

First Light

John H. Wise^{*†}

*Center for Relativistic Astrophysics, Georgia Institute of Technology, 837 State Street, Atlanta,
GA 30332, USA*

E-mail: jwise@physics.gatech.edu

The first stars in the universe are thought to be massive, forming in dark matter halos with masses around 10^6 solar masses. Recent simulations suggest that these metal-free (Population III) stars may form in binary or multiple systems. Because of their high stellar masses and small host halos, their feedback ionizes the surrounding 3 kpc of intergalactic medium and drives the majority of the gas from the potential well. The next generation of stars then must form in this gas-poor environment, creating the first galaxies that produce the majority of ionizing radiation during cosmic reionization. I will review the latest developments in the field of Population III star formation and feedback and its impact on galaxy formation prior to reionization. In particular, I will focus on the numerical simulations that have demonstrated this sequence of events, ultimately leading to cosmic reionization.

*Frank N. Bash Symposium New Horizons In Astronomy,
October 9-11, 2011
Austin, Texas*

^{*}Speaker.

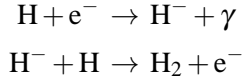
[†]The speaker appreciated the hospitality and efforts by the symposium organizers and the invitation to speak at this venue. This review covers some of my own work, which could not have been accomplished without the help of my collaborators, Tom Abel, Marcelo A. Alvarez, Renyue Cen, Michael L. Norman, and Matthew J. Turk.

1. Introduction

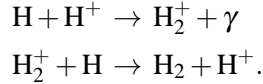
The universe was a very dark place in the first tens of millions of years before any luminous structure had formed. This epoch is sometimes referred to as the “Dark Ages”, when dark matter (DM) collapsed into bound objects but hosted no stars whatsoever. These DM halos collected a primordial mix of primarily hydrogen and helium in their potential wells after they reached the cosmological Jeans mass $M_J \sim 5 \times 10^3 [(1+z)/10]^{3/2}$ [9]. The first DM halos to cool and collapse produced the first stars in the universe that, in turn, produced the first metals to spark the transition to galaxy formation. Before reviewing the current status of research on the first stars and galaxies, it is worthwhile to step back, pose three simple but informative questions, and review historical pieces of literature that addressed these questions.

The first question we can ask ourselves is: *Why do all observed stars contain metals?* [54] focused on the Milky Way (MW) stellar population and observed (i) that the oldest Population II stars were metal-poor, (ii) a high frequency of white dwarfs, and (iii) a red excess in elliptical galaxies. These points led them to the conclusion that the “original Population II contained a large number of relatively massive stars”.

The next question that naturally follows is: *Without any metals, how does gas cool and condense to form stars?* Metal-enriched gas cools mainly through H_2 formation on dust grains and other fine-structure transitions in heavy elements. [40] recognized that H_2 can slowly form in the gas phase through the following reactions:



or less efficiently



[51] were the first to realize that H_2 formation in the gas-phase was important in star formation in the early universe. They used these reactions to determine that H_2 cooling dominates the collapse of a pre-galactic cloud at number densities $n > 10^4 \text{ cm}^{-3}$. These high density regions can cool to $\sim 300 \text{ K}$ and continue to collapse. [47] suggested that globular clusters were the first bound objects in the universe with masses $\sim 5 \times 10^5 M_\odot$. In their calculations, they first compute the properties of these objects from linear perturbation theory and then follow the initial contraction of the cloud, including H_2 cooling. They find that molecular hydrogen cooling is indeed efficient enough to drive a free-fall collapse, in which only a small fraction of the total gas mass forms stars due to the inside-out nature of the collapse.

The third pertinent question is: *When and where do the first stars form?* Applying the properties of cooling primordial gas to the cold dark matter model, [21] determined that the first objects to cool and collapse due to H_2 formation would be hosted in DM halos with masses $\sim 10^6 M_\odot$ at $z = 20 - 30$. A decade later, [58] used a detailed chemical model to follow the formation of H_2 in virialized objects, starting from recombination. They found that the redshift-dependent minimum DM halo mass to host H_2 cooling, rising from $5 \times 10^3 M_\odot$ at $z \sim 100$ to $10^6 M_\odot$ at $z \sim 15$.

These early analytical works provided the theoretical basis for current and recent simulations that focus on the formation of the first stars and galaxies in the universe. Here I review the progress that the field has made in the past decade.

2. Population III star formation

Following a cosmological gaseous collapse over many orders of magnitude in length makes such a simulation technically difficult, but with improvements in algorithms and physical models, several groups have been able to make substantial progress. In the late 1990's and early 2000's, two independent groups used three-dimensional simulations to study Population III star formation. Using smoothed particle hydrodynamics (SPH) simulations of isolated and virialized dark matter halos with masses $2 \times 10^6 M_\odot$ at $z = 30$, one group found that the object cooled to 300 K through H_2 formation, using the chemical network of [30], and fragmented into a filamentary structure with a Jeans mass of $10^3 M_\odot$ [13, 14]. In the second paper, they followed the collapse to higher gas densities of 10^8 cm^{-3} and studied the continued formation of dense clumps with the same $10^3 M_\odot$ characteristic mass. The other group used cosmological adaptive mesh refinement (AMR) simulations to focus on the formation of a molecular cloud hosted by a $7 \times 10^5 M_\odot$ DM halo [1, 3, 4]. In each successive paper, the H_2 chemistry model [2, 8] was improved to include more processes, such as the three-body H_2 formation process, to follow the central collapse to gas densities up to $3 \times 10^{13} \text{ cm}^{-3}$. Both groups came to the conclusion that further fragmentation was suppressed because of a lack of cooling below 300 K and that Population III stars were *very massive* in the range $30 - 300 M_\odot$.

These simulations only represented a limited sample of collapses and could not provide much insight to the Population III initial mass function (IMF). Twelve additional AMR simulations were conducted to look at any variations in primordial gas collapses [45]. They found that the collapses occurred in DM halos with masses in the range $1.5 - 7 \times 10^5 M_\odot$ with the scatter caused by differing halo formation histories. The mass accretion rate onto the central molecular cloud was higher at $10^{-4} M_\odot \text{ yr}^{-1}$ at $z \sim 30$, and it can increase by two orders of magnitude at $z \sim 20$ in some halos, agreeing with [4].

Following the collapse to densities higher than 10^{13} cm^{-3} required the inclusion of collisionally induced emission, chemical heating from H_2 formation, and gas opacity above 10^{18} cm^{-3} . [77] found with SPH simulations that the initial collapsing region did not fragment as it condensed to protostellar densities $n \sim 10^{21} \text{ cm}^{-3}$, forming a protostellar shock in the process. The inner $10 M_\odot$ had an accretion rate varying between 0.01 and $0.1 M_\odot \text{ yr}^{-1}$, possibly growing to $10 M_\odot$ within 1000 yr.

In the past few years, multiple groups have been focusing on the subsequent growth of these protostars over several dynamical times, improving upon the earlier works that stopped at the first collapse. This has proved to be challenging because of the ever-decreasing Courant factors at higher densities. One workaround is the creation of ‘‘sink particles’’ that accrete nearby gravitationally-bound gas, allowing the simulation to progress past the first collapse; however, one loses all hydrodynamical information above some density threshold. In one out of five realizations in AMR calculations without sink particles, [65] found that the collapsing core fragmented at a density of 10^{11} cm^{-3} into two clumps that are separated by 800 AU with $100 M_\odot$ of gas within a sphere with

radius twice their separation. At the same time, [56] also found that disk instabilities causes fragmentation into a binary system with a $40 M_{\odot}$ and $10 M_{\odot}$. This was later confirmed by simulations of a collapse of an isolated Jeans-unstable primordial gas cloud that fragmented into many multiple systems with some very tightly bound to separations less than an AU [19]. Utilizing a new moving mesh code, [29] studied the collapse in five different primordial DM halos, and they evolved them for 1000 yr after the first protostar forms. By evolving these protostars further, they included the effects of protostellar radiative feedback in the infrared in the optically-thin limit. In all cases, the molecular cloud fragments into ~ 10 sink particles, some of which later merge to form more massive protostars. The mass function from these simulations is relatively flat, i.e. a top-heavy IMF.

After the protostar has reached $\sim 10 M_{\odot}$, radiative feedback from ionizing radiation will begin to suppress further accretion. Only recently has this been incorporated into numerical simulations of Population III star formation. Starting from initial conditions extracted from a cosmological simulation [77], two-dimensional axi-symmetric radiation hydrodynamical simulations showed that an accretion disk forms around a new protostar with the ionizing radiation preferentially escaping through the polar regions [32]. The disk itself is slowly photo-evaporated, halting accretion after 70,000 yr. At this point, the final mass of the Population III star is $43 M_{\odot}$. Without any radiative feedback, the protostar would have continued to grow to $\sim 100 M_{\odot}$. In a cosmological setting, [57] found a binary system still forms in the presence of radiative feedback. Without feedback, the primary star grows to $28 M_{\odot}$ over 5,000 yr. With feedback, the primary and secondary stars only grow to 19 and $10 M_{\odot}$, respectively. An extrapolation of the mass accretion history shows that both stellar masses will asymptote to $30 M_{\odot}$, creating an equal-mass binary. Once the stars have entered the main sequence, they will start to ionize and heat their cosmic neighborhood, which I will review next.

3. Population III radiative feedback

Some of the first calculations of the growth and overlap of cosmological H II regions originating from quasars concluded that they could not fully account for reionization. Other radiation sources must have contributed to the photon budget [55]. Later with $z > 4$ galaxy observations, it was clear that low-luminosity galaxies were the primary source of ionizing photons [e.g. 12, 23, 59]. However, Population III preceded galaxy formation, and they were the first sources of ionizing radiation, starting cosmic reionization. They are thought to have a top-heavy IMF, as discussed in the previous section, and zero-metallicity stellar models were constructed to estimate their luminosities, lifetimes, and spectra as a function of mass [15, 53, 64]. One key feature is mass-independent surface temperature of 10^5 K above $40 M_{\odot}$, caused by a lack of opacity from metal lines. Thus, Population III are copious producers of ionizing photons with an average photon energy ~ 30 eV and also H_2 dissociating radiation, which is < 13.6 eV where the neutral universe is optically-thin. Because the formation of Population III stars is primarily dependent on H_2 formation, any H_2 dissociating radiation can suppress Population III star formation from large distances [22, 34, 38, 46, 69].

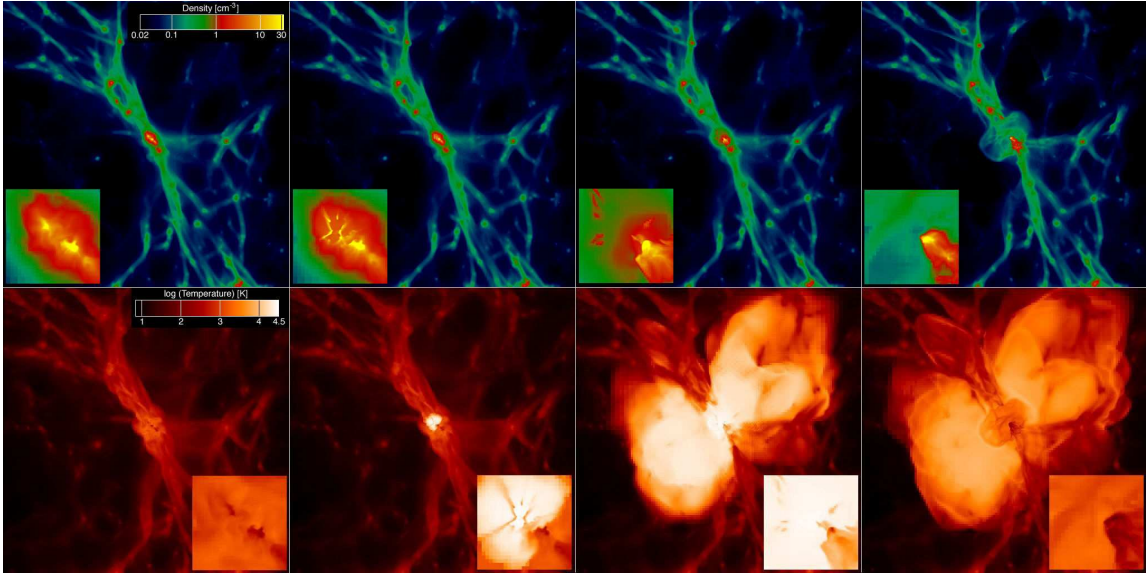


Figure 1: The formation of a H II region from a Population III star, shown with projections of gas density (top) and temperature (bottom) of a ~ 3 proper kpc region, centered on the first star at $z = 20$. From left to right, the depicted times correspond to 0, 1, 2.7, and 8 Myr after the star formed. The insets correspond to the same times, have the same color scale, and show the central 150 pc. From [6].

3.1 H II regions from Population III stars

Combining the main sequence properties of Population III stars and the endpoints of cosmological simulations, one-dimensional radiation hydrodynamics simulations followed the growth of an H II region from Population III stars with masses ranging from 25 to 500 M_{\odot} [36, 66]. The ionization front drives a 30 km s^{-1} shock wave. Because the escape velocity of $10^6 M_{\odot}$ halos is only $\sim 3 \text{ km s}^{-1}$, approximately 90% of the gas is expelled from the DM halo, leaving behind a warm ($T \sim 3 \times 10^4 \text{ K}$) and diffuse ($\rho \sim 0.1 \text{ cm}^{-3}$) medium. At the end of the star’s lifetime, a 100 M_{\odot} star creates an H II region with a radius ~ 3 kpc.

Shortly afterward, it became feasible to include radiative transfer in cosmological simulations, either through moment methods or ray tracing. In three dimensions, it is possible to investigate the ionization of a clumpy and inhomogeneous medium and any ionization front instabilities [67] that might arise. [7] found that between 70% and 90% of the ionizing photons escaped into the IGM, using ionization front tracking and an approximate method to calculate the thermodynamic state behind the front. This calculation also showed that some nearby halos are not fully photo-evaporated, leaving behind a neutral core. Furthermore, nearby filamentary structure is slower to ionize, and the ionization front grows faster in the voids, creating a “butterfly” shape [5]. The first three-dimensional radiation hydrodynamics simulations uncovered multi-fold complexities that were not seen in previous simulations, such as cometary structures and elephant trunks seen in nearby star forming regions [6]. Figure 1 shows the growth of the H II region emanating from the host minihalo. The density structures in the nearby filaments were largely unaffected by the radiation because they are self-shielded. The 30 km s^{-1} shock wave collects $10^5 M_{\odot}$ of gas into a shell over the lifetime of the star, which is Jeans stable and is dispersed after the star’s death.

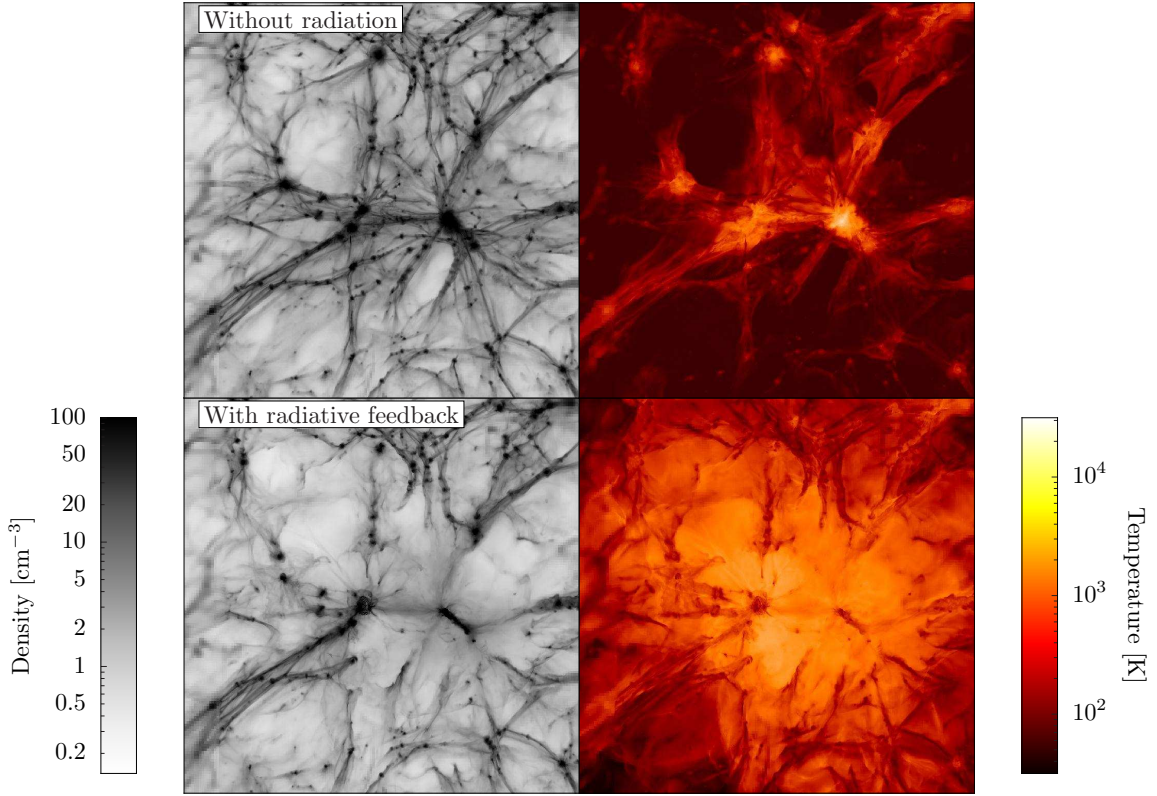


Figure 2: The effects of radiative feedback from the first stars, shown in projections of gas density (left) and temperature (right) in a field of view of 8.5 proper kpc in a region heated and ionized by tens of Population III stars at $z = 16$. Notice how most of the nearby substructures are photo-evaporated. From [70].

As the H II region grows up to 3 kpc in radius, nearby halos become engulfed in a sea of ionized gas. Because free electrons are the catalyst for H_2 formation, a boosted electron fraction promotes more efficient cooling; furthermore, HD cooling becomes relevant in the collapse of these halos in relic H II regions [41, 44, 75, 76]. Instead being limited to a 300 K temperature floor, this gas cools to ~ 50 K, resulting in a Jeans mass a factor of $\sim 5/2$ lower. Thus, it is expected that these Population III stars will have a lower characteristic mass in the approximate range of 5–60 M_\odot . After this discovery, it was felt that these two different populations needed to be separated, where metal-free stars forming in an unaffected region are termed “Population III.1”, and metal-free stars forming in ionized gas were coined “Population III.2” [43].

3.2 Contribution to reionization

The H II regions from metal-free stars are much larger than present-day H II regions and can have a sizable impact on the reionization history. [70] found that Population III stars can ionize up to 25% of the local IGM in a biased region, surrounding a rare $3 - \sigma$ overdensity. Because Population III stars are short lived (~ 3 Myr), the H II regions are fully ionized only for a short time and then quickly recombines over the next ~ 50 Myr. Within a local cosmological region, there are many relic H II regions but only a handful of active H II regions with $T > 10^4$ K. Once the

H II regions start to overlap, each star can ionize a larger volume as the neutral hydrogen column density decreases. At the end of the simulation, one in ten ionizing photons results in a sustained ionization in the intergalactic medium (IGM). In addition to ionizing the IGM, the photo-heating of the host halo and IGM delays further local star formation by smoothing out gas overdensities in nearby minihalos and IGM, which is depicted in Figure 2. Reducing the IGM clumpiness reduces the recombination rate, which is measured by the clumping factor $C = \langle \rho \rangle^2 / \langle \rho^2 \rangle$, by 50% [70].

This simulation only considered a small region (1 comoving Mpc³) and cannot make predictions for global reionization history. To address cosmic reionization, simulations with sizes ~ 100 Mpc are necessary. Here the small-scale clumpiness cannot be resolved, and clumping factor plays a key role in subgrid models. In general, H II regions from Population III stars generate more small-scale power, and at late times, they are quickly overrun by nearby H II regions produced by larger galaxies [33]. In addition, Population III H II regions start reionization earlier and prolongs reionization [61].

4. Supernovae from Population III

Massive metal-free stars can end their lives in a unique type of supernova, a pair-instability SN [e.g. 10, 11, 31]. Non-rotating models find that this occurs in a mass range between 140 and 260 M_{\odot} , where nearly all of the helium core with mass $M_{\text{He}} \approx 13/24(M_{\star} - 20 M_{\odot})$ is converted into metals in an explosion of $10^{51} - 10^{53}$ erg. The ejecta can be an order of magnitude greater than typical Type II SNe [73] and hypernovae [42]! The chemical abundance patterns are much different than those in typical explosions with the carbon, calcium, and magnesium yields independent of mass. These pair-instability SNe are one possible cause for carbon-enhanced damped Ly α absorbers [e.g. 20, 48].

These very energetic SNe can exceed the binding energy of halos with masses $M \lesssim 10^7 M_{\odot}$. [16] investigated two explosion energies, 10^{51} and 10^{53} erg, in a cosmological halo with $M \sim 10^6 M_{\odot}$, neglecting any radiative feedback. Nevertheless, they found that over 90% of the gas was expelled into the IGM, and metals propagate to distances of ~ 1 kpc after 3–5 Myr. They argued that pair-instability SNe could have resulted in a nearly uniform metallicity floor in the IGM of $\sim 10^{-4} Z_{\odot}$ at high redshifts. Subsequent works built upon this idea of a IGM metallicity floor with various techniques: (i) volume-averaged semi-analytic models [24, 52, 74], (ii) models using hierarchical merger trees [37, 50, 63], (iii) post-processing of cosmological simulations with blastwave models [35, 62], and (iv) direct numerical simulations with stellar feedback [39, 49, 60, 72].

Because blastwaves do not penetrate overdensities as efficiently as a rarefied medium, the voids will be preferentially enriched [18]. This raises the following questions. Will the first galaxies have a similar metallicity as the IGM? How much metal mixing occurs in the first galaxies as they accrete material? The complex interplay between radiative and supernova feedback, cosmological accretion, and hydrodynamics are best captured by numerical simulations. Two groups [27, 71] showed that the enrichment from pair-instability SNe resulted in a nearly uniform metallicity in a $10^8 M_{\odot}$ halo at $z \sim 10 - 15$. These types of halos can efficiently cool through atomic hydrogen cooling, and the halo will form a substantial amount of stars for the first time. Both groups find that the metals are well-mixed in the galaxy because of turbulence generated during virialization

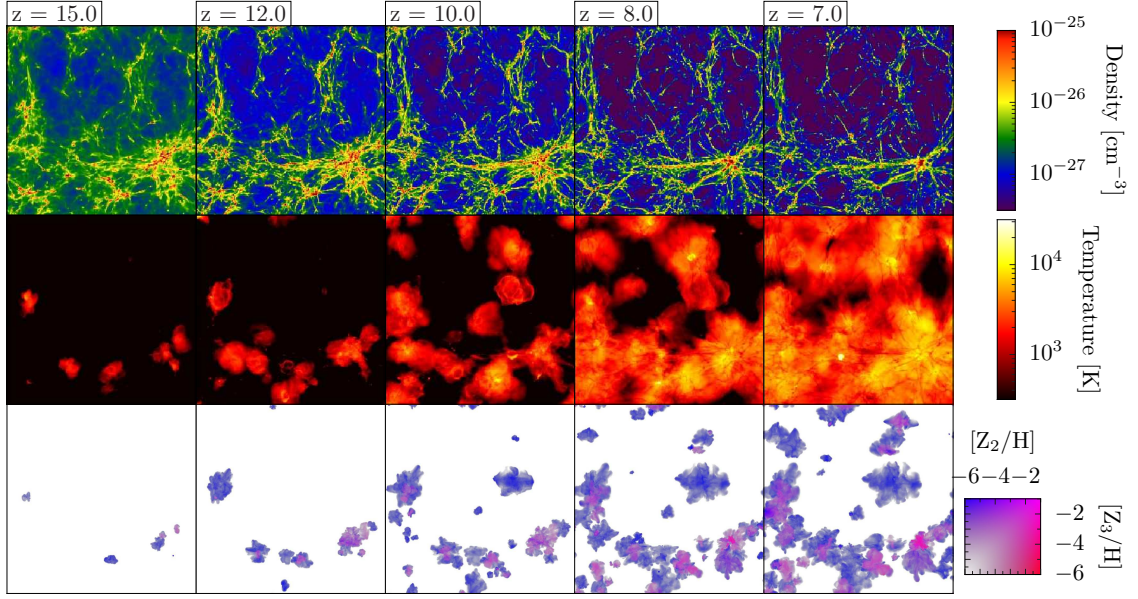


Figure 3: Evolution of the entire simulation volume ($L_{\text{box}} = 1 \text{ Mpc}$) at redshifts 15, 12, 10, 8, and 7 (left to right) that follows the formation of 38 dwarf galaxies and over 300 Population III stars. Pictured here are the density-weighted projections of density (top), temperature (middle), and metallicity (bottom). Note how the stellar radiative feedback from low-mass galaxies reionize the majority of the volume. The metallicity projections are a composite image of metals originating from Pop II (red) and III (blue) stars with magenta indicating a mixture of the two. From [72].

[28, 68] to a metallicity $Z/Z_{\odot} = 10^{-3} - 10^{-4}$. In these simulations, about 60% of the metals from SNe are reincorporated into the halo, whereas the remaining fraction stays in the IGM. In the end, Population III star formation is ultimately halted by the enrichment of the minihalos from nearby or previously hosted supernovae (SNe), marking the transition to galaxy formation.

5. High-redshift dwarf galaxies

The first galaxies are generally defined as halos that can undergo atomic line cooling, are metal-enriched, and can host sustained star formation [17]. Here I present some of the highlights of our latest numerical work on the formation of the first galaxies [72]. These radiation hydrodynamics AMR simulations tracked the formation and feedback of over 300 Population III stars and the buildup of 38 low-mass galaxies in a 1 comoving Mpc^3 volume until $z = 7$. The cosmic Population III star formation rate (SFR) is nearly constant at $3 \times 10^{-5} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ from $z = 15$ to $z = 7$. The largest galaxy has a final total and stellar mass of $1.0 \times 10^9 M_{\odot}$ and $2.1 \times 10^6 M_{\odot}$, respectively. Galaxies above $10^8 M_{\odot}$ generally have a mass-to-light ratio between 5 and 30, whereas the very low-mass galaxies have mass-to-light ratios between 100 and 3000 because of their inability to efficiently form stars.

The evolution of the density, temperature, and metallicity of the entire volume is shown in Figure 3. At $z = 7$, 76% of the volume is ionized, and 6.5% (1.9%) of the mass (volume) is enriched above $10^{-3} Z_{\odot}$. We focused on the buildup of the largest galaxy and an isolated dwarf

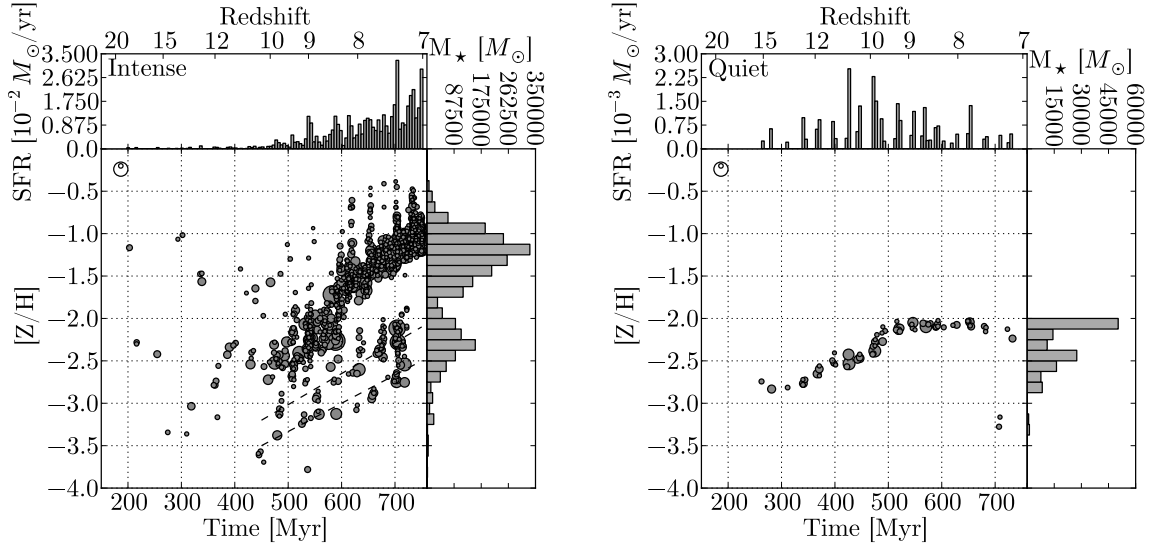


Figure 4: The scatter plots show the metal-enriched (Pop II) star formation history of a $10^9 M_\odot$ (left) and a $10^8 M_\odot$ (right) halos as a function of total metallicity, i.e. the sum of metal ejecta from both Pop II and Pop III SNe, at $z = 7$. Each circle represents a star cluster, whose area is proportional to its mass. The open circles in the upper right represent 10^3 and $10^4 M_\odot$ star clusters. The upper histogram shows the SFR. The right histogram depicts the stellar metallicity distribution. The larger halo shows a large spread in metallicity at $z > 10$ because these stars formed in progenitor halos that were enriched by different SN explosions. At $z < 10$, the majority of stellar metallicities increase as the halo is self-enriched. The spikes in metallicity at $t = 620, 650,$ and 700 Myr show induced star formation with enhanced metallicities in SN remnant shells. The dashed lines in the left panel guide the eye to two stellar populations that were formed in two satellite halos, merging at $z = 7.5$. The smaller halo evolves in relative isolation and steadily increases its metallicity to $[Z/H] \sim -2$ until there is an equilibrium between *in-situ* star formation and metal-poor inflows from filaments. From [72].

galaxy with a total mass of $10^8 M_\odot$. Figure 4 shows the metallicity of the star formation history and metallicity distribution functions in both halos. The mass resolution of this simulation captures the formation of all star-forming minihalos with $M > 10^5 M_\odot$.

The smaller galaxy experiences rapid mass accretion until $z \sim 12$ and afterward it evolves in relative isolation. It begins forming metal-enriched stars after a nearby pair-instability SN enriches a nearby halo to $\sim 10^3 Z_\odot$. This may be a peculiar case at high redshift, where a halo is enriched from a neighboring halo and does not form any Population III stars itself. It begins to form stars in a bursts at a rate of $5 \times 10^{-4} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$, peaking at $2 \times 10^{-3} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$ at $z = 10$. The galaxy is self-enriched by these stars, gradually increasing from $10^{-3} Z_\odot$ to $10^{-2} Z_\odot$ by $z = 10$. Afterward there is an equilibrium between metal-rich outflows and metal-poor accretion from the filaments, illustrated by the plateau in stellar metallicities in Figure 4.

The larger galaxy forms in a biased region of 50 comoving kpc on a side with ~ 25 halos with $M \sim 10^6 M_\odot$ at $z = 10$. About half of these halos form Population III stars with a third producing pair-instability SNe, enriching the region to $10^{-3} Z_\odot$, the metallicity floor that has been extensively studied in previous works. However, the metal-rich ejecta does not fully escape from the biased region, and most of it falls back into the galaxies or surrounding IGM, leaving the voids pristine.

After $z = 10$, these ~ 25 halos hierarchically merge to form a $10^9 M_\odot$ halo at $z = 7$ with two major mergers at $z = 10$ and $z = 7.9$. At late times, this galaxy grows mainly through mergers with halos above the filtering mass [25, 26, 70], i.e. gas-rich halos that are not photo-evaporated, and the gas fraction increases from 0.08 to 0.15 over the last 200 Myr of the simulation. The left panel of Figure 4 shows a large scatter in metallicity at early times, which is caused by inhomogeneous metal enrichment of its progenitors. Once it hosts sustained star formation after $z = 10$, the metallicity trends upwards as the stars enriches its host galaxy. In contrast with the smaller halo, the larger galaxy undergoes a few mergers with halos with an established stellar population. This creates a superposition of age-metallicity tracks in the star formation history.

This simulation of the early stages of galaxy formation only covered a handful of galaxies and did not explore the differing galaxy populations. However, it has given us a clear picture of the inner workings of these galaxies and the important physical processes involved in shaping the first galaxies and their connections to the first stars. We hope to improve on this work to survey a larger galaxy population and focus on larger galaxies that the *Hubble Space Telescope* has already observed and the *James Webb Space Telescope* will observe at $z > 6$.

6. Summary

I have provided a brief review of the formation of the first stars and their radiative, chemical, and mechanical feedback that affects subsequent structure and galaxy formation. Over the past decade, many groups have used numerical simulations to study these astrophysics events in the first billion years of the universe. Currently, the general consensus is that Population III stars are still very massive with a characteristic mass of tens M_\odot with an unknown fraction in binaries. The prospect of Population III binaries is exciting, and their impact on the universe prior to reionization, such as pre-ionization from X-rays, will be addressed in future studies. To summarize, the radiation from Population III expels most of the gas from the host halos, creating gas-poor halos that cannot form stars for 10–50 Myr. The SNe from the first stars enriches the first galaxies to a nearly uniform $\sim 10^{-3} Z_\odot$, and ultimately leads to the demise of this unique population of stars. The gas depletion, IGM pre-heating, and chemical enrichment all have a lasting impact on the formation of the first galaxies. Hopefully we can utilize these imprints to disentangle Population III stellar properties from the most distant galaxies in the universe.

References

- [1] T. Abel, P. Anninos, M. L. Norman, and Y. Zhang, *First Structure Formation. I. Primordial Star-forming Regions in Hierarchical Models*, *ApJ*, 508 (1998), pp. 518–529.
- [2] T. Abel, P. Anninos, Y. Zhang, and M. L. Norman, *Modeling primordial gas in numerical cosmology*, *New Astronomy*, 2 (1997), pp. 181–207.
- [3] T. Abel, G. L. Bryan, and M. L. Norman, *The Formation and Fragmentation of Primordial Molecular Clouds*, *ApJ*, 540 (2000), pp. 39–44.
- [4] ———, *The Formation of the First Star in the Universe*, *Science*, 295 (2002), pp. 93–98.

- [5] T. Abel, M. L. Norman, and P. Madau, *Photon-conserving Radiative Transfer around Point Sources in Multidimensional Numerical Cosmology*, *ApJ*, 523 (1999), pp. 66–71.
- [6] T. Abel, J. H. Wise, and G. L. Bryan, *The H II Region of a Primordial Star*, *ApJL*, 659 (2007), pp. L87–L90.
- [7] M. A. Alvarez, V. Bromm, and P. R. Shapiro, *The H II Region of the First Star*, *ApJ*, 639 (2006), pp. 621–632.
- [8] P. Anninos, Y. Zhang, T. Abel, and M. L. Norman, *Cosmological hydrodynamics with multi-species chemistry and nonequilibrium ionization and cooling*, *New Astronomy*, 2 (1997), pp. 209–224.
- [9] R. Barkana and A. Loeb, *In the beginning: the first sources of light and the reionization of the universe*, *Phys. Rep.*, 349 (2001), pp. 125–238.
- [10] Z. Barkat, G. Rakavy, and N. Sack, *Dynamics of Supernova Explosion Resulting from Pair Formation*, *Physical Review Letters*, 18 (1967), pp. 379–381.
- [11] J. R. Bond, W. D. Arnett, and B. J. Carr, *The evolution and fate of Very Massive Objects*, *ApJ*, 280 (1984), pp. 825–847.
- [12] R. J. Bouwens, G. D. Illingworth, R. I. Thompson, J. P. Blakeslee, M. E. Dickinson, T. J. Broadhurst, D. J. Eisenstein, X. Fan, M. Franx, G. Meurer, and P. van Dokkum, *Star Formation at $z \sim 6$: The Hubble Ultra Deep Parallel Fields*, *ApJL*, 606 (2004), pp. L25–L28.
- [13] V. Bromm, P. S. Coppi, and R. B. Larson, *Forming the First Stars in the Universe: The Fragmentation of Primordial Gas*, *ApJL*, 527 (1999), pp. L5–L8.
- [14] ———, *The Formation of the First Stars. I. The Primordial Star-forming Cloud*, *ApJ*, 564 (2002), pp. 23–51.
- [15] V. Bromm, R. P. Kudritzki, and A. Loeb, *Generic Spectrum and Ionization Efficiency of a Heavy Initial Mass Function for the First Stars*, *ApJ*, 552 (2001), pp. 464–472.
- [16] V. Bromm and A. Loeb, *Formation of the First Supermassive Black Holes*, *ApJ*, 596 (2003), pp. 34–46.
- [17] V. Bromm and N. Yoshida, *The First Galaxies*, *ARA&A*, 49 (2011), pp. 373–407.
- [18] R. Cen and M. A. Riquelme, *Lower Metal Enrichment of Virialized Gas in Minihalos*, *ApJ*, 674 (2008), pp. 644–652.
- [19] P. C. Clark, S. C. O. Glover, R. J. Smith, T. H. Greif, R. S. Klessen, and V. Bromm, *The Formation and Fragmentation of Disks Around Primordial Protostars*, *Science*, 331 (2011), pp. 1040–.
- [20] R. Cooke, M. Pettini, C. C. Steidel, G. C. Rudie, and R. A. Jorgenson, *A carbon-enhanced metal-poor damped Ly α system: probing gas from Population III nucleosynthesis?*, *MNRAS*, 412 (2011), pp. 1047–1058.

- [21] H. M. P. Couchman and M. J. Rees, *Pregalactic evolution in cosmologies with cold dark matter*, *MNRAS*, 221 (1986), pp. 53–62.
- [22] A. Dekel and M. J. Rees, *Physical mechanisms for biased galaxy formation*, *Nature*, 326 (1987), pp. 455–462.
- [23] X. Fan, C. L. Carilli, and B. Keating, *Observational Constraints on Cosmic Reionization*, *ARA&A*, 44 (2006), pp. 415–462.
- [24] S. R. Furlanetto and A. Loeb, *Is Double Reionization Physically Plausible?*, *ApJ*, 634 (2005), pp. 1–13.
- [25] N. Y. Gnedin, *Effect of Reionization on Structure Formation in the Universe*, *ApJ*, 542 (2000), pp. 535–541.
- [26] N. Y. Gnedin and L. Hui, *Probing the Universe with the Ly α forest - I. Hydrodynamics of the low-density intergalactic medium*, *MNRAS*, 296 (1998), pp. 44–55.
- [27] T. H. Greif, S. C. O. Glover, V. Bromm, and R. S. Klessen, *The First Galaxies: Chemical Enrichment, Mixing, and Star Formation*, *ApJ*, 716 (2010), pp. 510–520.
- [28] T. H. Greif, J. L. Johnson, R. S. Klessen, and V. Bromm, *The first galaxies: assembly, cooling and the onset of turbulence*, *MNRAS*, 387 (2008), pp. 1021–1036.
- [29] T. H. Greif, V. Springel, S. D. M. White, S. C. O. Glover, P. C. Clark, R. J. Smith, R. S. Klessen, and V. Bromm, *Simulations on a Moving Mesh: The Clustered Formation of Population III Protostars*, *ApJ*, 737 (2011), pp. 75–+.
- [30] Z. Haiman, A. A. Thoul, and A. Loeb, *Cosmological Formation of Low-Mass Objects*, *ApJ*, 464 (1996), p. 523.
- [31] A. Heger and S. E. Woosley, *The Nucleosynthetic Signature of Population III*, *ApJ*, 567 (2002), pp. 532–543.
- [32] T. Hosokawa, K. Omukai, N. Yoshida, and H. W. Yorke, *Protostellar Feedback Halts the Growth of the First Stars in the Universe*, *Science*, 334 (2011), pp. 1250–.
- [33] I. T. Iliev, G. Mellema, P. R. Shapiro, and U. Pen, *Self-regulated reionization*, *MNRAS*, 376 (2007), pp. 534–548.
- [34] J. L. Johnson, T. H. Greif, and V. Bromm, *Local Radiative Feedback in the Formation of the First Protogalaxies*, *ApJ*, 665 (2007), pp. 85–95.
- [35] T. Karlsson, J. L. Johnson, and V. Bromm, *Uncovering the Chemical Signature of the First Stars in the Universe*, *ApJ*, 679 (2008), pp. 6–16.
- [36] T. Kitayama, N. Yoshida, H. Susa, and M. Umemura, *The Structure and Evolution of Early Cosmological H II Regions*, *ApJ*, 613 (2004), pp. 631–645.

- [37] Y. Komiya, A. Habe, T. Suda, and M. Y. Fujimoto, *Formation History of Metal-poor Halo Stars with the Hierarchical Model and the Effect of Interstellar Matter Accretion on the Most Metal-poor Stars*, *ApJ*, 717 (2010), pp. 542–561.
- [38] M. E. Machacek, G. L. Bryan, and T. Abel, *Simulations of Pregalactic Structure Formation with Radiative Feedback*, *ApJ*, 548 (2001), pp. 509–521.
- [39] U. Maio, S. Khochfar, J. L. Johnson, and B. Ciardi, *The interplay between chemical and mechanical feedback from the first generation of stars*, *MNRAS*, 414 (2011), pp. 1145–1157.
- [40] M. R. C. McDowell, *On the formation of H₂ in H I regions*, *The Observatory*, 81 (1961), pp. 240–243.
- [41] I. D. McGreer and G. L. Bryan, *The Impact of HD Cooling on the Formation of the First Stars*, *ApJ*, 685 (2008), pp. 8–20.
- [42] K. Nomoto, N. Tominaga, H. Umeda, C. Kobayashi, and K. Maeda, *Nucleosynthesis yields of core-collapse supernovae and hypernovae, and galactic chemical evolution*, *Nuclear Physics A*, 777 (2006), pp. 424–458.
- [43] M. L. Norman, *Population III Star Formation and IMF*, in *First Stars III*, B. W. O’Shea & A. Heger, ed., vol. 990 of American Institute of Physics Conference Series, Mar. 2008, pp. 3–15.
- [44] B. W. O’Shea, T. Abel, D. Whalen, and M. L. Norman, *Forming a Primordial Star in a Relic H II Region*, *ApJL*, 628 (2005), pp. L5–L8.
- [45] B. W. O’Shea and M. L. Norman, *Population III Star Formation in a LCDM Universe. I. The Effect of Formation Redshift and Environment on Protostellar Accretion Rate*, *ApJ*, 654 (2007), pp. 66–92.
- [46] ———, *Population III Star Formation in a Λ CDM Universe. II. Effects of a Photodissociating Background*, *ApJ*, 673 (2008), pp. 14–33.
- [47] P. J. E. Peebles and R. H. Dicke, *Origin of the Globular Star Clusters*, *ApJ*, 154 (1968), p. 891.
- [48] B. E. Penprase, J. X. Prochaska, W. L. W. Sargent, I. Toro-Martinez, and D. J. Beeler, *Keck Echelle Spectrograph and Imager Observations of Metal-poor Damped Ly α Systems*, *ApJ*, 721 (2010), pp. 1–25.
- [49] M. Ricotti, N. Y. Gnedin, and J. M. Shull, *The Fate of the First Galaxies. III. Properties of Primordial Dwarf Galaxies and Their Impact on the Intergalactic Medium*, *ApJ*, 685 (2008), pp. 21–39.
- [50] S. Salvadori, R. Schneider, and A. Ferrara, *Cosmic stellar relics in the Galactic halo*, *MNRAS*, 381 (2007), pp. 647–662.
- [51] W. C. Saslaw and D. Zipoy, *Molecular Hydrogen in Pre-galactic Gas Clouds*, *Nature*, 216 (1967), pp. 976–978.

- [52] E. Scannapieco, R. Schneider, and A. Ferrara, *The Detectability of the First Stars and Their Cluster Enrichment Signatures*, *ApJ*, 589 (2003), pp. 35–52.
- [53] D. Schaerer, *On the properties of massive Population III stars and metal-free stellar populations*, *A&A*, 382 (2002), pp. 28–42.
- [54] M. Schwarzschild and L. Spitzer, *On the evolution of stars and chemical elements in the early phases of a galaxy*, *The Observatory*, 73 (1953), pp. 77–79.
- [55] P. R. Shapiro, *Cosmological H II regions and the photoionization of the intergalactic medium*, *PASP*, 98 (1986), pp. 1014–1017.
- [56] A. Stacy, T. H. Greif, and V. Bromm, *The first stars: formation of binaries and small multiple systems*, *MNRAS*, 403 (2010), pp. 45–60.
- [57] ———, *The First Stars: Mass Growth Under Protostellar Feedback*, ArXiv e-prints (1109.3147), (2011).
- [58] M. Tegmark, J. Silk, M. J. Rees, A. Blanchard, T. Abel, and F. Palla, *How Small Were the First Cosmological Objects?*, *ApJ*, 474 (1997), pp. 1–+.
- [59] R. I. Thompson, D. Eisenstein, X. Fan, M. Rieke, and R. C. Kennicutt, *Evidence for a $z < 8$ Origin of the Source-subtracted Near-Infrared Background*, *ApJ*, 666 (2007), pp. 658–662.
- [60] L. Tornatore, A. Ferrara, and R. Schneider, *Population III stars: hidden or disappeared?*, *MNRAS*, 382 (2007), pp. 945–950.
- [61] H. Trac and R. Cen, *Radiative Transfer Simulations of Cosmic Reionization. I. Methodology and Initial Results*, *ApJ*, 671 (2007), pp. 1–13.
- [62] M. Trenti, M. Stiavelli, and J. M. Shull, *Metal-free Gas Supply at the Edge of Reionization: Late-epoch Population III Star Formation*, *ApJ*, 700 (2009), pp. 1672–1679.
- [63] J. Tumlinson, *Chemical Evolution in Hierarchical Models of Cosmic Structure. I. Constraints on the Early Stellar Initial Mass Function*, *ApJ*, 641 (2006), pp. 1–20.
- [64] J. Tumlinson and J. M. Shull, *Zero-Metallicity Stars and the Effects of the First Stars on Reionization*, *ApJL*, 528 (2000), pp. L65–L68.
- [65] M. J. Turk, T. Abel, and B. O’Shea, *The Formation of Population III Binaries from Cosmological Initial Conditions*, *Science*, 325 (2009), pp. 601–.
- [66] D. Whalen, T. Abel, and M. L. Norman, *Radiation Hydrodynamic Evolution of Primordial H II Regions*, *ApJ*, 610 (2004), pp. 14–22.
- [67] D. J. Whalen and M. L. Norman, *Radiation hydrodynamical instabilities in cosmological and galactic ionization fronts*, *AP&SS*, 336 (2011), pp. 169–174.
- [68] J. H. Wise and T. Abel, *Resolving the Formation of Protogalaxies. I. Virialization*, *ApJ*, 665 (2007), pp. 899–910.

- [69] —, *Suppression of H_2 Cooling in the Ultraviolet Background*, *ApJ*, 671 (2007), pp. 1559–1567.
- [70] —, *How Very Massive Metal-Free Stars Start Cosmological Reionization*, *ApJ*, 684 (2008), pp. 1–17.
- [71] —, *Resolving the Formation of Protogalaxies. III. Feedback from the First Stars*, *ApJ*, 685 (2008), pp. 40–56.
- [72] J. H. Wise, M. J. Turk, M. L. Norman, and T. Abel, *The Birth of a Galaxy: Primordial Metal Enrichment and Stellar Populations*, *ApJ*, 745 (2012), p. 50.
- [73] S. E. Woosley and T. A. Weaver, *The Evolution and Explosion of Massive Stars. II. Explosive Hydrodynamics and Nucleosynthesis*, *ApJS*, 101 (1995), pp. 181–+.
- [74] N. Yoshida, V. Bromm, and L. Hernquist, *The Era of Massive Population III Stars: Cosmological Implications and Self-Termination*, *ApJ*, 605 (2004), pp. 579–590.
- [75] N. Yoshida, S. P. Oh, T. Kitayama, and L. Hernquist, *Early Cosmological H II/He III Regions and Their Impact on Second-Generation Star Formation*, *ApJ*, 663 (2007), pp. 687–707.
- [76] N. Yoshida, K. Omukai, and L. Hernquist, *Formation of Massive Primordial Stars in a Reionized Gas*, *ApJL*, 667 (2007), pp. L117–L120.
- [77] —, *Protostar Formation in the Early Universe*, *Science*, 321 (2008), pp. 669–.