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The First Galaxies

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Abstract. An important open frontier in astrophysics is to understand how the first sources of light, the first stars and galaxies, ended the cosmic dark ages at redshifts $z \simeq 15-20$. Their formation signaled the transition from the simple initial state of the universe to one of ever increasing complexity. We here review recent progress in understanding the assembly process of the first galaxies with numerical simulations, starting with cosmological initial conditions and modelling the detailed physics of star formation. The key drivers in building up the primordial galaxies are the feedback effects from the first stars, due to their input of radiation and of heavy chemical elements in the wake of supernova explosions. In addition, the conditions inside the first galaxies are governed by the gravitationally-driven turbulence generated during the virialization of the dark matter host halo. Our theoretical predictions will be tested with upcoming near-infrared observatories, such as the *James Webb Space Telecope*, in the decade ahead.

Keywords. cosmology: theory, early universe — galaxies: formation — stars: formation, supernovae

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1. Introduction

After the parameters of the cosmological background model have now been successfully determined to high precision, the next frontier of cosmology is to understand structure formation. Galaxy formation, however, is very complex, and we still lack a first-principle based theoretical picture. Within the hierarchical ΛCDM model, the key to galaxy formation might lie in its initial stages, when the first, low-mass, building blocks, the first galaxies, emerged. With the formation of the first stars, the so-called Population III (Pop III), the universe was rapidly transformed into an increasingly complex, hierarchical system, due to the energy and heavy element input from the first stars and accreting black holes (Barkana & Loeb 2001; Bromm & Larson 2004; Ciardi & Ferrara 2005; Miralda-Escudé 2003). Currently, we can directly probe the state of the universe roughly a million years after the Big Bang by detecting the temperature anisotropies in the cosmic microwave background (CMB), thus providing us with the initial conditions for subsequent structure formation. Complementary to the CMB observations, we can probe cosmic history all the way from the present-day universe to roughly a billion years after the Big Bang, using the best available ground- and space-based telescopes. In between lies the remaining frontier, and the first stars and galaxies are the sign-posts of this early, formative epoch.

To simulate the build-up of the first stellar systems, we have to address the feedback from the very first stars on the surrounding intergalactic medium (IGM), and the formation of the second generation of stars out of material that was influenced by this feedback. There are a number of reasons why addressing the feedback from the first stars and understanding second-generation star formation is crucial:
(i) The first steps in the hierarchical build-up of structure provide us with a simplified laboratory for studying galaxy formation, which is one of the main outstanding problems in cosmology.
(ii) The initial burst of Pop III star formation may have been rather brief due to the strong negative feedback effects that likely acted to self-limit this formation mode

(Greif & Bromm 2006; Yoshida *et al.* 2004). Second-generation star formation, therefore, might well have been cosmologically dominant compared to Pop III stars.
(iii) A subset of second-generation stars, those with masses below $\simeq 1\ M_{\odot}$, would have survived to the present day. Surveys of extremely metal-poor Galactic halo stars therefore provide an indirect window into the Pop III era by scrutinizing their chemical abundance patterns, which reflect the enrichment from a single, or at most a small multiple of, Pop III SNe (Beers & Christlieb 2005; Frebel *et al.* 2007; Karlsson *et al.* 2008). Stellar archaeology thus provides unique empirical constraints for numerical simulations, from which one can derive theoretical abundance patterns to be compared with the data.

Existing and planned observatories, such as HST, Keck, VLT, and the *James Webb Space Telescope (JWST)*, planned for launch around 2013, yield data on stars and quasars less than a billion years after the Big Bang. The ongoing *Swift* gamma-ray burst (GRB) mission provides us with a possible window into massive star formation at the highest redshifts (Lamb & Reichart 2000; Bromm & Loeb 2002, 2006). Measurements of the near-IR cosmic background radiation, both in terms of the spectral energy distribution and the angular fluctuations provide additional constraints on the overall energy production due to the first stars (Santos *et al.* 2002; Magliocchetti *et al.* 2003; Dwek *et al.* 2005; Fernandez & Komatsu 2006; Kashlinsky *et al.* 2005). Understanding the formation of the first galaxies is thus of great interest to observational studies conducted both at high redshifts and in our local Galactic neighborhood.

2. Primordial Star Formation

The first stars in the universe formed a few 100 Myr after the Big Bang, when the primordial gas was first able to cool and collapse into dark matter (DM) minihalos with masses of the order of $10^6\ M_{\odot}$ (Abel *et al.* 2002; Bromm *et al.* 2002; Yoshida *et al.* 2006). These stars are believed to have been very massive, with masses of the order of $100 M_{\odot}$, owing to the limited cooling ability of primordial gas in minihalos via the radiation from H_2 molecules. While the initial conditions for the formation of the very first stars are known from precision measurements of cosmological parameters (Spergel *et al.* 2007), the situation for the subsequent generations of stars is much more compex. It has become evident that Pop III star formation might actually consist of two distinct modes: one where the primordial gas collapses into a DM minihalo, and one where the metal-free gas becomes significantly ionized prior to the onset of gravitational runaway collapse (Johnson & Bromm 2006). To clearly indicate that both modes pertain to *metal-free* star formation, we here follow the new classification scheme suggested by Chris McKee (see McKee & Tan 2008; Johnson *et al.* 2008). Within this scheme, the minihalo Pop III mode is termed Pop III.1, whereas the second mode is called Pop III.2.

While the formation of the very first, Pop III.1, stars in minihalos relied on H_2 cooling, the HD molecule can play an important role in the cooling of primordial gas in several situations, allowing the temperature to drop well below 200 K (Abel *et al.* 2002; Bromm *et al.* 2002). In turn, this efficient cooling may lead to the formation of primordial stars with masses of the order of $10\ M_{\odot}$, the so-called Pop III.2 (Johnson & Bromm 2006). In general, the formation of HD, and the concomitant cooling that it provides, is found to occur efficiently in primordial gas which is strongly ionized, owing ultimately to the high abundance of electrons which serve as catalyst for molecule formation in the early universe (Shapiro & Kang 1987). Efficient cooling by HD can be triggered within the relic H II regions that surround Pop III.1 stars at the end of their brief lifetimes (Alvarez *et al.* 2006), owing to the high electron fraction that persists in the gas as it cools and recombines (Johnson *et al.* 2007; Yoshida *et al.* 2007b). The efficient formation of HD

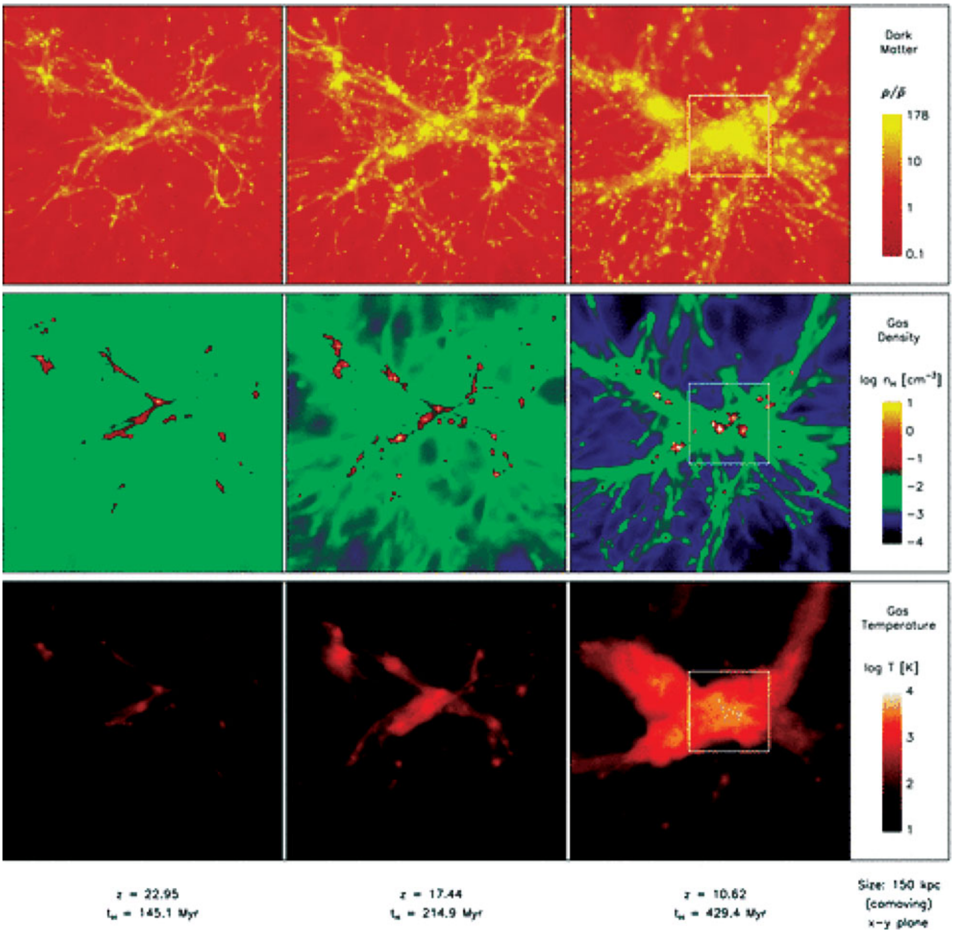

Figure 1. Assembly of the first galaxy (from Greif *et al.* 2008). Gravity is assembling the dark matter (*top row*) and pristine gas (*middle row*) into a primordial galaxy. Shown is the evolution at three different stages (*from left to right*). White crosses indicate individual Pop III stars, which form prior to the first galaxy. The assembly process is accompanied by powerful virialization shocks that heat up the infalling gas to $> 10^4$ K (*bottom row*).

can also take place when the primordial gas is collisionally ionized, such as behind the shocks driven by the first SNe or in the virialization of massive DM halos (Machida *et al.* 2005; Johnson & Bromm 2006; Shchekinov & Vasiliev 2006).

There might thus be a progression of characteristic masses of the various stellar populations that form in the early universe. In the wake of Pop III.1 stars (typically with $M_* \sim 100 M_\odot$) formed in DM minihalos, Pop III.2 star formation (with $M_* \sim 10 M_\odot$) ensues in regions which have been previously ionized, typically associated with relic H II regions left over from massive Pop III.1 stars collapsing to black holes, while even later, when the primordial gas is locally enriched with metals, Pop II (with $M_* \sim 1 M_\odot$) stars begin to form (Bromm & Loeb 2003; Greif & Bromm 2006). Recent simulations confirm this picture, as Pop III.2 star formation ensues in relic H II regions in well under a Hubble time, while the formation of Pop II stars after the first SN explosions is delayed by more than a Hubble time (Greif *et al.* 2007; Yoshida *et al.* 2007a,b; but see Whalen *et al.* 2008).

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3. The First Galaxies and the Onset of Turbulence

How massive were the first galaxies, and when did they emerge? Theory predicts that DM halos containing a mass of $\sim 10^8 M_\odot$ and collapsing at $z \sim 10$ were the hosts for the first bona fide galaxies. These dwarf systems are special in that their associated virial temperature exceeds the threshold, $\sim 10^4$ K, for cooling due to atomic hydrogen (Oh & Haiman 2002). These so-called 'atomic-cooling halos' did not rely on the presence of molecular hydrogen to enable cooling of the primordial gas. In addition, their potential wells were sufficiently deep to retain photoheated gas, in contrast to the shallow potential wells of minihalos (Dijkstra *et al.* 2004). These are arguably minimum requirements to set up a self-regulated process of star formation that comprises more than one generation of stars, and is embedded in a multi-phase interstellar medium.

One of the important consequences of atomic cooling is the softening of the equation of state below the virial radius, allowing a fraction of the potential energy to be converted into kinetic energy (Wise & Abel 2007; Greif *et al.* 2008). This implies that perturbations in the gravitational potential can generate turbulent motions on galactic scales, which are then transported to the centre of the galaxy. In this context the distinction between two fundamentally different modes of accretion becomes important (Greif *et al.* 2008). Gas accreted directly from the IGM is heated to the virial temperature and comprises the sole channel of inflow until cooling in filaments becomes important. This mode is termed hot accretion, and dominates in low-mass haloes at high redshift. The formation of the virial shock and the concomitant heating in an atomic cooling halo are visible in Fig. 1. The second mode, termed cold accretion, becomes important as soon as filaments are massive enough to enable molecule reformation, which allows the gas to cool and flow into the central regions of the nascent galaxy with high velocities. Although the assembly of the first galaxies provides us with an idealized laboratory for galaxy formation in general, the degree of complexity that is exhibited in the corresponding merger tree (see Fig. 2) is already considerable. Still, current supercomputer simulations have just reached the capacity to address the first galaxy formation process in an a-priori fashion, one star at a time.

Cold accretion is a viable agent for driving turbulence, due to the large amount of kinetic energy it brings to the center of the galaxy. Two physically distinct mechanisms are responsible for creating shocks (Greif *et al.* 2008). The virial shock forms where the ratio of infall velocity to local sound speed approaches unity, while a multitude of unorganized shocks forms near the center of the galaxy and is mostly caused by accretion of cold, high-velocity gas from filaments. These are more pronounced than the virial shock and have a significantly higher angular component. They create transitory density perturbations that could in principle become Jeans-unstable and trigger the gravitational collapse of individual clumps. In concert with metal enrichment by previous star formation in minihaloes, metal mixing in the first galaxies will likely be highly efficient and could lead to the formation of the first low-mass star clusters (Clark *et al.* 2008), in extreme cases possibly even to metal-poor globular clusters (Bromm & Clarke 2002). Some of the extremely iron-deficient, but carbon and oxygen-enhanced stars observed in the halo of the Milky Way may thus have formed as early as redshift $z \simeq 10$ (Karlsson *et al.* 2008).

4. Outlook

Understanding the formation of the first galaxies marks the frontier of high-redshift structure formation. It is crucial to predict their properties in order to develop the optimal

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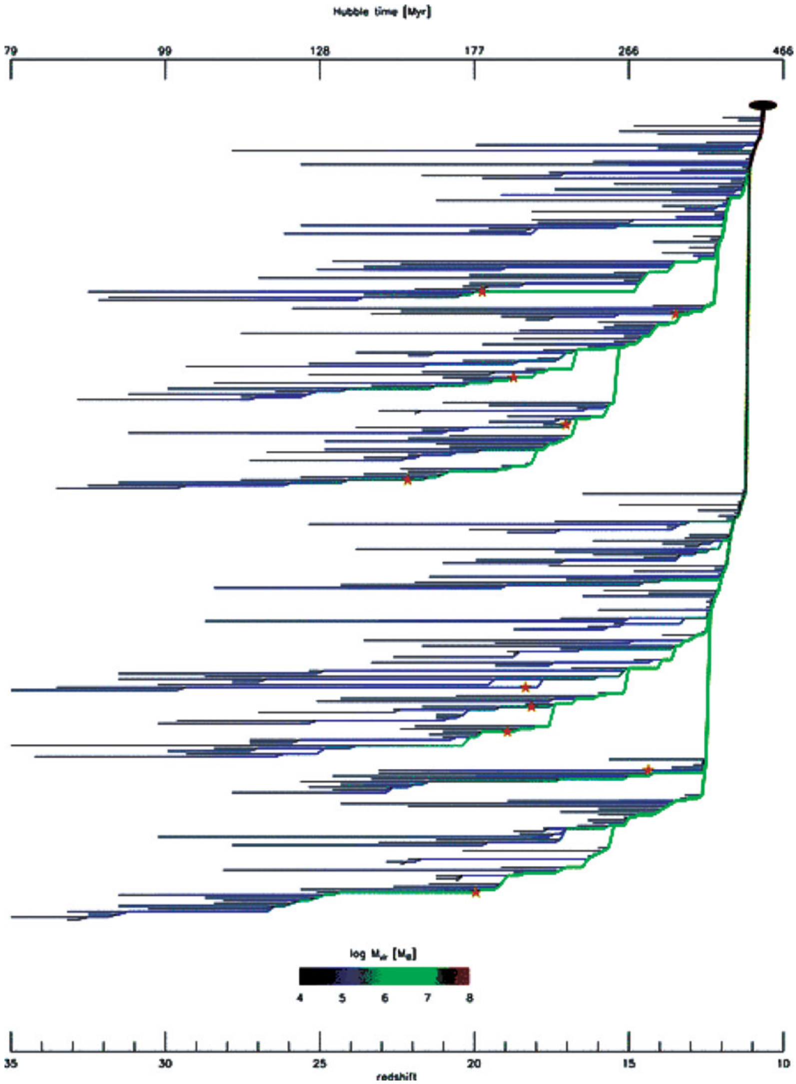

Figure 2. Hierarchical assembly of the first galaxy, expressed in the corresponding merger tree (from Greif *et al.* 2008). Each line represents an individual progenitor halo and is color-coded according to its mass. The target halo hosting the galaxy is represented by the rightmost path, which ultimately attains $\sim 10^8 M_\odot$, thus fulfilling the criterion for the onset of atomic hydrogen cooling (*red oval*). Star symbols denote the formation of Pop III.1 stars in minihalos. Here, ~ 10 such stars form prior to the assembly of the first galaxy. Their feedback will set the initial conditions for the formation of the second generation of stars inside the galaxy.

search and survey strategies for the *JWST*. Whereas *ab-initio* simulations of the very first stars can be carried out from first principles, and with virtually no free parameters, one faces a much more daunting challenge with the first galaxies. Now, the previous history of star formation has to be considered, leading to enhanced complexity in the assembly of the first galaxies. One by one, all the complex astrophysical processes that play a role in more recent galaxy formation appear back on the scene. Among them are external radiation fields, comprising UV and X-ray photons, and possibly cosmic rays produced in the wake of the first SNe. There will be metal-enriched pockets of gas which could be pervaded by

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dynamically non-negligible magnetic fields, together with turbulent velocity fields built up during the virialization process. However, the goal of making useful predictions for the first galaxies is now clearly drawing within reach, and the pace of progress is likely to be rapid.

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