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The impact of streaming velocities: delaying the formation of the first stars

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Abstract. In some regions of the Universe, there is a relative offset between the velocity of the dark matter and baryons, the so-called streaming velocity. The root–mean–squared value of the streaming velocity, $\sigma_{\rm rms} = 30\,{\rm km\,s^{-1}}$ at recombination, decays with $(z+1)$ and is still significant at redshifts of $z \approx 15$, where the first stars form. We study the effects of the streaming velocity in a large sample of minihaloes with highly resolved cosmological simulations performed with the moving-mesh code AREPO. We find that the baryon fraction in these minihaloes is reduced in regions with non-zero streaming velocity. Consequently, the formation of the first stars is suppressed and shifted to larger halo masses. In addition, regions with $3\,\sigma_{\rm rms}$ streaming velocity might be the ideal environments for direct collapse black hole formation.

Key words. Early universe – Dark ages, reionisation, first stars – Stars: Population III

1. Introduction

It has recently been discovered that relative velocities between baryons and dark matter exist at recombination, which are important in the context of the formation of the first stars (Tseliakhovich & Hirata 2010). This study shows that this relative velocity is coherent over several comoving Mpc with a root–mean–squared value at $z \approx 1100$ of $\sigma_{\rm rms} \approx 30$ km s^{-1}. Although this relative velocity decreases as $v \sim (1 + z)$ as the Universe expands, it nevertheless has profound effects on the formation of dark matter minihaloes. Streaming leads to a reduced baryon fraction in the haloes (Naoz et al. 2012) and a lower halo number density (Tseliakhovich et al. 2011; Naoz et al. 2013), as it is harder for baryons to settle into the host dark matter haloes. As a consequence, Population III (Pop III) star formation is delayed (Greif et al. 2011b; Fialkov et al. 2012, see however Stacy et al. 2011) and the minimum halo mass required for efficient H_2 cooling is increased. We are now providing a statistical sample of minihaloes created in cosmological simulations. A full network of primordial chemistry is included, allowing us to study the thermal evolution of the gas. Our parameter space accounts for regions of the Universe with streaming velocities of 0, 1, 2 and 3 times $\sigma_{\rm rms}$.

2. Simulations

We carry out five cosmological simulations using the moving-mesh code AREPO (Springel 2010). AREPO solves the equations of hydrodynamics on an unstructured mesh defined by the Voronoi tessellation of a set of mesh-generating points that move with the flow of the gas. Dark matter is included using a Barnes & Hut (1986) oct-tree.

To model the chemical and thermal evolution of the gas, we use an updated version of the primordial chemistry network and cooling function implemented in AREPO by Hartwig et al. (2015). In addition, a simplified treatment of hydrogen deuteride is included. More details on the chemical network can be found in Schauer et al. (2017b).

The simulations are initialised at redshift $z = 200$ with the code MUSIC (Hahn & Abel 2011) and run down to redshift $z = 14$. Four have a box length of 1 cMpc/h, where h is the dimensionless Hubble constant and c stands for comoving, and one has a box length of 4 cMpc/h. We explore a parameter space of 0, 1, 2 and 3 $\sigma_{\rm rms}$ that translates into 0, 6, 12 and 18 km s^{-1} at redshift $z = 200$. For the simulation with 3 $\sigma_{\rm rms}$, we run the small and the big box, for all other values, we only run the small box.

3. Results

3.1. Baryon fractions in minihaloes

As a first result, we investigate the baryon fraction in minihaloes with masses of $M_{\rm halo} \geq 10^5$ M$_\odot$. Figure 1 shows the baryon fraction as a function of redshift for all small box simulations. We can see that the baryon fraction for the simulation without streaming velocity approaches the cosmic mean. For the simulations with 1, 2 or 3 $\sigma_{\rm rms}$, the haloes have a lower baryon fraction that can reach below 2% for $v = 3\sigma_{\rm rms}$.

3.2. Minimum halo mass for first star formation

In our statistical sample of minihaloes, we want to investigate not only the baryon fraction, but also the fraction of gas that is able to form Pop III stars. We therefore measure the cold gas in each halo[1].

We investigate which haloes contain at least one cold gas cell. We expect these objects to be the sites of Pop III star formation and are therefore interested in the halo masses. At each redshift, we find the least massive halo that contains cold gas, a quantity we term minimum halo mass. In addition, we are also interested in at which halo mass more than 50% of haloes contain cold gas.

Both quantities can be seen in Figure 2 as a function of redshift for all different streaming velocities. In a region of the Universe with zero streaming velocity, we find that the minimum mass above which a halo forms cold gas in its centre is $M_{\rm halo,min} \approx 4.8 \times 10^5$ M$_\odot$. The minimum halo mass increases to 1.4×10^7 M$_\odot$ at 3 $\sigma_{\rm rms}$. We do not see a dependence of this mass on redshift.

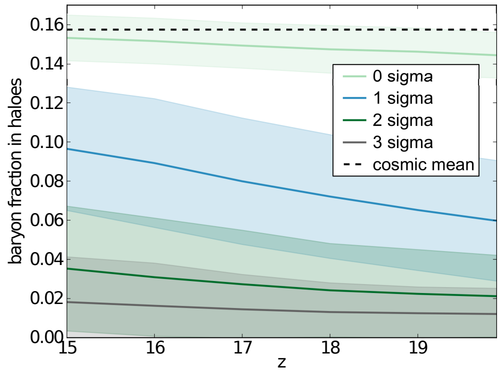

Fig. 1. Baryon fraction as a function of redshift for all small box simulations. We show the baryon fraction for all haloes with masses $M_{\rm halo} \geq 10^5$M$_\odot$.

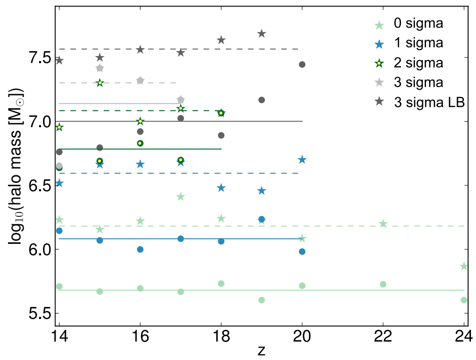

Fig. 2. Minimum halo mass (circles) and halo mass above which 50% of all haloes (stars) contain cold gas as a function of redshift for all simulations.

[1] We denote gas as cold if its number density $n \geq 100\,{\rm cm}^{-3}$, its temperature $T \leq 500$ K and its H_2 abundance $\xi \geq 10^{-4}$.

3.3. High streaming velocity regions: Environments for DCBHs

For regions with the highest streaming velocity values we investigate, $3\,\sigma_{\rm rms}$, the halo mass required for effective cooling shifts above the atomic cooling mass[2].

We investigate all haloes whose centres have collapsed to number densities of $n \geq 10^4\,{\rm cm}^{-3}$ (see Schauer et al. 2017b). All of them contain molecular hydrogen and their centres are cold. As H_2 formation is not suppressed, gas in these haloes will not collapse without fragmentation and form a supermassive star (and subsequently a very massive black hole), giving rise to Pop III star formation.

In the synchronized halo model (as e.g. discussed by Regan et al. 2017), two neighbouring haloes are needed for DCBH formation that need to be well-synchronized in time and distance. One needs to collapse a few kyr to Myr earlier than the other, igniting a large star burst. The resulting Lyman-Werner (LW) radiation is then incident on the neighbouring halo, destroying its H_2. When this second halo collapses, it then forms one massive object as fragmentation is suppressed.

For this scenario to work, it is crucial that neither of the haloes are pre-enriched by metals. In $3\,\sigma_{\rm rms}$ streaming velocity regions, Pop III star formation in minihaloes is suppressed. We conclude that these small haloes stay pristine and metal-free. Consequently, close pairs of atomic cooling haloes forming in regions of the Universe with $v_{\rm stream} \geq 3\sigma_{\rm rms}$ are good candidates for the formation sites of DCBHs.

Combining the number densities of the synchronized halo pairs estimated by Visbal et al. (2014b) and the volume fraction of the Universe with streaming velocity of $3\,\sigma_{\rm rms}$ or higher, we find a number density for DCBHs of $\sim 1\,{\rm cGpc}^{-3}$. This value is very close to the observed number density of high redshift quasars that has been estimated to be $\sim\ 0.7\,{\rm cGpc}^{-3}$ (Fan et al. 2006). We therefore might explain the existence of these massive, early quasars with our model.

[2] The mass scale at which cooling is dominated initially by atomic hydrogen rather than H_2.

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