

Which Globular Clusters contain Intermediate-mass Black Holes?

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ABSTRACT

It has been assumed that intermediate-mass black holes (IMBHs) in globular clusters can only reside in the most centrally concentrated clusters, with a so-called ‘core-collapsed’ density profile. While this would be a natural guess, it is in fact wrong. We have followed the evolution of star clusters containing IMBHs with masses between $125 \leq M_{BH} \leq 1000 M_{\odot}$ through detailed N -body simulations, and we find that a cluster with an IMBH appears to have a relatively large ‘core’ in projection, with surface brightness only slightly rising toward the center. This makes it highly unlikely that any of ‘core-collapsed’ clusters will harbor an IMBH. On the contrary, the places to look for an IMBH are those clusters that can be fitted well by medium-concentration King models.

The velocity dispersion of the visible stars in a globular cluster with an IMBH is nearly constant well inside the apparent core radius. For a cluster of mass M_C containing an IMBH of mass M_{BH} , the influence of the IMBH becomes significant only at a fraction $2.5M_{BH}/M_C$ of the half-mass radius, deep within the core, where it will affect only a small number of stars. In conclusion, observational detection of an IMBH may be possible, but will be challenging.

Subject headings: black hole physics—globular clusters—methods: N-body simulations—stellar dynamics

1. Introduction

Over the last few years, four lines of evidence have accumulated pointing to the possible presence of a $\sim 10^3 M_{\odot}$ black hole in some globular clusters. The first hint follows from an extrapolation of the $M_{bh}-M_{bulge}$ relation found for super-massive black holes in galactic nuclei (Magorrian et al. 1998), which leads to a prediction of a typical central black hole mass $\sim 10^3 M_{\odot}$ for globular clusters (Kormendy & Richstone 1995). The empirical $M_{bh} - M_C$ relation also comes out naturally from rapid mass segregation and the Spitzer instability applied to a standard IMF in young, dense star clusters (Gürkan et al. 2004).

The second hint is related to the discovery of a new class of ultra-luminous, compact X-ray sources (ULXs). Their high luminosities and

strong variability suggest that they are IMBHs, rather than binaries containing a normal stellar-mass black hole, and they may occur preferentially in young star clusters (Zezas et al. 2002).

The third hint stems from an analysis of the central velocity dispersions of specific globular clusters. Gerssen et al. (2002, 2003) and Gebhardt et al. (2002) have published evidence for black holes in M15 and G1 with masses of order of 10^3 and $10^4 M_{\odot}$, respectively (since M31’s G1 is an order of magnitude more massive than typical globular clusters in our galaxy, both values fall on the $M_{bh}-M_{bulge}$ relation).

The fourth hint is based on detailed N -body simulations by Portegies Zwart et al. (2004) of the evolution of a young (~ 10 Myrs) star cluster in M82, the position of which coincides with an ULX with luminosity $L > 10^{40}$ ergs/sec. They found that runaway merging of massive stars could have led to the formation of an IMBH of $\sim 10^3 M_{\odot}$. Since globular clusters in their youth may have resembled this type of star cluster, it is altogether likely that at least some globulars harbor IMBHs.

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None of these four hints in itself carries enough weight to be convincing. Given our lack of understanding of the formation process of globulars, there is no strong reason to expect the $M_{bh}-M_{bulge}$ relation to carry over to globular clusters. ULXs may just be unusual forms of X-ray binaries containing a massive but still stellar-mass black hole. The velocity dispersion profiles of M15 and G1 can be reproduced by simulations without central black holes (Baumgardt et al. 2003a,b). Still, the fact that the four arguments are so different in character does suggest that we have to take the possible existence of IMBHs very seriously.

The question arises: which globular clusters contain IMBHs? The intuitive answer would be: clusters with a steep central luminosity profile, both because a higher density might suggest an easier formation of a large black hole, and because such a black hole could be expected to draw more stars inward.

The main message of this letter is: both of these arguments are wrong. Since the most plausible formation scenario of an IMBH is run-away merging in the first 10^7 years after the formation of a cluster, dynamical relaxation makes a comparison with current conditions irrelevant, and thus invalidates the first intuitive argument. More importantly, dynamical N -body simulations reported in this paper clearly show that the second intuitive argument is false as well. We find that IMBHs, whenever they are formed, quickly puff up the core to a size far larger than that of the so-called ‘core collapsed’ clusters. In fact, we show that globular clusters with IMBHs have the appearance of normal King model clusters, except in the central regions. We discuss the observational implications in section 4, after describing our simulation methods in section 2 and our numerical results in section 3.

2. Modeling Method

The reason why clusters with unresolved cores have been the primary candidate for harboring an IMBH is that there should be a density cusp with $\rho \propto r^{-7/4}$ around the black hole. The formation of such a cusp was first predicted by Bahcall & Wolf (1976) and later confirmed by numerical simulations (Cohn & Kulsrud 1978; Marchant & Shapiro 1980; Baumgardt, Makino & Ebisuzaki 2004a).

The projected density profile therefore should have a cusp with slope $-3/4$.

A cusp in density, however, does not necessarily imply the existence of a cusp in luminosity, since there is no guarantee that M/L is constant. Quite the contrary, numerical simulations of core collapse have demonstrated that in post-core-collapse clusters M/L shows a sharp rise toward the center: neutron stars and heavy white dwarfs dominate the central regions as a result of mass segregation (Baumgardt et al. 2003a). A similar rise in M/L must exist in the density cusp around an IMBH.

In previous studies, Baumgardt, Makino & Ebisuzaki (2004a,b) have followed the evolution of star clusters with central black holes with masses of 1 to 10% of the cluster mass. They found a distinct density cusp around the central black hole, but no clear luminosity cusp, since the central cusp is dominated by remnant stars. The projected luminosity profile was effectively flat at the center, and the evolved clusters looked just like normal King clusters. Unfortunately, the black hole mass used in Baumgardt, Makino & Ebisuzaki (2004b) was too large to allow a direct comparison with observations of globular clusters. In this letter, we report the results of new simulations, starting with a more realistic central black hole with a mass of 0.1 to 1% of the total cluster mass.

The set-up of our runs is similar to that of the runs made by Baumgardt, Makino & Ebisuzaki (2004a,b) and we refer the reader to these papers for a detailed description. We simulated the evolution of star clusters using the collisional N -body program NBODY4 (Aarseth 1999) on the GRAPE-6 computers at Tokyo University. Our simulations include two-body relaxation, stellar evolution and the tidal disruption of stars by the central black hole. Initially no binaries were present in our models. Each cluster started with a spectrum of stellar masses between 0.1 and $30 M_{\odot}$, distributed according to a Kroupa (2001) mass-function, and massive central black holes initially at rest at the cluster center. Stellar evolution was modeled according to the fitting formulae of Hurley et al. (2000), assuming a retention fraction of neutron stars of 15%. Simulations were run for $T = 12$ Gyrs.

If the $M_{bh}-M_{bulge}$ relation found by Magorrian et al. (1998) for galactic nuclei holds for globular clusters as well, the mass expected for the central

Table 1: Results of the N -body runs.

M_{BH} [M_{\odot}]	N	W_0	R_{Hi} [pc]	M_{Cf} [M_{\odot}]	R_{Hf} [pc]	R_{HP} [pc]	R_C [pc]	R_C/R_{HP}	$\lg T_{RH}$ [yrs]
125	65536	5	2.03	21451.3	10.12	4.14	0.55	0.13	9.54
125	65536	9	2.03	21749.6	12.34	6.20	0.65	0.11	9.67
125	131072	7	4.91	45534.8	12.31	5.98	0.81	0.14	9.82
250	131072	7	4.91	45311.2	12.60	6.46	0.71	0.11	9.84
500	131072	7	4.91	44771.1	13.70	7.76	0.64	0.08	9.89
1000	131072	7	4.91	45300.4	14.07	7.96	0.58	0.08	9.91

black hole in an average globular cluster of mass $M = 1.5 \cdot 10^5 M_{\odot}$ would be around $1000 M_{\odot}$. Black hole masses of 10^3 to $3 \cdot 10^3 M_{\odot}$ were also found as the end-result of runaway merging of massive stars in the dense star cluster MGG-11 by Portegies Zwart et al. (2004), although their values are likely to be upper limits since stellar mass-loss of the runaway star was not included.

Since it is not yet possible to perform a full N -body simulation of a massive globular cluster over a Hubble time, we have to scale down our simulations. Scaling down can be achieved by simulating either a smaller- N cluster while keeping the mass of the central black hole unchanged, as done by Baumgardt, Makino & Ebisuzaki (2004b), or by scaling down the black hole mass and the cluster mass simultaneously while keeping the ratio of both constant. The first method has the advantage that the ratio of black hole to stellar mass is the same as in a real cluster, while the second method is most suitable to compare the final velocity and density profile of a star cluster with observations. In the present paper we decided to employ both strategies and made several runs of star clusters containing $N = 65536$ (64K) and $N = 131.072$ (128K) cluster stars, and central black holes with masses of $M_{BH} = 125, 250, 500$ and $1000 M_{\odot}$ respectively. For a $N = 128K$ star clusters the final cluster mass is around $M_C = 45.000 M_{\odot}$, so a cluster with a $250 M_{\odot}$ IMBH would follow the Magorrian et al. (1998) relation.

The results of our runs are listed in Table 1 which gives, respectively, the mass of the black hole, the initial number of cluster stars, the initial depth of the central potential, the initial half-mass radius, the final cluster mass, the final half-mass radius, the projected final half-light radius, the final core radius, the ratio of the last two quantities,

and the logarithm of the final half-mass relaxation time (Spitzer 1987):

$$T_{rh} = 0.138 \frac{\sqrt{M_C} R_H^{3/2}}{\langle m \rangle \sqrt{G} \ln \Lambda} , \quad (1)$$

where $\langle m \rangle$ is the mean mass of all stars in the cluster and $\ln \Lambda$ is the Coulomb logarithm and is of order 10. The core radius was determined as the radius where the surface density has dropped to half its central value.

3. Results

3.1. Density profile

We first discuss the density profile of a cluster with an IMBH after it has evolved for a Hubble time. Portegies Zwart & McMillan (2002) and Rasio et al. (2004) have shown that a globular cluster has to start with a short enough central relaxation time to form an IMBH by runaway merging of main-sequence stars. Specific examples have been provided by Portegies Zwart et al. (2004), who found that the star cluster MGG-11 in the starburst galaxy M82, which has a mass of $3.5 \cdot 10^5 M_{\odot}$ and an initial half-mass radius of $R_H = 1.2$ pc, could have formed an IMBH while in the slightly larger cluster MGG-9 with a half-mass radius of $R_H = 2.6$ pc, the time for spiral-in of heavy mass stars was already too long and no runaway merging occurred. In order to study the dynamical evolution of clusters concentrated enough to form IMBHs, we first simulated two $N = 64K$ clusters starting with a 3D half-mass radius of $R_H = 2.0$ pc. These clusters have half-mass relaxation times equal to MGG-11. Both clusters start with black holes of $125 M_{\odot}$, in agreement with the Magorrian relation. Since the initial density profile could in principle influence the final density profile and the

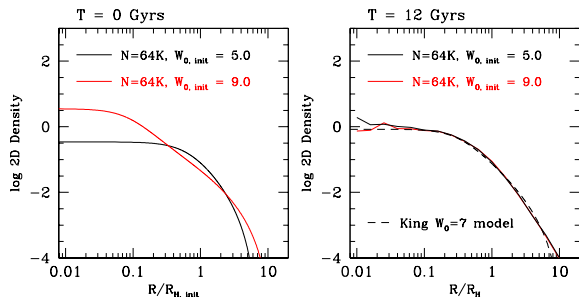


Fig. 1.— 2D density profile of bright stars for two $N = 64K$ clusters starting with half-mass radii of $r_h = 2.0$ pc but different values for the initial central potential W_0 . The initial relaxation time was short enough that both clusters expanded by a factor $R_H \sim 5 R_{H,init}$ and evolved toward the same density profile after a Hubble time.

dynamical evolution of the cluster, we simulated two clusters starting from a King $W_0 = 5$ and a higher concentration $W_0 = 9$ model respectively.

Fig. 1 depicts the projected density profile of bright stars in both clusters at the start of the simulations and after a Hubble time. We defined bright stars to be all giants and all main-sequence stars with masses larger than 90% of the mass of turn-off stars. In order to improve statistics, we overlaid 10 snapshots spaced by 50 Myrs and centered at 12 Gyrs. Although initially quite different, the density profiles have become virtually indistinguishable after a Hubble time. The reason is that both clusters have expanded strongly: the final half-mass radii are about 5 to 6 times larger than the initial ones, and the expansion has erased the initial profile.

As shown in the right panel, this density profile can be fitted rather well by a King $W_0 = 7$ model in the range $0.1 \leq R/R_H \leq 5$. Inside $R/R_H = 0.1$, there is some indication that the clusters have developed a weak cusp.

In order to improve statistics for the inner parts, it was necessary to add more particles to the simulation. We have simulated a set of $N = 128K$ clusters, containing a range of IMBH masses between $125M_\odot \leq M_{BH} \leq 1000M_\odot$. The starting density profile was chosen to be a King $W_0 = 7$ model, close to the equilibrium profile found above. These calculations are quite challenging: the total amount of computing time used is well

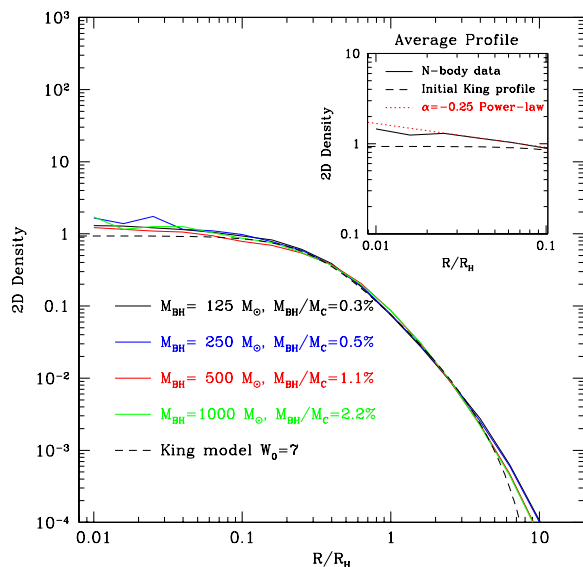


Fig. 2.— Projected density distribution of bright stars after $T = 12$ Gyrs for four clusters containing black holes between $125 \leq M_{BH} \leq 1000M_\odot$ and $N = 128K$ stars. All clusters can be fitted by profiles where the density is equal to a King $W_0 = 7$ model outside $R = 0.1R_H$, followed by a density increase in the inner parts. The profiles in the inner parts are nearly the same for all models. The inset shows the average profile of all N -body runs. Between $0.01 < R/R_H < 0.1$, it can be fitted by a power-law with slope $\alpha = -0.25$. This is significantly flatter than the value found for galactic core-collapsed clusters, $\alpha = -0.8$.

over 10^{19} floating point operations and was only possible through the use of the GRAPE-6 system in the astronomy department of Tokyo University.

Figure 2 depicts the projected density distribution of bright stars after the cluster evolution was simulated for 12 Gyrs. Between $0.1 < R/R_H < 3$, the final profiles can be fitted by King $W_0 = 7$ profiles, and by almost-flat power-law profiles $\rho \sim r^\alpha$ inside $R/R_H = 0.1$. The measured slopes α lie between -0.1 and -0.3 for the different models, with no clear trend with the mass of the central black hole. The mean profile of all models has a slope of $\alpha = -0.25$ (see inset). A look at the projected profiles of other stars shows that the heavy mass stars, i.e. the heaviest white dwarfs and neutron stars, follow significantly steeper slopes near -0.5 , reflecting their strong mass segregation.

According to Noyola & Gebhardt (2004), slopes of the central surface brightness profiles of galactic globular clusters span a range of values between constant density core models and models with steep cusps up to $\alpha = -0.8$. The latter value would correspond to the luminosity profile expected for a cluster in core-collapse (Baumgardt et al. 2003a). The above results show that core-collapse density profiles are too steep for clusters which contain IMBHs, but that several clusters in the list from Noyola & Gebhardt (2004) have slopes compatible with the assumptions that they contain IMBHs. We will come back to this point in section 4.

3.2. Velocity dispersion profile

We next discuss the chances of detecting an IMBH through observations of the radial velocity or proper motion profiles of a star cluster. The dots in Fig. 3 show the projected velocity dispersion profile for four $N = 128K$ star clusters. The lines show the predicted profiles calculated from Jeans equation under the assumption that the velocity dispersion is isotropic, using as input the potential from the black hole and the cluster stars. These predictions form a very good fit to the N -body data, including the region where the influence of the black hole begins to dominate that of the stars, an effect that becomes stronger with increasing black hole mass.

Eqs. 2 and 3 of Baumgardt, Makino & Ebisuzaki (2004a) predict a linear relation between the radius R where the stellar velocity dispersion is affected more by the IMBH than by the stars alone: $R/R_H = \gamma M_{BH}/M_C$, where M_C is the cluster mass. The results in Fig. 3 are compatible with this relation and give $\gamma \approx 2.5$. The error bars in Fig. 3 show the statistical error for a star cluster containing $5 \cdot 10^5$ stars and in which the brightest 5% of all stars can be observed in the center. For the cluster with the lowest mass black hole, the black hole dominates only at radii $R < 0.005R_H$ corresponding to radii of $R < 0.5$ arcsec for a typical globular cluster. There are too few stars inside this radius, so the velocity error is too large to discern between the black hole and the no black hole case. IMBHs with masses $M_{BH}/M_C < 0.3\%$ can therefore not be detected by radial velocity measurements in star clusters. For the cluster with a $M_{BH} = 250M_\odot$ black hole, the detection

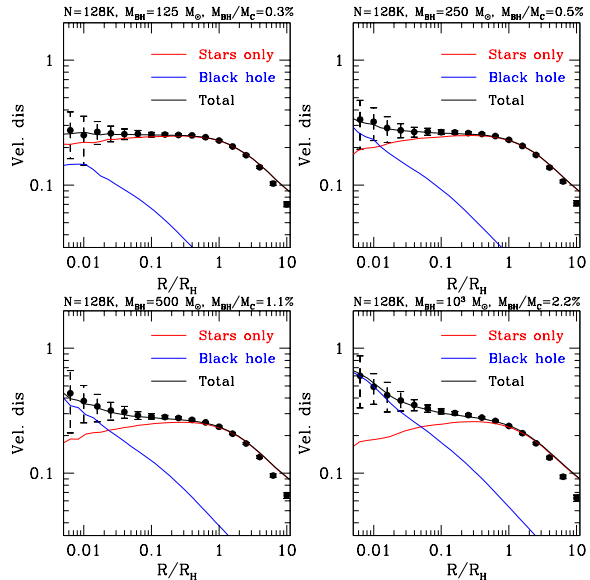


Fig. 3.— Velocity dispersion profiles for four cluster simulations that started with $N = 128K$ stars and $M = 125, 250, 500$ and $1000M_\odot$ black holes. Filled circles with error bars are the velocity dispersion of visible stars in the N -body runs. The influence of the central black hole grows with increasing mass. Also shown are estimates for observational error bars for a cluster with $5 \cdot 10^5$ stars in which the brightest 5% of all stars can be observed all the way into the center.

might be possible at the 2σ level and higher mass black holes might be detected even under less favorable conditions. Nevertheless, even the largest simulated IMBH with $1000 M_\odot$, which has a mass significantly above the Magorrian et al. relation, creates a central rise that is hardly significant if only the brightest cluster stars can be observed. Observational detection of an IMBH in a star cluster will therefore be a challenging task.

4. Galactic globular cluster candidates

In this section we will compare the projected density profile of bright stars in our simulations with the observed central surface brightness profiles of galactic globular clusters. Noyola & Gebhardt (2004) have determined surface brightness profiles for 37 globular clusters from previously published HST WFPC2 images. They found that the slopes of central surface brightness profiles fol-

Table 2: GC candidates which could contain IMBHs from the list of Noyola & Gebhardt (2004)

Name	Central Slope	$\log M_C$ [M_\odot]	R_{HP} [pc]	R_C [pc]	R_C/R_{HP}	c	$\log T_{rh}$ [yrs]
NGC 5286	-0.20 ± 0.02	5.67	2.44	0.18	0.08	1.46	9.72
NGC 5694	-0.21 ± 0.10	5.35	3.28	0.34	0.10	1.84	9.76
NGC 6093	-0.13 ± 0.04	5.51	1.89	0.24	0.13	1.95	9.48
NGC 6266	-0.15 ± 0.04	5.90	1.92	0.20	0.08	1.70	9.68
NGC 6388	-0.14 ± 0.03	5.99	1.53	0.20	0.10	1.70	9.58

low a range of values, from 0 (i.e. flat cores) to -0.8 . As was shown in section 3.1, the most promising candidate clusters for IMBHs have central surface brightness slopes of -0.25 and outer profiles that can be fitted by King models with $W_0 = 7$, corresponding to a concentration parameter $c = 1.5$. Slightly different values for W_0 and c might be possible if the tidal field plays an important role and removes stars in the halo.

Table 2 lists all clusters whose profiles are compatible with a central slope between -0.2 and -0.3 and incompatible with a flat core from the list of Noyola & Gebhardt (2004). Not shown are NGC 5824, 6397 and 6541 since their central slopes are rather steep and their concentrations c are more compatible with core-collapsed clusters and NGC 6715 which has a half-mass relaxation rather long compared to what our clusters reach after a Hubble time. Table 2 lists the central concentration c , the projected half-light radii as given by Trager et al. (1995) and the core radii as determined by Noyola & Gebhardt (2004), transformed into physical units with the cluster distances from Harris (1996). The final column gives the half-mass relaxation times, calculated from the cluster masses and the half-light radii, assuming that the (3D-)half-mass radius is twice as large as the (2D-)half-light radius. This is approximately the case in our runs. It can be seen that the central slopes, the ratio of the core to the half-light radius and the relaxation times are in good agreement of what we would predict for a cluster with an IMBH, making them good candidates for clusters with IMBHs.

5. Conclusions

We have followed the evolution of star clusters containing central IMBHs with masses $125 \leq M_{BH} \leq 1000 M_\odot$. All clusters show a final density profile corresponding to a King $W_0 = 7$ model

outside the cluster core. Inside the core, the projected distribution of bright stars is almost flat, with only a weak rise toward the center in the form of a power-law of slope $\alpha \sim -0.25$. We conclude that the luminosity profiles of several galactic globular clusters are in good agreement with the assumption that they contain IMBHs.

A definite detection of an IMBH in a globular cluster can only be made through observations of the velocity dispersion profile of stars deep within the core, since the radius where the influence of the black hole dominates over the cluster stars is given by $R/R_H = 2.5 M_{BH}/M_C$. This radius is an order of magnitude smaller than the core radius, if the IMBH mass follows the Magorrian relation. About 25 stars would have to be observed inside this radius to detect the black hole at a 2σ -level.

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