Impact of radiation backgrounds on the formation of massive black holes

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Resumen / La existencia de agujeros negros supermasivos de mil millones de masas solares a muy alto corrimiento al rojo, nos ha motivado a estudiar como estos objetos tan masivos se forman durante los primeros miles de millones de años después del Big Bang. Un modelo prometedor que se ha propuesto es el colapso directo de nubes de gas protogalácticas. Este escenario requiere altas tasas de acreción para crear rápidamente objetos masivos y la inhibición del enfriamiento que causa H_2 I, el cuál es importante en el proceso de fragmentación. Estudios recientes mostraron que, si usamos un fondo radiativo fuerte, el hidrógeno molecular se destruye, favoreciendo las altas tasas de acreción y por lo tanto formando objetos de muy alta masa. En este trabajo estudiamos el impacto de campos de radiación UV en una nube de gas primordial, usando el código *GRADSPH-KROME* para investigar el proceso de fragmentación en escalas de unidades astronómicas y por lo tanto la formación de los primeros agujeros negros supermasivos. Encontramos que para suprimir la formación de H_2 I es necesario un valor de J_{21} muy alto ($\sim 10^5$). Como se mostró en un trabajo previo, tales fondos de radiación fuertes son muy raros, por lo que el colapso directo es dificil de conseguir. Por lo tanto, este método dificilmente podría explicar la formación de los primeros agujeros negros supermasivos.

Abstract / The presence of supermassive black holes (SMBHs) of a few billion solar masses at very high redshift, has motivated us to study how these massive objects formed during the first billion years after the Big Bang. A promising model that has been proposed to explain this, is the direct collapse of protogalactic gas clouds. In this scenario, very high accretion rates are needed to form massive objects early on, and the suppression of H_2 I cooling is important in regulating the fragmentation. Recent studies have shown that if we use a strong radiation background, the hydrogen molecules are destroyed, favoring the high accretion rates and therefore producing objects of very high mass. In this work, we study the impact of UV radiation fields in a primordial gas cloud using the recently coupled code *GRADSPH-KROME* for the modeling of gravitational collapse, including primordial chemistry to explore the fragmentation in AU scales and hence the formation of thr first SMBHs. We found that, to suppress the formation of H_2 I, a very high value of J_{21} is required ($\sim 10^5$). As shown in a previous work, such strong radiation backgrounds are very rare, so that the direct collapse may be difficult to achieve. Therefore, this method could hardly explain the formation of the first SMBHs.

Keywords / black hole physics — cosmology: theory — early Universe — stars: formation — hydrodynamics

1. Introduction

More than 100 supermassive black holes (SMBHs) with masses of about 10^9 $M_\odot$ at very high redshift ($z \geq 6$) have been discovered in the last years through several surveys (Gallerani et al., 2017; Schleicher, 2018). The highest-redshift quasar observed are at $z = 7.54$ with a mass of 8×10^8 $M_\odot$ (Bañados et al., 2018), and another one at $z = 7.085$ with a mass of 2×10^9 $M_\odot$ (Mortlock et al., 2011). The formation of the first structures is not yet understood, and the formation of the first SMBHs is still an open question in cosmology. Among the models that have been proposed to explain the formation of SMBHs in the early universe, the direct collapse of protogalactic gas clouds (Loeb & Rasio, 1994; Bromm & Loeb, 2003; Shlosman et al., 2016) is a very promising scenario as it provides the most massive black holes seeds ($M \sim 10^5$ $M_\odot$), which can then grow at relatively moderate accretion rates to form SMBHs.

The formation of direct collapse black holes (DCBHs) requires an efficient accretion rate of gas to the central object ($\dot{M} \approx 1$ $M_\odot$ yr^{-1}), and the suppression of fragmentation of the cloud (Schleicher et al., 2013; Hosokawa et al., 2013). These conditions can be achieved if the gas collapses isothermally at a temperature of $T \approx 10^4$ K (Omukai et al., 2008). Such a collapse is possible if the gas has zero metallicity and the main cooling mechanism in the early universe (H_2 I cooling) is suppressed, due to an intense radiation background (Bromm & Loeb, 2003; Visbal et al., 2014).

In order to study the cooling process of the gas cloud, we need to include the chemical reactions involved in the formation (via gas-phase reactions) of H_2 I:

$$H + e^- \rightarrow H^- + \gamma, \quad (1)$$

$$H + H^- \rightarrow H_2 + e^-. \quad (2)$$

Once the first generation of stars (Pop III) are formed, they will irradiate the intergalactic medium

(IGM) with a UV flux and pollute it with metals, through supernova explosions, leading to the formation of the second generation of stars (Pop II). The UV flux produced by these stellar populations, can destroy H_2 I through the Solomon process (Eq. 3) and photo-detach electrons from H^- (Eq. 4).

$$H_2 + \gamma_{LW} \rightarrow H + H, \quad (3)$$
$$H^- + \gamma_{0.76} \rightarrow H + e^-. \quad (4)$$

Thus, massive primordial haloes of $10^7 - 10^8$ $M_\odot$ that formed in the early universe and irradiated by nearby star-forming regions of Pop II and Pop III at $z = 15-20$, are the most plausible cradles for DCBH formation. The available flux from star-forming regions is measured in units of J_{21}, with $J_{21} = 1$ corresponding to a flux of 10^{-21} erg cm^{-2} s^{-1} Hz^{-1} sr^{-1} at the Lyman limit. We assume for simplicity that the shape of the spectrum corresponds to that of a blackbody.

In a recent study, Latif et al. (2015) performed three-dimensional (3D) cosmological simulations to determine the critical UV flux $J_{21}^{\rm crit}$ above which H_2 I cooling is suppressed in protogalactic gas clouds of $10^7 - 10^8$ $M_\odot$, including the impact of X-ray ionization and realistic Pop II spectra. They found that $J_{21}^{\rm crit}$ for realistic Pop II spectra, is a few times 10^4 and weakly depends on the adopted radiation spectra in the range between $T_{\rm rad} = 2 \times 10^4 - 10^5$ K, and that the impact of X-ray ionization is negligible. These results suggest that DCBHs could be rarer than previously thought.

2. Computational Methods

In this work, we performed our simulations with the coupling of the Smoothed Particle Hydrodynamics (SPH) code *GRADSPH** (Vanaverbeke et al., 2009) with the chemistry package *KROME*** (Grassi et al., 2014). This combined code, called *GRADSPH-KROME*, allows us to include the chemistry and cooling in hydrodynamical simulations of the star forming gas. The code was previously employed by Riaz et al. (2018c) to explore the fragmentation process for the formation of binary systems. Here we explore the chemical conditions in the presence of different UV fluxes, to determine the flux that is required for an atomic collapse.

2.1. GRADSPH

GRADSPH is a parallel SPH code combined with a tree code gravity (TCG) method for evolving 3D self-gravitating, astrophysical fluids. It uses the standard M4-kernel or a cubic spline kernel with a compact support that contains particles within a smoothing sphere of size $2h_i$ (Price & Monaghan, 2007). This smoothing length is determined by $h_i = \eta\,(m_i/\rho_i)^{1/3}$, where η is a dimensionless parameter which determines the size of the smoothing length of the SPH particle given its mass and density. It is important to know that the mass contained within the smoothing sphere of each particle should be held constant. Also, *GRADSPH* implemented a second-order PEC (predict-evaluate-correct) scheme combined with an individual particle time stepping method, to solve the system of ordinary differential equations that updates the positions and velocities of the particles. The work presented in Riaz et al. (2018a) and Riaz et al. (2018b) are examples of simulations with *GRADSPH*.

*http://www.swmath.org/software/1046

**http://www.kromepackage.org

2.2. Chemistry, cooling and UV background

The *KROME* package allows us to model chemical network in numerical simulations. In this work, we prepare a chemical network based on the network react_xrays provided by *KROME*, with the chemical reactions presented in Glover (2015a) and Glover (2015b), giving a total of 35 chemical reactions with 9 different chemical species (e^-, H^-, H I, H II, He I, He II, He III, H_2 I, H_2 II). The initial mass fraction of these chemical species are: $f_{\rm H} = 0.75$, $f_{\rm H_e} = 0.24899$, $f_{\rm H_2} = 10^{-3}$, $f_{\rm H} = 8.2 \times 10^{-4}$, $f_{\rm e^-} = 4.4 \times 10^{-8}$, while for the other species is set to zero.

2.3. Setup

Our spherical primordial gas cloud is modeled as a distribution of 507 443 SPH particles, with an initial temperature of 10^4 K. This cloud has a total mass of $M_{cloud} = 6.4 \times 10^6$ $M_\odot$, a radius of $R_{cloud} = 80.4$ pc and an initial density of $\rho_{cloud} = 2.0 \times 10^{-22}$ g cm^{-3}. Additionally, the gas is in solid body rotation with an angular velocity of $\omega = 2.3 \times 10^{-15}$ rad s^{-1}, and is turbulent with a Mach number $\mathcal{M} = 1.0$.

3. Results

Fig. 1 shows the thermal and species profiles for different strengths of the UV flux. We can see that, for the weaker value of J_{21}, the cooling due to H_2 I becomes effective, thus, the gas initialized with a temperature of 10^4 K, cools down to about 10^3 K. For $J_{21} = 10^4$ we can see that the H_2 I formation remains suppressed until a density of 10^{-20} g cm^{-3}, which illustrates the presence of two gas phases at the same density, similar to Fig. 3 in Latif et al. (2014). For the higher value of J_{21} we see that the gas is in an atomic state in which H_2 I remains suppressed, due to the high radiation, and it remains in a hot phase following the theoretical expectations. Nevertheless, the value of $J_{21}^{\rm crit}$ that we found is very high, in the range of $10^4 - 10^5$. Also, the right panel of Fig. 1 shows the evolution of H_2 I, H II and e^-. As they act as catalysts, we see that for the weaker values of J_{21}, the amount of e^- and H II is the same after the reaction and recombination have taken place, and their number densities are depleted due to the formation of H_2 I. For $J_{21} = 10^5$ the H II and e^- number densities increase and become constant, because the formation of H_2 I remains inhibited.

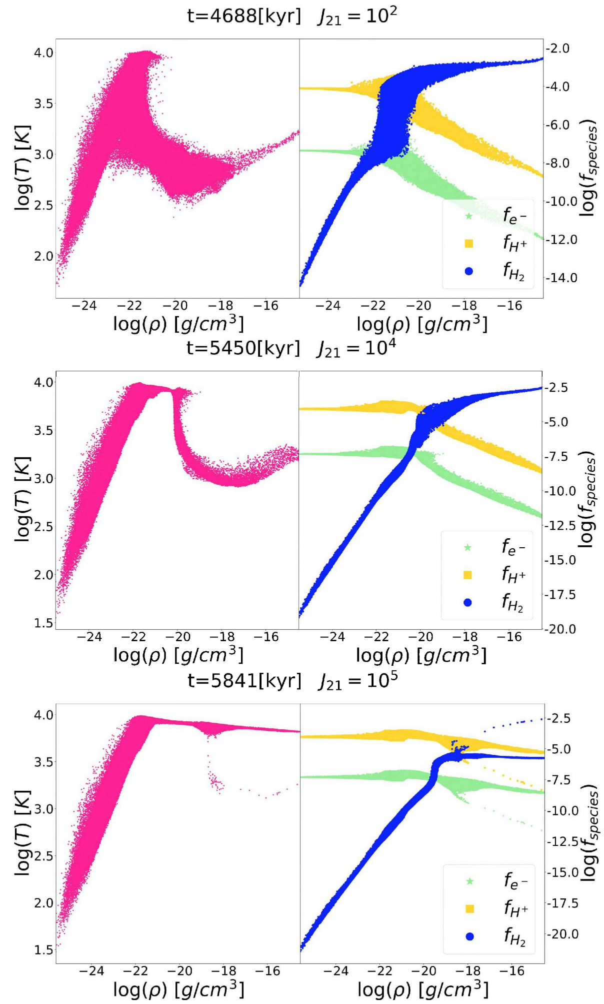

Figure 1: Thermal and species profiles (H_2 I in blue dots, H II in yellow squares and e^- in green stars) for different strengths of UV flux. Upper panel is for $J_{21} = 10^2$ middle panel for $J_{21} = 10^4$ and bottom panel for $J_{21} = 10^5$.

4. Conclusions and Outlook

To form a supermassive star or a massive black hole seed, we need high accretion rates, as shown in Schleicher et al. (2013) and Hosokawa et al. (2013), these high accretion rates requires large sound speeds and therefore a hot gas. For such a hot gas to remain atomic, we found a very high value of J_{21} is required, in the range of $10^4 - 10^5$. As shown in Dijkstra et al. (2014), these high values occur very rarely. This is because, in order to obtain the necessary high values of J_{21} for the DCBHs formation sites, we have to consider very nearby star-forming galaxies. The later includes galactic winds, that will produced metal enrichment suppressing the predicted DCBHs formation sites. Also, Dijkstra et al. (2014) estimated the DCBH number density (n_{DCBH}) finding at $z = 10$ that $n_{DCBH} \sim 10^{-3}$ cMpc^{-3} for $J_{21} = 30$, and $n_{DCBH} \sim 10^{-10} - 10^{-5}$ cMpc^{-3} for $J_{21} = 300$. Sugimura et al. (2014) re-estimate this value but for $J_{21} = 1400$, finding that $n_{DCBH} \sim 10^{-10}-10^{-7}$ cMpc^{-3} at $z = 10$. We can see that n_{DCBH} decreases if we increase the value of J_{21} so, with our values of J_{21}, n_{DCBH} will be much lower. For comparison, the observed high redshift SMBH number density is $n_{SMBH} \sim 10^{-9}$ cMpc^{-3} at $z \sim 6$, thus we conclude that black hole formation via direct collapse is efficiently suppressed and could hardly explain all the observed quasars at high redshift. This is because the formation of DCBHs requires $n_{DCBH} \gg n_{SMBH}$ to provide a viable mechanism for SMBHs. However, we can consider alternative pathways to form SMBHs, such as collisions in primordial star clusters (Reinoso et al., 2018; Boekholt et al., 2018), among others (for additional formation channels see Latif & Ferrara, 2016 and Woods et al., 2018).

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