No. ________

国立天文台 天文学データ解析計算センター
成果報告書 (平成 17 年度)

提出期限：平成 18 年 3 月 20 日 (月)17:00 必着

応募カテゴリ（いずれかを選択）　C
システム（いずれかを選択）　GRAPE

プロジェクト ID: g04c04

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研究課題名

(和文)	高密度星団中での中質量ブラックホール形成に対する質量分離の効果
(英文)	The Effect of Mass Segregation on the Formation of Intermediate Massive Black Holes in Dense Star Clusters

研究分担者

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成果に関連して出版、もしくは印刷、投稿中の論文リスト

(1) このプロジェクト（同様の過去のプロジェクトも含む）での成果
　今年度中に出版された論文、国際会議集録、国際会議、学会、研究会発表、その他出版物（印刷中、投稿中の場合はその旨を記載すること）
Domestic conference :

- Ardi, E., Baumgardt, H., Mineshige, S. Formation of intermediate mass black holes in low central-density clusters with mass segregation. Spring Annual Meeting of Astronomical Society of Japan, Wakayama, March 27-29, 2006 (on schedule)

(2) これまでのプロジェクトの今年度中の成果
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Journal :

- Ardi, E., Spurzem, R., Mineshige, S. Dynamical evolution of rotating single-mass stellar cluster. JKAS 38, 207 (2005)
- Trenti, M., Ardi, E., Mineshige, S., Hut, P. Primordial binaries and intermediate mass black holes in globular clusters. Submitted to ApJ (astro-ph/0508517)
- Stephanie, P., Ardi, E. Effects of stellar mass distribution on dynamical evolution of star clusters. Journal Mathematics and Sciences - ITB Indonesia (in preparation)

International conference :

- Ardi, E., Spurzem, R., Mineshige, S. N-body simulations for rotating globular clusters. The 9-th Asian-Pacific Regional IAU Meeting, Bali - Indonesia, July 26-29, 2005

成果の概要

(必要に応じてページを加えて下さい。)
Written in separate papers :

- Ardi, E., Baumgardt, H., Mineshige, S. Could intermediate mass black holes form in low central-density clusters with mass segregation ? (2006)

Could intermediate mass black holes form in low central-density clusters with mass segregation ?

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ABSTRACT

We investigated the effect of mass segregation within dense star clusters, that, in coupling with initial concentration of clusters, could lead to formation of IMBH through runaway merging. The evolutions of multiple-mass dense star clusters have been followed by direct N-body simulations of up to 131072 stars until 3 Myrs. Mass of stars was distributed according to the Salpeter IMF.

A wide variety of initial cluster models are considered, including initial mass segregation and initial concentration. Initial mass segregation was realized by varying the minimum mass within a certain lagrangian radius of the initial mass function, as well as by changing the lagrangian radius within which the initial mass segregation takes place. In this present study, we examined cluster models with central potential of W_0 = 3.0,5.0,7.0,and 9.0.

We found that, without mass segregation, runaway merging could not happen in clusters with central potential less than $W_0 = 9$, which is in agreement with Portegies Zwart et al. (2004). Taking into account the effect of mass segregation, we found that clusters with central potential $W_0 = 7$ or less indeed show runaway mergings which produce IMBH up to $\approx 3300\ M_\odot$.

Subject headings: stellar dynamics — globular clusters: general — methods: n-body simulations

1. Introduction

Recent progress of observations by Chandra and Hubble Space Telescope has supported the idea that some star clusters could harbor a central black hole (BH). Discovery of an ultra-luminous X-ray source in the center of M82, which corresponds to a BH with a minimum mass of 700 solar masses (Matsumoto et al. 2001; Kaaret et al. 2001) -if the source is not

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beamed and accretes at the Eddington rate - could be a first hint for the existence of so called intermediate-mass black holes (IMBH). IMBH bridge the gap between stellar-mass black holes which form as the end-product of normal stellar evolution and the supermassive black holes observed at the centers of galaxies. Detection of existence of IMBHs has been reported also for M15 and G1 (Gerssen et al. 2003; Gebhardt et al. 2002, 2005), although numerical models of Baumgardt et al. (2003) showed that both M15 and G1 can be obtained without a central BH.

Hence how IMBHs can form is still an open question. Ebisuzaki et al. (2001) proposed a first scenario of IMBH formation of IMBH through successive merging of massive stars in dense star clusters. Dense star clusters whose stellar mass segregation is faster than stellar evolution of massive stars, those massive stars sink into the center of the cluster by dynamical friction and form a dense inner core. In this inner core massive stars undergo a runaway stellar merging and a very massive star forms with a mass exceeding 100 solar masses. This very massive star eventually collapses into a BH, which continues to grow by swallowing nearby massive stars.

Direct N-body simulations of up to 65536 stars by Portegies Zwart & McMillan (2002) showed that runaway merging could bring the most massive stars grow to a super massive star with mass up to 0.1% of cluster total mass before manifest itself to IMBH.

Portegies Zwart et al. (2004) found that the dense star cluster MGG-11, in which the ULX in M82 is located, can form an IMBH if its initial central concentration was high enough. An initial concentration $\geq W_0 = 9.0$ was required for runaway growth through collisions to form an IMBH. Unfortunately, such a high concentration leads to a central density $\rho \geq 10^6 M_\odot/pc^3$ which is very rarely found in star clusters today.

One possible condition which allow the runaway collision occurs in a lower central density cluster is the existence of initial mass segregation. As initial mass segregation allows the massive stars to start their life near to the cluster center, we would expect to reduce the time which is needed to bring the massive stars to sink to the cluster center rather than through natural mass segregation.

Some observational evidence for initial mass segregation in globular clusters as well as in the open cluster were reported by Bonnell & Davies (1998); Raboud & Mermilliod (1998); de Grijs et al. (2004). The tendency for massive stars to be formed preferentially near the cluster center is expected as a result from star formation feedback in dense gas cloud (Murray & Lin 1996) and from competitive gas accretion onto protostars and merger between them (Bonnell et al. 2001; Bonnell & Bate 2002).

In this project we examine if initial mass segregation could lower the density required for runaway collisions. Initial mass segregation within a cluster could decrease the dynamical friction time scale and increase the chances for collisions between stars. Both things would increase the chances for the formation of an IMBH through runaway collisions of massive stars. Therefore, there is the possibility that initial mass segregation within a cluster could lead to runaway formation even if the central concentration of the cluster is not as high as found necessary by Portegies Zwart et al. (2004). If our prediction is right, this would have important consequences since then the formation of IMBHs could happen in a much larger number of star clusters.

In order to seek the answer of a challenging question written on the title of this paper, we manage simulations with various initial conditions which are addressed in the next section. Results of these simulations are given in Section 3 while the discussion is presented on section 4. Finally we conclude our work on section 5.

2. Numerical simulations:

We investigate the effect of mass segregation within dense star clusters, that, in coupling with initial concentration of clusters could lead to formation of IMBH. For this purpose, we conduct N-body simulations using the program NBODY4 (Aarseth, 1999) to follow the evolution of multiple-mass dense star clusters until 3 Myrs. The direct N-body simulations of up to 131072 stars are performed on the GRAPE-6 special purposes computer provided by ADAC-NAO Japan.

A wide variety of initial cluster models are considered, including initial mass segregation and initial concentration. In this present study, we examine the evolution of cluster models with central potential $W_0 = 3.0,5.0,7.0,9.0$.

Mass of stars m within a cluster is distributed according to the Salpeter IMF

$$m(X) = m_{min}\Big\{1 + X\Big(\Big(\frac{m_{max}}{m_{min}}\Big)^{1-\alpha} - 1\Big)\Big\}^{1/(1-\alpha)} \quad (1)$$

Here m_{min} and m_{max} are minimum and maximum mass respectively, α is the IMF slope and X is a random number between 0 and 1.

The mass-function of normal star clusters is given by a Salpeter mass-function between 1.0 $M_\odot$ and 100 $M_\odot$. This IMF is applied for King model clusters with central concentration $W_0 = 9.0$ until $W_0 = 3.0$. Table 1 presents detail models of clusters without initial mass segregation.

In order to examine the effect of initial mass segregation, we variate the minimum mass m_{min} within a certain lagrangian radius of the cluster. Since we are interested to find out the critical conditions to set on the runaway merger, here the initial mass segregation is considered starting from an extreme case when the cluster center within the lagrangian radius 0.05 contains massive stars between 10 $M_\odot$ – 100 $M_\odot$. Detail models of various initial mass segregation are given in table 2.

We keep the density within the 5% lagrangian radius R_{005} to be the same for all cluster with same W_0. Therefore increasing the minimum mass m_{min} within a certain shell i.e. from 1 $M_\odot$ for normal cluster to a higher mass for cluster with initial mass segregation will consequently decrease the number of star within that shell. The number of stars within each cluster is presented in the second column of table 1 and table 2.

The evolution of all clusters is followed until 3 Myr, the typical time scale when the super massive star explodes as a supernova and evolves to BH (Portegies Zwart et al. 2004).

We report the conditions under which runaway collision of stars can occur, including the time needed for the IMBH formation and the mass of the IMBH which can be form, also the rate of collision.

3. Results

3.1. Cluster without mass segregation

We arrange simulations of 4 cluster models which initially having mass spans from 1 until 100 $M_\odot$ distributed according to the Salpeter IMF, without initial mass segregation. Each of the cluster contains 131072 stars. They represent clusters with different central potential W_0, as shown in the first column of table 1. Third column of that table shows that cluster with higher central potential has smaller 5% lagrangian radius (R_{005}).

As expected for cluster with mass spectrum, dynamical friction works efficiently to bring massive stars sink to the cluster center. Figure 1 shows a massive star of $W_0 = 9.0$ cluster, which later becomes a runaway star, sinks into the core. This massive star initially having 72 $M_\odot$. It sinks into the cluster center in about 0.5 Myr.

Dynamical friction is characterized by a time scale t_{df} (Spitzer & Hart 1971)

$$t_{df} = \frac{< m >}{M*} \frac{0.138N}{ln(0.11M/M*)} \left(\frac{R^3}{GM} \right)^{1/2}. \qquad (2)$$

Here $< m >$ is the mean stellar mass, $M*$ is the mass of the massive star, N is the number of star within the cluster, M is the total mass of cluster, R and G are half-mass radius and gravitational constant respectively. Under this time scale a massive star in a roughly circular orbit sinks to the cluster center.

We find that the dynamical friction time for a 100 $M_\odot$ star in $W_0 = 9.0$ cluster is about 3 Myrs in agreement with MGG-11 cluster simulated by citetpor04.

Once the massive star falls into the core, density of the core increases. This core collapse occurs soon after that as shown in figure 2. Here core collapse happened at t $\approx$ 0.7 Myr. Inner shells which contain less than 0.04 of total mass contract during the core collapse, while outer shells slowly expand after that.

The collapse of the cluster core may initiate physical collision between stars. First collision is likely occurs among the most massive stars in the cluster core. If the center density of the cluster is high enough, the massive star is therefore experience subsequent collision, resulting in a collision runaway (Portegies Zwart et al. 1999; Portegies Zwart & McMillan 2002). The runaway star grows into a supper massive star.

Our simulations of four models of clusters without initial mass segregation report that only one dense star cluster (N=131072) with highest central concentration ($W_0 = 9.0$) indeed experiences the runaway stellar merging. Some of massive stars within lower density clusters experience collisions but none of them experiences subsequent collisions which leads to a supper massive star.

As shown at table 1, within its inner core, the massive stars of $W_0 = 9.0$ cluster undergo a runaway stellar merging started on 0.54 Myr and a very massive star form with a mass exceeding 2800 $M_\odot$.

Figure 3 depicts increasing of the mean mass of the inner shells of the $W_0 = 9.0$ cluster. Mean mass of the inner most shell increases so much as a result of increasing mass of the very massive star in the cluster center by runaway merging.

The growth of the very massive star in the cluster center is presented in figure 4. The very massive star which initially having mass less than 100 $M_\odot$ grows through runaway stellar merging until its mass exceeds 2800 $M_\odot$. This supper massive star finally collapses into an IMBH within 3 Myrs.

3.2. Clusters with initial mass segregation

As shown in table 2, we examine seven models of clusters with initial mass segregation. They represent clusters with central concentration $W_0 = 3.0, 5.0$ and 7.0. We let the deep inner shells, which is the 5 % lagrangian radius (R_{005}), to be filled with massive stars whose mass is higher or equal than the mass written on the fourth column of table 2.

Initial mass segregation allows massive stars start their life near the cluster center. Therefore the time needed for them to sink to the core becomes shorter. Consequently core collapse happens earlier. In figure 5 we present evolution of lagrangian radius of a $W_0 = 7.0$ cluster with initial mass segregation : its 5 % lagrangian radius is filled by massive stars with minimum mass 30 $M_\odot$. Core collapse occurs around $t \approx 0.2$ Myr in this cluster. Comparing to figure 2 we see that initial mass segregation in a lower concentration cluster ($W_0 = 7.0$ cluster) could bring the cluster to collapse earlier than in a higher concentration cluster ($W_0 = 9.0$ cluster).

The early core collapse consequently bring the cluster to relax earlier. A characteristic time scale that measure the degree of relaxation occurring in the central parts of the cluster is the central relaxation time t_{cr}. The central relaxation time is defined as

$$t_{cr} = \frac{\sigma_{3D}^3}{4.88\pi G^2 (\ln 0.11N) n < m >^2} \tag{3}$$

where σ, n and $< m >$ are the three-dimensional velocity dispersion, number density and average of stellar mass at the cluster center (Spitzer 1987).

By consider the 5 % lagrangian radius as the cluster center, we calculate the central relaxation time. The results are given in the column 7 of tables 1 and 2. Comparing clusters with same central concentration, we see that initial mass segregation indeed decreases the central relaxation time of the clusters. The heavier the massive stars within the cluster center, the shorter the t_{cr} is.

3.3. Criteria for runaway mergers

The existence of initial mass segregation within a cluster would decrease its central relaxation time. However, table 2 shows that initial mass segregation does not always allow occurring the runaway mergers of massive stars. As an example, although initial mass segregation is present, runaway mergers could not occurs within $W_0 = 3.0$ cluster. Density within the core has an important role to start the subsequent stellar collisions. Table 2 reports that unless the cluster central concentration higher or equal than $W_0 = 5.0$, the initial mass segregation has no impact to produce IMBH through runaway mergers. Therefore we propose two criteria which allow the process of runaway mergers happens: the central relaxation time and the central density of the clusters. Initial mass segregation would lower the central relaxation time or accelerate the core collapse but in the same time high central density is needed as a trigger of occurring runaway collisions. Considering clusters without and with initial mass segregation, our results in tables 1 and 2 show that IMBH would be form through runaway mergers of stars if physical parameters of clusters satisfy both criteria : logarithmic of the central relaxation time in Myr is ≤ 2.92 and logarithmic of the central density is $\geq 5.90\ M_{\odot}/pc^3$.

4. Conclusions

Our simulations show a good agreement with Portegies Zwart et al. (2004) that central concentration $W_0 \geq 9.0$ is required for runaway merger to form IMBH. However, by taking into account the effects of initial mass segregation, we found that IMBH formation could happen in clusters where the central concentration is much smaller. If initial mass segregation is present, this limit can be significantly reduced down to $W_0 = 5.0$, but only if the core filled with massive stars higher than 50 $M_{\odot}$. This brings important consequences since then the formation of IMBHs could happen in a much larger number of star clusters.

Initial mass segregation within the cluster decreases the central relaxation time and increases the number of collisions between stars. Both things increase the chances for the formation of an IMBH through runaway mergers of massive stars. Our simulations propose that IMBH could be form through runaway mergers within a dense star cluster whose satisfy both criteria that its logarithmic of the central relaxation time in Myr is ≤ 2.92 and logarithmic of the central density is $\geq 5.90\ M_{\odot}/pc^3$. However, IMBH could not be form through runaway collisions of stars within very low density clusters $W_0 \leq 3.0$ although initial mass segregation exists.

This work is supported in part by the Grants-in-Aid of the Ministry of Education, Science, Culture, and Sport,(14079205; EA, SM). Numerical simulations have been done using GRAPE-6 machine provided by Astronomical Data Analysis Center, National Astronomical Observatory, Japan.

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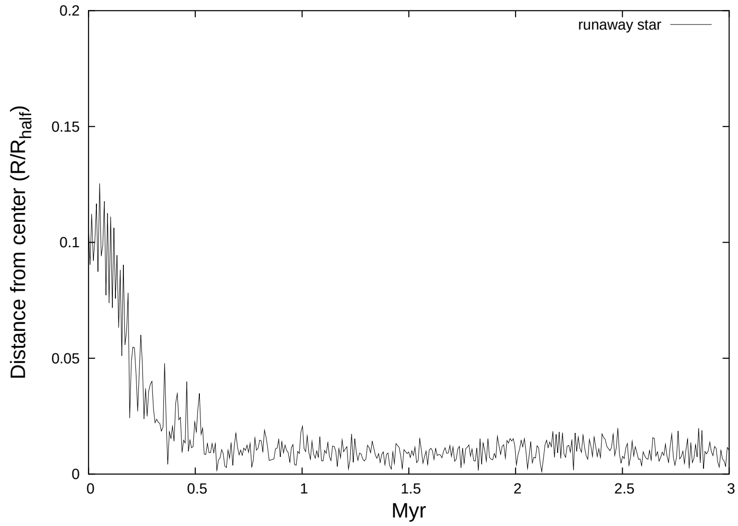

Fig. 1.— The evolution of the distance of the very massive star, which becomes the runaway star, from the center of the $W_0 = 9.0$ cluster. The distance is given in the unit of half mass radius R_{half}. This figure shows how dynamical friction brings it to move closer to the cluster center.

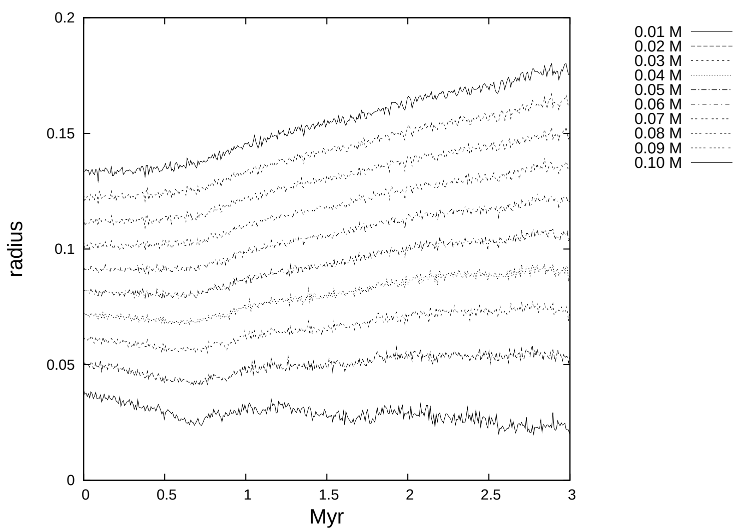

Fig. 2.— Evolution of lagrangian radius of inner shells of $W_0 = 9.0$ cluster. Shells which contain less than 0.04 M shows contraction around t = 0.7 Myr, followed by slowly expansions. Other inner shells gradually expand after the core collapse.

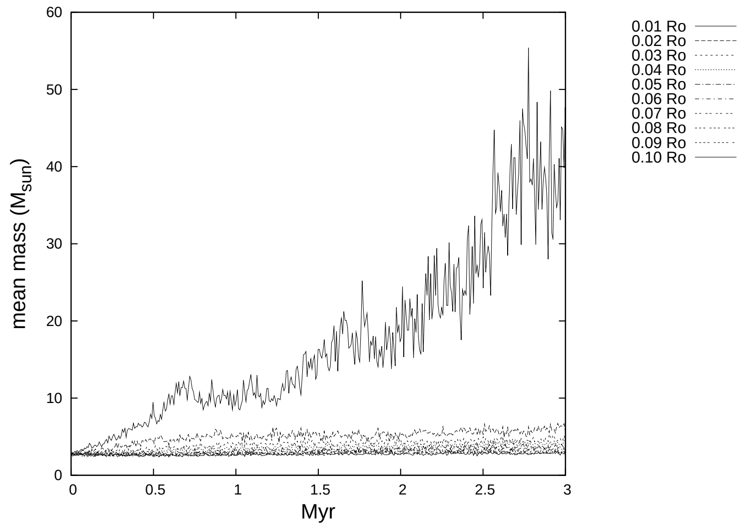

Fig. 3.— Mean mass within the inner shells of $W_0 = 9.0$ cluster (right). Each shell has a certain radius whose unit is given in the initial radius R_0. Mean mass of the inner most shell (0.01 R_0) increases so much as a result of increasing mass of the very massive star in the cluster center by runaway merging.

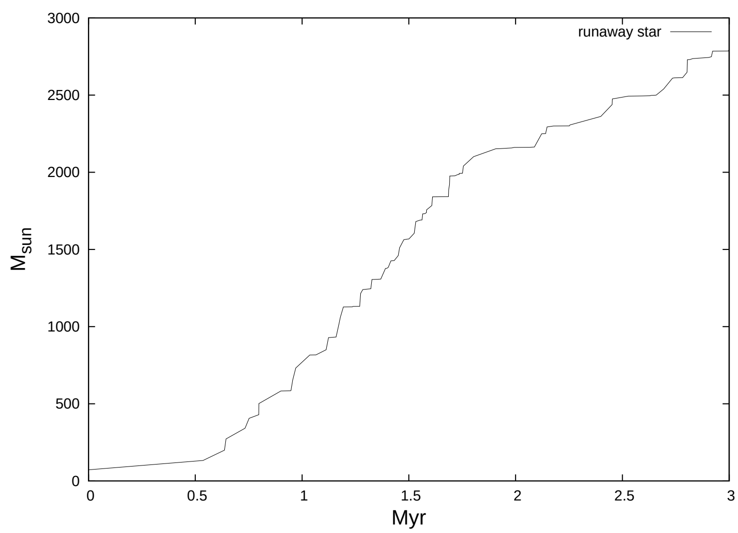

Fig. 4.— The growth of the runaway star in the center of the cluster. Starting with mass less than 100 $M_\odot$, it grows through runaway stellar merging until its mass exceeds 2800 $M_\odot$ within 3 Myr.

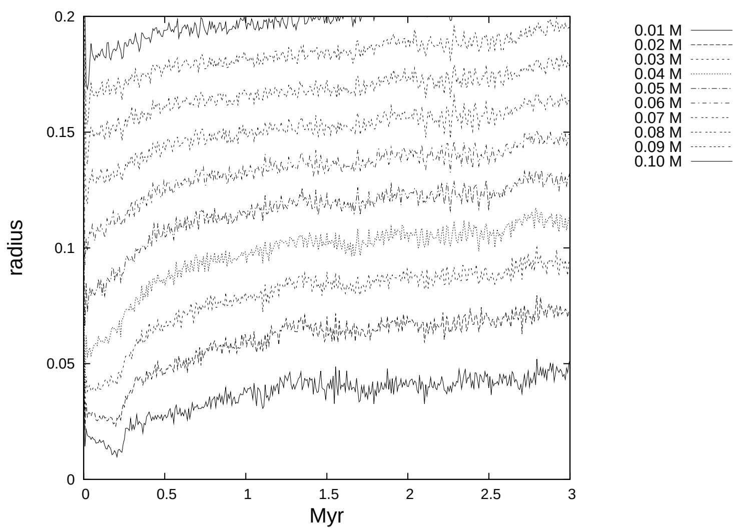

Fig. 5.— Evolution of lagrangian radius of inner shells in a $W_0 = 7.0$ cluster with initial mass segregation (minimum mass within R_{005} is 30 $M_\odot$). Contractions appears on the inner shells which contain 0.01 M - 0.02 M around t = 0.2 Myr, continued by moderate expansions. This indicates that core collapse happens very early as a consequence of initial mass segregation within the core.

Table 1: Clusters without initial mass segregation

W_0	$Nstar$	R_{005} (pc)	m_{min} $(M_\odot)$	T_{rm} (Myr)	M_{bh} $(M_\odot)$	$log\ t_{cr}$ (Myr)	$Coll$	$log\ Density$ $(M_\odot/pc^3)$	RM (Y/N)
9.0	131072	0.11	1.00	0.54	2786	2.92	96	7.21	Yes
7.0	131072	0.21	1.00	-	-	3.66	-	6.32	No
5.0	131072	0.30	1.00	-	-	4.13	-	5.88	No
3.0	131072	0.37	1.00	-	-	4.44	-	5.60	No

Note. — We report central density potential W_0 in the first column, followed by number of stars within the cluster, and lagrangian radius R_{005} which contains 5 % of cluster's total mass. The mass of the cluster is initially distributed according to the Salpeter IMF with minimum mass 1 $M_\odot$ and maximum mass 100 $M_\odot$. The fifth column reports the time when the runaway merging start going on, followed by the BH mass produced at the end of the runaway merging process. The seventh column presents the logarithmic of central relaxation time. In this case, the central relaxation time refers to the region within R_{005}. Collision frequency is reported in the eighth column, followed by the logarithmic of central density. The last entry reports whether the runaway merging happens or not.

Table 2: Clusters with initial mass segregation

W_0	$Nstar$	R_{005} (pc)	m_{min} $(M_\odot)$	T_{rm} (Myr)	M_{bh} $(M_\odot)$	$log\ t_{cr}$ (Myr)	$Coll$	$log\ Density$ $(M_\odot/pc^3)$	RM (Y/N)
7.0	124297	0.15	50.00	0.14	3333	1.90	64	6.81	Yes
7.0	124420	0.16	30.00	0.22	1293	2.10	20	6.72	Yes
7.0	124967	0.19	10.00	0.24	361	2.50	4	6.48	Yes
5.0	124829	0.29	50.00	0.43	2343	2.72	40	5.90	Yes
5.0	124940	0.29	30.00	-	-	2.78	-	5.89	No
5.0	125438	0.30	10.00	-	-	3.05	-	5.88	No
3.0	124543	0.37	50.00	-	-	2.99	-	5.61	No

Note. — On this table we report same physical parameters as presented on table 1. However, in order to create clusters with initial mass segregation, we change the minimum mass within the R_{005} with the mass higher than 1 $M_\odot$, as written in the fourth column.