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Exploring the formation of supermassive black holes in protostar clusters, incorporating a hydrodynamic treatment

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Resumen / Los agujeros negros supermasivos tienen un origen enigmático y los modelos que pretenden explicar su formación, en particular el escenario de colapso directo, enfrentan problemas sustanciales. Estos se basan en los requisitos simultáneos de metalicidades extremadamente bajas y fuertes fondos de radiación. Aquí, exploramos un modelo alternativo de formación de semillas de agujeros negros supermasivos a través de la creación de un cúmulo de estrellas inicial en una nube de gas primordial donde las colisiones estelares dan lugar a la formación de objetos masivos. Nos enfocamos principalmente en incorporar una descripción hidrodinámica físicamente motivadora del gas dentro de la interface AMUSE. Nuestros cálculos muestran que la interacción entre la dinámica estelar y la dinámica del gas es particularmente importante, ya que impacta en la estabilidad del sistema y por lo tanto en la acumulación de gas. Concluimos que es posible formar un objeto masivo mediante acreción y colisiones.

Abstract / Supermassive black holes have an enigmatic origin and models that aim to explain their formation, in particular the direct collapse scenario, face substantial problems. These are based on the simultaneous requirements of extremely low metallicities and strong radiation backgrounds. Here, we explore an alternative model of supermassive black hole seed formation through the creation of an initial star cluster in a primordial gas cloud where stellar collisions give rise to the formation of massive objects. We focus primarily on incorporating a physically motivating hydrodinamical description of the gas within the AMUSE framework. Our calculations show that the interaction between stellar dynamics and gas dynamics is particularly important, as it impacts the stability of the system and therefore the accumulation of gas. We conclude that it is possible to form a massive object through accretion and collisions.

Keywords / stars: black holes — methods: numerical — cosmology: theory — early universe — stars: Population III

1. Introduction

Over the last years, more than 200 supermassive black holes (SMBHs) with masses 10^9 [M$_\odot$] have been discovered at high redshift $z > 6$ (Shen et al., 2019). One needs very massive initial seeds of the order of at least 10^4 [M$_\odot$] to reach the masses that were observed, especially when realistic spin parameters and accretion disc models are taken into account (Shapiro, 2005). The possible scenarios leading to the formation of a SMBH were already outlined by Rees (1984), which are: the direct collapse of massive gas clouds either to a black hole or to a supermassive star, which later collapses to a black hole via general relativistic instabilities, or the formation of a dense stellar cluster, which may either collapse into a black hole seed through relativistic instabilities or evolve due to stellar mergers.

Direct collapse is considered the most promising scenario, because it can produce the most massive seeds. Numerical simulations have shown that the only possibility for the direct collapse scenario to occur is if the cooling is efficiently suppressed, which can be achieved when a strong radiation background photodissociates the molecular hydrogen, therefore preventing strong fragmentation of the gas cloud (Latif et al., 2013). However, the need to have very strong radiation backgrounds, while keeping the gas metal-free, can at best be satisfied under very rare conditions (Agarwal et al., 2017). Additionally, the need for a large value of J_{21} strongly limits the number of massive black holes that could be produced via the direct collapse scenario (Dijkstra et al., 2014). Another promising but little investigated pathway is the formation of a SMBH seed via dynamical processes, in cases where direct collapse fails and fragmentation occurs, so it causes a cluster of protostars to form. When such a cluster is still embedded in gas, the growth of the most massive object could still occur via collisions and accretion; recent works show that the protostellar radii can be considerably enhanced in the presence of accretion, reaching radii of 100 to 1 000 [$R_\odot$] for protostars with 10 to 100 [$M_\odot$] (Hosokawa et al., 2013; Haemmerlé et al., 2018). This provides additional motivation to consider the interplay between collisions and accretion.

In the context of supermassive black holes, this possibility was first explored by Boekholt et al. (2018), where they considered a protostellar cluster with a Plummer distribution, embedded in a gas reservoir of $\sim 10^5$ M$_\odot$. From the exploration of the parameter space, they found that it is feasible to form quite massive objects of 10^4 up to 10^5 solar masses in these scenar-

Poster contribution

ios. Also, Reinoso et al. (2020) explored the impact of an external potential on the dynamics and the collision probability, where they found a reduction of the number of binary systems due to larger velocities and that the relaxation time of the cluster increases in the presence of an external potential. However, only a few models have been explored that take into account the dynamics of the gas (Chon & Omukai, 2020a) and how its physical processes affect the accretion and finally the formation of a supermassive object. In our work we investigate the impact of a hydrodynamical gas treatment through SPH particles in a Lagrangian description and N-body dynamics for the protostars with sink particles. In this proceeding we briefly mention our method adopted and the primary results.

2. Numerical method

We know that modeling the early evolution of a Pop III protostar clusters embedded in a primordial gas cloud is a great challenge, because we must take into account gravitational, hydrodynamical, accretion and stellar collisions processes. For the development of this work, we used the Astrophysical Multi-purpose Sofware Enviroment *AMUSE* (Portegies Zwart et al., 2018). Our physical system consists of Pop. III protostars embedded in a natal gas cloud. For simplicity, we assume that the gas and protostars are distributed equally, i.e. both the cluster and gas follow a Plummer distribution (Plummer, 1911).

For the description of the fluid flow we use the Lagrangian description, which consists of following the motion of a fluid element, developed through the Smoothed Particle Hydrodynamics method, where each fluid element is represented by particles, in particular we used the hydrodynamic code *FI* (Pelupessy et al., 2004). The gravitational interactions between protostars was modeled via a pure N-body code that solves Newton´s equations of motion without free physical parameters, where most have the capacity to flag special events, such as close encounters. In particular we use the pure N-body code *ph4* (McMillan & Hut, 1996) which is based on the fourth-order Hermite predictor-corrector scheme (Makino & Aarseth, 1992) in combination with the time symmetric integration scheme of Hut et al. (1995). To couple the gravitational interactions between gas and protostars we use the BRIDGE method (Fujii et al., 2007), so that protostars experience both the gravitational force from each other as well as from the gas and vice versa.

We solved the collisions between two protostars by taking the sticky-sphere approach, which means that a collision occurs when the separation d between two stars is smaller than the sum of the radii of stars. In our initial exploration we do not consider mass loss, therefore we assume that during the collision the total mass is conserved. The radius of the new star is determined by the mass-radius parameterization of Hosokawa et al. (2012) which is completely defined by their mass m and their accretion rate $\dot{m}$, where this radius is updated for each time step.

For the characterization of the protostars we use the sink particles, in particular the model of *NewSink* proposed by Hubber et al. (2013). They introduce a new quality to the sink particles, called the interaction-zone R_s. Compared to traditional models the interaction-zone contains live SPH particles j, that have not yet been completely accreted by the point-mass s. The accreted mass $\delta M_{\rm ACC}$, depends on the accretion time $t_{\rm ACC}$, which in turn depends on two scenarios for the accretion by pre-existing sink particles, from equations (8) and (10) in Hubber et al. (2013), these are timescale for the spherical symmetric radial accretion (Eq.1) and disc accretion (Eq.2):

$$\langle t_{\rm RAD}\rangle_s = \frac{\sum_j \{m_j\} w}{4\pi \sum_j \{|\Delta r_{js}| \Delta r_{js} \cdot \Delta v_{js} m_j W(|\Delta r_{js}|, H_s)\}} \,,(1)$$

$$\langle t_{\rm DISC}\rangle = \frac{(GM_s)^{1/2}}{\alpha_{SS}\ w} \sum_j \left\{ \frac{|\Delta r_{js}|^{1/2} m_j W(|\Delta r_{js}|, H_s)}{\rho_j a_j^2} \right\} \,.(2)$$

Where the weighting is through the kernel-function, W, H_s is the smoothing length of the sink and w ensures that the sum is normalised. Here ρ, a, m, v are the density, acceleration, mass, velocity and Δr_{js} is the position of particle j relative to s. For the disc accretion, α_{SS} conflates all possible angular momentum transport mechanisms. Depending on the properties of the gas particles in the interaction-zone and comparing the rotational and gravitational energy, we determine the timescale for the accretion with the following equations,

$$t_{\rm ACC} = \langle t_{\rm RAD}\rangle_s^{(1-f)} \langle t_{\rm DISC}\rangle_s^{f} \,, \qquad (3)$$

$$f = {\rm MIN}\left\{ \frac{2E_{\rm ROT}}{|E_{\rm GRAV}|}, 1 \right\} \,. \qquad (4)$$

Here $E_{\rm ROT}$ and $E_{\rm GRAV}$ are the net rotational and gravitational energies of the SPH particles in the interaction-zone, relative to the point-mass.

3. Results

The main results of our first simulations are presented in this section. We show a proof of concept that many accretion-induced collisions can lead to the formation of a single massive object.

The setup we chose for this first simulations was $\rm M_{Gas} = 3\,000$ [$\rm M_\odot$], $\rm M_{Stars}$ = 25,6 [$\rm M_\odot$], $\rm R_{Stars} = R_{Gas} = 0.14$ [pc], assuming that both the gas and the protostars follow a plummer distribution. We also assume an isothermal gas with an initial temperature of 8 000 [K]. This initial setup was chosen to have a good mass resolution of the SPH particle, this being ≈ 0.022 [$\rm M_\odot$] for each SPH particle. The evolution of the mass in gas, stars and the most massive object as a function of time are shown in Fig. 1, where we note that in this configuration the accretion occurs gradually and that the gas mass decreases by around 60%, while the stellar mass increases by the same amount, given that we do not include mass loss in this simulation. In the second panel we can see that much of the mass of the protostars belongs to a single massive object, where around 70% of the mass accreted from the gas is found in this massive object.

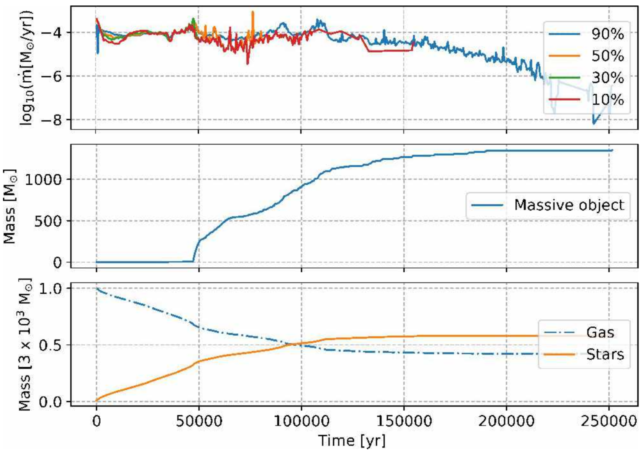

Figure 1: Evolution time of a cluster with $N = 256$ stars, total mass $M_{\mathrm{Stars}} = 25,6$ [$M_\odot$], $R_{\mathrm{Stars}} = 0.14$ [pc]. The *top panel* shows accretion rates of the stars in 90%, 50%, 30% and 10% Lagrangian radii, the *middle panel* shows the mass of the most massive object in the system and the *bottom panel* shows the total gas mass, total stellar mass and the mass from the gas is outside the system.

In Fig. 2 we show the Lagrangian radii of 90%, 50%, 30% and 10% of the protostars, of the gas and of the complete system. We can see that the protostars experience an initial contraction, as a result of the collapse of the gas and the steepening of the potential and later there is a slight expansion of the cluster. Much of the mass of the protostars is concentrated in the core of the cluster, as well as the gas mass. However, we can see from the lower panel that much of the mass of the system is concentrated in the nucleus, therefore it favors accretion both for protostars near the center and for the most massive object, thus causing a widening of the protostar radius and improving the probability of collisions occur.

4. Conclusions

The results presented so far show that the formation of a central massive object is a posible outcome, in the regime of a protostellar cluster embedded in a primordial gas cloud, incorporating a physically consistent gas treatment, where more than 50% of the mass of the gas cloud is transferred to the protostars through accretion and subsequently accumulated in a massive object through collisions. At least under the conditions explored here, the formation of a massive object appears to be feasible. In this work we have not yet implemented cooling or heating processes, but (Chon & Omukai, 2020b) explored similar scenarios including tabulated density-temperature values pre-calculated with one-zone models and our results agree with their low metalliciy cases ($< 10^{-4}$ [$Z_\odot$]) and based on the other models we expect more fragmentation and lower accretion rates when cooling is more efficient. The final masses and mass distributions need to be explored in future work.

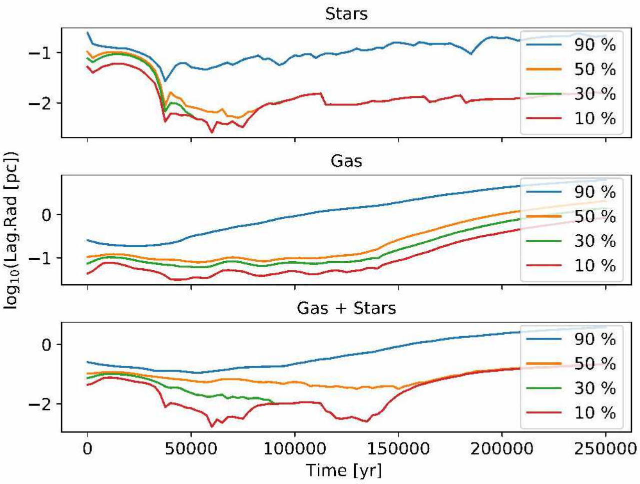

Figure 2: Evolution time of a cluster with $N = 256$ stars, total mass $M_{\mathrm{Stars}} = 25,6$ [$M_\odot$], $R_{\mathrm{Stars}} = 0.14$ [pc]. The *top panel* shows the Lagrangian radii of 90%, 50%, 30% and 10% of the protostar cluster, the *middle panel* shows the Lagrangian radii of the gas with the same percentages and the *bottom panel* shows the Lagrangian radii of the complete system.

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