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Formation of very massive objects via collisions of main-sequence Pop. III stars in primordial clusters with a background potential

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Resumen / La asombrosa existencia de agujeros negros supermasivos en el Universo primitivo es uno de los grandes misterios sin respuesta en astrofísica, en particular, cómo obtienen sus grandes masas tan rápido. Aquí nuestro interés consiste en explorar un nuevo escenario de formación de agujeros negros masivos: la formación por colisiones estelares catastróficas en cúmulos estelares densos. Nuestros sistemas están localizados en el universo temprano, con las denominadas estrellas de población III las cuales son muy masivas y, por tanto, cúmulos de estrellas de población III son sistemas estelares muy densos y masivos. Nuestras simulaciones de N cuerpos fueron corridas con el código *NBODY6++GPU* y pueden ser divididas en dos grupos, uno con y otro sin potencial de fondo. Se ha establecido una masa crítica para la cual el número de colisiones es tan alto que puede llegar a formar objetos mas masivos al interior de estos cúmulos estelares de estrellas de población III. Aquí, nuestro objetivo es testear la existencia de esta masa crítica en un caso simplificado de cúmulos de estrellas de población III de igual masa. En términos de la eficiencia para la formación de un objeto masivo, encontramos que ocurre una transición, ya que la eficiencia es muy pequeña para masas considerablemente por debajo del valor de masa crítica, alcanzando valores de $\sim 20\,\%$ una vez que comenzamos a acercarnos a la escala de masa crítica en nuestras simulaciones. Nuestros resultados sugieren que ocurre una transición crítica dependiendo de la masa del cúmulo y los objetos más masivos alcanzan masas de aproximadamente $1.7 \times 10^5 \mathrm{M}_\odot$.

Abstract / The amazing existence of supermassive black holes in the primitive Universe is one of the great mysteries without answer in astrophysics, in particular, how they get their great masses so fast. Here our interest consists in exploring a new scenario for the formation of massive black holes: the formation by catastrophic stellar collisions in dense star clusters. Our systems are located in the early universe, with the so-called population III stars which are very massive, and therefore population III star clusters are very dense and massive stellar systems. Our N-body simulations were run with the code *NBODY6++GPU* and can be divided into two groups, one with and the other without a background potential. A critical mass has been established for which the number of collisions is so high that most massive objects can form within these Population III star clusters. Here, our goal is to test the existence of this critical mass in a simplified case of Population III star clusters of equal mass. In terms of the efficiency for the formation of a massive object, we find a transition to occur, as the efficiency is very small for masses considerably below the critical value while reaching values of $\sim 20\%$ once we start approaching the critical mass scale in our simulations. Our results thus suggest such a critical transition to occur depending on the mass of the cluster and the most massive objects reaching masses of about $1.7 \times 10^5 \mathrm{M}_\odot$.

Keywords / black hole physics — early universe — stars: Population III — methods: numerical

1. Introduction

For many years it was thought that black holes (BHs) were just a mathematical and not a physical solution to Einstein's equations. We have recently been able to observe the shadows of two BHs: the supermassive black hole (SMBH) in the center of the giant elliptical galaxy M87 (M87*) and the SMBH in the Center of our galaxy the Milky Way Sagittarius A* (Sgr A*), thanks to the E.H.T. Collaboration et al. (2019) and Collaboration et al. (2022) respectively. Some paths that have been mainly proposed for the formation of Massive Black Holes (MBHs) (Rees, 1984; Volonteri, 2010) are: the direct collapse of a primordial cloud, the growth by gas accretion and/or mergers of a stellar/intermediate mass BH and the formation of an MBH by catastrophic stellar collisions in dense stellar clusters. In this paper, we test on a new MBH formation scenario proposed by Escala (2021) in which nuclear star clusters (NSCs) and BHs have different evolutionary paths and mechanisms within a common origin and these BHs could have been formed by collisions of stars in NSCs. In the early Universe, the gas from which the first stars (Pop. III stars) were formed was composed mainly of hydrogen and helium. Collisions in primordial star clusters have been studied by Reinoso et al. (2018) and we know that Pop.

III clusters are dense and massive systems and therefore can be good candidates to produce very massive objects.

2. Methodology

We model idealized dense star clusters in virial equilibrium using a Plummer distribution for the stars (Plummer, 1911). Half of our simulations included an analytic background potential, which helps us simulate the effects of the gas within the cluster, that also follows a Plummer density profile. Simulated clusters here are not considering stellar evolution, tidal captures, and primordial binaries. We consider that a collision occurs if the separation d between two stars is smaller than the sum of the radii of the stars $d \leq R_1 + R_2$, where R_1 and R_2 are the radii of each star. So when a collision occurs the mass of the new star is conserved with $M_{\rm new}$ being equal to the sum of the masses of the stars before the collision $M_{\rm new} = M_1 + M_2$, where M_1 and M_2 are the two masses of the stars. The radius of the new star $R_{\rm new}$ is calculated using the following equation $R_{\rm new} = R_1[(M_1 + M_2)/M_1]^{1/3}$. The initial mass of the cluster $M_{\rm cluster}$ is related to the number of stars N and the mass of the star $M_{\rm star}$ as $M_{\rm star} = M_{\rm cluster}/N$. When we consider an external potential the total mass of the system is calculated as $M_{\rm cluster} = M_{\rm stars} + M_{\rm ext}$. The crossing time is defined as $t_{\rm cross} = \sqrt{R_{\rm v}^3/GM_{\rm stars}}[1/(1+q)]$, where $q = M_{\rm ext}/M_{\rm stars}$. The effects of a background potential on the evolution of star clusters have been studied previously by Reinoso et al. (2020) the results of this research show that the background potential increases the velocities of the stars, causing an overall delay in the evolution of the clusters and the runaway growth of a massive star at the center. The increase of kinetic energy of the stars implies that the population of binary stars is lower reducing the number of stellar collisions. The condition proposed by Escala (2021) can be applied to Pop. III star clusters (PSCs) that have $t_{\rm coll} \leq t_{\rm H}$, in which runaway collisions can happen over the whole system and (at least) the inner parts of such PSCs will probably collapse towards the formation of an most massive object (MMO) at the center of the clusters. This condition for instability is equivalent to:

$$M \geq [4\pi M_{\rm star}/(3\Sigma_0 t_{\rm H} G^{1/2})]^{2/3} R^{7/3} \tag{1}$$

In principle, PSCs that fulfils Eq. 1 but also that have $t_{\rm relax} \leq t_{\rm H}$ might also expand considerably their effective radius before collisions become important, moving a cluster that initially fulfils Eq. 1 to the collisional stable region ($t_{\rm coll} \geq t_{\rm H}$). This second condition for cluster expansion can be written as:

$$R \leq [((t_{\rm H} M_{\rm star})/0.1) \ln{(M/M_{\rm star})}]^{2/3} \left(G/M\right)^{1/3} \tag{2}$$

Nevertheless, previous numerical experiments (Vergara et al., 2023) found, even for simulations initially with $t_{\rm relax} \leq t_{\rm coll}$, that catastrophic collisions produce such a fast violent behaviour allowing the formation of a MMO before the cluster expansion and moreover, with the MMO having a relevant fraction of the whole cluster mass. Therefore, we will simply define a critical mass as the mass at which the virial radius of the clusters fulfills the condition that the collision time is equal to or shorter than the age of the system $t_{\rm coll} \leq t_{\rm H}$ (i.e. only requiring to fulfil the condition given by Eq. 1), where M_{star} is the mass of one of the stars, Σ_0 is the effective cross-section, $t_{\rm H}$ is the age of the system and G is the gravitational constant. The effective cross section is defined as $\Sigma_0 = 16\sqrt{\pi}R_{star}^2(1+\Theta)$, where Θ is the Safronov number $\Theta = 9.54((M_{star}\ \ {\rm R}_{\odot})/(\ {\rm M}_{\odot} R_{star}))((100\ \ {\rm km\,s^{-1}})/(\sigma))^2$. Note that σ is the velocity dispersion of a virialized system $\sigma = \sqrt{GM/R}$, where M is the total mass and R the characteristic radius of the system. In that work no physical mechanism is actually being proposed for BH formation, but simply a comparison between time-scales and observational inferences of putative BHs, from which a threshold/separatrix mass is obtained. To run the simulations we used the code *NBODY6++GPU*[⋆] which is mostly written in Fortran. The different NBODY codes were initially developed by Aarseth (1999) with an extension for parallel computers designed by Spurzem (1999). The code uses the more realistic physics as considered in Reinoso et al. (2020). Here, we ran 24 simulations until 1, 5, and 10 Myr in which all simulations have the same number of stars $N = 10^4$ and the stars have the same mass and radius initially. The masses and radii of the Pop. III stars are $M_{\rm star}$=15, 30, 50, 100 M$_\odot$ and the radii $R_{\rm star}$=1.51, 2.12, 2.86, 4.12 R$_\odot$ respectively. The mass-radius relations for Pop. III stars are specified by Windhorst et al. (2018). Different combinations of the initial conditions were made between the virial radius of the cluster varied as $R_{\rm v}$=0.05, 0.1, 0.5 pc and the masses of the clusters as $M_{\rm cluster}$=3 × 10^5, 6 × 10^5, 1 × 10^6, 2 × 10^6 M$_\odot$ in which the total masses of the stars $M_{\rm stars}$ are equal to the masses of the external potential $M_{\rm ext}$=1.5 × 10^5, 3 × 10^5, 5 × 10^5, 1 × 10^6 M$_\odot$ while the radius of the external potential $R_{\rm v,ext}$ is the same as the virial radius of the stellar distribution (as can be seen in Fig. 1). We use totally hypothetical PSCs to evaluate the collisional effects.

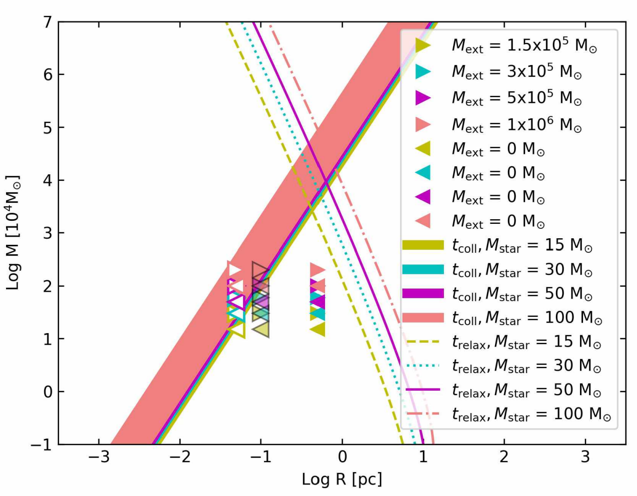

Figure 1: Mass vs. radius diagram. The solid lines satisfy the condition given by Eq. 1. The dashed lines satisfy the condition given by Eq. 2. The shaded regions represent the different sigmas associated with each initial condition.

[⋆] `https://github.com/nbodyx/Nbody6ppGPU`

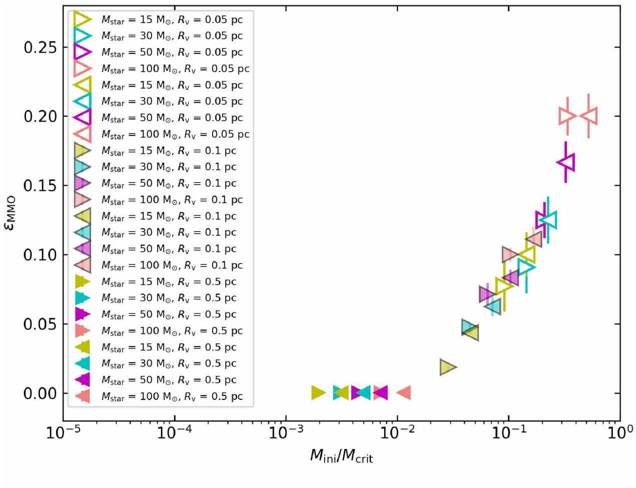

Figure 2: Efficiencies at which MMOs are formed are calculated with the equation Eq. 3. The x-axis shows the initial stellar mass of the cluster $M_{\rm ini}$ divided by the critical mass $M_{\rm crit}$ until 10 Myr.

3. Results

The initial stellar mass of the cluster $M_{\rm ini}$ is related to the mass of the PSC remaining at the end of the simulation $M_{\rm PSC,final}$, the mass of the MMO as $M_{\rm MMO}$ and the mass of escaping stars $M_{\rm esc}$ as $M_{\rm ini} = M_{\rm PSC,final} + M_{\rm MMO} + M_{\rm esc}$. Note that in this work the mass of the central massive object $M_{\rm CMO}$ is $M_{\rm CMO} = M_{\rm PSC} + M_{\rm MMO}$. The efficiency for MMO formation $\epsilon_{\rm MMO}$ is:

$$\epsilon_{\rm MMO} = (1 + M_{\rm PSC}/M_{\rm MMO})^{-1}, \tag{3}$$

where the mass of the MMO can be calculated as $M_{\rm MMO} = \epsilon_{\rm MMO} M_{\rm CMO}$ and the mass of the PSC is calculated as $M_{\rm PSC} = (1 - \epsilon_{\rm MMO}) M_{\rm CMO}$ used in Fig. 2. These MMOs can also be understood as very massive stars (VMS). The results of our simulations, for the case where we add a background potential, show that the mass of the MMOs for virial radii of $R_{\rm v} = 0.05$ pc ($t_{\rm coll} \leq t_{\rm H}$) varies in the range $M_{\rm MMO} \approx 1.1 \times 10^4 - 1.7 \times 10^5$ M$_\odot$ for the different masses and radii of Pop. III stars (an example can be seen in Fig. 3). For virial radii of $R_{\rm v} = 0.1$ pc ($t_{\rm coll} \leq t_{\rm H}$) the mass of the MMOs varies in the range of $M_{\rm MMO} \approx 2.7 \times 10^3 - 9.6 \times 10^4$ M$_\odot$. Finally for virial radii of $R_{\rm v} = 0.5$ pc ($t_{\rm relax} \leq t_{\rm H}$) almost no collisions occur so the masses reached vary between $M_{\rm MMO} \approx 30 - 200$ M$_\odot$. For the case where we do not add a background potential, the mass of the MMOs for virial radii of $R_{\rm v} = 0.05$ pc ($t_{\rm coll} \leq t_{\rm H}$) varies in the range of $M_{\rm MMO} \approx 1.2 \times 10^4 - 1.3 \times 10^5$ M$_\odot$ for the different masses and radii of Pop. III stars. For virial radii of $R_{\rm v} = 0.1$ pc ($t_{\rm coll} \leq t_{\rm H}$) the mass of the MMOs varies in the range of $M_{\rm MMO} \approx 5.8 \times 10^3 - 8.9 \times 10^4$ M$_\odot$. Finally for virial radii of $R_{\rm v} = 0.5$ pc ($t_{\rm relax} \leq t_{\rm H}$) almost no collisions occur so the masses reached vary between $M_{\rm MMO} \approx 15 - 200$ M$_\odot$. Furthermore, the number of stars that escaped $N_{\rm esc}$ from these clusters is equal to 1 until 10 Myr when we add a background potential in all simulations, and when we do not add a background potential the number of stars that escaped varies between $N_{\rm esc} \approx 1.6 \times 10^3 - 2.6 \times 10^3$ for $R_{\rm v} = 0.05$ pc, $N_{\rm esc} \approx 8.2 \times 10^2 - 1.6 \times 10^3$ for $R_{\rm v} = 0.1$ pc and $N_{\rm esc} \approx 1.3 \times 10^1 - 1.3 \times 10^2$ for $R_{\rm v} = 0.5$ pc. For some clusters (the larger ones) there is not enough time for collisions to act due to the relatively short life times of Pop. III stars. Even more when the physics of star evolution is not here included.

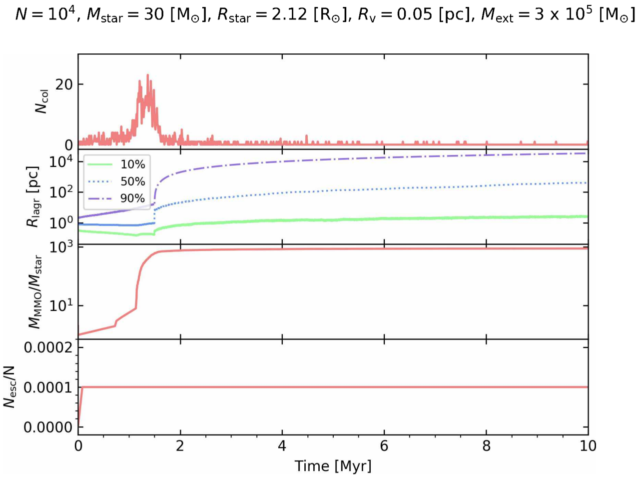

Figure 3: Evolution of one of our clusters up to 10 Myr.

4. Conclusions

From our simulations even for parameters of realistic Pop. III stars there is a delay in the collapse time compared to simulations without potential, in agreement with previous works. On the other hand, the maximum efficiency obtained is a value of ≈ 20% is, due to the smaller radii that Pop. III stars would have. Also, by including a background potential the efficiencies are slightly lower. Future observations with *James Webb Space Telescope (JWST)*[**] will help us.

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[**] `https://webbtelescope.org`