Formation of massive black hole seeds in the early Universe: Runaway stellar collisions in the first star clusters

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Resumen / La presencia de agujeros negros supermasivos cuando el Universo tenía solo mil millones de años de edad, presenta un gran desafío para los modelos actuales de formación y crecimiento de agujeros negros, dado el corto tiempo que se impone para reunir 10^9 $M_\odot$ en un solo objeto compacto. En este trabajo presentamos un mecanismo de formación de agujeros negros de masa intermedia (10^3 $M_\odot$) que consiste en repetidas fusiones entre estrellas de población III.1 en los primeros cúmulos estelares densos formados en el Universo.

Abstract / The presence of supermassive black hole seeds when the Universe was only one billion years old, presents a big challenge to the actual models for the formation and growth of black holes, due to the short time imposed to gather 10^9 $M_\odot$ in a single compact object. In this work, we present a mechanism for the formation of intermediate mass black holes (10^3 $M_\odot$), which consists in repeated mergers between population III.1 stars in the first dense star clusters formed in the Universe.

Keywords / stars: Population III — cosmology: dark ages, reionization, first stars — galaxies: star clusters: general

1. Introduction

Stellar collisions and mergers have been invoked to explain the formation of massive stars (Bonnell et al., 1998; Clarke & Bonnell, 2008) and quantitative studies suggest that in present-day star clusters the fraction of stars that participate in this process is about $0.1 - 1\%$(Baumgardt & Klessen, 2011). While in the present-day Universe this mechanism does not produce very massive products given the small amount of physical collisions, the conditions predicted for the early Universe are much more favorable. Computational hydrodynamics simulations have found evidence for fragmentation during the collapse of the clouds at densities of 10^9 cm^{-3} or higher (e.g., Smith et al., 2012; Latif et al., 2013), especially if dust is present early on (e.g., Klessen et al., 2012; Bovino et al., 2016). These densities can lead to the formation of compact stellar systems with a half mass radius of $r_h = 0.1$ pc or even less.

The high temperature due to the low metallicity of the primordial gas contributes to the high accretion rates of $\sim 10^{-3} - 10^{-1}$ $M_\odot$ yr^{-1} found in numerical simulations (Abel et al., 2002; Yoshida et al., 2006). Some first stellar evolution models by Stahler et al. (1986) or Omukai & Palla (2003) suggest that these stars can become as large as 300 $R_\odot$, and that this can be enhanced in the presence of variable accretion rates (Smith et al., 2012). The most extreme cases with accretion rates of ~ 0.1 $M_\odot$ yr^{-1} have produced the largest stars, potentially reaching more than 1000 $R_\odot$ for a 100 $M_\odot$ star (Schleicher et al., 2013; Haemmerlé et al., 2017).

Due to these considerations, it is natural to think that stellar mergers between population III (Pop. III) stars could play an important role in the formation of very massive objects and black hole seeds in the early Universe. Indeed, this process was mentioned as an important pathway in Rees (1984), and taken into account in models by Devecchi et al. (2012) and Boekholt et al. (2018). Furthermore, N-body simulations using initial conditions given by the output of cosmological simulations have yield black holes with masses as large as 10^3 $M_\odot$ (Lupi et al., 2014; Katz et al., 2015; Sakurai et al., 2017).

We present a systematic investigation to understand the process of repeated mergers in the first star clusters of the Universe and how the final object depends on the number of stars and their radii. We describe our setup in Sec. 2., we present our results in Sec. 3. and give a final summary in Sec. 4..

2. Setup

We performed a total of 280 N-body simulations of isolated, gas free star clusters modeled with a single stellar population, without including an IMF but using equal mass and equal radii stars. The simulations were performed using a modified version of NBODY6 * (Aarseth, 2000).

2.1. Star clusters

We employ a simplified model of the first star clusters of the Universe, modeling these systems as a Plummer distribution(Plummer, 1911) with a total mass of $M_{\rm cluster} = 10^4$ M$_\odot$ and a half mass radius of $r_{\rm h} = 0.1$ pc. The clusters are initially virialized, and our parameter space is formed by combinations of the number of stars that we varied as $N = 100, 500, 1000, 5000$ and the stellar radius that we varied as $R_{\rm star} = 20, 50, 100, 200, 500, 1000, 5000$ R$_\odot$. The clusters are formed by equal mass stars with $M_{\rm star} = M_{\rm cluster}/N$. No mass loss is included in our calculations. We decided to stop the simulations at 3 Myr given that at this point the merger process has stopped in all the clusters.

2.2. Stellar mergers

Stellar mergers are automatically activated in NBODY6 when using the stellar evolution package based on the work by Hurley et al. (2000), however, these routines do not cover the metallicity range of the Pop. III stars. For this reason, we had to deactivate these routines and instead specify explicitly the radius of the stars and the radius of the merger product. A physical collision occur when the separation d of two stars becomes equal or smaller to the sum of their radius ($d \leq R_1 + R_2$). In this case the two stars are replaced by a new star in the center of mass of the previous configuration. We assume no mass loss during the merger, therefore $M_{\rm new} = M_1 + M_2$, then we calculate the radius by requiring that the density remains constant, that is, $R_{\rm new} = R_1 \left((M_1 + M_2)/M_1\right)^{1/3}$. We assume that the new star quickly settles into a new equilibrium configuration in which the density is the same of an unperturbed star of the same mass. This is consistent with previous calculations by e.g. Haemmerlé et al. (2017).

3. Results

3.1. Evolution of the clusters

In the presence of mergers, before a core-collapse (Heggie, 1979) occurs during the evolution of the clusters, there are several physical collisions that yield stars more massive than the average, and these mergers occurs at distances not larger than the half-mass radius. This is specially important for clusters containing a larger number of stars, i.e. $N = 1000$ and $N = 5000$, in which there are several mergers that do not involve the most massive object at first, but these products sink to the center, contributing finally to the mass enhancement of the most massive object, which eventually encompasses around 10% of the total mass of the cluster. We find that the total fraction of collisions in a cluster, i.e. the total number of mergers divided by the initial number of stars, $f_{\rm coll} = N_{\rm col}/N$, depends mainly on the stellar radius, ranging from $0.01 - 0.02\%$ for 20 R$_\odot$ stars, to 0.08% for 200 R$_\odot$ stars. The total number of mergers depend on the number of stars, therefore, so does the mass enhancement of the most massive object. Thus, the most promising case for producing massive black holes is when the number of stars in the cluster is large, however, as we will see later, not large enough so that the onset of the mass growth is not delayed too much. The latter is important if we consider a time-limit given by the lifetime of the stars that could explode as a supernova and destroy the cluster, halting the process of mergers.

3.2. Modelling the runaway growth

The runaway growth is the process of repeated mergers involving the same object, which grows very rapidly in mass and becomes the most massive object. We want to find an expression that allow us to estimate the mass of the most massive object before the death of the massive stars in the cluster. To do this, we reconstruct the merger history of the most massive star, i.e. the amount of mergers experienced by the most massive object in a given time interval during the simulation. We then fit to this data the following function,

$$N_{\rm col} = A \int_0^t \exp\left(-\frac{(t - t_{\rm delay})^2}{2t_{\rm duration}^2}\right) dt. \qquad (1)$$

The function in Eq. 1 depends on three parameters: $t_{\rm delay}$, which is the time-delay until the runaway growth begins; $t_{\rm duration}$, which is the duration of the runaway growth; and A, a normalization factor related to the total number of mergers. The number of mergers as a function of time experienced by the most massive object in each of our simulations is fitted, using as a fitting model the Eq. 1, so we can understand how the three parameters of that function depend on the number of stars N and the radius of the stars $R_{\rm star}$.

We find that $t_{\rm delay}$ increases with the number of stars because the onset of the runaway growth is related to the half-mass relaxation time-scale which in turn increases with the number of stars, but at the same time, $t_{\rm delay}$ decreases with the stellar radius given that the onset of mergers begins earlier with larger stars. We also find that, as expected, the normalization factor A related to the total number of mergers increases with both N and $R_{\rm star}$. We did not find a clear relation between $t_{\rm duration}$ and the stellar radius, we just find an increase in the duration time with the number of stars. These relations are described in Eqs. 2, 3 and 4. In these equations $\log(x)$ refers to a base 10 logarithm of x.

*Webpage NBODY6:
https://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm

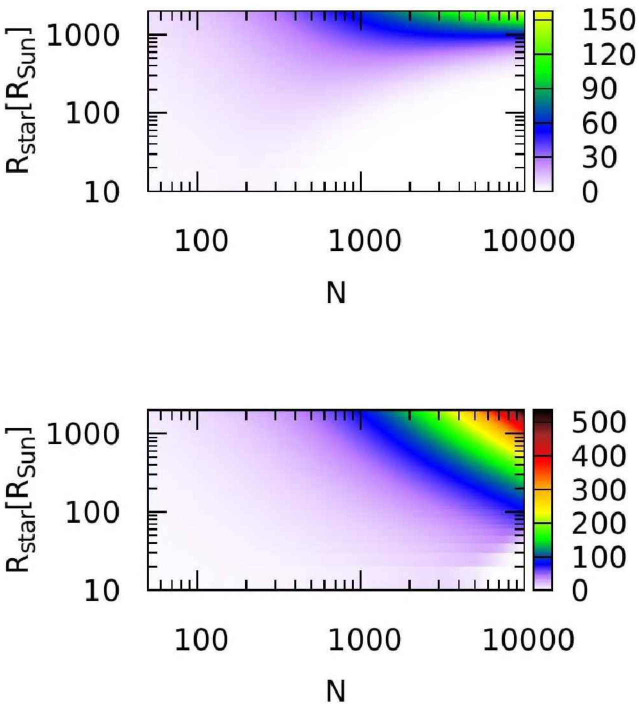

Figure 1: Total number of mergers with the most massive object after 1 Myr (upper panel) and after 10 Myr (bottom panel) in color scale (right axis) depending on the initial number of stars of the cluster (x-axis) and the stellar radius in $R_\odot$ (y-axis). The most promising scenario for forming black holes is favoured for a large number of stars if the time is enough (bottom panel) and if the radius of the stars is large, as expected.

$$\log(A) = \left[0.16\log\left(\frac{R_{\rm star}}{R_\odot}\right) - 0.05\right]\log(N) + 0.06\log\left(\frac{R_{\rm star}}{R_\odot}\right) - 1.43, \quad (2)$$

$$\log\left(\frac{t_{\rm delay}}{t_{\rm cros}}\right) = \left[1.09 - 0.21\log\left(\frac{R_{\rm star}}{R_\odot}\right)\right]\log(N) + 0.30\log\left(\frac{R_{\rm star}}{R_\odot}\right) - 0.79, \quad (3)$$

$$\log\left(\frac{t_{\rm duration}}{t_{\rm cros}}\right) = 0.34\log N + 0.34. \quad (4)$$

With these equations we can then find the number of mergers for a broad combination of N and $R_{\rm star}$ as presented in Fig.1 (Reinoso et al., 2018) where we calculated the number of mergers up to 1 Myr (top panel) and up to 10 Myr (bottom panel) by integrating Eq. 1 for different combinations of N and $R_{\rm star}$, and a time limit of 1 and 10 Myr (See Fig. 1).

4. Summary

We performed a total of 280 N-body simulations of isolated, gas free and virialized star clusters formed by Pop. III stars. We found that these systems evolve towards the phase of core-collapse and quickly the merger process takes place, being faster for clusters with less stars but producing more massive objects in clusters with a larger number of stars. If we set a time-limit to this process given by the life-time of the Pop. III stars, that we consider somewhat in between 1 and 10 Myr, then the most plausible case for producing massive black hole seeds is for clusters containing stars with radius larger or equal to 100 $R_\odot$ in which we can expect a minimum enhancement of 15 times the initial mass of the stars and up to 100 times if the time-limit is 10 Myr and the cluster contains 10 000 stars with 100 $R_\odot$.

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