The Effects of Radiative Feedback and Supernova-induced Turbulence on Early Galaxies

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Abstract

The recently launched James Webb Space Telescope promises unparalleled advances in our understanding of the first stars and galaxies, but realizing this potential requires cosmological simulations that capture the key physical processes that affect these objects. Here, we show that radiative transfer and subgrid turbulent mixing are two such processes. By comparing simulations with and without radiative transfer but with exactly the same physical parameters and subgrid turbulent mixing model, we show that tracking radiative transfer suppresses the Population III star formation density by a factor \(\approx 4\). In both simulations, \(\gtrsim 90\%\) of Population III stars are found in the unresolved pristine regions tracked by our subgrid model, which does a better job at modeling the regions surrounding proto-galaxy cores where metals from supernovae take tens of megayears to mix thoroughly. At the same time, radiative transfer suppresses Population III star formation, via the development of ionized bubbles that slow gas accretion in these regions, and it results in compact high-redshift galaxies that are surrounded by isolated low-mass satellites. Thus, turbulent mixing and radiative transfer are both essential processes that must be included to accurately model the morphology, composition, and growth of primordial galaxies.

Unified Astronomy Thesaurus concepts: Radiative transfer simulations (1967); Hydrodynamical simulations (767); Galaxy formation (595); Population III stars (1285); Early universe (435); Early astronomical instruments (433)

1. Introduction

The search to observe the first stars and galaxies is one of the most active frontiers in astronomy. Using the James Webb Space Telescope (JWST), researchers will soon be able to measure galaxies out to redshift 10 and beyond, probing the era in which the first generation of stars was formed (Gardner et al. 2006). As such, it is important to have physical models that predict the density of early galaxies well beyond the redshift and luminosity limits of current surveys (e.g., Finkelstein 2016; Ishigaki et al. 2018; Bouwens et al. 2019).

The first stars were formed of primordial gas made up of hydrogen, helium, and trace amounts of lithium, and are believed to have been much more massive than the Sun (e.g., Abel et al. 2002; Bromm et al. 2002; O’Shea & Norman 2007; Susa et al. 2014). While the very first stars were composed solely of primordial gas, it is also believed that stars with traces of heavier elements less than a critical metallicity, \(Z_{\text{crit}}\), also share their characteristics (Schneider et al. 2012). These Population III (Pop III) stars have a strong impact on the luminosity of early galaxies (Yajima & Khochfar 2017) due to their lower opacity, higher surface temperatures, and enhanced UV spectra (Raiter et al. 2010), and may be observable individually through the use of strong lensing (e.g., Windhorst et al. 2018; Welch et al. 2022).

However, the physical processes governing the formation and characteristics of Pop III stars are poorly understood (Ishiyama et al. 2016). The lack of confirmed, direct observations of Pop III stars has led to an abundance of numerical and theoretical studies (e.g., Mackey et al. 2003; Scannapieco et al. 2003; O’Shea & Norman 2007; Ahn & Shapiro 2007; Wise et al. 2012; Pallottini et al. 2014; Xu et al. 2016), each of which focuses on a particular subset of the relevant physics. Important among these are the models for radiative and supernova (SN) feedback, both of which heat the gas, helping it resist collapse. However, SN feedback also pollutes the gas with heavy elements that help gas cool more efficiently (Hirano & Yoshida 2013) and begins the transition to lower-mass Population II (Pop II) star formation.

The pollution of pristine gas depends on at least two parameters: the critical metallicity and the rate at which metals ejected by SN are distributed throughout early star-forming halos (Pan et al. 2013). The first parameter is poorly understood, but is believed to lie between \(10^{-6}Z_{\odot}\) and \(10^{-3}Z_{\odot}\) (Schneider et al. 2012; Dopcke et al. 2013). This is a range of values that is low enough such that the uncertainty in \(Z_{\text{crit}}\) has a very weak impact on predictions of the evolution of the Pop III stars (Sarmento et al. 2019).

Instead, the transition from Pop III to Pop II star formation is governed by another critical component: the transport of SN ejecta into the primordial gas. This process determines the degree to which a specific parcel of gas is polluted with heavy elements, and hence whether it will subsequently form metal-free Pop III or metal-enriched Pop II stars (Sarmento et al. 2016). Because metallicity relates to cooling, the level of pollution also dictates the star formation timescale. Thus, the combined effects of supernovae and turbulent mixing led to a spatially-inhomogeneous Pop III/Pop II transition, the details of which are key to understanding the structure and evolution of the earliest galaxies (Scannapieco et al. 2003; Wise et al. 2012; Crosby et al. 2013; Johnson et al. 2013; Pan et al. 2013; Pallottini et al. 2014).

Our previous work has emphasized the importance of turbulent mixing in this transition, developing a new approach that allows us to track the effects of subgrid mixing in each resolution element. By using a self-convolution model developed in Pan et al. (2012, 2013) to estimate the rate at which turbulence mixes pollutants, we were able to show that...
thorough mixing can take several eddy turnover times. This means that modeling turbulent mixing is at least as important as modeling large-scale inhomogeneities when determining the Pop III star formation history. In fact, we found an increase of \( \approx 3 \) times the Pop III star formation rate density as compared to similar cosmological simulations that did not account for subgrid mixing (Sarmento et al. 2016), and were able to account for this effect in order to make several detailed predictions as to the evolution of the first stars and galaxies (Sarmento et al. 2018, 2019).

However, this picture is further complicated by the presence of radiative feedback. Pop III stars and massive Pop II stars produce copious amounts of ultraviolet radiation in both the H-ionizing and Lyman–Werner (LW) bands, which has a significant impact on the rate of star formation. LW radiation dissociates molecular hydrogen, which is the primary coolant of primordial gas and the predominant cooling channel for Pop III star formation (Ahn et al. 2009; Safranek-Shrader et al. 2012). Hydrogen reionizing photons, on the other hand, provide an additional heating source that inhibits the formation of stars in low-mass galaxies (Dawoodbhoy et al. 2018; Katz et al. 2020).

Dedicated radiative-transfer simulations have studied reionization in detail, tracking the propagation of ionization fronts outward from early galaxies and continuing until the H\textsc{ii} regions bounded by these fronts overlap, fully ionizing the universe. These were initially carried out by post-processing cosmological density fields from simulations of large-scale structure formation (e.g., Abel et al. 1999; Gnedin 2000; Nakamoto et al. 2001; Ciardi et al. 2001, 2006; Sokasian et al. 2004; Zahn et al. 2011), but later these advanced to the point where gas dynamics and radiative transfer could be simulated self-consistently (e.g., Iliev et al. 2007; Gnedin & Kaurov 2014; Ocvirk et al. 2015; Pawlik et al. 2017; Ocvirk et al. 2020). Together, these simulations described an extended process by which H\textsc{ii} regions first formed around the highly clustered densest sources, grew in size and number, became more aspherical with time, and finally percolated to ionize the remaining islands of neutral material (e.g., Furlanetto et al. 2006; Zahn et al. 2007).

Several authors have performed simulations to model the feedback effects of both SN and ionizing radiation on the Pop III/II SFR. Many of these models employed a simplified heating or global radiation model (e.g., Tornatore et al. 2007; Johnson et al. 2008; Greif et al. 2008; Jaacks et al. 2018), while others employed a self-consistent locally generated radiation field (e.g., Wise et al. 2012; Pawlik et al. 2013; Johnson et al. 2013; Wells & Norman 2022). However, no one has yet combined self-consistent radiative transfer and SN feedback with a subgrid turbulent mixing model for SN ejecta.

This work describes the impact of modeling radiative transfer in the context of the very high-redshift universe. To that end, we describe the differences between two pilot simulations. The RTsim tracks a self-consistently generated radiation field coupled with SN feedback and turbulent mixing. The nonRTsim replaces radiative transfer with a homogeneous UV background (Haardt & Madau 1996) switched on at \( z = 9 \), while still retaining SN feedback and turbulent mixing. Together, these simulations allow us to tease out the effects of radiative feedback on the formation of the first galaxies.

The work is structured as follows. In Section 2, we describe our methods, including the spectral energy distribution (SED) models used to model radiation from our stars. In Section 3, we compare the nonRTsim and RTsim simulations, focusing on the impact of radiative transfer on the overall evolution and the spatial distribution of Pop III stars. Our conclusions are discussed in Section 4.

2. Methods

Our simulations use a modified version of RAMSES-RT (Rosdahl et al. 2013; Rosdahl & Teyssier 2015), a cosmological adaptive mesh refinement (AMR) simulation with coupled radiation hydrodynamics (RHD), to which we added our specialized model of turbulent mixing. Here, we describe the key features and parameters of the simulations.

2.1. Radiative Transfer and Turbulent Mixing

RAMSES-RT is an extension of RAMSES (Teyssier 2002) that models the interactions between dark matter, stellar populations, and baryons via gravity and hydrodynamics. RAMSES-RT adds stellar radiation and radiative transfer as well as nonequilibrium radiative heating and cooling. The simulation advects photons between cells using a first-order moment method with full local M1 closure for the Eddington tensor (Levermore 1984). To keep the radiative transfer computations manageable, we group photons into four energy ranges: the H\textsc{ii} dissociating LW band, H ionizing radiation, and two levels for He ionizing radiation, which correspond to

\[
11.20 \text{ eV} \leq \epsilon_{\text{LW}} < 13.60 \text{ eV}, \quad 13.60 \text{ eV} \leq \epsilon_{\text{H}} < 24.59 \text{ eV}, \quad 24.59 \text{ eV} \leq \epsilon_{\text{He}} < 54.42 \text{ eV}, \quad \text{and} \quad 54.42 \text{ eV} \leq \epsilon_{\text{He}}. \]

RAMSES-RT models the thermochemistry, photon absorption, and emission (Rosdahl et al. 2013; Rosdahl & Teyssier 2015; Nickerson et al. 2018). The ionization states are modeled self-consistently with the temperature and radiation field in terms of photon density and flux for each of the photon groups, and the ionization fractions \( x_{\text{H}}, x_{\text{He}}, x_{\text{He}} \) are computed, stored, and advected between cells. The photon densities and fluxes, \( N_{\gamma} \) and \( F_{\gamma} \), for each photon group, are computed using moment-based radiative transfer that essentially treats the photons as a fluid. Source photon abundances are generated for star particles (SPs) using an externally specified spectral energy density (SED) model. We use Starburst99 (Leitherer et al. 2011) and the work of Raiter et al. (2010) to model stellar radiation from populations with metallicities \( 0 \leq Z \leq Z_{\odot} \) and ages between 10 kyr and a Gyr. Photon energies are also discretized across our four bins, resulting in four average photon energies. The simulation employs a reduced speed of light approximation (Ocvirk et al. 2019), which greatly increases the allowable time step, and we adopt 0.01c for this value.

The hydrodynamic flux between cells is computed using a Harten–Lax–van Leer contact (HLLC) Riemann solver (Toro et al. 1994). It is used to advect the typical cell-centered gas variables, the RT ionization states, as well as the hydro scalars added by Sarmento et al. (2016) that track the turbulent velocity, the pristine gas mass fraction, and the metals generated by Pop III supernova (SNe).

We use the self-convolution model developed by Pan et al. (2013) to follow subgrid mixing of SN ejecta into the pristine gas. The fraction of pristine gas in each cell is modeled as a
scalar value \( P \) that evolves as
\[
\frac{dP}{dt} = -\frac{n}{\tau_{\text{con}}} P(1 - P^{1/n}),
\]
where \( \tau_{\text{con}} \) is the convoluted timescale that is inversely proportional to the turbulent stretching rate (Pan & Scannapieco 2010; Pan et al. 2012, 2013) and \( n \) is a measure of the locality of mixing. The scalar \( P \) is tracked for each cell and computed at each time step when \( P > 0 \).

By modeling the unmixed fraction of gas in each simulation cell, we can estimate the fraction of Pop III versus Pop II stars formed in these actively mixing regions. This leads to an enhanced Pop III star formation rate density, as compared to the rate derived in simulations that do not track \( P \) and instead assume that Pop III stars form in cells composed solely of primordial gas. We adopt the name “Classical Pop III” for stars formed in these regions, to distinguish them from the overall Pop III stellar distribution, which also includes stars formed in polluted cells with nonzero pristine fractions.

2.2. Star Formation

Stars are modeled as collisionless particles and are evolved using a particle-mesh solver with cloud-in-cell interpolation (Guillet & Teyssier 2011). We assume an ideal gas with a ratio of specific heats \( \gamma = 5/3 \). Star particles (SPs) are created in regions of gas according to a Schmidt (1959) law with
\[
\rho_\star = \epsilon_* \frac{\rho_{\text{gas}}}{t_{\text{ff}}} \rho (\rho_{\text{gas}} - \rho_{\text{th}}),
\]
where \( \epsilon_* = 0.10 \) is the star formation efficiency, \( t_{\text{ff}} = \sqrt{3\pi/(32G\rho)} \) is the gas freefall time, \( \rho_{\text{gas}} \) is the local gas density, and the Heaviside step function, \( \theta \), guarantees star formation occurs only when the gas density \( \rho_{\text{gas}} \) also exceeds a threshold value \( \rho_{\text{th}} \). Here, we set \( \rho_{\text{th}} \) to the larger of 0.05 \( H \) cm\(^{-3}\) and 200 \( \pi \), where \( \pi \) is the mean density of the simulation. The former criteria is derived from the Jeans condition such that \( 4\Delta_{\text{best}} \geq \lambda_j \), where \( \lambda_j \) is the Jeans length and \( \Delta_{\text{best}} \) is the highest-resolution cell size. The latter criterion ensures star formation only occurs in collapsed objects (Rasera & Teyssier 2006; Trebitsch et al. 2017). Our \( \rho_{\text{th}} \) and \( \epsilon_* \) result in a star formation rate density (SFRD) in reasonable agreement with observations (Finkelstein 2016; Madau & Dickinson 2014), see Figure 1, while ensuring we do not form stars in high-density regions of the cosmological flow.

Each SP represents an initial mass function (IMF) of stars. The SP mass is set by the star-forming density threshold and our star resolution, resulting in \( m_{\star} = (0.05 \, H \, cm^{-3}) \Delta_{\text{best}}^3 \approx 2.6 \times 10^3 M_\odot \). The final mass of each SP is drawn from a Poisson process such that it is a multiple of \( m_{\star} \).

2.3. Feedback

For Pop II stars \( (Z > Z_{\text{crit}}) \), we assume a Salpeter IMF such that 10% of each SP’s mass represents stars that are more massive than 8 \( M_\odot \), and go supernova in 10 Myr (e.g., Raskin et al. 2008; Somerville et al. 2008). For Pop III SPs \( (Z \leq Z_{\text{crit}}) \), we assume a log-normal, top-heavy IMF such that 99%, by mass, explode within 10 Myr (Larson 1973; Tumlinson 2006; Raiter et al. 2010) of the SP’s formation. These fractions also represent the fractions of SP mass recycled into the ISM for Pop II, \( f_{\text{sn}} = 0.10 \), and Pop III SPs, \( f_{\text{snIII}} = 0.99 \), respectively.

The impact of these SNe are parameterized by the mass fraction of ejecta, described above, and the kinetic energy per unit mass of the explosion, \( E_{\text{SN}} \). We use \( E_{\text{SN}} = 10^{51} \text{erg}/10 M_\odot \) for all stars formed throughout the simulation. The fraction of new metals in SN ejecta is 0.15 even though metal yields and energy from Pop III SNe are likely to have been higher (Scannapieco et al. 2003; Scannapieco 2005).

As discussed above, RAMSES-RT tracks the ionization states of \( H_2 \), \( \text{H} \), and \( \text{He} \), along with the radiation field, to compute heating and cooling. The model self-consistently follows collisional and photoinduced ionization, photodissociation, and recombination, but does not include cosmic-ray heating. Finally, we use the on-the-spot approximation (Rosdahl et al. 2013), such that recombination photons are reabsorbed in the same cell in which they are emitted.

The nonRTsim uses standard RAMSES heating and cooling (Teyssier 2002), with the addition of a simple molecular cooling model described in Sarmento et al. (2016). The non-RT \( H_2 \) cooling is only effective before the first stars form, because they generate enough LW photons to dissociate all of the \( H_2 \) within the nonRTsim box (e.g., Greif & Bromm 2006). The nonRTsim model is initialized with a constant \( H_2 \) fraction, \( f_{\text{H}_2} = 10^{-6} \), (Reed et al. 2005) whereas the RTsim initializes the \( H_2 \) fraction from the simulation’s starting temperature and density.

The photon escape fraction is set to \( f_{\text{esc}} = 0.5 \). This parameter scales the fraction of stellar photons that escape the local star-forming cell. Note that \( f_{\text{esc}} \) is distinct from the galactic escape fraction, which is highly uncertain in the early universe (Tanaka & Hasegawa 2020). The \( f_{\text{esc}} \) parameter in the simulation is used to scale SED radiation (Rosdahl et al. 2018). A value \( f_{\text{esc}} < 1 \) is typically interpreted as accounting for unresolved overdensities or underestimated recombination rates that trap radiation locally. A value of \( f_{\text{esc}} > 1 \) is typically
used to boost stellar luminosities and compensate for chimneys and unresolved turbulence in the interstellar/galactic medium. As such, \( f_{\text{exc}} \) is largely a free parameter used to tune RT simulations. We will explore its effects on the overall SFRD in future work.

Finally, we did not include black holes (BH) in our simulation, because BH feedback is not likely to be significant for our very early galaxies (Scannapieco & Oh 2004; Somerville et al. 2008). For the non\( RT_{\text{sim}} \), we turn on the UV background at \( z=9 \), the point at which the RT\( sim \) approaches 50% reionization.

### 2.4. Simulation Parameters

We adopt a set of cosmological parameters from Komatsu et al. (2011), with \( \Omega_m=0.267 \), \( \Omega_{\Lambda}=0.733 \), \( \Omega_b=0.0449 \), \( h=0.71 \), \( \sigma_8=0.801 \), and \( n=0.96 \), where \( \Omega_m \), \( \Omega_{\Lambda} \), and \( \Omega_b \) are the total matter, vacuum, and baryonic densities, in units of the critical density; \( h \) is the Hubble constant in units of 100 km s\(^{-1}\); \( \sigma_8 \) is the variance of linear fluctuations on the 8 h\(^{-1}\) Mpc scale; and \( n \) is the “tilt” of the primordial power spectrum (Larson et al. 2011).

We evolve two 3 h\(^{-1}\) comoving Mpc (cMpc) on-a-side simulations to \( z=6 \). This is approximately the volume of the local Milky Way (MW) Group. The RT\( sim \) includes feedback from stellar photons and radiative transfer, while the non-RT\( sim \) does not. Otherwise, the two simulations share all common parameters described below. Note that the small size of our simulation volumes means that they will not capture the large-scale fluctuations, due to the patchy structure of reionization, which occurs on scales of 10 Mpc or larger (Furlanetto et al. 2004) and requires simulations boxes at least 100 Mpc across to be adequately reproduced (Iliev et al. 2014).

On the other hand, our simulations are well-suited to draw conclusions about the small-scale features of radiative feedback on the very low-mass galaxies within which the first stars were formed.

We set the initial refinement level to \( \ell_{\text{min}}=9 \), corresponding to a coarse (initial) grid resolution \( \Delta x_{\text{max}}=5.86 \) h\(^{-1}\) comoving kpc (ckpc)—a compromise that provides reasonable resolution of the intergalactic medium (IGM) without creating an excessive computational load. We adopt a quasi-Lagrangian approach to refinement, such that cells are refined as they become approximately 8x overdense. This strategy attempts to keep the amount of mass in each cell roughly constant as the simulation progresses.

Allowing for up to six additional levels of refinement results in a best average resolution of 91.6 h\(^{-1}\) comoving pc (cpc) in refined regions. The initial grid scale and simulation size sets the dark matter (DM) particle mass. For this simulation, \( M_{\text{DM}}=1.75 \times 10^6 M_\odot \), resulting in approximately 300 DM particles needed to resolve a minihalo of \( 5.25 \times 10^9 M_\odot \)—a mass near the atomic cooling limit (Wise et al. 2014).

Initial conditions were identical for both simulations and were generated using Multi-Scale Initial Conditions (MUSIC; Hahn & Abel 2013). The initial gas metallicity was \( Z=0 \), and we define \( Z_{\text{crit}}=10^{-7} Z_\odot \), the boundary between Pop III and Pop II star formation. The nonlinear length scale at the end of the simulation, \( z=6 \), was 39 h\(^{-1}\) ckpc, corresponding to a mass of \( 1.8 \times 10^7 h^{-1} M_\odot \).

### 3. Results

#### 3.1. Overall Evolution

While our volume is too small to characterize the high-redshift luminosity function, it is well-suited to drawing conclusions about the impact of modeling RT and turbulent mixing on some of the properties of early galaxies. As shown in Figure 1, star formation in the RT\( sim \) begins slightly earlier than in the nonRT\( sim \). This is due to the more efficient nonequilibrium cooling used in the RT\( sim \) (Rosdahl et al. 2013) coupled with different starting H\(_2\) fractions for the two simulations, as discussed above. However, although the initial conditions are slightly more favorable for early star formation in the RT\( sim \), by \( z=17 \) it generates stars at a much slower rate than in the nonRT\( sim \). This is because stellar radiation adds energy to star-forming regions in the RT\( sim \), heating the gas and greatly impeding its ability to collapse and form stars (Johnson et al. 2013; Pawlik et al. 2013; Hopkins et al. 2020). Between 10 < \( z < 18 \), the nonRT\( sim \) generates \( \approx 9 \times \) more mass in SPs than the RT\( sim \).

At \( z=9 \) in the nonRT\( sim \), the Haardt & Madau (1996) UV background is turned on (the gray region in Figure 1) when the gas has already been heated to an average of \( \approx 7500 \) K, as seen in Figure 2. At this point, the RT\( sim \) is \( \approx 50\% \) reionized. Shortly after, by \( z=7.5 \), this background raises the average gas temperature in the nonRT\( sim \) to \( \gtrsim 9000 \) K. This is also the point at which the SFRD in the RT\( sim \) begins to overtake the rate in the nonRT\( sim \). This is now possible because of the excess gas in the RT\( sim \) as compared to the nonRT\( sim \). The RT\( sim \) continues to generate more stars than the nonRT\( sim \) for the remainder of the simulation.

Both simulations generate roughly the same mass in Classical Pop III stars (indicated by the dotted line in Figure 1) at each epoch, down to \( z \approx 8 \). These stars, by definition, are formed in fully pristine gas (cells) unpolluted by SN ejecta (Sarmento et al. 2016). These are areas far enough away from previous star-forming regions that turbulent mixing of ejecta has not begun. These regions are also necessarily separated from existing star-forming regions such that they are not strongly heated by stellar photons. This agreement in the Classical Pop III SFRD between the two simulations would seem to indicate that modeling RT is not crucial to accurately modeling Pop III star formation in the early universe.
However, the overall Pop III SFRD (dashed line in Figure 1) is higher in the nonRTsim than in the RTsim. In fact, over the redshift range $8 \leq z \leq 18$, it is four times higher in the nonRTsim. Thus, the excess of Pop III stars in the nonRTsim must be formed in regions of incomplete mixing, and the nonRTsim forms more Pop III stars in this region. Since SNe are the primary driver of turbulent mixing, we conclude that radiative heating suppresses Pop III star formation in areas actively stirred by SN energy.

Note that the overall Pop III star formation rate in the RTsim is approximately 10 times that of the Classical Pop III rate, demonstrating the need to track Pop III star formation in unresolved cells. By contrast, our earlier 3 Mpc h$^{-1}$ study in Sarmento et al. (2016) displayed an overall-to-Classical Pop III SFRD ratio of $\approx 4$. The difference is due to the different maximum resolutions used in these studies. In Sarmento et al. (2016), we used a maximum resolution four times higher than the one used here. The increased resolution results in a nonRTsim such that it is now hotter than the gas in the nonRTsim during earlier epochs. In fact, the larger number of SN in the nonRTsim, while the gas in the region outside of the main filaments has been effectively smoothed out in the RTsim. Furthermore, SPs in the RTsim are more closely aligned with the dense filaments than they are in the nonRTsim—again, evidence that areas of gas compressed by SN shocks provide regions for star formation. This is hard to determine quantitatively from these plots. However, the importance of accounting for radiative-transfer effects when modeling the morphology of high-redshift galaxies is exemplified by this difference between the simulations.

### 3.2. Distribution of Pop III Stars

To illustrate this result in more detail, we examine the gas and SP characteristics centered on a 400 ckpc box around the first region to form stars in Figure 3. By $z = 15$, about 40 Myr after the start of star formation, the nonRTsim has generated $\approx 10$ times the mass in stars as compared to the RTsim. However, approximately 90% of the nonRTsim’s SPs in this region are Pop II, indicating ongoing star formation in regions heavily polluted by previous SN. For the RTsim, the Pop II fraction is approximately 50%, indicating relative suppression in polluted regions. This again suggests that the RTsim generated fewer stars in the regions closest to the original starburst where pollution is highest. A high fraction of Pop III stars may aid in the detection of these early galaxies in future surveys (Welch et al. 2022; Windhorst et al. 2018), possibly via lensing and caustic crossings. While the gas temperatures around existing star-forming regions are comparable between the two simulations, heating is more extensive and likely much more rapid in the RTsim.

Continuing with Figure 3, by $z = 13$ we see that 97% of the nonRTsim’s stellar mass is contained in Pop II stars compared to 94% in the RTsim. The intervening $\approx 62$ Myr between $z = 15$ and $z = 13$ has enhanced the mixing in this region, and we see the RTsim generating many more Pop II stars than during earlier epochs. In fact, the larger number of SN in the nonRTsim has heated the gas in the central region of the nonRTsim such that it is now hotter than the gas in the RTsim. However, there are many more areas of dense gas in the nonRTsim as compared to the RTsim. These appear to be the result of the SN shock fronts, and they harbor star formation in these partially mixed regions as indicated by the red arrow in the left panel, $z = 13$. This “more diffuse” star formation is a characteristic of the nonRTsim as compared to the RTsim, as will be further demonstrated.

By $z = 10$, both simulations have approximately 99% of their stellar mass tied up in Pop II stars, while the nonRTsim has $\approx 3$ times the mass in stars as compared to the RTsim. Overall, we see more star formation away from the central, dense cores in the nonRTsim, as a result of star formation in surviving SN-induced over densities. The SN shock fronts are far more well-defined in the nonRTsim than in the RTsim, and these make more diffuse star formation possible. This effect is most pronounced at $z = 10$ and 8. The star-forming regions in both simulations are heated to $\gtrsim 10,000$ K. However, the overdensities induced by SN shocks are far more prominent in the nonRTsim, while the gas in the area outside of the main filaments has been effectively smoothed out in the RTsim. Furthermore, SPs in the RTsim are more closely aligned with the dense filaments than they are in the nonRTsim—again, evidence that areas of gas compressed by SN shocks provide regions for star formation. This is hard to determine quantitatively from these plots. However, the importance of accounting for radiative-transfer effects when modeling the morphology of high-redshift galaxies is exemplified by this difference between the simulations.

### 3.3. The Two-point Correlation Function in Time and Space

To more directly quantify this effect, we turn to a measure of the spatial and temporal distribution of star-forming regions. The mass-weighted two-point spatial correlation function, $\xi_2(r)$, is defined as the excess probability that two star particles are separated by a distance $r$ relative to a uniform distribution. It can be computed from the star particles in our simulation as

$$
\xi_2(r_k) = \frac{\sum_{i,j} m_i^* m_j^*}{\rho^2 V_k} - 1,
$$

where $m_i^*$ and $m_j^*$ are the masses of star particles $i$ and $j$, $\rho$ the total mass and mass density of stars in the simulation, and the sum is over all pairs $i$ and $j$ such that the separation of the particles is within $k$ along $x$ and $y$ and with a corresponding volume $V_k = \frac{4}{3} \pi (r_k^3 - r_{k-1/2}^3)$, where $r_{k-1/2}$ and $r_{k+1/2}$ are the inner and outer boundaries of the bin.

Similarly, we can define the two-point temporal-spatial correlation function, $\xi_2'(r_k, t_l)$, as the excess probability that the positions and formation times of star particles are separated by a distance $r$ and time $t$ relative to a uniform distribution (uniform in both time and space). This can be computed as

$$
\xi_2'(r_k, t_l) = \frac{\sum_{i,j,k} m_i^* m_j^*}{\rho^2 V_k E_t} - 1,
$$

where the sum is now over all pairs $i$ and $j$ such that the separation of the particles is within $k$ along $l$ and the difference in formation times between the two particles is within $l$ along $k$, centered on $t_l$ and with a corresponding difference in birth times within a bin $E_t = \frac{1}{2} (t_{l+1/2} - t_{l-1/2})$, where $t_{l-1/2}$ and $t_{l+1/2}$ define the boundaries of temporal bin and the factor of two accounts for the fact that the bin is defined to be the absolute value of the difference of the birth times of the two star particles.

Figure 4 depicts $\xi_2'(r_k, t_l)$ for all the SPs in our simulations at $z = 10$. Considering the spatial dimension (y-axis), the $\xi_2'(r_k, t_l)$ plot for the nonRTsim, top left, displays SPs that...
smoothly approach a uniform distribution as $\Delta r \rightarrow 500$ ckpc, the top of the plot. Unsurprisingly, this captures the fact that star formation is concentrated in galaxy cores, and on large scales the star particle distribution approaches uniformity. Examining the time dimension (x-axis), on the other hand, we see that star formation occurs in bursts of $\approx 20$ Myr, followed by a gradual decline to $\Delta t \rightarrow 50$. This effect is most pronounced at $\Delta r \lesssim 1$ ckpc, indicating the typical scale of a star-forming region is roughly this size. The plot allows us to

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**Figure 3.** The impact of radiative transfer on the gas, metallicity, and stellar distributions of a representative star-forming region at $z = 15$ (top row), $z = 13$ (next down), $z = 10$ (second from bottom), and $z = 8$ (bottom row). Each panel includes a gas temperature plot (left) with SP locations & metallicity overlaid along with a gas density plot (right; arbitrary units) with Pop III SP (blue dots & stars) locations overlaid. The plots depict the density-weighted projection for a 400 ckpc wide region around the earliest star-forming region in the simulations. The inset density plot is a zoom-in of the central star-forming region, with blue circles for Pop III SPs older than 10 Myr, and blue stars for Pop III SPs 10 Myr or younger. The left column depicts the nonRTsim, and the right depicts the RTsim. Note the smoothing effect on the density field caused by radiative feedback. At $z = 13$, we see (red arrow) Pop III stars forming in a shock-induced overdensity. This region has been smoothed out in the RTsim by radiative heating. The radiative smoothing of the gas is very apparent at $z = 9$, where we see very centralized star formation as compared to the nonRTsim.
see both the temporal and spatial suppression of star formation by SN in the case of the nonRTsim.

The RTsim/nonRTsim plot, in the top right of this figure, depicts the relative probabilities for SP spatial and temporal separations in the RTsim as compared to the nonRTsim. In the central star-forming regions at a scale $r < 1$ kpc (the blue region), we see relative suppression in the RTsim. This simulation has a lower probability of forming stars as compared to the nonRTsim. This indicates that radiative heating and pressure has moved star formation in the RTsim outside of the cores into the volume with $\Delta r > 1$ kpc. This suppression can be as strong as a factor of $\approx 5$ over a timescale of $\approx 20$ Myrs. This timescale is in agreement with the typical extent of a star-forming burst (as identified in the upper left panel) in the nonRTsim. It then becomes more moderate as $\Delta t \rightarrow 50$, finally resulting in a mild enhanced probability of star formation as the starburst fades away and the gas cools and becomes dense once again.

Also in the RTsim/nonRTsim plot, we see that the RTsim generates SPs with a higher probability as compared to the nonRTsim in the range $1 \leq \Delta r \leq 10$ kpc. This result, along with the relative suppression of SP formation in the halo cores, suggests that thermal pressure due to radiation is pushing star formation out to distances $\approx 1$ kpc. The enhancement in this region correlates with the expected radius of the Strömgren ionization radius caused by stars in the RTsim:

$$R_i = \left( \frac{3}{4\pi n T_e^{3/4}} \right)^{1/3},$$

where $S_\star$ is the stellar flux in ionizing photons per solar mass, $n$ is the gas number density in units of $\text{H}^{-1}$, and $T_e = 2 \times 10^{-10} T_e^{3/4}$ with units $\text{cm}^{-3} \text{s}^{-1}$ and is the recombination rate in terms of the effective temperature $T_e$. Assuming our stars generate $3 \times 10^{47}$ ionizing photons per solar mass (Leitherer et al. 1999; Scannapieco et al. 2003; Leitherer et al. 2011), this can be expressed as

$$R_i = 2.3 \text{kpc} \left( \frac{n_i}{n} \right)^{-2/3} T_e^{1/4} (1 + z),$$

where $\Phi$ is the star formation rate in units of solar masses per year, $n_i = n / \text{cm}^{-3}$, and $T_4 = T_e / 10^4 K$, and the factor of $(1+z)$ ensures we are in kpc. For the largest halo in our RTsim at $z = 10$, we have $n_i = 3$, $T_4 = 1$ and $\Phi = 0.022$ computed between $z = 12$ and $z = 10$, which results in $R_i = 3.4$ kpc, a little larger than the start of the relative increase in SP formation seen in Figure 4, as expected from values that are taken from the most massive halo in the simulation. Hence, we conclude that the thermal pressure from the ionized gas pushes most star formation out to approximately the Strömgren radius.
With these overall trends in mind, we turn to Pop III star formation. Figure 4, lower left, shows $\xi_2^r(r_k, t_l)$ for Classical Pop III stars in the nonRTsim, which again are defined as those that form in simulation cells composed solely of unpolluted gas. Here, we see a nearly complete lack of Classical Pop III star formation after 10 Myr, the lifetime of massive stars, in volumes with $\Delta r \lesssim 1$ ckpc. This polluted region in which Classical Pop III are suppressed then expands to $\approx 5$ ckpc by 50 Myr, an average rate of 1 ckpc per 10 Myr or $\approx 100$ km s$^{-1}$.

Finally, in Figure 4, lower right, we show $\xi_2^r(r_k, t_l)$ for the full Pop III star population, including those that form in incompletely mixed regions captured by our subgrid model. This figure displays continued Pop III star formation in the nonRTsim that trails off smoothly as a function of the separation in both time and space. Like the overall stellar population, Pop III stars are formed in star-forming regions with a typical scale of $\Delta r \lesssim 1$ ckpc, but Pop III star formation trails off more rapidly in time, as metals mix and unpolluted gas becomes more scarce with time.

We can also compare the $\xi_2^r(r_k, t_l)$ for Pop III stars to the ratio of $\xi_2^r(r_k, t_l)$ in the RTsim/nonRTsim to understand how suppression by radiative transfer will directly affect the Pop III stellar population. The comparison shows that Pop III stars are not only clustered spatially on the scales that are suppressed by radiative feedback, but also clustered temporally on the timescale at which radiative feedback is most significant. It is the combination of both types of clustering, then, that explains the strong differences in the Pop III star formation rate visible in Figures 1 and 3.

We can also see the effect of radiative feedback on the location and morphology of this group of proto-galaxies in Figure 5, which depicts the $z = 12$ to $z = 9$ evolution of the gas density and Pop III and Pop II stellar distributions in a 160 ckpc region around the densest section in the simulations. At each redshift, the RTsim generates more compact proto-galaxies as exhibited in the extent of the enclosing density contours. By $z = 10$, the RTsim's stellar mass is almost two times more compact than in the nonRTsim, and by $z = 9$ the RTsim galaxies are, for this example, at least three times more compact when considering the 80% stellar mass contour. By this epoch, both simulations have generated almost the same mass in stars in this region. This supports the analysis of stellar clustering depicted using $\xi_2$ above.

By $z = 10$, the lower-density gas is effectively removed from halos in the RTsim, leaving only the higher-density filamentary structures as the areas that shield the gas from the effects of the radiation. This initially results in enhanced star formation in regions typically at least 1 ckpc away from the initial cores. This is proto-galaxy satellite formation that is not seen in the nonRTsim. Again, the nonRTsim produces more connected structures. By $z = 8$, we see that the RTsim proto-galaxy has coalesced into a much more compact object that is approximately the same mass as its counterpart found in the nonRTsim. However, 80% of the mass of the RTsim is contained in a region with a major axis $\approx 20$ ckpc, while in the nonRTsim, the comparable mass is enclosed in a region almost four times that size.

4. Conclusions

The next decade will bring unparalleled advances in the observational study of the first stars and galaxies, but realizing the full potential of these observations requires simulations that capture the key physical processes that affected these objects. Here, we have used cosmological simulations to demonstrate
the importance of modeling both radiative transfer and turbulent mixing when studying primordial galaxy morphology, composition, and growth.

By comparing simulations with and without a detailed model for radiative transfer but with exactly the same physical parameters and turbulent mixing model, we are able to directly quantify how radiative transfer and mixing work together to determine the evolution of Pop III stars and galaxies. Of course, radiative transfer has an impact on all stars, and the star formation rate density in the RTsim is lower at high redshift and higher at low redshift, as compared to the nonRTsim, which assumes that reionization occurs instantaneously at \( z = 9 \). This difference is due to the additional thermal pressure that ionized pockets of gas feel at high redshift in the RTsim, which is not captured in the nonRTsim.

But the most interesting impact of radiative transfer is on the evolution of Pop III stars. In fact, the overall rate of Pop III star formation rate density is suppressed by a factor of \( \approx 6 \) in the RTsim at all redshifts, both before and after \( z = 9 \), when the nonRTsim assumes instantaneous reionization. This indicates that understanding the simultaneous propagation of ionization fronts and mixing of heavy elements is essential to understanding Pop III evolution, and that radiative transfer is necessary to capture the detailed properties of this interplay.

Likewise, an assumption that all polluted regions are instantaneously mixed leads to an inaccurate picture: identifying less than 10% of total number of Pop III stars in the simulations, and failing to capture the suppression of Pop III star formation that occurs as radiative feedback slows gas accretion and provides more time for mixing to pollute a larger fraction of star-forming gas. Note that even high-resolution simulations like ours cannot capture this suppression in Pop III stars in the RTsim without a subgrid model of the mixing time required to distribute metals throughout a given region. It is simply not possible with the current generation of supercomputers to simulate a representative cosmological volume through the full process of reionization while still tracking the formation of individual stars.

To better understand the impact of radiative transfer on Pop III star formation, we have made use of the two-point temporal-spatial correlation function \( \xi_{2}(k_{b}, b) \), which quantifies the excess probability of forming stars with a given separation in time and space. This measure confirms and quantifies that star formation in proto-galaxies proceeds more rapidly in the halo cores of the nonRTsim as compared to the RTsim, and that supernova feedback alone does not quench star formation as effectively as the combination of SN and radiative feedback in regions of size \( \lesssim 1 \) ckpc and at times \( \lesssim 25 \) Myr. Hence, the cores of young galaxies in the RTsim experience a relative suppression of star formation in the first \( \approx 25 \) Myr after a starburst, during which radiative feedback from massive stars is strongest, followed by an enhanced probability of forming stars at \( \approx 40 \) Myr as massive stars die and the UV flux drops dramatically allowing gas to reaccrete.

Note that the \( \approx 1 \) ckpc size of the region in which this suppression and reaccretion occur correlates with the Strömgren radius for the typical density and stellar mass of a high-redshift starbursting proto-galaxy. At distances larger than the Strömgren radius, on the other hand, we find that radiative feedback pushes gas out to distances between 1 and 10 ckpc, encountering the dense filaments feeding the galaxy. It is here that we find ongoing star formation in the RTsim that is enhanced to a rate \( 4-10 \times \) higher than in the same region in the nonRTsim. This results in numerous, low-mass satellites at \( z \geq 10 \), which are spatially separated to a far higher degree than stars making up the nonRTsim galaxies.

Relating these changes to metal mixing helps explain the impact of radiative transfer on Pop III evolution. If we limit ourselves to the “Classical” Pop III, which form in simulation zones in which there are no metals, then the impact of radiative transfer is minimal. These are the very first stars to form in a new burst of star formation, and they are quickly extinguished as soon as SNe begin to enrich the medium. Accounting for the time it takes metals to mix into the gas, on the other hand, completely changes the picture. Pop III stars formed in areas of active mixing are formed continually out to 50 Myr after the start of a starburst, and hence they are strongly impacted by radiative feedback.

Finally, we examine impact of radiative transfer on galaxy morphology. Without RT and the associated heating/ionization of the gas out to the Strömgren radius, the nonRTsim generates far more stars in the central ckpc of halos than the RTsim. At the same time, the nonRTsim generates a much smoother and extended stellar density profile, while more isolated low-mass satellites are seen in the RTsim. By \( z = 8 \), the initially unused, heated gas in the RTsim has mostly cooled and is converted into stars, resulting in galaxies that are, counting the mass of the satellites, of comparable mass in both simulations. Given the short lifetimes of massive Pop III stars, the final composition of the galaxies in the two simulations converges at these later epochs. However, the lasting impact of these two growth paths is the morphology of the galaxies, and the nonRTsim galaxies remain more extended at all redshifts we studied.

With the recent launch of JWST, we are now on the cusp of a momentous change in our observational understanding of the first stars and galaxies. Here, we have shown that fully capitalizing on these advances will require a new generation of cosmological simulations that include both radiative transfer and turbulent mixing. Without radiative transfer, simulations will overestimate the prevalence of Pop III stars, and without mixing, simulations will vastly underestimate the Pop III content of galaxy cores. The net effect of modeling radiative transfer and subgrid mixing is a fourfold increase in the mass fraction of Pop III stars at \( 9 \leq z \leq 13 \) as compared to simulations that do not include these physical processes. Furthermore, modeling RT is important for understanding the morphology of early galaxies. Stellar radiation from the first stars results in galaxies that are more compact and less luminous than those generated by non-RT simulations. Given our results, we predict that future JWST observations will bear out these qualitative properties. These properties, in turn, will have a direct impact on predictions of the luminosities and surface brightness profiles of the galaxies most likely to contain Pop III stars. We will explore these observational properties in a future publication using a significantly larger simulation volume.

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