Runaways collisions in nuclear stellar clusters

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Resumen / Los cúmulos nucleares de estrellas son los sistemas estelares más densos de la naturaleza. El centro de las galaxias puede albergar un cúmulo nuclear de estrellas o un agujero negro supermasivo, también puede albergar ambos al mismo tiempo. El origen de los agujeros negros supermasivos y su evolución no está claro; aquí presentamos un nuevo escenario donde las colisiones fuera de control en un cúmulo estelar nuclear son un mecanismo para la formación de agujeros negros supermasivos. La dinámica estelar en el cúmulo incluye encuentros cercanos de estrellas que generalmente ocurren a alta velocidad en el núcleo debido al profundo potencial gravitacional. A veces, después de estos encuentros, algunas estrellas pueden ser expulsadas del sistema con algo de energía cinética, lo que desencadena una redistribución de la energía que produce un colapso del núcleo y hace que un solo objeto experimente casi todas las colisiones, volviéndose muy masivo. Nuestras simulaciones muestran una eficiencia de formación de agujeros negros de $14-33\,\%$ después de 1 Myr de evolución. Nuestros sistemas estelares muestran que la formación de un agujero negro supermasivo es posible a través de colisiones en un cúmulo estelar nuclear.

Abstract / Nuclear stellar clusters (NSCs) are the densest stellar systems in nature. The center of galaxies can host a NSC or a supermassive black hole (SMBH) they can also host both at the same time. The origin of SMBHs and their evolution is not clear; here we present a new scenario where runaway collisions in a nuclear stellar cluster are a mechanism for the formation of supermassive black holes. The stellar dynamics in the cluster include close encounters of stars that usually occur at high speed in the core due to the deep gravitational potential. Sometimes after these encounters, some stars can be ejected from the system with some kinetic energy, triggering a redistribution of the energy producing a core collapse, and causing one object to experience almost all collisions, becoming very massive. Our simulations show a black hole formation efficiency of $14-33\%$ after 1 Myr of evolution. Our stellar systems show that the formation of a supermassive black hole is possible through collisions in a nuclear stellar cluster.

Keywords / stars: black holes — methods: numerical

1. Introducción

The SMBH is the densest astrophysical object of the Universe (Volonteri, 2010), while NSC are the most compact star systems in nature (Böker et al., 2002). The center of a galaxy can host a NSC (Côté et al., 2006) or a SMBH (Kormendy & Ho, 2013); it can even host both at the same time. Sometimes they are thus jointly called the central massive object (CMO) (Ferrarese et al., 2006; Neumayer et al., 2020).

Some observations show a correlation between the mass of the SMBH and the mass of the galaxy bulge (Magorrian et al., 1998; Marconi & Hunt, 2003; Häring & Rix, 2004) and also show a correlation between the SMBH mass and stellar velocity. This suggests a co-evolution between the SMBHs and their host galaxy (Ferrarese & Merritt, 2000; Gültekin et al., 2009).

There are pieces of evidence of the presence of SMBHs in the early Universe, such as the observation of the most massive quasar by Wu et al. (2015) with a mass of 1.2×10^{10} $M_\odot$ at redshift $z=6.3$ or the observation of Bañados et al. (2018) of the most distant AGN at redshift $z=7.5$ with a mass equal to 8×10^{8} $M_\odot$; also the study of Bañados et al. (2016) at redshift $5.6 \lesssim z \lesssim 6.7$ of more than a hundred quasars. Recently, the first image from the Event Horizon Telescope has shown that these objects are in fact black holes (Event Horizon Telescope Collaboration et al., 2019).

However, the origin of these monsters is unknown, thus there are different theories about their formation (Woods et al., 2019) including the remnants of population III stars (Madau & Rees, 2001; Yoshida et al., 2006), the direct collapse of a massive gas cloud (Bromm & Loeb, 2003; Latif et al., 2013; Latif & Schleicher, 2015), or the collisions and mergers of stars in a cluster (Rees, 1984; Sakurai et al., 2017, 2019; Reinoso et al., 2018, 2020; Vergara et al., 2021), which is the focus of this paper.

2. Methodology

The gravitational interactions of the stars within the cluster are strongest in the center due to the deep gravitational potential that allows close encounters at high speed. After these encounters, the stars can be ejected

Poster contribution

from the cluster dragging some kinetic energy to the outside producing a redistribution of energy that allows a core collapse of the cluster (Lynden-Bell & Wood, 1968; Spitzer, 1987). When the core of the cluster collapses, the stars will begin to collide, causing most collisions to occur with a single object and increasing its mass exponentially (Portegies Zwart et al., 1999; Portegies Zwart & McMillan, 2002). Binney & Tremaine (2008) defined two characteristic times, the first is the relaxation time (t_{relax}) which quantifies the exchange of kinetic energy between stars through two bodies (star-star) interactions and its impact in their orbits, while the second is the collision time (t_{coll}) that quantifies the occurrence of runaway collisions.

The investigation of Escala (2021) shows that in regimes where the collisions are dynamically relevant, there are observations of well-resolved massive black holes, while in regimes where the collisions are irrelevant one finds NSCs. However, if a NSC is more massive than 10^8 M$_\odot$ and is in virial equilibrium, the collisions timescale must be shorter than the relaxation timescale ($t_{coll} < t_{relax}$). This stellar configuration is very dense and globally unstable against collisions, thus this scenario allows the collapse of a great part of the stellar mass of the system into a massive black hole.

The mass of the CMO can be easily determined as the sum of the mass of the nuclear stellar cluster and the black hole $M_{CMO} = M_{NSC} + M_{BH}$. For the black hole formation efficiency ϵ_{BH}, the mass of the BH must be $M_{BH} = \epsilon_{BH} M_{CMO}$ and the mass of the NSC is $M_{NSC} = (1 - \epsilon_{BH}) M_{CMO}$, therefore the black hole formation efficiency is defined as:

$$\epsilon_{BH} = (1 + M_{NSC}/M_{BH})^{-1}. \quad (1)$$

We are testing this new scenario of BH formation in NSCs using Plummer (1911) models of equal-mass stars. We run simulations of 1 Myr. The mass-radius relation is based on Bond et al. (1984) and Demircan & Kahraman (1991) and given as:

$$\frac{R_*}{\mathrm{R}_\odot} = 1.6 \times \left(\frac{M_*}{\mathrm{M}_\odot}\right)^{0.47}, 10 \le M_* < 50\mathrm{M}_\odot, \quad (2)$$

$$\frac{R_*}{\mathrm{R}_\odot} = 0.85 \times \left(\frac{M_*}{\mathrm{M}_\odot}\right)^{0.67}, 50\mathrm{M}_\odot \le M_*. \quad (3)$$

In Table 1 we summarize our initial conditions for models A, B and C.

Table 1: The virial radius is R_v, M_{ini} is the initial mass of the cluster, N is the initial stars number. The stellar mass and radius are M_* and R_*, respectively.

Models	R_V [pc]	M_{ini} [M$_\odot$]	N	M_* [M$_\odot$]	R_* [R$_\odot$]
A	10^{-2}	10^4	10^3	10	4.7
B	10^{-2}	5×10^4	10^3	50	11.7
C	10^{-2}	10^5	10^4	10	4.7

3. Code

We use NBODY6++GPU to run our simulations, a direct N-body simulation code of high precision based on NBODY6 (Aarseth, 2000) and the parallel multi-node code NBODY6++ (Spurzem, 1999). The optimization of the calculation of the gravitational forces between particles is calculated using Graphics Processing Units (GPUs) (Nitadori & Aarseth, 2012; Wang et al., 2015). This code uses the Hermite 4$^{\mathrm{th}}$ order integrator scheme developed by Makino (1991), who improved on the previous standard scheme developed by Aarseth (1985), which had trouble solving higher-order integrators. Also, it includes a spatial hierarchy to speed up computational calculations, There are two lists the regular and irregular force, which are related to the distance of the neighbour from the particle (Ahmad & Cohen, 1973), as well as an algorithm to solve close encounters and binaries (Kustaanheimo & Stiefel, 1965) and multiple systems (Mikkola & Aarseth, 1990, 1993).

4. Results

Note that the masses of the stellar systems are related as follows:

$$M_{ini} = M_{CMO} + M_{esc} = M_{NSC} + M_{BH} + M_{esc}. (4)$$

Where M_{esc} is the cummulative mass of the stars that escapes form the stellar system.

Our main results of models A, B and C are summarized in Table 2.

Table 2: M_{esc} is the cummulative mass of the escapers, M_{CMO} is the mass of the central massive object, M_{NSC} is the mass of the nuclear stellar cluster, the final black hole mass is M_{BH} and the black hole formation efficiency is ϵ_{BH}

Models	M_{esc} [M$_\odot$]	M_{CMO} [M$_\odot$]	M_{NSC} [M$_\odot$]	M_{BH} [M$_\odot$]	ϵ_{BH}
A	2190	7810	6650	1160	14%
B	17500	32500	24450	8050	25%
C	21840	78160	52580	25580	33%

In Fig. 1 we show the time evolution of model C. The top panel shows the cumulative mass of the stars that escape from the system normalized by the initial mass (M_{ini}); the stellar system loses around 22% of the initial mass. The first middle panel displays the total number of collisions normalized by the initial number of stars; there are around 2600 collisions in 1 Myr. The second middle panel shows the black hole formation efficiency ϵ_{BH} reaching a value of 33%. The stellar system forms a single massive object with a mass of 25580 M$_\odot$. The bottom panel shows the Lagrangian radii at 90%, 50%, and 10% of the enclosed mass. The outer zone of the stellar system (ie 90%) shows an expansion until about 0.3 Myr, when it loses 10% of the initial stellar mass, thus remaining constant. The middle zone (i.e 50%) shows a smooth expansion all the time while the inner zone at 10% of the enclosed mass shows a deep decrease before 0.1 Myr.

This stellar system shows a deep core collapse at the beginning of the simulation, which is related to the first stellar collisions. Then there is a considerable increase in the number of collisions, a large part of these collisions occurred with a single object, increasing the black hole formation efficiency.

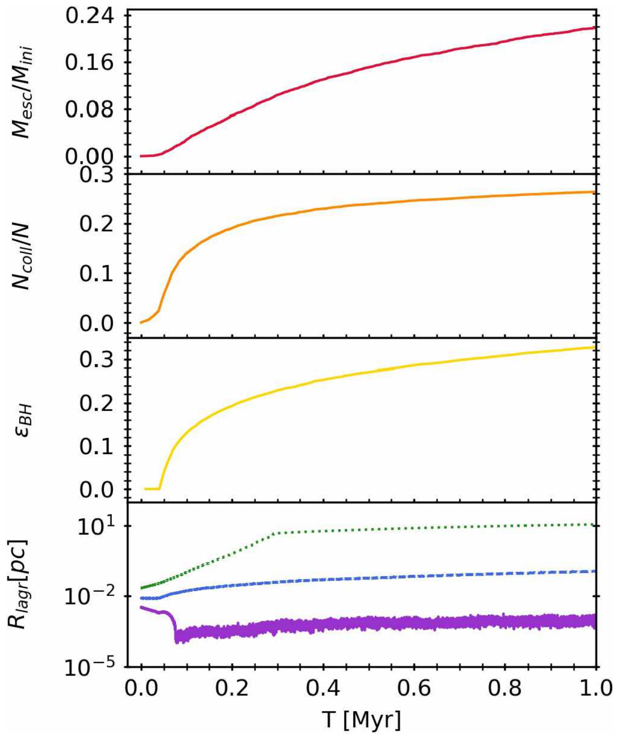

Figure 1: Evolution over time of model C. *Top panel*: The cumulative mass of escapers normalized by the intial mass M_{ini}. *First middle panel*: The number of collisions normalized by the initial number of stars N. *Second middle panel*: The black formation efficiency ϵ_{BH}. *Bottom panel*: Lagrangian radii for the 90%, 50%, and 10% of the enclosed mass.

5. Conclusions

In this investigation, we explore the behavior of a dense stellar configuration and how collisions form a SMBH. Our simulations show that in 1 Myr, the systems lose around $10-30\%$ of the initial mass due to the stars that escape from the system, and the black hole formation efficiency reaches a value of $14-33\%$. Model C is denser than Models A and B, thus we expect that in even denser clusters the black hole formation efficiency may reach even higher values.

Future simulations of non-isolated clusters could show that the stars that escapes from the systems could be replaced by new neighborhood stars, which fall towards the center, increasing the rate of collisions.

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