

From Darkness to Light: The First Stars in the Universe

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Abstract. Paramount among the processes that ended the cosmic ‘dark ages’ must have been the formation of the first generation of stars. In order to constrain its nature, we investigate the collapse and fragmentation of metal-free gas clouds. We explore the physics of primordial star formation by means of three-dimensional simulations of the dark matter and gas components, using smoothed particle hydrodynamics. We find characteristic values for the temperature, $T \sim$ a few 100 K, and the density, $n \sim 10^3 - 10^4 \text{ cm}^{-3}$, characterising the gas at the end of the initial free-fall phase. The corresponding Jeans mass is $M_J \sim 10^3 M_\odot$. The existence of these characteristic values has a robust explanation in the microphysics of H_2 cooling, and is not very sensitive to the cosmological initial conditions. These results suggest that the first stars might have been quite massive, possibly even very massive with $M_* > 100 M_\odot$.

1 Introduction

The history of the universe proceeded from an extremely uniform initial state to the highly structured present-day one. When did the crucial transition from simplicity to complexity first occur? Recently, this question has become the focus of an intense theoretical effort (e.g., [1,2,3,4,5,6,10,12]). There must have been a time, between the last scattering of the CMB photons at $z \sim 1000$ and the formation of the first luminous objects at $z > 6$, when the universe contained no visible light. This era has been called the cosmic ‘dark ages’, and the key question is how and when it ended (e.g., [15]).

In the context of hierarchical scenarios of structure formation, as specified by a variant of the cold dark matter (CDM) model, the collapse of the first baryonic objects is expected at redshifts $z \simeq 50 - 10$, involving dark matter halos of mass $\sim 10^6 M_\odot$ [16]. The question arises how one can make any progress in understanding primordial star formation, given the lack of direct observational constraints. The physics of the first stars, however, is characterized by some important simplifications, as compared to the extreme complexity of present-day star formation [9]. The absence of metals, and consequently of dust, leaves atomic and molecular hydrogen as the main agent of radiative cooling and the source of opacity. Magnetic fields were likely to be dynamically insignificant, prior to the onset of efficient (stellar) dynamo amplification. The chemistry and heating of the primordial gas was not yet complicated by the presence of a

UV radiation background. The intergalactic medium (IGM) must have been a rather quiescent place, with no source to sustain turbulent motion, as long as the density perturbations remained in their linear stage. Only after the explosion of the first supernovae, and the associated input of mechanical and thermal energy, is this state of primordial tranquility bound to change [8]. Therefore, the physics of primordial star formation is mainly governed by gravity, thermal pressure, and angular momentum. This situation renders the problem theoretically more straightforward and tractable than the highly complex present-day case which continues to defy attempts to formulate a fundamental theory of star formation. Finally, the initial conditions for the collapse of a primordial star forming cloud are given by the adopted model of cosmological structure formation.

The importance of the first stars and quasars derives from the crucial feedback they exert on the IGM. A generation of stars which formed out of primordial, pure H/He gas (the so-called Population III) must have existed, since heavy elements can only be synthesized in the interior of stars. Population III stars, then, were responsible for the initial enrichment of the IGM with heavy elements. From the absence of Gunn-Peterson absorption in the spectra of high-redshift quasars, we know that the universe has undergone a reionization event at $z > 6$. UV photons from the first stars, perhaps together with an early population of quasars, are expected to have contributed to the reionization of the IGM [8,7,11].

To probe the time when star formation first started entails observing at redshifts $z > 10$. This is one of the main purposes of the *Next Generation Space Telescope* (NGST) which is designed to reach \sim nJy sensitivity at near-infrared wavelengths. In preparation for this upcoming observational revolution, the study of the first stars is very timely, providing a theoretical framework for the interpretation of what NGST might discover, less than a decade from now.

2 Simulations

Our code is based on a version of TREESPH which combines the Smoothed Particle Hydrodynamics (SPH) method with a hierarchical (tree) gravity solver. To study primordial gas, we have made a number of additions. Most importantly, radiative cooling due to hydrogen molecules has been taken into account. In the absence of metals, H₂ is the main coolant below $\sim 10^4$ K, the typical temperature range in collapsing Population III objects. The efficiency of H₂ cooling is very sensitive to the H₂ abundance. Therefore, it is necessary to compute the nonequilibrium evolution of the primordial chemistry (see [4] for details).

We have devised an algorithm to merge SPH particles in high density regions to overcome the otherwise prohibitive timestep limitation, as enforced by the Courant stability criterion. To follow the simulation for a few dynamical times, we allow SPH particles to merge into more massive ones, provided they exceed a pre-determined density threshold, typically $10^8 - 10^{10} \text{ cm}^{-3}$ [4].

We have carried out a comprehensive survey of the relevant parameter space, and focus in the following on one select example that is representative for the overall results.

2.1 The Fragmentation of Primordial Gas

We model the site of primordial star formation as an isolated overdensity, corresponding to a high- σ peak in the random field of density perturbations. The numerical simulations are initialized at $z_i = 100$ by endowing a spherical region, containing dark matter and gas, with a uniform density and Hubble expansion. Small-scale density fluctuations are imprinted on the dark matter according to the CDM power spectrum. We assume that the halo is initially in rigid rotation with a given angular velocity, prescribed in accordance with the prediction for the spin parameter λ , as found in cosmological N-body simulations.

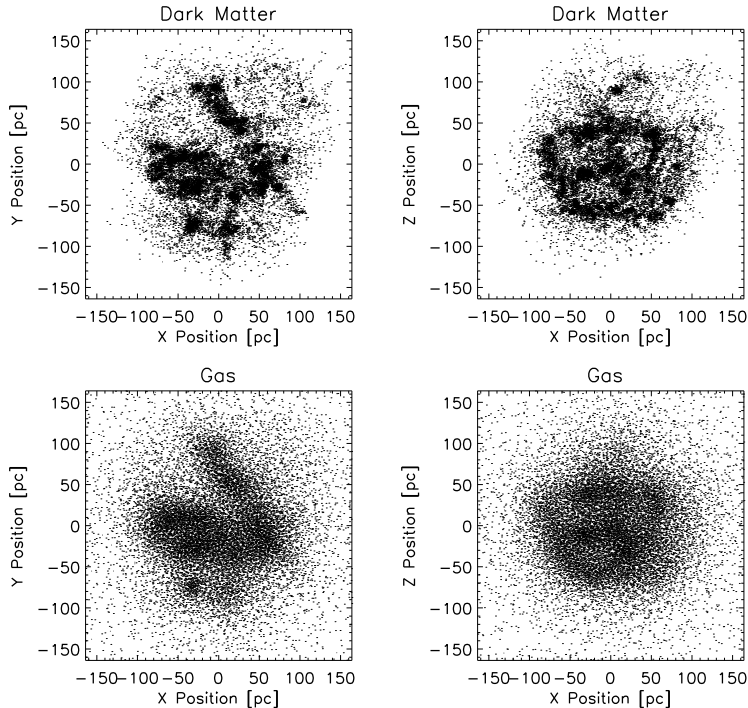


Fig. 1. Collapse of a primordial star forming cloud (from [4]). The halo has a total mass of $2 \times 10^6 M_\odot$, and will collapse at $z_{vir} \simeq 30$. Shown here is the morphology at $z = 33.5$. *Top row:* DM particles. *Bottom row:* Gas particles. *Left panels:* Face-on view. *Right panels:* Edge-on view. The DM has developed significant substructure, and the baryons are just beginning to fall into the corresponding potential wells.

Fig. 1 shows the situation at $z = 33.5$, briefly before the virialization of the dark matter. In response to the initially imprinted k^{-3} -noise, the dark matter has developed a pronounced substructure. The baryons have just begun to fall into the potential wells which are created by the DM substructure. Thus, the

DM imparts a ‘gravitational head-start’ to certain regions of the gas, which subsequently act as the seeds for the formation of high-density clumps.

At the end of the free-fall phase, the gas has developed a very lumpy, filamentary structure in the center of the DM potential. The gas distribution is very inhomogeneous, and the densest regions are gravitationally unstable. The ensuing runaway collapse leads to the formation of high-density sink particles or clumps. These clumps are formed with initial masses close to $M \sim 10^3 M_\odot$, and subsequently gain in mass by the accretion of surrounding gas, and by merging with other clumps (see Fig. 2).

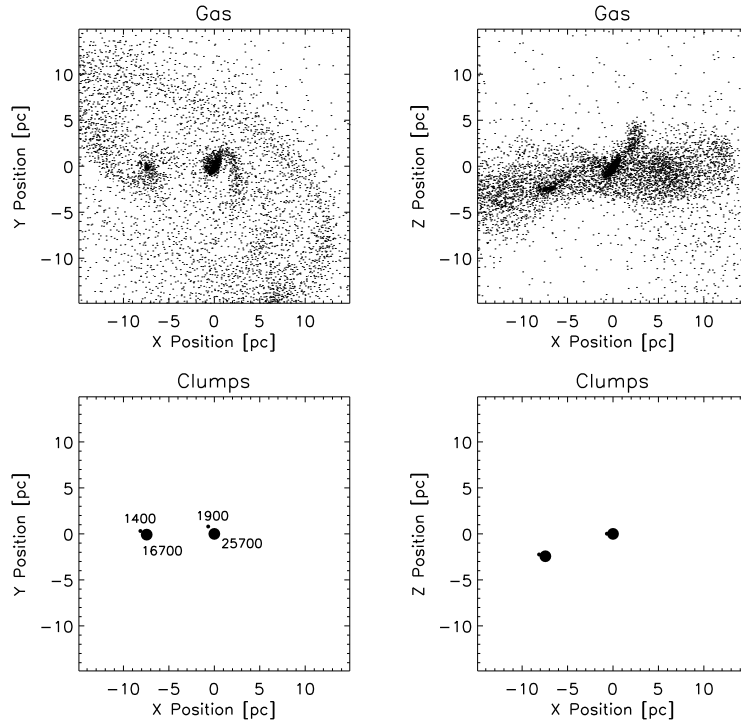


Fig. 2. Fragmentation into high density clumps (from [4]). Shown here is the situation at $z = 28.9$ in the innermost 30 pc. *Top row:* The remaining gas in the diffuse phase. *Bottom row:* Distribution of clumps. The numbers next to the dots denote clump mass in units of M_\odot . *Left panels:* Face-on view. *Right panels:* Edge-on view. The gas has settled into an irregular configuration with two dominant clumps. The clumps are formed with initial masses of $\sim 10^3 M_\odot$, and subsequently grow in mass by accretion and merging with other clumps, up to $\sim 20,000 M_\odot$.

There is a good physical reason for the emergence of high-density clumps with initial masses $\sim 10^3 M_\odot$. To understand this, consider the thermodynamic and chemical state of the gas, as summarized in Fig. 3. Since the abundances,

temperature and density are plotted for every SPH particle, this mode of presentation has an additional dimension of information: Particles accumulate (‘pile up’) in those regions of the diagram where the evolutionary timescale is long. In panel (c) of Fig. 3, one can clearly discern such a preferred state at temperatures of a few 100 K, and densities of $10^3 - 10^4 \text{ cm}^{-3}$. These characteristic values have a straightforward physical explanation in the microphysics of H_2 cooling. A temperature of $T \sim 100 - 200 \text{ K}$ is the minimum one attainable via H_2 cooling. The corresponding critical density, beyond which the H_2 rotational levels are populated according to LTE, is then $n_{crit} \simeq 10^3 - 10^4 \text{ cm}^{-3}$. Due to the now inefficient cooling, the gas ‘loiters’ and passes through a phase of quasi-hydrostatic, slow contraction.

To move away from this loitering regime, and to attain higher densities, the gas has to become gravitationally unstable. Evaluating the Jeans mass for the characteristic values $T \sim 200 \text{ K}$ and $n \sim 10^3 - 10^4 \text{ cm}^{-3}$ results in $M_J \sim 10^3 M_\odot$. When enough gas has accumulated in a given region to satisfy $M > M_J$, runaway collapse of that fluid region ensues. We find that the gas becomes self-gravitating ($\rho_B > \rho_{DM}$) coincident with the onset of the Jeans instability.

2.2 Protostellar Collapse

To further constrain the characteristic mass scale for Population III stars, we have investigated the collapse of a clump to even higher densities. As our starting configuration, we select the first region to undergo runaway collapse in one of the lower resolution simulations and employ a technique of refining the spatial resolution in the vicinity of this region, which in the unrefined simulation would have given rise to the creation of a sink particle.

In the refined simulation, three-body reactions become important, and lead to the almost complete conversion of the gas into molecular form [14].

Only $\sim 5000 \text{ yr}$ after the onset of runaway collapse, the central, highest-density region has already evolved significantly. As can be seen in Fig. 4, an elongated, spindle-like structure has formed, which comprises a mass of $\sim 20 M_\odot$, and has a characteristic size of $L_{char} < 10^{-4} \text{ pc} \simeq 20 \text{ AU}$. By examining the surrounding velocity field, which is characterized by Mach numbers of $\sim 3 - 5$, it is evident that matter continues to fall onto the central object. To derive an estimate for the accretion rate, we consider the average mass flux, $\langle \rho v_r \rangle$, through a spherical surface around the density maximum with radius $r = 10^{-3} \text{ pc}$. Here, v_r is the radial velocity component, and velocities are measured relative to the density maximum. Assuming spherical accretion, one finds for the accretion rate

$$\dot{M}_{acc} = -4\pi r^2 \langle \rho v_r \rangle \sim 1 M_\odot \text{ yr}^{-1} \quad . \quad (1)$$

This is likely to be an overestimate, since the assumption of spherical symmetry is only a rough approximation to the complex kinematics of the flow. Nevertheless, it is clear that the central object will rapidly grow in mass, on a timescale $t_{acc} \sim M/\dot{M}_{acc} \sim 20 \text{ yr}$. We find no indication for further subfragmentation in this simulation. These results suggest that the first stars might have been quite massive, possibly even very massive with $M_* > 100 M_\odot$.

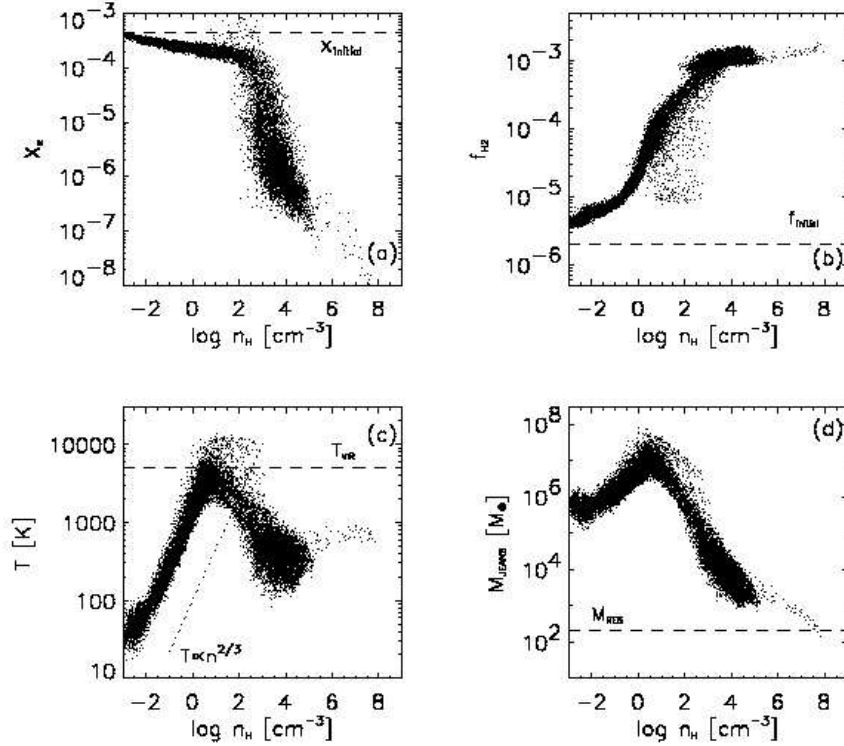


Fig. 3. Gas properties at $z = 31.2$ (from [4]). (a) Free electron abundance vs. hydrogen number density (in cm^{-3}). (b) Hydrogen molecule abundance vs. number density. (c) Gas temperature vs. number density. At densities below $\sim 1 \text{ cm}^{-3}$, the gas temperature rises because of adiabatic compression until it reaches the virial value of $T_{\text{vir}} \simeq 5000$ K. At higher densities, cooling due to H_2 drives the temperature down again, until the gas settles into a quasi-hydrostatic state at $T \sim 300$ K and $n \sim 10^4 \text{ cm}^{-3}$. Upon further compression due to the onset of the gravitational instability, the temperature experiences a modest rise again. (d) Jeans mass (in M_{\odot}) vs. number density. The Jeans mass reaches a value of $M_J \sim 10^3 M_{\odot}$ for the quasi-hydrostatic gas in the center of the DM potential well.

Important caveats remain, however. The question of how massive the incipient star in the center of the collapsing clump will eventually be, cannot be answered with any certainty at present. Our attempts in doing so are foiled by our ignorance of the complex and rather unexplored physics of accretion from a dust free envelope. This, then, is the frontier of our current knowledge [13].

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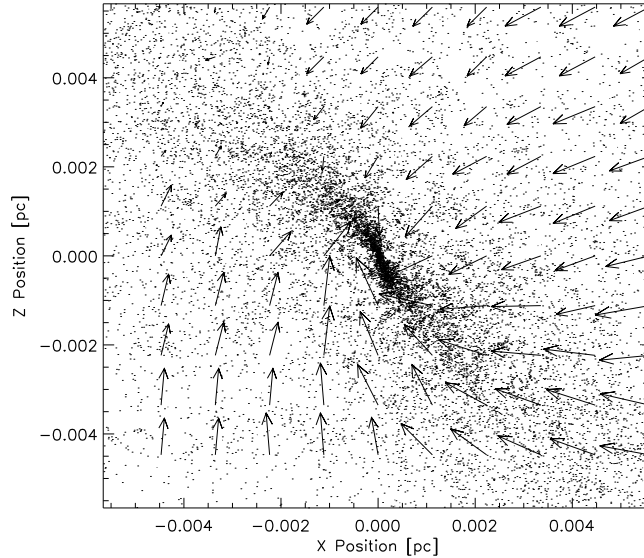


Fig. 4. Gas morphology and kinematics in the vicinity of the density maximum. Shown is the situation ~ 5000 yr after the onset of runaway collapse in a box of linear size ~ 2500 AU. The small dotted symbols give an indication of the gas density, and the overplotted arrows depict the velocity field in the x - z plane. The length of an arrow scales with speed such that the largest one corresponds to ~ 14.5 km s $^{-1}$. It is evident that a highly concentrated, spindle-like structure has formed in the center which comprises a few tens of solar masses at this instant. The surrounding flow field is supersonic with typical Mach numbers of $\sim 3 - 5$.

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