

Do Small-Scale Dark Matter Fluctuations Govern the Fragmentation of Primordial Gas?

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Abstract. In order to constrain the initial mass function of the first generation of stars (Population III), one has to study the fragmentation properties of primordial gas. We present results from 3D simulations, based on Smoothed Particle Hydrodynamics, which explore the idea that small-scale fluctuations in the (cold) dark matter recreate a filamentary and clumpy structure in the gas component on scales smaller than the initial Jeans mass, where all primordial fluctuations would have been wiped out.

INTRODUCTION

In order to ascertain the influence of the very first generation of stars (Population III) on cosmology, one has to address the problem of how primordial (pure H/He) gas collapses and fragments. Whether the outcome of this process is a supermassive object or a cluster of lower-mass stars, is determined by the Population III initial mass function (IMF), which might differ substantially from the present-day one. The fragmentation properties depend crucially on the adopted initial conditions for the cloud collapse. In principle, these are given by the underlying model of cosmic structure formation. It is straightforward to specify the global properties of the gas cloud in terms of its average temperature, density, and chemical abundances [1].

Much less well-defined are the density and velocity fields inside the cloud. The nature of these initial perturbations could govern the ensuing fragmentation of the gas. There is no direct connection, however, between them and the fundamental physics which determines the primordial power spectrum of density perturbations, since primordial fluctuations in the baryon component below the Jeans length have been wiped out by pressure forces, as described by the small-scale cutoff in the baryon power spectrum:

$$|\delta_B(k)|^2 = \frac{|\delta_{DM}(k)|^2}{(1 + \gamma k^2)^2} \quad , \quad (1)$$

where $|\delta_{\text{B,DM}}(k)|^2$ are the power spectra in the baryon and dark matter (DM) components, respectively, k is the comoving wavenumber, and $\gamma^{\frac{1}{2}} \simeq 1h^{-1}\text{kpc}$ is the comoving Jeans length (cf. [2]).

In this paper, we investigate whether the small-scale fluctuations in the (cold) dark matter component, which have not been erased, do govern the fragmentation of the baryons, which might start with a completely smooth distribution. At first, the baryons would not be able to follow the growing DM clumping, due to the opposing effect of pressure forces. In the course of a nearly isothermal collapse, however, the Jeans mass decreases as $M_J \propto \rho^{-\frac{1}{2}}$, allowing the baryons to fall into the resulting DM condensations.

In the following, we present first results on how the baryons evolve in this scenario.

SIMULATIONS

For our 3D hydrodynamics/dark matter simulations, we use a variant of TREESPH [3], into which we have incorporated the relevant chemistry of the formation and destruction of molecular hydrogen, which is the main coolant below 10^4 K in the absence of metals. We use an improved version of the H_2 cooling function which takes into account quantum effects at low temperatures ($T < 600$ K) [4]. In order to follow the evolution well into the regime of highly developed clumping, we have devised an algorithm to merge high-density particles (corresponding to excessively small timesteps) into more massive ones, which enables us to follow the evolution beyond the point where otherwise the Courant-condition would force the calculation to a halt. The merging mechanism allows the high-density particles to continually accrete nearby particles, thereby modelling the physics of accretion and merging in an approximate way.

Our starting model consists of a spherical configuration with a total mass of $M = 10^6 M_\odot$, a radius of $R = 80 \text{ pc}$, and a spin parameter of $\lambda = 0.05$. In CDM-like scenarios, these are typical values for a 3σ peak, virializing at $z \simeq 30$ [1]. On top of the originally homogeneous DM mass distribution, we imprint fluctuations by assigning initial velocities to the DM particles, as prescribed by the Zel'dovich approximation [5]. The Zel'dovich velocity field is calculated with a power spectrum $|\delta_{\text{DM}}(k)|^2 = Ak^{-2.9}$, corresponding to the small-scale end of the standard CDM spectrum. The amplitude A is chosen to match $\sigma_{M=10^6 M_\odot} = 0.5$ at $z \simeq 30$, appropriate for a collapsing 3σ peak. Embedded in the DM halo is a homogeneous gas cloud with $\Omega_{\text{B}} = 0.05$, an initially isothermal $T_i = 1000$ K, an H_2 fraction of 10^{-3} , and a free electron abundance of 10^{-4} (cf. [1]). With the exception of the always present SPH shot-noise ($\propto N^{-\frac{1}{2}}$), there are no density fluctuations in the baryonic component.

We have performed the simulations with $N = 65536$ particles in each component, as well as a comparison calculation at low resolution ($N = 8192$). Fig. 1 shows the DM and baryon distribution after one free-fall time. The collapsing dark matter has

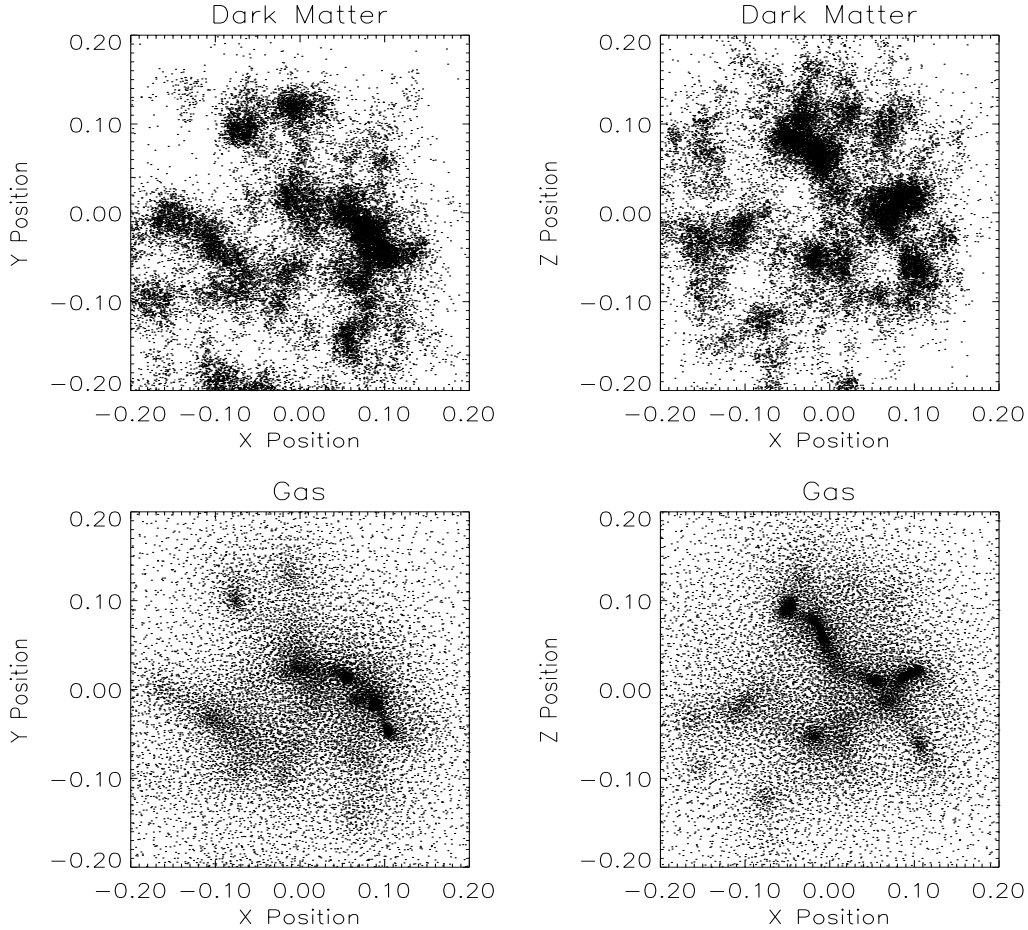


FIGURE 1. *Left column:* Face-on view. *Right column:* Edge-on view. Dark matter and baryon distribution after one free-fall time. $N_{\text{SPH}} = N_{\text{DM}} = 65536$. Shown is a blow-up of the central region, where a dimensionless length of 0.1 corresponds to 8pc. The baryons start to fall into the DM troughs.

been organized into a pronounced structure of filaments and clumps, in response to the initial Zel’dovich velocity field. The cooling baryons have begun to condense into the DM troughs, closely following the DM morphology. Consequently, gas fragmentation is induced before the DM fluctuations are washed out by the process of violent relaxation, which will eventually lead to a smooth (roughly isothermal) mass distribution.

In Fig. 2, we present the distribution of gas at a slightly later time, $t = 1.2t_{\text{ff}}$, for the low-resolution run. Here, most of the gas ($\sim 60\%$) resides in high-density clumps, which are a result of the merging procedure. The resulting mass spectrum of these merged clumps follows a power-law with roughly the Salpeter slope. This result should be taken *cum grano salis*, and its robustness has to be tested in runs with higher resolution and with different initial conditions.

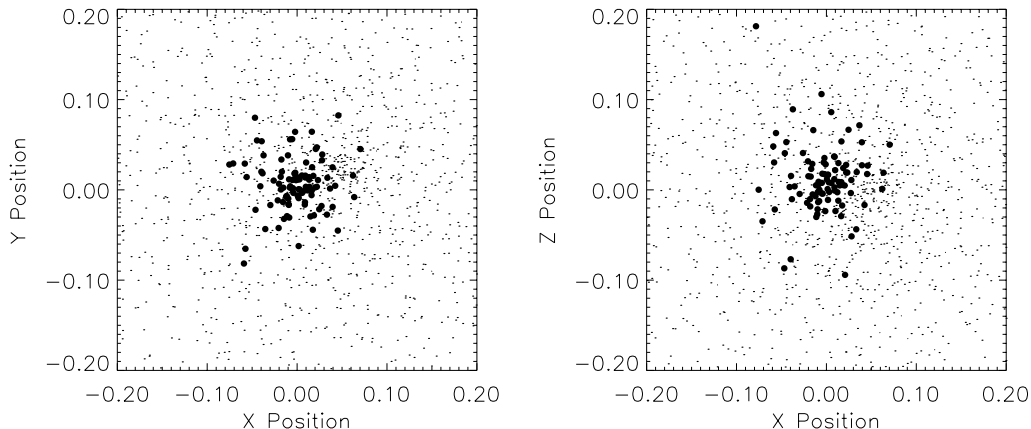


FIGURE 2. Gas distribution after $t = 1.2t_{\text{ff}}$. $N_{\text{SPH}} = N_{\text{DM}} = 8192$. Same units as in Fig. 1. Most of the gas has been incorporated into high-density clumps (*heavy dots*).

OUTLOOK

Although idealized, the appeal of the above scenario lies in the promise of being able to specify the initial conditions of the primordial star formation problem in a non-arbitrary way, directly connected to the underlying model of cosmic structure formation. But there remain many caveats which have to be explored. Does it make sense to treat a high- σ peak in isolation? Is the initial baryon distribution really smooth, or instead structured through complex processes which are difficult to specify without simulating a much larger region of the Universe?

We hope to gain a better understanding of these issues by comparing our results with those from large-scale cosmological simulations. Independent of the particular model proposed above, it makes sense to study the fragmentation of primordial gas in a broad range of circumstances (e.g., using various spectral indices and amplitudes for both the baryon and DM components). Currently, we are undertaking such a comprehensive study, on which we will report elsewhere.

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REFERENCES

1. Tegmark, M., Silk, J., Rees, M.J., Blanchard, A., Abel, T. & Palla, F. 1997, ApJ, 474, 1
2. Peebles, P.J.E. 1993, Principles of Physical Cosmology (Princeton: Princeton University Press), p. 636
3. Hernquist, L. & Katz, N. 1989, ApJS, 70, 419
4. Galli, D. & Palla, F. 1998, A&A, 335, 403
5. Zel'dovich, Y.B. 1970, A&A, 5, 84