

Cosmological Impact of the Population III Hypernovae

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Abstract. We investigate the stellar feedback of Pop III hypernovae by using cosmology simulations with **GADGET**. Recent studies of the Pop III star formation suggested that these stars might be very massive and many of them might have died as hypernovae, which are about ten times more energetic than conventional core-collapse supernovae. Such exotic supernovae might posit a strong impact on the early universe by injecting a large amount of energy and heavy elements. For investigating the cosmological impact of the first hypernovae, we use the realistic Pop III stellar evolution models including the relevant physics to simulate the formation, evolution, and hypernova explosion of a $60 M_{\odot}$ Pop III star. Our results show that the gas inside the host minihalo is effectively blown out by the ramp pressure of radiation and hypernova shock. It delays the star formation inside the halo for at least 50 million years. More importantly, the pristine gas of the intergalactic medium around the halo is chemically enriched to an average metallicity of $10^{-4} - 10^{-3} Z_{\odot}$, out to ~ 2 kpc within five hundred million years after the star dies. Such metal enrichment is able to transform the later star formation mode from Pop III to Pop II.

1. Introduction

One of the most important problems in modern cosmology is to understand how the first luminous objects such stars, accreting black holes (BHs) and galaxies, that shaped the early universe at the end of the cosmic dark ages [1, 2]. A key driver of this dramatic transformation was the gradual enrichment of the pristine universe with heavy chemical elements out of the first supernova (SN) explosions [3]. According to the modern theory of cosmological structure formation [4], the hierarchical assembly of dark matter (DM) halos provided the gravitational potential wells that allowed gas to form stars and galaxies inside them. Extending this model to the highest redshifts, one can determine the sites where the first stars, the so-called Population III (Pop III) stars, formed out of the pure hydrogen and helium gas created in the birth of the universe. Within this framework, Pop III stars are predicted to form inside of DM minihalos with total masses (DM and gas) of about $10^6 M_{\odot}$ at redshifts of $z \sim 20 - 30$ [5, 6, 7].

The first stars affected the evolution of the early universe in several different ways. Massive Pop III stars were strong sources of hydrogen and helium ionizing photons that built up extensive H II, He II, and He III regions [8]. The metals forged inside Pop III stars were later dispersed into the intergalactic medium (IGM) when they died as SNe, thus quickly polluting the primordial



gas such that the second generation of (Population II) stars could form. It is convenient to classify Pop III feedback mechanisms into different classes, specifically radiative feedback [9, 10], mechanical and chemical feedback due to SNe [11, 12], and X-ray feedback from accreting BH remnants [13, 14].

In the Pop III star-forming regions, metal cooling was absent because the primordial gas consisted almost exclusively of hydrogen ($\sim 76\%$ by mass) and helium ($\sim 24\%$). Molecular hydrogen was thus the dominant coolant, but owing to its quantum-mechanical structure, it was unable to cool the gas to the low temperatures typically encountered in star forming clouds today. The primordial gas, therefore, remained relatively warm, with typical temperatures of several hundred Kelvin. Hence the Jeans mass was correspondingly larger, as well, leading to the expectation that Pop III stars might have been more massive than stars formed today, with a predicted mass scale of $50 M_{\odot} - 100 M_{\odot}$ [15, 16]. Because of their high surface temperatures [17, 18], Pop III stars could effectively produce copious amounts of ionizing UV photons. Extended H II regions with size of several kpc were created before the stars died. Given the shallowness of the gravitational potential well of the host DM halos, the surrounding gas was subject to strong photo-heating, thus being able to easily escape the host minihalos [19]. This photo-evaporation suppressed further star formation inside the minihalos, thus delaying further star formation until more massive host halos emerged [20].

The character of Pop III feedback sensitively depends on the fate encountered by massive Pop III stars when they die after their short lifetime of a few million years. The fates of massive Pop III stars fall into four categories, depending upon their helium core mass at death [21]. Stars with helium cores of $2 - 8 M_{\odot}$ (main sequence masses $M_* = 10 - 25 M_{\odot}$) die in core-collapse SNe. Stars with helium cores of $8 - 35 M_{\odot}$ ($M_* = 25 - 90 M_{\odot}$) likely collapse to black holes unless they rotate very rapidly, in which case hypernovae might result. When the helium core is above $35 M_{\odot}$, it eventually encounters the electron/positron pair-instability. It either ejects a series of shells known as the pulsational pair-instability supernova for $M_* = 90 - 140 M_{\odot}$ [22], Or completely destroys the star in one cataclysmic explosion, pair-instability supernovae (PSN) for $M_* = 140 - 260 M_{\odot}$ [23, 24, 25]. A new type of supernova due to the GR instability in supermassive stars at $\sim 55,000 M_{\odot}$, which may have formed in the early universe, has now also been found in [26]. Because vast amounts of metals are ejected during a PSN explosion, even a single event could enrich about $10^7 M_{\odot}$ of primordial gas up to $10^{-4} Z_{\odot} - 10^{-3} Z_{\odot}$ [11, 12]. Even a small amount of metals could change the subsequent star formation process and might cause a transition of the stellar initial mass function (IMF) from the top-heavy mode predicted for Pop III stars to the standard IMF for later (Pop I and Pop II) generations with typical masses comparable to that of our Sun [27]. However, the results from stellar archeology [28], which studies the most metal-poor stars in the Local Group that retained the imprints from nucleosynthesis in the early universe, possibly including those from Pop III stars, in general do not support the chemical abundance pattern predicted for PSN enrichment. Theoretical PSN yields exhibit a pronounced odd-even effect resulting from a low neutron excess. In addition, the lack of any neutron capture process results in the absence of all elements heavier than the Fe peak (no r- or s-process). The Pop III core-collapse SNe and hypernovae models [29], however, can produce abundance patterns in good accord with the observation of metal poor stars. Thus, we study the Pop III hypernovae feedback using cosmology simulations with the realistic Pop III stellar models.

The structure of this paper is as follows: in Section 2, we describe our initial setup, as well as our numerical methods. The simulation results are presented in Section 3, and we conclude by discussing the broader implications in Section 4. All of the results presented in this paper use physical coordinates instead of comoving coordinates.

2. Numerical Methodology

The major tool used for our simulations is the well-tested, massively-parallel cosmological code **GADGET** [30], which computes gravitational forces with a hierarchical tree algorithm and represents fluids by means of smoothed particle hydrodynamics (SPH). In order to simulate the feedback exerted by the first stars and their SNe, additional physical processes, such as cooling and chemistry of the primordial gas, radiative transfer of ionizing photons, and SN explosions, are needed and have been included in our modified version of **GADGET**.

Our simulations use the initial conditions based on [12], starting at $z = 100$ in a periodic box of linear size of 1 Mpc (co-moving). The Λ CDM cosmological parameters are matter density $\Omega_m = 0.3$, baryon density $\Omega_b = 0.04$, Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, spectral index $n_s = 1.0$, and normalization $\sigma_8 = 0.9$, based on the WMAP cosmic microwave background (CMB) measurement [31]. Our simulations marginally resolve the corresponding Jeans mass of $M_J \simeq 500 M_\odot$. The cooling and chemistry network of the primordial gas include all relevant cooling mechanisms of primordial gas, such as H and He collisional ionization, excitation and recombination cooling, bremsstrahlung, and inverse Compton cooling; in addition, the collisional excitation cooling via H_2 and HD is also taken into account. For H_2 cooling, collisions with protons and electrons are explicitly included. We use the sink particles to mimic the star formation based on the algorithm of [32]. The important criterion for sink creation, and subsequent accretion of further SPH particles, is that the gas density exceeds a pre-specified density threshold, $n_c \sim 10^4 \text{ cm}^{-3}$, but we also test for gravitational boundedness, and whether the gas is part of a converging flow, where $\nabla \cdot \vec{v} < 0$. The sink particles provide markers for the position of a Pop III star and its remnants, such as a black hole or SN, to which detailed sub-grid physics can be supplied.

When a Pop III star has formed inside the minihalo, the sink particle representing it immediately turns into a point source of ionizing photons to mimic the birth of a star. Instead of simply assuming constant rates of emission, we use the results of one-dimensional stellar evolution calculations from [29] to construct the luminosity history of the Pop III star. Indeed, luminosities exhibit considerable time variability when taking the evolution off the main sequence into account. The photons streaming from the star then establish an ionization front and build up H II regions. To trace the propagation of photons and the ionization front, we use the ray-tracing algorithm from [9]. The radiation transport is coupled to the hydrodynamics of the gas through its chemical and thermal evolution. The transfer of the H_2 -dissociating photons in the Lyman-Werner (LW) band (11.2 – 13.6 eV) is also included.

When the star reaches the end of its lifetime, we initialize a SN blast wave by distributing the explosion energy among the gas SPH particles surrounding the sink. Because the resolution of the simulation is about 1 pc, we cannot resolve individual SNe in both mass and space. Instead, we select the particles within a region of 10 pc to share the supernova's thermal energy and metal yield. The gas within this region has mean temperatures about several million Kelvin. On this scale, the blast wave is still close to its energy-conserving phase. The explosion energy of hypernovae can be up to $10^{52} - 10^{53}$ erg, whereas a conventional core-collapse SN has about 10^{51} erg. Since we here cannot resolve the fine-grained mixing due to fluid instabilities in the early SN ejecta, developing on a scale far below 1 pc. However, we approximately model the coarse-grain mixing on cosmologically relevant timescales by applying the SPH diffusion scheme from [33] which approximately model the effect of unresolved, sub-grid turbulence as a diffusion process, linking the corresponding transport coefficients to the local physical conditions at the grid scale.

After the SN explosion, metal cooling must be considered in the cooling network. We assume that C, O, and Si are produced with solar relative abundances, which are the dominant coolants for the gas contaminated by the first hypernovae. There are two distinct temperature regimes for these species. In low temperature gas, $T < 2 \times 10^4 \text{ K}$, we use a chemical network presented

in [34], which follows the chemistry of C, C⁺, O, O⁺, Si, Si⁺, and Si⁺⁺, supplemental to the primordial species discussed above. At high temperatures, $T \geq 2 \times 10^4$ K, due to the increasing number of ionization states, a full non-equilibrium treatment of metal chemistry becomes computationally prohibitive. Instead of directly solving the cooling network, we use the cooling rate table based on [35], which gives effective cooling rates for hydrogen and helium line cooling, as well as bremsstrahlung, at different metallicities. Dust cooling is not included because it would only become important at densities much higher than what is reached in our simulations.

We choose a $60 M_{\odot}$ Pop III star from the library of [29] as the target of study. This star evolves in total for about 3.7 Myr before it dies as a hypernova with an explosion energy of 10×10^{51} erg = 10 B and a metal yield of $20.6 M_{\odot}$.

3. Results

The $60 M_{\odot}$ Pop III star is expected to form inside a minihalo, with a total mass of about $10^6 M_{\odot}$ and a virial radius of ~ 100 pc, located in the region with the highest mass resolution at $z \sim 27$. This allows us to resolve key small-scale features of the ensuing stellar feedback. Once the gas density inside the star-forming cloud exceeds the threshold for sink creation, a single $60 M_{\odot}$ Pop III star promptly forms and immediately represents fully developed Pop III stars, acting as sources of UV radiation. The gas inside the halo is rapidly photo-heated up to temperatures of $T \approx 2 \times 10^4$ K. This drives the sound speed up to 30 km s^{-1} , whereas the escape velocity of the host halo is only about 3 km s^{-1} . The photo-heated gas is thus blown out of the shallow potential well of the minihalo. UV photons not only heat up the gas but also ionize the neutral hydrogen and helium. The ionization-front (I-front) propagation begins with a short supersonic phase (R-type), then switches to a subsonic phase (D-type), because the I-front is trapped behind a hydrodynamical shock [36, 19]. The I-front eventually breaks out, jumping ahead of the shock, and supersonically propagates into the low-density IGM. A giant bubble of hot, ionized, gas is created around the central star, with an inner region that has reached temperatures in excess of 10^4 K. The shape of this bubble is very irregular due to the inhomogeneous and anisotropic distribution of the gas in the surrounding IGM. The bubble sizes reflect the strength of the UV emission rates, which highly depend on stellar mass. This $60 M_{\odot}$ star creates a bubble with a size of about 5 kpc.

After about 3.7 Myr evolution, the star eventually dies as a hypernova. The explosion creates a strong shock wave, traveling with a velocity of $v_{\text{sn}} \approx 10^4 \text{ km s}^{-1}$. The energy carried by the shock is able to reheat the relic H II region for an additional $t_{\text{sn}} \approx r_h / V_{\text{sn}} \approx 0.4$ Myr, assuming H II region radii of $r_h \approx 4$ kpc. The shock heating in the simulation is roughly about 0.6 Myr because the shock velocity is slowed down due to radiative cooling. After the shock dissipates, a hot and metal-rich ejecta is left behind in the IGM and continues to expand for about another 5 million years, with an increasingly ill-defined boundary. Eventually, the thermal energy of the initial ejecta is radiated away, and the expansion stalls. The mixing of the metals with primordial gas predominantly occurs before stalling. This metal-enriched bubble has reached radial sizes of ~ 2 kpc with corresponding metallicities of $10^{-4} - 10^{-2} Z_{\odot}$. The strong SN blast waves substantially suppress the gas density in the host halo, resulting in $n < 0.01 \text{ g cm}^{-3}$, similar to that of the background IGM at this redshift of $z \sim 26$. We show the pre and post feedback from a single $60 M_{\odot}$ star in Figure 1. The resulting feedback significantly enhances the IGM temperature, smoothes out density structures in nearby halos, and enriches the primordial gas over regions of ~ 2 kpc.

4. Conclusions

We have presented the results from the cosmological simulations of the impact of a pop III hypernova. We improve on earlier simulations by using updated Pop III stellar models. A

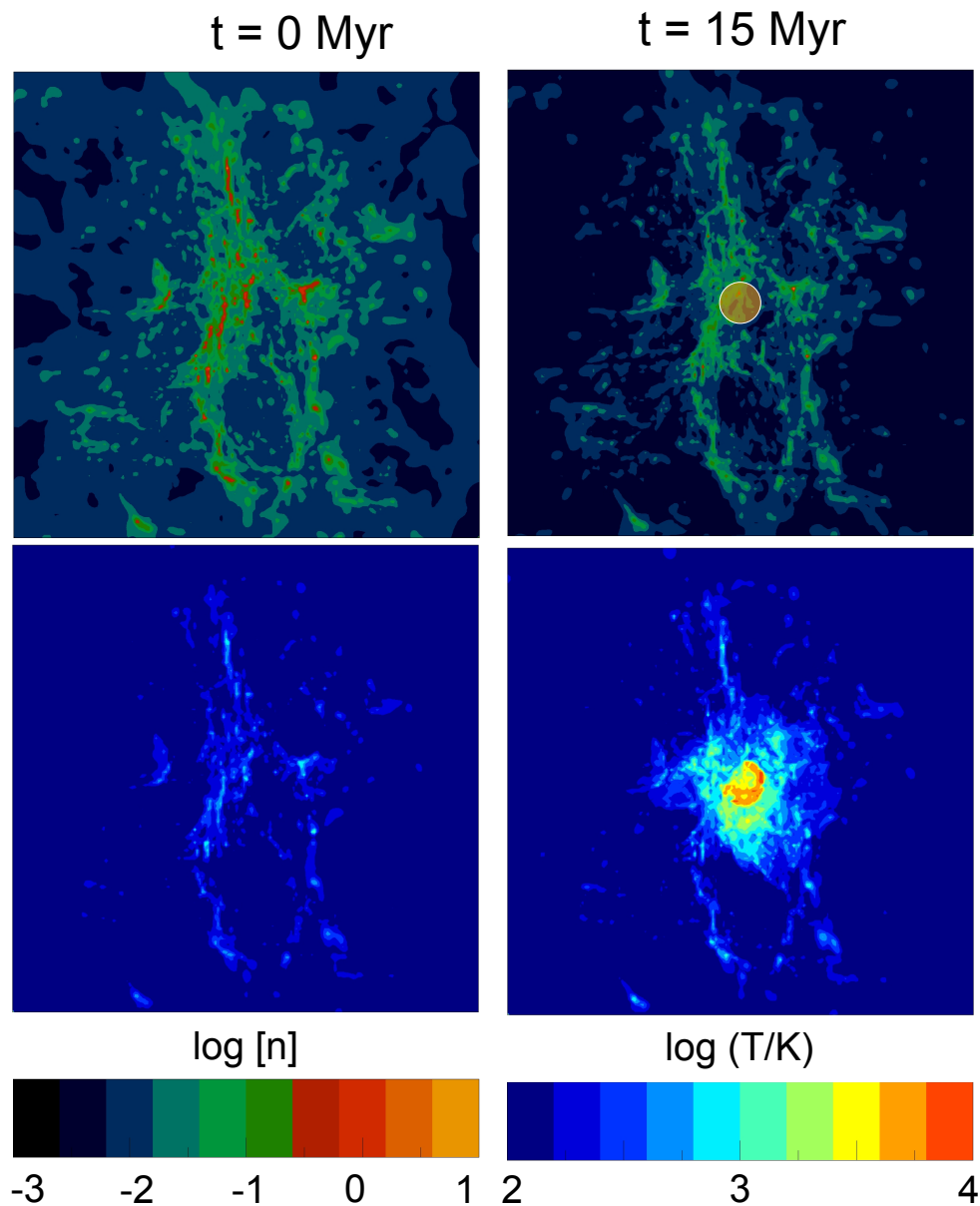


Figure 1. Cosmological impact of a $60 M_{\odot}$ pop III star. Panels show temperatures and densities before/after the stellar feedback from a $60 M_{\odot}$ star. The size of each panel is about $10 \times 10 \text{ kpc}^2$. Some higher density clumps have been smoothed due to radiative and SN feedback which also chemically enriches the pristine gas within the orange circle of radius $\sim 1 \text{ kpc}$. Both radiative and supernova feedback heat up the gas and change its chemistry on a scale of $3 - 4 \text{ kpc}$.

single, energetic hypernova can impact the early universe on cosmological scales of several kpc. However, without a rapid rotation, a $60 M_{\odot}$ Pop III star has a high probability of collapsing into a BH without any chemical enrichment. The imprint from the violent death of Pop III stars, in all their variety, might soon be amenable to empirical testing with the *James Webb Space Telescope* (*JWST*), to be launched around 2018.

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