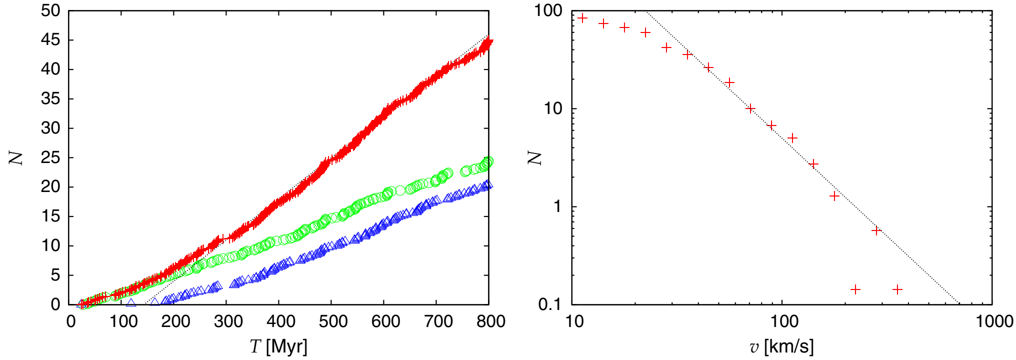

Figure 2. Left: cumulative distribution of HVSs escaping with velocity above $50\,\mathrm{km\,s^{-1}}$. The red, green and blue symbols correspond to all stars, main-sequence stars and compact objects, respectively. The thin dotted line indicates escape rate of 7 stars per 100 Myr. Right: Number counts of escaping stars in logarithmically equal-width velocity bins. The thin dotted line indicates function $N \propto v^{-2}$ which corresponds to the distribution given by eq. (4.1).

4. High velocity escapers

In model BH-BIN, we found a considerable number of stars ejected out of the cluster with velocities exceeding several tens of $\mathrm{km\,s^{-1}}$, i.e., well above what is expected from two-body relaxation in this setup. The distribution of escaping stars in the time and velocity domain can be well approximated for $v_{\rm esc} \gtrsim 30\,\mathrm{km\,s^{-1}}$ with an empirical formula,

$$\frac{\mathrm{d}N_{\rm hvs}}{\mathrm{d}v_{\rm esc}\,\mathrm{d}t} \approx 350 \left(\frac{v_{\rm esc}}{\mathrm{km\,s^{-1}}} \right)^{-3} \left(\mathrm{km\,s^{-1}} \right)^{-1} \mathrm{Myr}^{-1} \tag{4.1}$$

which, e.g., gives $N_{\sf hvs}(v_{\rm esc} > 50\,\mathrm{km\,s^{-1}}) \approx 7/100\,\mathrm{Myr}$ (see Fig. 2).

Even though the main output from the integrator which stores positions and velocities of all stars (bodies) at equidistant time steps is too sparse to allow detailed tracking of passages of binaries around the IMBH, analysis of the regularisation logs indicated that all stars that were ejected with high velocities interacted with the IMBH shortly before it. Another indicator that it is, indeed, the Hills mechanism which acts as the accelerator is the fact that other models (BH and BIN) ejected on average less than one star with velocity above $30\,\mathrm{km\,s^{-1}}$ per run. In both of them, some component (either stellar binary or massive BH) needed for the Hills mechanism to operate is missing. At later stages ($\gtrsim 200$ Myr), the ejection rates of compact remnants is comparable to that of the main-sequence stars even though the first group is by a factor of ≈ 8 less numerous. This is a clear indication of mass-segregation taking place on that time-scale.

Let us also note that velocity of the ejected star is increasing with increasing binding energy of the incoming binary (Hills 1988; Perets & Šubr 2012). Consequently, the velocity distribution of the ejected stars is given (beside other influences) by the distribution of the semi-major axes of the binaries in the cluster. A larger abundance of tightly bound binaries would lead to a larger number of high-velocity escapers.

5. Low velocity escapers

The Hills mechanism has been originally proposed as a source of high velocity stars $100\,\mathrm{km\,s^{-1}} \lesssim v_{\rm esc} \lesssim 1000\,\mathrm{km\,s^{-1}}$ and a similar focus can be found in the previous section. The process of tidal separation of a binary in the tidal field of a massive body, however, may operate at different scales. Less energetic binaries which separate further away from the IMBH undergo qualitatively the same scenario. The only difference is a lower ejection velocity in comparison to more tightly bound binaries. Still, the kinetic energy gain of

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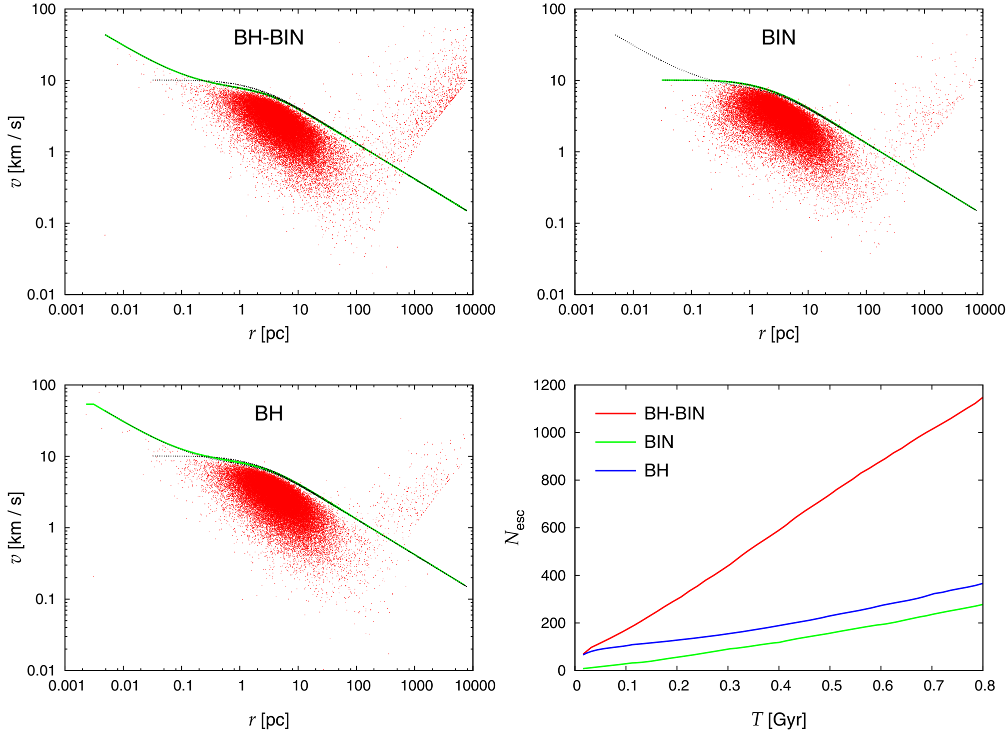

Figure 3. Positions of all stars from arbitrarily chosen realisations of all three models of star clusters in the r–v space at the end of integration ($T = 0.8$ Gyr). The green lines indicate escape velocity limit estimates for each case. Bottom right panel shows temporal evolution of the number of star above the escape velocity limit.

one of the stars may be sufficient for it to cross the escape velocity limit and to be ejected out from the star cluster. In accord with expectations, Figure 3 shows that model BH-BIN has considerably enhanced evaporation rate in comparison to models BH and BIN.

This indicates a possibility that, beside the relatively rare high velocity escapers, an enriched halo of marginally unbound stars may serve as an indicator of an IMBH residing in the cluster core. This straightforward idea, however needs further examination as halos of real star clusters are, among other things, affected by the galactic tidal field which is not present in our current models. In the more realistic setup, the evaporation rate will be supported by the tidal stripping which may mask the effect described here.

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