External Enrichment of Mini Halos by the First Supernovae

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Abstract

Recent high-resolution simulations of early structure formation have shown that externally enriched halos may form some of the first metal-enriched stars. This study utilizes a 1 comoving Mpc3 high-resolution simulation to study the enrichment process of metal-enriched halos down to z = 9.3. Our simulation uniquely tracks the metals ejected from Population III stars, and we use this information to identify the origin of metals within metal-enriched halos. These halos show a wide range of metallicities, but we find that the source of metals for ∼50% of metal-enriched halos is supernova explosions of Population III stars occurring outside their virial radii. The results presented here indicate that external enrichment by metal-free stars dominates the enrichment process of halos with virial mass below 10^6 M_⊙ down to z = 9.3. Despite the prevalence of external enrichment in low-mass halos, Population II stars forming due to external enrichment are rare because of the small contribution of low-mass halos to the global star formation rate combined with low metallicities toward the center of these halos resulting from metal ejecta from external sources mixing from the outside in. The enriched stars that do form through this process have absolute metallicities below 10^{-3} Z_⊙. We also find that the fraction of externally enriched halos increases with time: ∼90% of halos that are externally enriched have M_{vir} < 10^6 M_⊙ and that pair-instability supernovae contribute the most to the enrichment of the intergalactic medium as a whole and are thus the predominant supernova type contributing to the external enrichment of halos.

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1. Introduction

In a quest to discover the characteristics of the first generation of stars, we inevitably run into the inconvenient fact that there are no observable first-generation (Population III) stars, so direct constraints on their characteristics are lacking. This difficulty has given rise to galactic archeology (i.e., Feltzing & Chiba 2013; Keller et al. 2014; Frebel & Norris 2015; Hernández et al. 2020) to determine the enrichment history of an object. Other observations attempt to constrain the Population III initial mass function (IMF), the number of enriching events, and typical supernova energy (Welsh et al. 2019), or to detect the unique metal signature of massive Population III supernovae (Bañados et al. 2019) by observing metal-poor damped Lyα (DLA) systems. In order to more fully understand the results from surveys measuring the metallicity of presently observed stars or DLAs, it is imperative to understand how Population III stars interacted with their environments. Prior works have investigated the effect of Population III supernovae at the extreme small scale (Cen & Riquelme 2008; Whalen et al. 2008; Smith et al. 2015; Chen et al. 2017). These studies illustrate that pristine mini halos can be enriched by external sources, such as Type II supernovae (SNe II) from Population III stars forming in nearby mini halos. Notably, these externally enriched mini halos could be the first sites of second-generation (Population II) star formation (Smith et al. 2015). These prior simulations had extremely fine small-scale resolution but were limited by the small simulation box size (~500 comoving kpc hr^{-1}) and the low number of halos present in the volume. Further, Smith et al. (2015) only considered the effects of 40 M_⊙ Population III stars, whereas a more comprehensive IMF would include a variety of stellar endpoints: SNe II, hypernovae (HNe), and pair-instability supernovae (PISNe). This study aims to extend Smith et al. (2015) by making use of a simulation similar to that in Paper II of the “Birth of a Galaxy” series (Wise et al. 2012a) that has a larger box size (1 comoving Mpc) and includes PISNe, HNe, and black hole collapse as Population III endpoints.

The remainder of this paper is organized as follows: Section 2 outlines the simulation design and reviews important stellar formation and feedback parameters. Sections 3 and 4 present our analysis on the prospects of external enrichment and star formation that occurs afterward. Finally, Section 5 compares our results to other studies, and Section 6 summarizes the main conclusions drawn from our analysis.

2. Simulation Setup

The simulation used for this analysis is the same simulation analyzed in Skinner & Wise (2020). Making use of the adaptive mesh refinement (AMR) simulation code Enzo (Bryan et al. 2014; Brummel-Smith et al. 2019), the 1 Mpc box has a base resolution of 256^3 cells and particles with up to 12 levels of local refinement, which results in a maximum comoving resolution of 1 pc and a dark matter mass-resolution of 2001 M_⊙. The simulation box is representative of a typical region of the universe (see Figure 2 in Skinner & Wise 2020) and is initialized at z = 130 using cosmological parameters consistent with the Planck 2014 constraints (Ade et al. 2014): Ω_m = 0.6825,
The simulation includes prescriptions for forming individual Population III stars and Population II star particles, described in detail in Wise et al. (2012b). Because star formation and destruction are instrumental in chemical evolution and enrichment, the details of how metals are calculated from stellar properties are restated here. When conditions for star formation are met in a cell, either a particle representing a single Population III star (if \([Z/H] < -5.3\))\(^{10}\) or a particle representing a cluster of Population II stars (if \([Z/H] > -5.3\)) is formed. The critical metallicity marks where dust cooling becomes efficient enough to cause fragmentation at high densities (e.g., Schneider et al. 2006). If the particle is Population III, the mass of the particle is sampled randomly from an IMF of the form

\[
f(\log M) dM = M^{-1.3} \exp\left[-\left(\frac{M_{\text{ch}}}{M}\right)^{1.6}\right] dM
\]

that behaves as a Salpeter IMF at high mass, but is exponentially suppressed below \(M_{\text{ch}} = 20 M_\odot\). The lower and upper limits of the IMF are set to 1 \(M_\odot\) and 300 \(M_\odot\), respectively. The Population III star particle is assigned zero metallicity despite the value in the cell that formed it. Alternatively, if \([Z/H] > -5.3\), a particle representing a coeval Population II star cluster is formed assuming a modified Salpeter IMF. The particle’s mass is taken to be 7\% of the cold gas within a sphere of radius \(R_{\text{ch}}\) such that the mean density inside \(R_{\text{ch}}\) is \(10^3\) cm\(^{-3}\) (see Wise & Cen 2009 for more details). An equivalent amount of gas is removed from cells within \(R_{\text{ch}}\) of the star-forming cell. The star’s metallicity is initialized to the mass-weighted average of the metallicities of the surrounding cells, which can be below \([Z/H] = -5.3\) if the cell is at or slightly above the threshold. As we wish the star particle to sample the massive end of the Salpeter IMF, we require that its mass exceed a minimum mass of \(10^3 M_\odot\). If it does not, \(R_{\text{ch}}\) is increased until the condition is met. For reference, the value of \(R_{\text{ch}}\) assuming a star particle mass of \(10^3 M_\odot\) and an enclosed medium that is entirely cold, is around 2 pc. After the Population II star particle has lived for 4 Myr, it begins losing mass by SNe and deposits metals continuously into the finest AMR level at every time step according to

\[
m_{\text{ej}} = \frac{0.25 \Delta t \times M_*}{t_0 - 4\text{Myr}}
\]

for \(t \leq t_0 = 20\text{ Myr}\) (the lifetime of the particle), \(t_0\) is the age of the star, and \(\Delta t\) is the current time step. The ejecta has solar metallicity \(Z = 0.01295\) and is tracked in a field dedicated to metals from Population II stars.

Metals from Population III stars are deposited impulsively by individual SN events. After a Population III star lives and radiates for its main sequence lifetime, it has different fates for different mass ranges. If 40 \(M_\odot < M_* < 140 M_\odot\) or \(M_* > 260 M_\odot\), the particle collapses to an inert, collisionless black hole. Otherwise, the particles explode as SNe with metal ejecta masses and energies taken from Nomoto et al. (2006). If 11 \(M_\odot < M_* < 40 M_\odot\), the star explodes with a metal ejecta mass given by

\[
\frac{M_{\text{ej}}}{M_\odot} = 0.1077 + 0.3383 \times \left(\frac{M_*}{M_\odot} - 11\right).
\]

This applies to both SNe II (11 \(M_\odot < M_* < 20 M_\odot\)) and HNe (20 \(M_\odot < M_* < 40 M_\odot\)). More massive stars in the range 140 \(M_\odot < M_* < 260 M_\odot\) will become PISNe (Heger & Woosley 2002) and eject metal with a mass

\[
\frac{M_{\text{ej}}}{M_\odot} = \left(\frac{13}{24}\right) \left(\frac{M_*}{M_\odot} - 20\right)
\]

at the end of their lifetime.

The blast wave is modeled by injecting the explosion energy and ejecta mass into a sphere of 10 pc, smoothed at its surface to improve numerical stability. Typically, an explosion occurring in a medium with density \(~10000\) g cm\(^{-3}\) would need to be resolved on scales of \(~1\) pc in order to resolve the Sedov–Taylor phase (Kim & Ostriker 2015), but because the mass of the medium surrounding the Population III star is reduced by photoevaporation during the star’s lifetime (Whalen et al. 2004), the medium in which explosion energy is deposited has a larger cooling radius, and the choice of 10 pc is thus sufficient to resolve the Sedov–Taylor phase in this case. After its destruction, the star is converted to a collisionless particle with a mass of \(10^{-20}\) times the mass of the original Population III star. This renders the particle mass negligible while still containing information about the progenitor star and allowing one to approximately track the center of mass position of the SN remnants. The metal contribution from the explosion is logged into a separate metallicity field for Population III stellar ejecta. Explosion energies are assigned as follows: SNe II have \(E_{51} = 1\); HNe have \(10 < E_{51} < 30\) depending on their mass; and PISNe have \(6.3 < E_{51} < 90\), according to Equation (3) of Wise et al. (2012b). Here, \(E_{51}\) is the explosion energy in units of \(10^{51}\) erg. For our choice of Population III IMF, the relative occurrence of SNe of different types are 38\% SNe II, 54\% HNe, and 8\% PISNe. We chose a Population III characteristic mass so that HNe would dominate the chemical enrichment process, as the chemical abundance of Mn, Co, Ni, Zn, Ca, and Cr relative to Fe of extremely metal-poor stars are better fit by HN models (Nomoto et al. 2006).

3. Enrichment of Halos

Halos can be enriched in three principal ways. Internally enriched halos are pristine halos that become enriched by SNe within their virial radii. Externally enriched halos are pristine halos that become enriched by mixing in enriched gas outside their virial radii. Finally, pre-enriched halos virialize in the presence of enriched gas. To distinguish them, we define the
variable,
\[ f_3 \equiv \log_{10} \left( \frac{M_{Z,p}}{M_{Z,0}} \right), \tag{5} \]

to describe the enrichment of halos. Here, \( M_{Z,p} \) is the maximum mass of Population III metals that could have originated from Population III stars within the virial radius of each halo. \( M_{Z,p} \) is calculated using Equations (3) and (4), given the Population III remnant particles inside the virial radius at the final redshift. \( M_{Z,0} \) is the Population III metal mass within the virial radius that is directly measured from the simulation. We label a halo as “enriched” if it satisfies \( \langle Z_3 \rangle > 10^{-5.3} Z_\odot \), where \( \langle Z_2 \rangle \) and \( \langle Z_3 \rangle \) are the mass-averaged Population II and Population III metallicities inside the virial radius. Otherwise, the halo is labeled as “pristine.” Using these definitions, \( f_3 < 0 \) corresponds to halos that contain more metals than could have come from internal sources, meaning that external enrichment must have occurred; \( f_3 = -\infty \) corresponds to halos that are enriched exclusively by external sources, and \( f_3 > 0 \) corresponds to halos that are primarily enriched by internal sources. A third case of enrichment exists for halos that form within a region of the intergalactic medium (IGM) that has already been enriched. We label this subset of halos as pre-enriched, and discuss their prevalence in our sample in Section 3.2.

An issue with this measure exists for the case where a halo undergoes a mix of internal and external enrichment, but is dominated by external enrichment in such a way that the total amount of metals confined within the halo is still less than the predicted value based on internal events \( M_{Z,p} \). This would result in a value of \( f_3 > 0 \) for a halo that is still primarily externally enriched. We argue that this is very a very unlikely occurrence because (1) very few halos actually experience internal SN events and are still dominated by external sources (this is explored in Section 3.1), and (2) this also requires most of the ejecta from the internal event to make it outside of the virial radius, which, while not necessarily uncommon given the assumed Population III characteristic mass, further limits the likelihood of an externally enriched halo being mislabeled in this way.

An example halo for each type of enrichment is shown in Figure 1. The left column shows a projection of each type of enriched halo just after the total mass-weighted average metallicity passes \( Z_{\text{crit}} \) while the right column shows the Population III metallicity profile of each halo at the same snapshot as the corresponding projection. For the internally enriched case, a Population III SN event occurs near the center of the selected halo. The corresponding Population III metallicity profile shows large, near-solar metallicities toward the center, with decreasing values going out to the virial radius. The external enrichment example shows the opposite behavior. An SN event occurs outside the virial radius, and, because there is turbulent mixing from the outside in, the metallicity profile shows the highest values toward the edges of the halo, with decreasing values going toward the center, which is comprised of nearly pristine gas. The example for pre-enrichment shows a halo that forms inside a medium that was already enriched by a nearby PISN event. The metal ejecta has had time to mix with the surrounding medium, so the resultant Population III metallicity profile for the pre-enriched halo is nearly flat, increasing outwards by less than an order of magnitude.

3.1. Externally Enriched Halos

The first question concerning external enrichment is simple: does external enrichment happen in an appreciable number of halos? To answer this question, halos are identified using ROCKSTAR (Behroozi et al. 2013a), and the value of \( f_3 \) is calculated for each. We find that the number of both internally and externally enriched halos increases over time, and as redshift decreases, external enrichment becomes the most common enrichment vector. At the final output, \( z = 9.3 \), the simulation hosts 1864 halos, including subhalos, with virial mass above our 100-particle resolution limit of \( 10^{5.3} M_\odot \) and 417 halos that are enriched to \( \langle Z_{\text{enriched}} \rangle > 10^{-5.3} Z_\odot \). Of the enriched halos, 264 (63.3%) are found to have \( f_3 < 0 \).

Figure 2 shows a Population III metallicity projection of the simulation at \( z = 9.3 \) indicating the location and virial radius of each halo and the location and type of all SN remnants. The regions with metallicities in excess of \( Z_{\text{crit}} = 10^{-5.3} Z_\odot \) tend to show more halo clustering. The halo-averaged Population III and Population II metallicity distribution functions are shown in Figure 3. The regions of high spatial density are where halos are more likely to be enriched externally. A calculation of the mean halo-to-halo nearest-neighbor distance gives a value of 0.66 proper kpc for externally enriched halos, whereas the mean nearest-neighbor distance across all halos is around 1.6 proper kpc. There is one region near \((x, y) = (-35 \text{ kpc}, -30 \text{ kpc})\) of Figure 2 that contains a particularly large volume of enriched gas that is the result of mixing between ejecta of many SN explosions. This region hosts the most massive halo in the simulation.

Figure 4 shows the \( f_3 \) cumulative probability distribution of enriched halos at \( z = 9.3 \) separated into five mass bins each containing the same number of halos between \( 10^{5.3} M_\odot \) and \( 10^{8.6} M_\odot \). The fraction of halos that undergo pure external enrichment generally increases with decreasing halo mass. Below \( 10^6 M_\odot \), the majority of halos are found to be enriched purely externally, while most of the halos above \( 10^6 M_\odot \) are enriched internally. There is a small minority of halos in the bins above \( 10^6 M_\odot \), that experience both internal and external enrichment by our measure, while the enrichment pathway for the remaining halos is either pure internal or pure external. In some cases (e.g., lower left-hand corner of Figure 2), there is one high-mass halo that injects large amounts of metals into its surroundings and draws multiple low-mass satellites into the enriched region, turning them into externally enriched halos.

Figure 5 shows the evolution of various number fractions over time. While the fraction of all halos that are enriched above \( Z_3 = 10^{-5.3} Z_\odot \) stays roughly constant, the fraction of those that are externally enriched increases over time. The externally enriched halo fraction follows the also-increasing volume fraction of enriched gas in the simulation, suggesting that the growing body of metal ejecta overtakes the halos over time or that the number of halos forming in the enriched IGM is increasing.

3.2. Pre-enriched versus Externally Enriched?

So far, we have assumed that every enriched halo that is not internally enriched is externally enriched by a nearby SN remnant. However, halos forming in an enriched region of the IGM will accrete gas from the environment during virialization and become enriched that way. We call this kind of halo pre-enriched. As the volume fraction of enriched gas increases, we would expect more
Figure 1. Examples of internally enriched (top), externally enriched (middle), and pre-enriched (bottom) halos just after the total mass-weighted average metallicity passes $Z_{\text{crit}}$. Left: Population III metallicity projection of a cubic subvolume centered on the halo indicated by the red circle, which has a radius equal to the halo’s virial radius. Arrows indicate the velocity fields, and the stars show the position of the Population III remnant particles (orange: SNe II, green: HNe, violet: PISNe). Right: Population III metallicity profile for the halo binned by proper distance from the center. The ordinate axis shows the mass-weighted average metallicity within each bin. All distance scales are in proper coordinates.
pre-enriched halos to form. Here we analyze the occurrence of pre-enrichment in our simulation. We flag halos as pre-enriched if their mass-weighted metallicity is above $10^{-5.3} Z_e$ in the first data output in which they appear; i.e., become resolved in our simulation. The time interval between the data outputs used here is 2–4 Myr, which is less than the lifetime of a typical Population III star, so it is unlikely we confuse an externally enriched halo with a pre-enriched halo.

Figure 6 plots the ratio of the number of pre-enriched halos to all enriched halos versus redshift. The black line is for the entire volume, while the blue line is only for halos within 10 proper kpc of the most massive halo. We see that pre-enriched halos form predominantly near the most massive galaxy for $z > 12$, but form throughout the volume in increasing numbers at lower redshift. At $z = 9.3$, 17.5% of all enriched halos formed pre-enriched, implying that external enrichment by...
nearby SN remnants remains the primary channel for halos that are not internally enriched.

### 3.3. Contribution of Different SN Types

In order to characterize the contribution of each type of SN in the simulation to the external enrichment process, we perform the following calculations. First, we identify the type of the nearest Population III remnant to each externally enriched halo at the output when the halo first crosses the metal-enrichment threshold of $10^{-3.5} Z_\odot$ and calculate the proper distance from the halo’s center to the remnant at that output. We then calculate the total ejecta of all Population III remnants within a 2 proper kpc radius of each externally enriched halo at the final output using Equations (3) and (4), and consider the type that has produced the largest summed Population III metal mass to be the dominant enricher of that halo. The mean distance from the externally enriched halo to all Population III remnants of the dominant enriching type is then recorded. The results of these calculations are shown in Figure 7. The left panel shows the results of the first calculation, while the right panel shows the results of the second.

As shown in the right panel of Figure 7, 54% of externally enriched halos are enriched primarily by PISNe by the last output, while approximately 44% and the remaining 2% are enriched primarily by HNe and SNe II, respectively. Taking into account the relative abundances of SN types set by the $20 M_\odot$ Population III characteristic stellar mass (54% are HNe, 38% are SNe II, and 8% are PISNe), it is surprising that PISNe are able to surpass HNe as the dominant enricher of the largest fraction of halos. While the statistics on this are poor, it suggests that PISNe enrich more halos per event on average, which is understandable because PISNe are $3\times-10\times$ times more energetic than HNe and produce $\sim$10 times more metals on average for our model.

The most massive halo in the simulation is a significant source of metal enrichment, enclosing 62 HN, 45 SN II, and 7 PISN Population III remnant particles by the last output. This is the most active region in the simulation, and the metallicity field surrounding the most massive halo is the result of mixing between many SN remnants of different types. Halos that form in this environment could initially be labeled as externally enriched by our measure, and the type of Population III SN that contributes the most to their enrichment is less clear. Because of this, the externally enriched halos that are within 10 proper kpc of the most massive halo by the final output are also identified in Figure 7. Of the 169 halos plotted in the right panel, 36 are within 10 proper kpc of the most massive halo. As seen in the right panel, the majority of halos near the most massive halo are identified as having been enriched primarily by PISNe by our measure. This makes sense because of the large concentration of PISN remnant particles in that particular region.

The median lines in Figure 7 give an indication of typical distances by which enrichment from each type of SN can occur. In both panels, there is a clear stratification between distances to SNe II, HNe, and PISNe (listed in order of increasing distance). In the left panel, the median distance to the nearest Population III remnant particle at the time of enrichment is 1.08 proper kpc for SNe II, 1.13 proper kpc for HNe, and 1.45 proper kpc for PISNe. In the right panel, the median distances are 0.599 proper kpc for SNe II, 1.87 proper kpc for HNe, and 2.44 proper kpc for PISNe. It should be noted that the SNe II bin in the right panel of Figure 7 only has four data points, so the median is less reliable for that one bin. The ordering in median distance to each type makes sense on energetic grounds, as PISNe are more energetic than HNe, which are more energetic than SNe II (see Section 2).

In order to further verify that the distances found in Figure 7 are reasonable, the following estimate is performed. The typical enriching radius of each type of SN is calculated by considering the average volume that each type enriches to $Z_3 > Z_{\text{crit}}$. This is calculated as follows:

$$
\langle V_{\text{enr}} \rangle_{\text{type}} = f_{\text{ej}} \left( \frac{V_{\text{enr}}}{N_{\text{type}}} \right)
$$

$$
\langle r_{\text{enr}} \rangle_{\text{type}} = \left[ \frac{3}{4\pi} (V_{\text{enr}})_{\text{type}} \right]^{1/3}.
$$

Here, $f_{\text{ej}}$ is the fraction of the total mass of ejected metals from each type of SN at $z = 9.3$, $N_{\text{type}}$ is the number of each type that has occurred, and $V_{\text{enr}}$ is the total volume of enriched gas at $z = 9.3$. By the final output, 93% of explosions that have occurred are Type II core-collapse SNe or HNe, while the remaining 7% are PISNe. By $z = 9.3$, there are 169 SNe II, 240 HNe, and 32 PISNe that have occurred. Interestingly, the few PISN explosions that occur contribute more metal ejecta than both of the other SN types combined. Using the ejecta Equations (3) and (4), these contribute $212.2 M_\odot$, $1494 M_\odot$, and $2753 M_\odot$ of Population III metal ejecta in each respective bin. Applying the formulae above, the calculation yields values of approximately 0.97 proper kpc, 1.5 proper kpc, and 3.6 proper kpc for the average enriching radius of SNe II, HNe, and PISNe, respectively. These radii are in rough agreement with those of the SN remnants simulated in Whalen et al. (2008), the visual presented in Figure 2, and the median distances in Figure 7. It should be noted that this calculation does not take
into account the age of the remnants, as an older remnant has had more time to expand. The calculation also does not account for overlapping SN remnants, gas collapse, or mixing as a result of halo mergers. The radii derived above therefore must be viewed as rough upper limits. A more detailed calculation would use the individual mass of each SN progenitor, rather than assigning the average bubble size to all SNe that are labeled as a given type, while adjusting $V_{\text{vir}}$ appropriately for gas dynamics. It should also be noted that these results are highly dependent on the IMF chosen for Population III star formation.

4. Star Formation

4.1. The First Population II Stars

Recall that in this simulation Population II star particles represent coeval star clusters formed out of gas that has been enriched by Population III SNe and/or prior generations of Population II star formation. One interesting question is how sensitive are the characteristics of the first Population II stars to form to the type of the first Population III SN to occur in the host halo’s history, as well as to the enrichment pathway leading to their formation. To shed light on this matter, for each halo, we compare the creation times of all Population II particles and Population III remnant particles within the halo’s virial radius at the final output. We then select the earliest particle of each type for further examination. The explosion type of the first Population III SN is logged, and an additional check is performed to determine if the first Population II star particle formed as a result of external enrichment. Here, a halo is considered externally enriched if it forms a Population II star particle without a Population III remnant particle inside the virial radius. The metallicity requirement from Section 3 has been dropped because we only consider halos that form Population II stars, and the formation of a Population II star particle is a direct indication that the halo has been enriched by some process. If the first Population II star particle forms inside a subhalo of a halo that contains Population III remnant particles, then the Population II particle is determined to have formed through external enrichment as long as none of the Population III remnant particles are inside the subhalo at the time of the Population II particle’s formation. Some 17% of all externally enriched halos that are not pre-enriched are subhalos of larger halos.

Figure 8 shows the type of the first Population III SN, the metallicity of the first Population II star particle, and the time delay between the first Population III SN and the formation of the first Population II particle for each star-forming halo. Note that Population II star particles exist with metallicities below $Z_{\text{crit}} = 10^{-5.3}Z_\odot$ because they are assigned the mass-weighted average metallicity of their birth cloud, which can be less than $Z_{\text{crit}}$. Because of our choice of 20 $M_\odot$ for the Population III characteristic mass, 78% of the star-forming halos are originally seeded by HNe, which explains their prevalence. PISNe are much rarer, again because our choice for the primordial IMF. The Population II particles that form following a PISN tend to have higher metallicity, with an average in log $(Z_{\text{II}}/Z_\odot)$ of $10^{-2.7}Z_\odot$ compared to the average for particles forming after HNe and SNe II of $10^{-3.3}Z_\odot$. The first Population II star particles with the highest metallicities form <5 Myr after a PISN. However, there are only seven star-forming halos that are seeded by PISNe, and for two of these halos, the first Population II star particles have metallicities below $10^{-5.3}Z_\odot$. Further study on this topic would require a larger sample size to draw reliable conclusions. Also shown in Figure 8 are the halos that form their first stars through external enrichment. Of the 41 star-forming halos in this sample, 5 formed their first Population II stars through external enrichment. All of the particles that formed through external
enrichment, including those that form following PISN explosions, have metallicity below $10^{-3} Z_\odot$.

The Population III and Population II epochs of star formation are typically thought of as separate, sequential phases in a halo’s history; however, it is possible for both types of star formation to take place simultaneously within the halo’s merger tree. While we do not find any cases of Population III and Population II particles coexisting within a single halo, we do find cases of the two types of particles coexisting in different branches of the tree. The issue of such halos suggests that chemical enrichment history is complicated, as ejecta from the contemporaneous Population III and Population II particles mix into the final halo by proxy of halo merging. The effective overlap between the star formation phases is demonstrated in Figure 9, which shows the time difference between each Population III SN and the formation of the first Population II star particle for each star-forming halo in the simulation as identified in the final output. While most halos show little to no overlap between the phases, there are seven halos in our sample with an overlap of over 100 Myr, with the longest overlap being nearly 300 Myr. The four most massive halos continue to form additional Population II particles during this overlap phase. Figure 9 also provides a measure of the maximum timescale for the Population III phase of the halos in this simulation, which is about 300 Myr. This timescale is entirely dependent on a halo’s merger history and is thus subject to change if the simulation progresses further and more halos were allowed the time to merge.

An important result of Figures 8 and 9 is that externally enriched Population II star formation is very rare in our simulation. We have already discussed that externally enriched halos primarily have low mass (i.e., Figure 4), which means that star formation in these halos is unlikely. However, it is also possible that we lack sufficient resolution at the center of these halos to discern the complex metallicity distribution in potential star-forming regions, which limits the performance of our criteria for selecting whether a newly formed star particle will represent a Population III star or a Population II star cluster because only the properties of the densest cell are taken into account when distinguishing between the two types of particles (see Section 2.1). Figure 10 shows the average Population III metallicity profile at the time of enrichment for each of the three types of enriched halo discussed in this study: internally enriched, externally enriched, and pre-enriched. While the internally enriched and pre-enriched average profiles have metallicities above $Z_{\text{crit}}$ at the center, the average externally enriched profile notably has metallicities $>4$ orders of magnitude below $Z_{\text{crit}}$ at the center where stars would form. Similarly to Figure 1, the externally enriched profile increases outwards from the center and does not cross $Z_{\text{crit}}$ until about 0.8 $R_{\text{vir}}$. It should be emphasized that the time of enrichment does not necessarily align with the time of star formation in star-forming externally enriched halos, so metal ejecta likely have more time to mix inwards by the time star formation takes place. Whether this turbulent mixing is efficient enough to introduce variations in metallicity on scales smaller than the
minimum cell size, 0.95 comoving pc (0.09 proper pc at the final output), to facilitate widespread Population II star formation in externally enriched halos requires further study, but the large standard deviation in the externally enriched panel of Figure 10 suggests that it is not unreasonable. The highly resolved externally enriched “action halo” in Smith et al. (2015) does achieve metallicities exceeding $Z_{\text{crit}}$ (there, $10^{-6} Z_{\odot}$) toward the center by the time gravitational collapse in the star-forming core begins, but it is uncertain whether this is a common occurrence among externally enriched halos.

### 4.2. The Most Massive Halo

In order to assess the importance of external enrichment in the star formation history of the most massive halo in the simulation, a merger tree was created using Consistent Trees (Behroozi et al. 2013b), and the most massive progenitor was tracked over time along with all of the stars that would eventually end up in the final halo. Figure 11 shows the Population II star formation history and final stellar metallicity distribution function (MDF) for the most massive halo in the simulation ($M_{*} = 3.71 \times 10^{9} M_{\odot}$), and distinguishes stars by whether or not they reside inside the most massive progenitor at a given redshift. Its first Population II star particle forms around $z = 20$ with a metallicity of about $10^{-3} Z_{\odot}$ outside of the most massive progenitor halo. Without double-counting due to stars forming within subhalos, the most massive halo has five separate Population II star-forming progenitors. Stars that form through external enrichment are logged in the same way as was done for Figures 8 and 9 in the previous section; however, the most massive halo’s history is devoid of externally enriched star formation. This is interesting because this halo contains 97% of the simulation’s Population II stellar mass and is a major source of enrichment for nearby externally enriched halos.

The right panel of Figure 11 shows the Population II stellar MDF for the most massive halo. For comparison, Figure 12 shows the MDF for all Population II particles in the simulation volume at the final output and highlights those that form in externally enriched halos. The distribution peaks near $Z = 10^{-2.4} Z_{\odot}$ and falls off dramatically below $Z = 10^{-3} Z_{\odot}$ with a minimum value of $Z = 10^{-5.1} Z_{\odot}$. There is no contradiction that the minimum metallicity is below $Z_{\text{crit}} = 10^{-5.3} Z_{\odot}$ for reasons discussed above. All of the externally enriched star formation exists in the long tail of the distribution below $10^{-3} Z_{\odot}$. The MDF for the most massive halo looks very similar, as it contains most of the Population II particles in the simulation, but it has fewer particles in the low-metallicity tail.

### 5. Discussion

External enrichment phenomena are studied in Jeon et al. (2017), where external enrichment leads to extremely low-metallicity Population II stars and allows halos to form Population II stars without ever hosting a Population III star. This study corroborates that these halos can exist (i.e., Figure 4) in

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**Figure 10.** Average Population III metallicity profiles for internally enriched (left), externally enriched (middle), and pre-enriched (right) halos at the time they first exceed a mass-weighted average metallicity of $Z_{\text{crit}}$. The halo counts are 136, 174, and 76, respectively. A profile for each halo of a given type is made with the same bins in $r/R_{\text{vir}}$. The average and standard deviation in $\log(Z_{\text{ini}}/Z_{\odot})$ are then taken over all the halos for each bin, resulting in the profile here. The blue line indicates the average, and the fill extends out to the standard deviation.

**Figure 11.** Left: Population II formation history of the most massive halo in the simulation ($M_{*} = 3.71 \times 10^{9} M_{\odot}$). Each data point represents a star particle in the merger tree. Red points correspond to star particles that are outside the most massive progenitor, while black points correspond to star particles that are inside. By the end of the simulation, the halo has a stellar mass of about $10^{6.3} M_{\odot}$. The discrete horizontal lines of points represent each individual star moving through time. Right: stellar metallicity distribution of the halo at the final output. The variable, $f_{M_{*}^i}$, is the fraction of the halo’s total stellar mass by the last output within each bin. The distribution peaks near $Z = 10^{-3} Z_{\odot}$. Top: histogram of $f_{M_{*}^i}$ vs. redshift of formation.
of the particles that form through external enrichment have metallicity below 0.3. Even though the critical metallicity for Population II star formation is $Z_{\text{crit}} = 10^{-5.3} Z_\odot$, this distribution peaks near $Z = 10^{-4.4} Z_\odot$. All of the particles that form through external enrichment have metallicity below $10^{-5} Z_\odot$. Top: histogram of $f_{\text{M}}$ vs. redshift of formation.

Figure 12. Left: metallicity of all Population II star particles in the simulation volume vs. redshift. Each gray data point represents a star particle, with horizontally aligned points tracking the star over time. Stars that form in externally enriched halos are signified with green horizontal lines. Right: metallicity distribution function by the mass fraction of Population II star particles at $z = 9.3$. Even though the critical metallicity for Population II star formation is $Z_{\text{crit}} = 10^{-5.3} Z_\odot$, this distribution peaks near $Z = 10^{-4.4} Z_\odot$. All of the particles that form through external enrichment have metallicity below $10^{-5} Z_\odot$. Top: histogram of $f_{\text{M}}$ vs. redshift of formation.

are exceptionally rare, surveys continue to identify stars with lower and lower chemical abundances. The current record holder is the carbon-enhanced SMSS J0313$-$6708, which has $[\text{Fe}/\text{H}] < -7.3$ (Keller et al. 2014). Despite its incredibly low iron abundance, the star’s abundances of carbon and oxygen have upper bounds of $10^{-2.4}$ and $10^{-2.3}$ of solar, respectively. This places its total metallicity near the peak of Figure 12, which shows an MDF of all Population II star particles in the simulation by the final output. We observe very broad ranges of metallicity for Population II stars; the lower bound here is a combined artifact of (1) our choice of critical metallicity to form Population II stars, and (2) the limited sample pool of Population II stars in the simulation.

Table 4 in Kirby et al. (2013) summarizes the MDFs for a collection of dwarf galaxies in the Local Group. The most massive halo in the simulation has a similar stellar mass and average Population II stellar metallicity as the dwarf spheroidal (dSph) Milky Way satellite, Ursa Minor, which has a stellar mass of $10^{5.73}$ or $10^{5.84} M_\odot$ and an average iron abundance ratio, $[\text{Fe}/\text{H}]$, of $-2.13 \pm 0.01$. The iron abundance ratio here is averaged over a sample of 190 stars that have been measured spectroscopically in the dwarf, and is thus a good indicator of the dwarf’s total metallicity. Also similar is the dSph, Sextans, with $M_s = 10^{5.84}$ or $10^{5.94} M_\odot$, and $[\text{Fe}/\text{H}] = -1.94 \pm 0.01$, averaged over 123 unique stars within. These two dwarf galaxies are characterized by their primarily old, metal-poor stellar populations, with the only significant bursts of star formation occurring early on in their lifetime (Carrera et al. 2002; Bettinelli et al. 2018).

In agreement with metal-poor DLA studies (Cooke et al. 2017; Welsh et al. 2019), the star-forming galaxies in our simulation have only had a few enriching events. Welsh et al. (2019) place an upper limit of $\lesssim 70$ enriching Population III SNe. We find our galaxies ($\sim 10^3$–$10^4 M_\odot$) to have $\lesssim 20$ enriching events, with the outlier most massive galaxy ($M_s \approx 10^{6.3} M_\odot$) displaying $>100$ events. We also find agreement in that most of the enriching events were HNe or SNe in the stellar mass range $10 < M_s / M_\odot < 40$, which is entirely due to the characteristic mass chosen for this simulation. However, these DLA studies have not found evidence for highly energetic PISNe, which are included here.

6. Conclusions

We have analyzed the formation and chemical evolution history of a sample of halos with mass $10^{5.3} \leq M_{\text{vir}}/M_\odot \leq 10^{8.6}$ derived from an Enzo AMR radiation hydrodynamic cosmology simulation that includes detailed models for Population III and Population II star formation and their chemical and radiative feedback within a 1 Mpc comoving box to a stopping redshift of $z = 9.3$. The simulation is a rerun of Wise et al. (2012a) with 1000 data outputs saved for subsequent analysis. By the final redshift, 417 of the 1864 halos analyzed are chemically enriched to $\langle Z_{\text{total}} \rangle > 10^{-5.3} Z_\odot$, where $\langle Z_{\text{total}} \rangle$ is the halo’s mass-averaged metallicity from both Population III and II stellar enrichment. With our high time resolution, we can distinguish among three enrichment pathways: (1) internally enriched: Population III stellar remnants within the halo’s virial radius could have supplied the Population III metals bound to it; (2) externally enriched: Population III stellar remnants within the halo’s virial radius could not have supplied the Population III metals bound to it, or contains no stellar remnants at all; and (3) pre-enriched: a halo is born enriched.
with no Population III stellar remnants. Based on our analysis, we can draw several conclusions:

1. Far from being the outlier, external enrichment is the dominant enrichment pathway that can provide enough metals to push the average metallicity of high-redshift mini halos above the critical value required for Population II star formation. Most halos that are enriched through this mechanism, however, are not massive enough to form stars. When external enrichment does trigger Population II star formation, the resulting star particles have low metallicity.

2. Internal enrichment is the dominant pathway for halos forming Population II stars in this simulation; however, most Population II star formation occurs in the most massive halo.

3. Only a small percentage of enriched halos form pre-enriched, increasing from 1% to 17.5% by the end of the simulation.

4. The fraction of halos that are externally enriched increases over time, and the majority of these halos have virial mass below $10^8 M_\odot$.

5. PISNe contribute the most to the enrichment of the IGM as a whole for our choice of primordial IMF and are consequently the predominant SN type contributing to the external enrichment of halos in spite of the fact that they only account for 8% by number of the Population III SN events.

6. The average Population III metallicity profile for externally enriched halos at the time of enrichment shows metallicities $>4$ orders of magnitude below the critical metallicity for Population II star formation, $Z_{\text{crit}}$, at the center, with values increasing outwards until they reach $Z_{\text{crit}}$ at about 0.8 $R_{\text{vir}}$. In contrast, the average profile for internally enriched halos has metallicities above $Z_{\text{crit}}$ throughout, with values decreasing outwards. The profile for pre-enriched halos also has metallicities above $Z_{\text{crit}}$ throughout, but it is flatter than the other two cases, increasing outwards by less than an order of magnitude.

7. The line between the Population III and Population II star formation phases in a merger tree is blurry, as a halo that is currently in the Population II phase can merge with a halo that is still in the Population III phase. The period of overlap, where both Population III and Population II star formation takes place within a merger tree, typically lasts around 100 Myr for the halos in this simulation.

We have found that during early star formation, the metal-enrichment process is not exclusively local to the host halo and must include the surrounding environment. The region that must be included will likely depend on many factors, e.g., halo mass, halo number density, baryon density between halos and enriching events, temperature, and the particular type of SN. A future study may be able to study these variables more precisely to determine their effect on the enrichment process.

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