

Effects of Stellar-Mass Black Holes on Massive Star Cluster Evolution

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Abstract. Recent observations have revealed the existence of stellar mass black hole (BH) candidates in some globular clusters (GC) in the Milky Way and in other galaxies. Given that the detection of BHs is challenging, these detections likely indicate the existence of large populations of BHs in these clusters. This is in direct contrast to the past understanding that at most a handful of BHs may remain in old GCs due to quick mass segregation and rapid mutual dynamical ejection. Modern realistic star-by-star numerical simulations suggest that the retention fraction of BHs is typically much higher than what was previously thought. The BH dynamics near the cluster center leads to dynamical formation of new binaries and dynamical ejections, and acts as a persistent and significant energy source for these clusters. We have started exploring effects of BHs on the global evolution and survival of star clusters. We find that the evolution as well as survival of massive star clusters can critically depend on the details of the initial assumptions related to BH formation physics, such as natal kick distribution, and the initial stellar mass function (IMF). In this article we will present our latest results.

Keywords. black hole physics—stellar dynamics—methods: n-body simulations—methods: numerical—globular clusters: general—kinematics and dynamics—galaxies: star clusters

1. Introduction

Massive star clusters, such as the GCs in the Milky Way (MW) and other galaxies are expected to form large numbers of BHs simply as a consequence of the IMF and the large initial numbers of stars (N) they are born with. What happens to these BHs after formation, due to a combination of BH formation physics, such as birth-kicks in supernova (SN), and overall dynamical evolution of the host cluster is a long standing unsolved question.

Following the classic work by Spitzer (1969), it was argued that the BHs, being more massive compared to typical cluster stars, will mass segregate on $\lesssim 10^2$ Myr timescales and form a compact subcluster that is dynamically decoupled from the rest of the cluster. Due to the small size, high density, and low (compared to the whole cluster) number of stars in this subcluster, frequent strong scattering interactions would eject most BHs from the cluster on \sim Gyr timescales. As a result the old GCs were expected to contain at most a few BHs at their current old ages (Kulkarni *et al.* 1993, Sigurdsson *et al.* 1993, Portegies Zwart & McMillan 2000, Kalogera *et al.* 2004). This understanding gained popularity because prior to 2012 all observed luminous X-ray sources (XRB) in the MW GCs were accreting neutron stars (NS; e.g., van Zyl *et al.* 2004, Lewin & van der Klis 2006, Altamirano *et al.* 2010, Altamirano *et al.* 2012, Bozzo *et al.* 2011), consistent with no bound accreting BHs in today's GCs.

This classical picture started to change with recent discoveries of candidate BHs in extragalactic as well as MW GCs (Maccarone *et al.* 2007, Irwin *et al.* 2010, Strader *et al.* 2012, Chomiuk *et al.* 2013). Interestingly, the GCs in the MW that contain the detected BH candidates, show large ranges in structural properties, indicating that presence of BHs in today's GCs may not be uncommon in general. Modern star-by-star, multi-physics simulations also find that BH ejection is not nearly as efficient as was previously thought. The primary reason for this difference compared to the earlier understanding comes from the fact that the BH subclusters do not stay decoupled from the rest of the cluster for prolonged periods. The same interactions that dynamically eject BHs from the cluster, also expands the subcluster and the subcluster again dynamically couples with the rest of the cluster (Breen & Heggie 2013, Morscher *et al.* 2015). As a result, the evaporation timescale for the BH subcluster increases dramatically, and even the old GCs may contain hundreds to thousands of BHs today. These simulations also find that only a small fraction of the bound BHs are binaries with one BH and one non-BH components. Thus, only a few such objects may become observable XRBs even when the actual number of bound BHs is high. Factoring in also the typical low duty cycles for these sources (Kalogera *et al.* 2004), detection of just a few BH candidates likely indicates the existence of a much larger number of BHs in these clusters (e.g., Strader *et al.* 2012; Umbreit 2012; Morscher *et al.* 2013, 2015).

In this article, we will focus on the effects of a large number of retained BHs on the global evolution of the host cluster. All past models usually made several initial assumptions related to the details of the BH-formation physics, and the IMF. Several of these so called standard assumptions are actually not well constrained from observations. We will explore the effects of changing some of these assumptions, namely the natal kick distribution for BHs, and the slope of the IMF ($dn/dM \propto M^{-\alpha_1}$) for high-mass stars ($M > 1 M_\odot$) on the global evolution of the star cluster. In § 2 we describe our numerical setup and assumptions. In § 3 we present our key results. Finally, in § 4 we conclude.

2. Numerical Models

We use a Hénon-type Monte Carlo code (Hénon 1971), CMC, developed and rigorously tested by Northwestern University's cluster dynamics group over the past decade (most recently, Fregeau & Rasio 2007; Chatterjee *et al.* 2010, 2013; Umbreit *et al.* 2012; Patabiraman *et al.* 2013). We follow the initial assumptions of Morscher *et al.* (2015) for our standard model (we call it **S**). This model initially contains $N = 8 \times 10^5$ stars, and overall binary fraction $f_b = 0.05$. The initial positions and velocities of the objects (single stars and center of mass of the binary stars) according to a King profile with $w_0 = 5$ (King 1962, 1965). The initial virial radius $r_v = 2$ pc. The cluster is at a galacto-centric distance $r_{GC} = 8$ kpc. The primary masses are chosen from an IMF presented in Kroupa (2001) for cluster stars between 0.1 to $100 M_\odot$. We adopt their middle values for the slopes in all mass ranges for **S**. The secondary masses are chosen assuming a uniform mass-ratio distribution between the primary mass and $0.1 M_\odot$. Initial binary periods (P) are drawn from a uniform distribution in $\log P$, between 5 times the sum of the stellar radii to the initial local hard-soft boundary. Eccentricities are thermal. We choose metallicity $Z = 0.001$. Single and binary stellar evolution is done using SSE and BSE (Hurley *et al.* 2000, 2002), updated to implement custom natal kicks for the NSs and BHs. All NSs are assumed to receive natal kicks drawn from a Maxwellian distribution with $\sigma_{NS} = 265 \text{ km s}^{-1}$. We adopt a momentum-conserving kick prescription for the BHs, where the kick magnitude is calculated by first drawing from the same Maxwellian as the NSs, but then scaling this velocity by the fallback fraction (Fryer & Kalogera 2001, Belczynski *et al.* 2002).

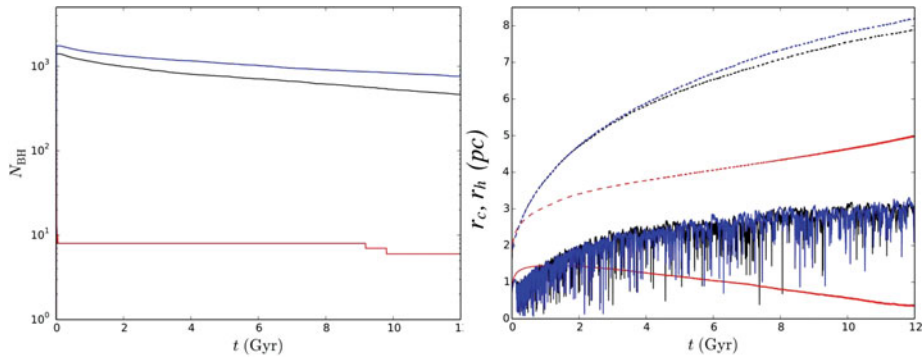


Figure 1. Evolution of the number of bound BHs in the cluster (left), and their structural properties, r_c , and r_h (right), for models S (black), K1 (red), and K0.1 (blue). The solid and dotted lines on the right panel denote r_c and r_h , respectively, for each model.

For example, if fallback fraction is $x_{\text{FB}} = 1$, i.e., no mass is lost during SN, the kick magnitude is zero.

While it is widely accepted that the NSs receive large natal kicks, the distribution of natal kicks for BHs is not well constrained either via observations or via theory. Detailed analysis of kick distributions of individual BH X-ray binaries result in widely varying constraints on kick velocities between these systems (e.g., Brandt *et al.* 1995; Nelemans *et al.* 1999; Willems *et al.* 2005; Gualandris *et al.* 2005; Dhawan *et al.* 2007; Fragos *et al.* 2009; Wong *et al.* 2012, 2014). On the other hand, recently, Repetto *et al.* (2012) suggested that the position offsets of the BH XRBs from the Galactic plane indicates that the natal kicks from BHs can be as high as NSs. Furthermore, they found that there is no clear correlation between the BH mass and its inferred kick magnitude, which would be expected if they all received momentum-conserving natal kicks based on x_{FB} . Modeling of core-collapse SN by Pejcha & Thompson (2015) also suggests that the natal kicks are not related in a simple way to the mass of the BHs. Clearly, the issue of natal kicks for BHs is far from settled. We simulate three additional models by changing our initial assumptions of the natal kick distribution for the BHs. In these models we assume that the natal kicks for the BHs are not mass-dependent. Instead, they receive kicks from a Maxwellian with $\sigma_{\text{BH}} = f \times \sigma_{\text{NS}}$, where f is a constant scaling fraction. We simulate two models with $f = 1$ and 0.1, and call these models K1 and K0.1, respectively. All other assumptions are exactly the same as in S.

The choice of IMF, especially α_1 , significantly affect the relative abundance of the high-mass stars, and as a result, the number of BHs a cluster with some given initial N would form. While, the middle values for the slopes presented in Kroupa (2001) are commonly adopted for most simulations, they have large 1σ errorbars, e.g., $\alpha_1 = 2.3 \pm 0.7$. We simulate two other models by changing α_1 to 1.6 and 3, and call these models I-1.6 and I-3, respectively. Our model S of course already adopts $\alpha_1 = 2.3$.

3. Results

In our model S, $\approx 2 \times 10^3$ BHs are initially formed. The BHs drive repeated core-collapse episodes (Fig. 1). The core re-expands via dynamical binary formation as well as BH ejections due to strong gravitational scattering encounters involving binaries. However, BH ejections are not nearly as efficient as what was previously suggested (Spitzer 1969). Based on the x_{FB} -dependent, momentum-conserving kicks adopted in model S, about 400 BHs remain bound to the cluster at integration stopping time $t = 12$ Gyr. This result is

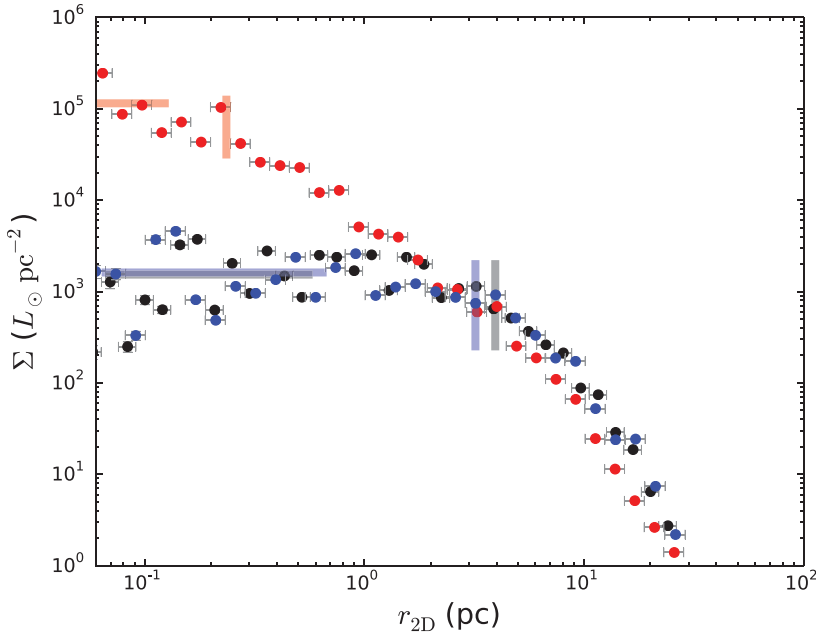


Figure 2. Surface brightness profiles at $t = 12$ Gyr for models **S** (black), **K0.1** (blue), and **K1** (red). The horizontal and vertical lines show the central density, and $r_{c,obs}$ according to the best-fit King profile. The surface brightness profile for **K1**, where most of the BHs were ejected due to large natal kicks, show a power-law rise of the density, typical of the so-called core-collapsed GCs in the MW. In contrast, the surface brightness profiles indicate rather large and low-density clusters for **S**, and **K0.1**, where large numbers of BHs are retained until $t = 12$ Gyr.

in agreement with other recent star cluster models (e.g., Breen & Heggie 2013; Morscher *et al.* 2015). The evolution of our model **K0.1** is very similar to **S**, except, **K0.1** retains just shy of 10^3 BHs at $t = 12$ Gyr.

We find that the distribution of natal kicks for the BHs can have a dramatic effect on the overall evolution of the host cluster. If the BHs receive kicks as large as the NSs, as is the case for our model **K1**, only ≈ 6 BHs are retained in the cluster at late times. Most of the BHs are ejected from the cluster simply because of the kicks received during formation. Dynamical ejections at late times are insignificant. As a result, model **K1**'s overall evolution is dramatically different from **S** and **K0.1**. In this case, since not many BHs are retained, the BH-driven core-collapse episodes are unseen. In absence of the BH-driven energy source at the cluster center, r_c starts contracting after about 1 Gyr. In comparison, r_c keeps expanding until integration stopping time of $t = 12$ Gyr due to BH-mediated energy production at the cluster core for models **S**, and **K0.1**.

The observable properties of the clusters are also significantly affected due to the difference in assumptions for the distribution of the BHs' natal kicks. For example, the surface brightness profiles (SBP) models **S** and **K0.1** would indicate a rather puffy and low-density cluster, whereas, the SBP for model **K0.1** would indicate a high-density core-collapsed cluster (Fig. 2). The only difference between the models is the persistent presence of the additional energy source from the hundreds of retained BHs in models **S** and **K0.1**, which is absent in model **K1**. Models **S** and **K0.1** show central surface luminosity densities ($\Sigma_{c,obs}$) between 10^3 to $2 \times 10^3 L_\odot \text{pc}^{-2}$. The best-fit King core radii for these models are $r_{c,obs} \approx 4$, and 3 pc , respectively. In contrast, the surface luminosity density profile for model **K1** show a power-law rise, typical of the core-collapse MW GCs

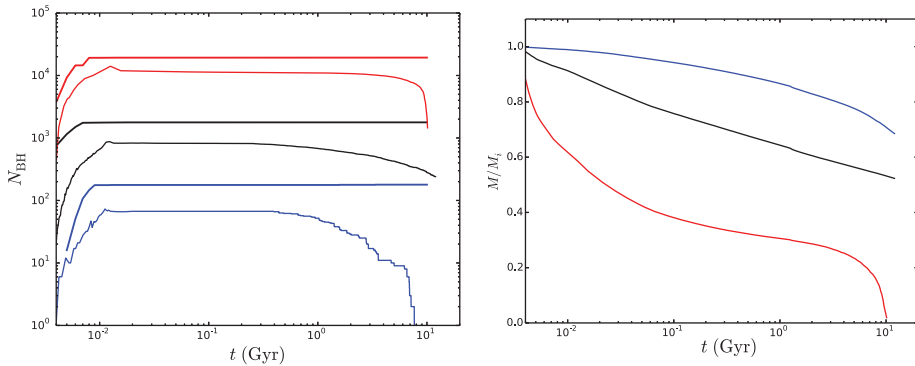


Figure 3. Left: Total number of BHs produced (thick lines) and retained (thin lines) in models I-1.6 (red), S (black), and I-3 (blue) as a function of cluster age. Right: Evolution of the cluster mass scaled by the initial mass of the cluster for models I-1.6 (red), S (black), and I-3 (blue). The model with the flat IMF slope, I-1.6, forms an order of magnitude higher number of BHs and dissolves within ~ 8 Gyr.

(e.g., Chatterjee *et al.* 2013). For K0.1, $\Sigma_{c,\text{obs}} \sim 8 \times 10^4 L_{\odot} \text{ pc}^{-2}$, and $r_{c,\text{obs}} = 0.2 \text{ pc}$. The half-light radii for models S, K0.1, and K1 are $r_{\text{hl}} = 5.5, 3.4$, and 2.5 pc , respectively.

Similar to the distribution in natal kicks for the BHs, the IMF for high-mass stars also significantly affect the evolution of the clusters. Model I-1.6, with an adopted $\alpha_1 = 1.6$ (see §2) forms $\sim 2 \times 10^4$ BHs, almost an order of magnitude more than in model S. The high amount of mass loss from stellar winds, compact object formation from the much higher number of high-mass stars, as well as the efficient energy source from the large number of BHs at the cluster's center leads to an eventual dissolution of this cluster after about 8 Gyr (Fig. 3). This is consistent with the predictions of the classic study by Chernoff & Weinberg (1990). We also find that a model with such a flat IMF for high-mass stars would always dissolve, no matter how low the BH natal kicks are. However, significantly different and lower wind mass loss (e.g, Vink *et al.* 2001) may result in clusters that survive longer. In model I-3, only about 200 BHs are formed. All of these BHs are ejected from the cluster within 8 Gyr. Devoid of bound BHs, r_c of model I-3 starts decreasing. At 12 Gyr, for I-3, $r_{\text{hl}} = 1.2 \text{ pc}$, $r_{c,\text{obs}} = 0.15 \text{ pc}$, and central surface density is $4 \times 10^5 L_{\odot} \text{ pc}^{-2}$.

4. Discussion

In this article we report results from an ongoing study that investigates the effects of the initial assumptions related to BHs on the overall evolution of the host cluster. Here we present results from two types of variations from a standard model that adopts commonly assumed initial properties. We change the distribution of natal kicks for the BHs and find that starting from clusters that are otherwise identical, variations in this assumption can dramatically alter the evolution of the cluster. For example, if the BHs receive birth kicks as large as the NSs, most BHs are ejected from the cluster and the cluster, at 12 Gyr, appears as a dense core-collapsed GC. On the other hand, if the BHs do not receive large natal kicks, hundreds of BHs may remain bound to the cluster till 12 Gyr, however, in these cases, the resulting cluster appears as puffy, low-density GCs.

Similar to the natal kicks, the power-law index of the IMF for stellar mass $M > 1 M_{\odot}$, α_1 , plays a crucial role in determining the fate of a star cluster. We find that adopting $\alpha_1 = 1.6$, which is within the reported 1σ errors presented in Kroupa (2001), results in

clusters that dissolve within ~ 8 Gyr (model I-1.6). For $\alpha_1 = 2.3$ (the middle value of the Kroupa 2001 IMF; S), the cluster, at 12 Gyr appears to be puffy, with a large r_c and low $\Sigma_{c,obs}$. For $\alpha_1 = 3$, (1σ upper limit in Kroupa 2001; I-3), the cluster with otherwise identical initial properties, attain properties similar to the core-collapsed GCs in the MW.

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