The Challenges of Identifying Population III Stars in the Early Universe

Harley Katz\textsuperscript{1,*}, Taysun Kimm\textsuperscript{2}, Richard S. Ellis\textsuperscript{3}, Julien Devriendt\textsuperscript{1}, & Adrianne Slyz\textsuperscript{1}

\textsuperscript{1}Sub-department of Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
\textsuperscript{2}Department of Astronomy, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea
\textsuperscript{3}Department of Physics and Astronomy, University of Oxford, Keble Road, Oxford OX1 3RH, UK

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The recent launch of JWST has enabled the exciting prospect of detecting the first generation of metal-free, Population III (Pop. III) stars. Determining the emission line signatures that robustly signify the presence of Pop. III stars against other possible contaminants represents a key challenge for interpreting JWST data. To this end, we run high-resolution (sub-pc) cosmological radiation hydrodynamics simulations of the region around a dwarf galaxy at $z \geq 10$ to predict the emission line signatures of the Pop. III/Pop. II transition. We show that the absence of metal emission lines is a poor diagnostic of Pop. III stars because metal-enriched galaxies in our simulation can maintain low [OIII] $5007\,\AA$ emission that may be undetectable due to sensitivity limits. Combining spectral hardness probes (e.g. Hett $1640\,\AA/\Halpha$) with metallicity diagnostics is more likely to probe the presence of metal-free stars, although contamination from Wolf-Rayet stars, X-ray binaries, or black holes may be important. The hard emission from Pop. III galaxies fades fast due to the short stellar lifetimes of massive Pop. III stars, which could further inhibit detection. Similarly, Pop. III stars may be detectable after they evolve off the main-sequence due to the cooling radiation from nebular gas or a supernova remnant; however, these signatures are also short-lived (i.e. few Myr), and contaminants such as flickering black holes might confuse this diagnostic. While JWST will provide a unique opportunity to spectroscopically probe the nature of the earliest galaxies, both the short timescales associated with pristine systems and ambiguities in interpreting key diagnostic emission lines may hinder progress. Special care will be needed before claiming the discovery of systems with pure Pop. III stars.

Key words: galaxies: evolution, galaxies: formation, galaxies: high-redshift, stars: formation, stars: Population III

1 INTRODUCTION

One of the most compelling scientific goals of the James Webb Space Telescope (JWST) is either detecting or placing strong constraints on the properties of the first generation of metal-free, Population III (Pop. III) stars (Gardner et al. 2006). Very little is known about their properties, such as when they started forming, when they stopped forming, their initial mass function (IMF), or metal yields because to date, there has yet to be a robust detection of Pop. III stars — despite there being speculation about a few peculiar objects (e.g. Sobral et al. 2015; Vanzella et al. 2020; Welch et al. 2022). The constraints we have on their characteristics are either derived from high-resolution numerical simulations (e.g. Abel et al. 2002; Bromm et al. 2002; Stacy et al. 2010; Greif et al. 2011; Hirano et al. 2014; Hosokawa et al. 2016) or from stellar archaeology around the Milky Way (e.g. Beers & Christlieb 2005; Frebel et al. 2007; Karlsson et al. 2013). Nevertheless, this is hopefully set to change with the recent launch of JWST or future facilities such as HARMONI on the ELT (Grisdale et al. 2021).

Even with optimistic assumptions on the Pop. III IMF and the redshift to which some gas in the Universe can remain pristine, it is unlikely that individual metal-free stars will be detectable with JWST (e.g. Zackrisson et al. 2011; Rydberg et al. 2013; Schauer et al. 2020). Although, prospects are better if Pop. III stars form in large groups and a significant amount of observing time is spent on lensing clusters (e.g. Stiavelli & Trenti 2010; Pawlik et al. 2011; Jeon & Bromm 2019; Vikaeus et al. 2022). Direct constraints on the Pop. III IMF may also arise from observing their SN, if they happen to be particularly bright, or result in a gamma-ray burst (Lazar & Bromm 2022).

One of the primary issues with robustly detecting Pop. III stars is determining the spectral signatures that differentiate them from other classes of objects that form in the early Universe. Such contaminants could include direct collapse black holes or a second generation of already metal enriched stars (Nakajima & Maiolino 2022). Due to their possible higher masses and metal-free nature, the spectra of Pop. III stars are expected to be considerably harder than their Pop. II counterparts (e.g. Schaerer 2002). For this reason, it has been postulated that spectral signatures from high-energy ionization states (e.g. HeII, Oh et al. 2001; Tumlinson et al. 2001) represent one possible indirect signature of Pop. III stars. However, strong HeII lines by themselves are not a definitive signature of metal-free stars because other sources, such as Wolf-Rayet stars, X-ray binaries, or black holes can similarly produce strong HeII emission (e.g. Erb et al. 2010; Inoue 2011; Schaerer et al. 2019; Nakajima & Maiolino 2022). Pop. III stars are also predicted to excite strong hydrogen emission
lines such a Lyα, Hα, and Hβ, although the former is unlikely to be detectable due to the optically thick IGM at high redshifts (Gunn & Peterson 1965; Inoue et al. 2014). Another possible contaminant are galaxies that have metals but the metal emission lines are simply too weak to be detected.

Given the recent launch of JWST, it is timely to revisit the spectral signatures of Pop. III stars in the context of fully coupled radiation hydrodynamics simulations that resolve much of the physics driving emission lines. This provides a complementary view to the various photoionization models that have been analysed on this topic (e.g. Inoue 2011; Nakajima & Maiolino 2022).

2 METHODS

For this work, we employ high-resolution cosmological radiation hydrodynamics simulations run with the RAMSES-RTZ code (Katz 2022), an extension of the RAMSES-RT code (Teyssier 2002; Rosdahl et al. 2013; Rosdahl & Teyssier 2015) that includes modules for radiation-coupled H₂ (Katz et al. 2017) and metal chemistry (Katz 2022). The underlying physics closely follows that presented in Kimm et al. (2017) and here we briefly highlight the features included in the simulation with a particular emphasis on the changes made for these runs.

The simulations follow gravity, hydrodynamics, radiation transfer, and various chemistry, cooling, and heating processes. The radiation is followed in 8 frequency bins (see Table 2 in Kimm et al. 2017) using the M1 method (Levermore 1984). To reduce the computational cost of the RT, we employ a reduced speed of light approximation, adopting \( c_{\text{sim}} = 0.01 c \). The radiation is coupled to the gas via photoionization, photoheating, and radiation pressure (both direct UV and multi-scattered IR). Similar to Kimm et al. (2017) we follow Hi, HII, e, Hε, HeII, and HeIII, but new for this work, we also follow various ionization states of O, C, N, Fe, Si, S, Ne, and Mg. Atomic data for each metal closely follows that adopted by CLOUDY (Ferland et al. 2017). Cooling for primordial species follows the methods presented in Rosdahl et al. (2013); Katz et al. (2017) and cooling for metals is calculated at low temperatures (\( T < 10^4 \) K) by computing the equilibrium level populations of certain ions and for high-temperatures (\( T \geq 10^4 \) K) by using look-up tables (see Oppenheimer & Schaye 2013; Katz 2022).

Cosmological initial conditions are generated for a halo with mass \( \sim 3 \times 10^8 M_\odot \) at \( z = 10 \) using MUSIC (Hahn & Abel 2011), assuming the following cosmology: \( \Omega_m = 0.311, \Omega_b = 0.045, \Omega_m = 0.689, \) and \( h = 0.6766 \) (Planck Collaboration et al. 2020). Due to the large computational expense of these simulations, we apply the zoom-in technique and place the bulk of our resolution elements around a single galaxy, ensuring that there is no contamination from low-resolution elements within the virial radius at any point. The dark matter particle mass within the high resolution region is 492 M_\odot. Throughout the course of the simulation, we allow the adaptive mesh to refine when either the Jeans length is not resolved by at least 8 cells, or the dark matter or gas mass of the cell grows to 8 times its initial value. The minimum cell size is 0.8 pc at \( z = 10 \) and remains constant in co-moving coordinates (resulting in even smaller cell sizes at higher redshifts).

When the gas becomes dense enough, star particles are allowed to form. This occurs when the turbulent Jeans length is unresolved (see e.g. Kimm et al. 2017) and the gas is converging on a local density maximum. If these criteria are satisfied, star formation proceeds in two different modes depending on metallicity. Pop. III stars can form when the gas metallicity is \( < 10^{-6} Z_\odot \), while Pop. II stars form at higher metallicities. In the case of Pop. II stars, particle masses are integer multiples of 500 M_\odot. The number of star particles formed is drawn from a Poisson distribution with the conversion rate calculated via a Schmidt law (Schmidt 1959). The efficiency of conversion depends on the thermo-turbulent properties of the gas calibrated on high-resolution molecular cloud simulations (Padoan & Nordlund 2011; Federrath & Klessen 2012). Pop. II star particles are assumed to host stellar populations that follow a Kroupa IMF (Kroupa 2001). In the case of Pop. III stars, when the star formation criteria are met, we draw individual star particle masses from a stellar IMF following Wise et al. (2012a).

Star particles impact their environment in numerous ways. During the course of their lifetime, they inject photons into their host cells. For Pop. III stars, we adopt the age and mass dependent SEDs from Schaerer (2002) and for Pop. II stars, we use the age, mass, and metallicity dependent SEDs from BPASS v.2.2.1 (Stanway & Eldridge 2018). When Pop. III stars reach the end of their lifetime, they can either explode via SN or directly collapse to a black hole. The energy per Pop. III SN and the mass ranges for SN versus direct collapse are adopted from Wise et al. (2012a), which are based on Woosley & Weaver (1995); Heger & Woosley (2002); Nomoto et al. (2006) (see Equations. 22 and 23 of Kimm et al. 2017). For Pop. II stars, we follow both type II core-collapse SN as well as SNIa. We randomly sample the stellar IMF to determine when to inject core-collapse SN following the age-mass distribution of Raiteri et al. (1996). When SN occur, momentum is injected into the simulations following the mechanical feedback model of (Kimm et al. 2015). Stellar winds

---

**Figure 1.** (Top) Maps of dark matter, gas, and oxygen in the simulation at \( z = 10 \). The white circle shows the virial radius (1.72 kpc) of the most massive halo in the simulation. (Bottom) Map of OI, OII, and OIII in the central regions of the most massive halo.
from AGB stars are also included using the method presented in Agertz et al. (2013).

During all of these energetic feedback processes, metals are released into the gas. In all cases, yields are dependent on stellar mass. For Pop. III stars, we consider individual SN yields from typical type II SN (Nomoto et al. 2006), hypernova (Nomoto et al. 2006), and pair-instability SN (Heger & Woosley 2002). The mass thresholds for each are described in Kimm et al. (2017). Metal yields for Pop. II core-collapse SN are adopted from Portinari et al. (1998), and pair-instability SN (Heger & Woosley 2002). The mass thresholds for each are described in Kimm et al. (2017). Metal yields for Pop. II core-collapse SN are adopted from Portinari et al. (1998), while SN yields are from Seitenzahl et al. (2013). Finally, AGB wind yields are from Pignatari et al. (2016). We follow the enrichment of O, N, C, Mg, Si, S, Fe, Ne, and Ca.

To analyse the simulations, we use the AMIGA halo finder (AHF) to identify the dark matter haloes (Gill et al. 2004; Knollmann & Knebe 2009) using the virial over-density criteria of Bryan & Norman (1998). For each halo, we compute the luminosities of various emission lines. Line emission from primordial species is computed following the fitting functions presented in Katz et al. (2022), while metal emission line luminosities are calculated with PyNeb (Luridiana et al. 2015). Due to the very low metallicities, we neglect the impact of dust on the presented emission line luminosities.

3 RESULTS

The two primary questions that we would like to address with our simulations are: What are the spectral features that differentiate Pop. III star formation from metal enriched stellar populations and are these signatures detectable? In this Section, we describe the general properties of the simulated galaxy population, discuss the spectral features of these simulated galaxies, and comment on the complexities of identifying a true Pop. III star or galaxy with observations.

3.1 High-Redshift Galaxy Properties

The simulation follows the formation and evolution of the region around a halo with mass $\sim 3 \times 10^8 \, M_\odot$ by $z = 10$. We study the population of haloes inside the high resolution Lagrange region of the main halo. The region contains 356 uncontaminated dark matter haloes with at least 300 particles. In Figure 1 we show maps of dark matter, gas, and oxygen, as well as a zoomed in distribution of OI, OII, and OIII at $z = 10$. At this redshift, the main halo has recently undergone a major merger (a relatively common event at high redshift). There is a significant gas concentration at the centre of the halo and a repeated series of star formation and SN events have enriched a large fraction of the volume with oxygen, some of which has escaped the halo, into the IGM. The structure in the centre of the halo is highly complex and filled with various ionization states of oxygen, dictated by both the local radiation field, SN feedback, and the presence of shocks.

More quantitatively, the first Pop. III stars formed at $z \sim 18$. This can be seen in the top panel of Figure 2, where we show the star formation rate as a function of time within the Lagrange region, split between Pop. III and Pop. II star formation. Due to the fact that not
all Pop. III stars explode via SN, the first metal enrichment does not occur until $z \sim 16.5$. This can be seen as the spike in the O, C, and Fe abundances in the bottom panel of Figure 2. The first SN increases the mass-weighted metallicity of the system up to $10^{-4}Z_\odot$ in O and Fe and $10^{-5}Z_\odot$ in C. The exact enrichment levels for each metal are highly dependent on the mass of the Pop. III stars that explode. We expect this to vary between haloes at high redshift.

Once the region becomes metal enriched, Pop. II star formation can proceed. This is shown as the magenta line in the top panel of Figure 2. There is a delay between when the first SN explode ($z \sim 16.5$) and when Pop. II stars form ($z < 15$) due to the fact that the gas has to re-settle in the halo that hosted the SN, and for the metals that escaped the halo, it takes time for them to be accreted onto neighbouring systems. A mixed mode of Pop. III and Pop. II star formation continues until $z \sim 11$. By this time, the mass-weighted metallicity has increased by about a factor of three, at which point star formation is completely dominated by Pop. II stars. We note that the exact length of the mixed-mode epoch and the redshift at which the Pop. II-dominant epoch begins are sensitive to both the individual histories of each halo and our definition for the metallicity threshold that separates Pop. II and Pop. III stars. If we adopted a higher metallicity threshold, the results here may change. This issue is further discussed below.

Slightly before $z = 10$, the halo undergoes a major merger that results in a steep increase in star formation and metal enrichment. By comparing the mass-weighted and volume-weighted gas metallicities in the Lagrange volume, we can analyze the enrichment of the ISM versus the IGM. While the mass-weighted metallicity continuously rises with decreasing redshift, the evolution of volume-weighted metallicity is more complex and sensitive to gas inflowing into the Lagrange region and the ability for stars to eject metals from the haloes. In general, the volume-weighted metallicity remains below the mass-weighted values suggesting that the metals are more concentrated in the haloes rather than in the IGM.

In the absence of heavy elements, H$_2$ is the primary coolant of the ISM. In Figure 3 we show the evolution of total masses of H$_2$, CII (one of the dominant coolants at higher metallicity), and CO (one of the dominant coolants at high density and high metallicity). At $z \geq 16.5$ a baseline level of H$_2$ is formed via reactions with H$^-$. Once the first metals are released into the ISM and IGM, CII can form as well and simultaneously the main-mode of H$_2$ formation transitions from the primordial channel to formation on dust. Future telescopes such as ngVLA will provide the opportunity to detect CII in the redshift interval $15 \leq z \leq 20$, which may help probe the properties of the first stars (Carilli et al. 2018). CO is also detectable at high-redshift with the ngVLA, which could also be interesting for placing constraints on the properties of the first stars; however, we

Figure 4. Flux ratios of [OIII]/H$eta$ (left), [OII]/H$eta$ (centre) or [OIII]/[OII] (right) for the simulated galaxy population in the redshift range $10 \leq z \leq 16$. The bottom row shows a zoomed in version of the top row. The data points from the simulation are coloured by their 10 Myr-averaged SFR. For comparison, we show results from the CLOUDY models of Inoue (2011) (grey) and Nakajima & Maiolino (2022) (cyan squares) for primordial stellar populations. Similarly, we show flux ratios for local Green Pea galaxies (Yang et al. 2017a), Blueberry galaxies (Yang et al. 2017b), and very low metallicity SDSS galaxies (Izotov et al. 2019) as different coloured triangles.
find the amount of CO remains limited until sufficient self-shielding can occur in the ISM.

Having described the star formation, metal enrichment, and molecular properties of the gas in the simulation, we continue our analysis by studying the spectral features of the simulated galaxies.

3.2 The Absence of Metallic Emission Lines

As Pop. III stars are by definition metal-free, their star forming clouds are also expected to be of pristine, primordial composition. The observation of a galaxy with strong He II 1640 Å, Hα, and Hβ emission with no metal emission lines is potentially a signature of Pop. III stars (Schaerer 2002; Raiter et al. 2010; Inoue 2011). From an observational perspective, the absence of metal emission lines will be difficult to prove because the finite integration times and sensitivity limits will only allow for upper limits on metal emission line strengths, rather than robustly proving that metal emission lines are completely absent. The key question is how strong are the metal emission lines expected to be with respect to the Balmer emission, in simulated high-redshift galaxies.

In Figure 4 we show the flux ratios of [OIII]/Hβ (left), [OIII]/Hβ (centre), and [OIII]/[OII] (right) for simulated galaxies in the redshift interval 10 ≤ z ≤ 16 coloured by their SFR. Oxygen emission lines are expected to be the brightest metal emission lines at these epochs due to the early enrichment from core-collapse SN (e.g. Maiolino & Mannucci 2019), and the collision strengths of these particular transitions. As the metallicity decreases, [OIII]/Hβ and [OII]/Hβ also decreases such that at 12 + log(H/He) = 6, our simulations predict flux ratios of ~ 10⁻² compared to Hβ. Such predictions are not unique to our simulations as CLOUDY models (see the grey lines and cyan points in Figure 4) of primordial galaxies predict similar flux ratios (Inoue 2011; Nakajima & Maiolino 2022). Considering that our predictions are completely independent of CLOUDY, it is encouraging that both methods are in reasonable agreement. However, because the simulation samples a diversity of ISM conditions and star formation histories, we do find additional scatter in our relations related to the star formation rate and ISM structure of the galaxy. This is because the star formation rate controls the number of ionizing photons, electron density, and temperature via radiative and SN feedback while the ISM structure dictates how well this feedback couples to the gas. At fixed metallicity, the simulated galaxies exhibit a wide diversity of star formation rates and ISM conditions. Such effects are not captured via simple photoionization models with a fixed uniform gas density and star formation rate.

For comparison, we also show the location of Green Pea galaxies (Yang et al. 2017a), Blueberry galaxies (Yang et al. 2017b), and low-metallicity, low-redshift SDSS galaxies (Izotov et al. 2019) in Figure 4. In general, we find good consistency between low-redshift “analogues” and our simulated data, providing further confidence in our predictions. The low metallicity galaxies from Izotov et al. (2019) tend to have very comparable [OIII]/Hβ, higher [OII]/Hβ, and slightly lower [OIII]/[OII] compared to the simulated galaxies and CLOUDY models (Inoue 2011; Nakajima & Maiolino 2022). Green Peas and Blueberries tend to be higher metallicity than the simulated galaxies (see also Katz et al. 2022). If we extrapolate the trends from our simulation to higher metallicities, we find no tension between these two galaxy populations and our high-redshift simulations.

3.3 The Absence of Metal Emission Lines with Strong He II 1640 Å

Although we argue that [OIII]/Hβ (or [OII]/Hβ) is, by itself, insufficient to identify a Pop. III stellar population, if we combine the [OIII]/Hβ ratio with the He II 1640 Å/Hα ratio, we do find a region of parameter space that is only populated by galaxies dominated by Pop. III stars. The red shaded region in the bottom right of Figure 5 shows that the parameter space with [OIII]/Hβ < 10⁻¹.5 and He II 1640 Å/Hα > 10⁻⁰.6 consists of only systems with stellar populations with a high Pop. III fraction. Consistent with previous claims in the literature (e.g. Schaerer 2002), we can confirm that weak metal emission lines and strong He II 1640 Å emission is a signature of Pop. III stars in our simulations.

Within this Pop. III parameter space, we find three interesting features. There are numerous systems that have [OIII]/Hβ = 0 (represented as downward arrows in Figure 5). These are genuine Pop. III stars forming in pristine, zero-metallicity gas clouds. These types of systems are what is typically expected of Pop. III stars.

Next we have a galaxy that appears as the blue point in the shaded region that hosts a stellar population that is a mix of Pop. II and Pop. III stars. Such mixtures are common in our simulation, although not all have high He II 1640 Å emission. A dark matter map of this galaxy with the locations of the Pop. II and Pop. III star particles is shown in Figure 6. These mixed systems add to the complexity of detecting a fully Pop. III dominated galaxy. Simulations with larger volumes may find similarly complex systems of this nature that potentially pollute the region of Figure 5 that we ascribe as being Pop. III.

Going into more detail on this specific galaxy, within 100 pc of the centre, we find two Pop. III star particles of ages 98 Myr and 124 Myr, the former of which exploded as a Pair-Instability SN (PISN) and the latter collapsed directly into a black hole. The third star particle is a 500 M_☉ cluster of Pop. II stars with an age of 20 Myr that is driving most of the line emission. This system is surrounded (within 2 kpc)
by three more Pop. III stars, one of which is 340 M⊙, with an age of 4.6 Myr, that is likely helping to drive some of the HeII emission externally.

It is also important to consider that the origin of strong HeII emission is unknown at low redshifts and it is possibly driven by X-ray binaries, Wolf-Rayet stars, or other sources (e.g. Erb et al. 2010; Schaerer et al. 2019). If our chosen BPASS SED neglects these sources, we are potentially underpredicting the HeII luminosities of our Pop. II galaxies. This would further pollute this diagnostic, making it more difficult to identify genuine Pop. III stars.

Finally, we find galaxies that are fully dominated by Pop. III stars but exhibit metal emission because we are observing a cooling SN remnant. Hence the presence of metal emission lines does not necessarily rule out the system from being Pop. III, even though this cooling phase is expected to be short-lived.

More specifically, there is a galaxy that is completely dominated by Pop. III stars but has [OIII]/Hβ = 10^{-1.5}. We show maps of the dark matter, gas, and temperature, and the surface brightness maps of HeII 1640Å, Hα, and [OII] 5007Å for this galaxy in Figure 7. This system hosted a single 180 M⊙ Pop. III star that recently exploded as a PISN. The PISN enriched the surrounding medium with metals so the emission that is seen is a combination of the recombinational emission due to photoionization from the star and the cooling radiation from the SN remnant. The interesting characteristic of this galaxy is that there is no stellar continuum. By definition (excluding the contribution from nebular continuum), the equivalent widths of all of the emission lines from this system are infinity. We discuss such systems further in Section 3.5. If another Pop. III star formed in this system before the first evolved off the main-sequence, we might expect an increase in luminosity for all emission lines, including those from metals.

3.4 Time Windows for Detection

If Pop. III stars were predominantly massive, their main-sequence lifetimes would be very short. Hence the emission line signatures are also expected to be short lived (e.g. Schaerer 2002, 2003). Therefore, Pop. III lifetime is an important parameter when considering their detectability (Zackrisson et al. 2012; Rydberg et al. 2013).

In the top panels of Figure 8, we show the time evolution of the HeII 1640Å, Hα, and Hβ emission for eight haloes in the simulation as a function of time after the formation of a Pop. III star. The lines are coloured based on the initial mass of the Pop. III star that formed in the halo. The luminosities have been normalized to the maximum luminosity of the line recorded after the star formation event. In most cases, the HeII 1640Å fades by nearly two orders of magnitude within 5 Myr and the Balmer emission shows similar properties. This result is unsurprising given that our Pop. III stars are in general massive and we have adopted the SED of Schaerer (2002). The unique aspect of this work is that we can see how this signal fades for a realistic gas distribution. In the bottom panel of Figure 8, we show the ratio of HeII 1640Å/Hα normalized to the value of this ratio after the star formation event. In general, the HeII 1640Å emission decreases faster than Hα. This explains why the Pop. III galaxies in Figure 5 that have no metal emission lines also show weak HeII 1640Å/Hα.

There is a single halo in our simulation where the HeII 1640Å emission remains strong for ~ 10 Myr. Looking at this system in more detail, we find that a second Pop. III star formed in the galaxy very soon after the first. The presence of the second Pop. III star maintains the ionizing luminosity needed to continually excite the HeII 1640Å line. This phenomenon is considerably rarer in our simulation than isolated Pop. III star formation, but we note that these predictions are highly IMF/model dependent. Nevertheless, for a top-heavy Pop. III IMF, the number densities of galaxies with HeII 1640Å emission may be lower than that for a more bottom-heavy IMF.

It is important to consider that the formation of a single massive

---

1 In the case where multiple Pop. III stars form, the line is coloured based on the mass of the first star to form.

2 Note that because the simulation outputs snapshots at fixed times, there is often some delay after the formation of each star before we can first measure the emission line luminosities. The time cadence of our snapshots is often < 5 Myr so we expect our curves to be reasonably time-resolved.
3.5 Pure Line Emitters as a Signature of Pop. III Stars

Due to the nature of our chosen Pop. III IMF, the stars can either end their lives as normal type-II SN, PISN, or by directly collapsing into black holes. In all three cases the gas in the host halo will emit for some period of time after the Pop. III star has evolved off the main sequence. In this case, the galaxy may appear to have strong emission lines (and possibly a nebular continuum), but no stellar continuum due to the fact that the star formed in isolation. We refer to these galaxies as pure line emitters (PLEs), although similar signatures have been found for AGN (e.g. Lintott et al. 2009).

We find two types of PLEs in the simulation: metal-enriched PLEs, which result from a single Pop. III SN, and metal-free PLEs that are generated by the formation of a Pop. III star that subsequently collapses directly into a black hole. Both are labelled in Figure 5. The two types of PLE have different emission line signatures (i.e. the presence of metals or not), but both seem to have emission lines that fade very fast. The gas density at which the SN explodes as well as the gas distribution (Blondin et al. 1998; Thornton et al. 1998) may impact the rate at which the SN remnant cools; thus the single PISN-driven PLE in our simulation may not be fully representative of the expected parameter space. Nevertheless, detecting these objects may be difficult due to their short-lived nature, but if equivalent widths can be constrained, they may provide an alternative metric for identifying Pop. III systems.

It is important to consider that there may be other types of objects that can be confused with PLEs. For example, a black hole that turns on and off in a pristine or even metal enriched galaxy could potentially show similar features to a PLE. Nakajima & Maiolino (2022) showed that the HeII 1640Å/Lα ratio (and therefore also HeII 1640Å/Hz) is similar between Pop. III stars and direct collapse black holes, peaking at a few percent. Only the equivalent width of HeII 1640Å could differentiate the two types of sources (when only these lines are observed). If the source turns off, the equivalent width cannot be measured. If star formation is very heavily dust obscured than the continuum may not be detectable, but if there is a gas cloud near the star-forming region that is not obscured, this could mimic a PLE. However, we would not expect hard spectral features unless the system contained, for example, X-ray binaries, Wolf-Rayet stars, a black hole, etc. We would not expect this setup to be confused with our metal-free PLEs unless the nearby gas cloud is also pristine or of very low metallicity.

4 CAVEATS

The primary systematic uncertainties with our work are the choices of Pop. III IMF, main-sequence lifetimes, SED, post main-sequence behaviour, metal yields, and the transition metallicity between Pop. III and Pop. II star formation. Ideally we could run more simulations to vary these parameters; however, the computational expense of these simulations poses a severe limitation. Nevertheless, one can speculate how changes to these assumptions will impact our results.

For example, moving to a less top heavy IMF may allow the spectral signatures of Pop. III stars to last much longer due to the extended main-sequence lifetimes. Making the SEDs less or more hard will impact the strength of the HeII 1640Å line with respect to the Balmer lines by making the ratios weaker or stronger, respectively. Depending on whether the Pop. III stars collapse directly to black holes or explode as SN, this could change the timescale for enrichment. The abundance patterns of the enriched gas will change depending on the ratio of PISN to normal core-collapse SN. Given that our models
are in good agreement with results from previous CLOUDY models (Inoue 2011; Nakajima & Maiolino 2022), barring the additional scatter due to SFR, galaxy structure, etc., varying these parameters in photoionization models will provide a good estimate for the expected signatures of Pop. II stars.

One of the key uncertainties with our modelling is whether Pop. III stars form in isolation or in large groups. Due to resolution, most Pop. III stars in our work form in isolation; however, higher resolution simulations that better resolve the star formation process show that Pop. III stars can form in binaries or small groups (e.g. Stacy et al. 2016). This could help increase the time period over which HeII is bright.

Due to computational expense, we have only run one simulation of the Lagrange region around a single halo. As described earlier, the onset of Pop. III star formation and length of the Pop. III-Pop. II transition will be halo and environment dependent. Nevertheless, we expect qualitatively similar behaviour in other environments. The galaxies in our simulation are intrinsically faint, but we expect the emission line ratios to hold for any more massive galaxy with similar ISM properties that may be more luminous. More simulations will be required to sample the true diversity of high-redshift galaxies.

5 CONCLUSIONS

We have run a high-resolution cosmological radiation hydrodynamics zoom-in simulation of the region around a dwarf galaxy at $z \geq 10$ with sub-pc resolution to predict the emission line signatures of the Pop. III/Pop. II transition. The simulations are uniquely run with the RAMSES-RTZ code (Katz 2022), which allows us to predict emission line signatures from both primordial species and metals in a fully non-equilibrium manner.

We predict that early metal enrichment from Pop. III stars can quickly increase the mass-weighted metallicity of the gas up to $10^{-4}Z_\odot$ as measured by O and Fe abundances, which is similar to the results of other simulations (e.g. Wise et al. 2012b). This metallicity floor is enough to initiate the formation of the first generations of Pop. II stars at $z \sim 16.5$. A mixed-mode of Pop. III and Pop. II star formation continues until $z \sim 11$, when the Lagrange region is sufficiently metal enriched enough so that Pop. II star formation dominates the volume.

We calculate emission line luminosities of [OIII] 5007Å, [OII] 3727Å, Heα, Hβ, and HeII 1640Å and show that even among metal enriched galaxies (i.e. those with $Z \geq 0.01Z_\odot$), the [OIII] 5007Å/Hβ ratio can remain below $10^{-2}$, consistent with CLOUDY calculations (Inoue 2011; Nakajima & Maiolino 2022), indicating that it will be difficult to identify a truly metal free galaxy with JWST due to sensitivity limits. Combining this ratio with HeII 1640Å/Hz, we find that there is parameter space with [OIII]/Hβ $< 10^{-1.5}$ and He II 1640Å/Hz $> 10^{-0.6}$ that is populated only by galaxies dominated by Pop. III star formation. However, this parameter space is spuriously populated because the HeII 1640Å emission fades very quickly (i.e. within a ~ 5 Myr) after the onset of star formation. Hard HeII 1640Å/Hα ratios can only be maintained for longer periods of time if multiple Pop. III stars form in sequence or with different masses in the same system, which is rare in our model. Finally, we show that galaxies with emission lines but no detectable continua (i.e. PLEs) could offer a signature of a Pop. III stars that either subsequently collapsed directly into a black hole (if there are no metal emission lines) or Pop. III stars that exploded via SN (if there are metal emission lines). These “infinite” equivalent width galaxies are also expected to be short lived, but could represent a further diagnostic of Pop. III star formation if detected.

In summary, JWST will provide an exciting probe of star formation and possibly even Pop. III star formation in the early Universe. However, our work demonstrates that there are significant challenges in robustly identifying a Pop. III stellar population that should be taken into consideration when analysing upcoming JWST data.

ACKNOWLEDGEMENTS

HK thanks Aayush Saxena, Martin Rey, Alex Cameron, Eric Andersson, Oscar Agertz, and Girish Kulkarni. This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No.693024). TK was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (No. 2020R1C1C1007079 and No. 2022R1A6A1A03053472). RSE acknowledges funding from the European Research Council under the European Union Horizon 2020 research and innovation programme (grant agreement No. 669253). Some of this work used the DiRAC@Durham facility managed by the Institute for Computational Cosmology on behalf of the STFC DiRAC HPC Facility (www.dirac.ac.uk). The equipment was funded by BEIS capital funding via STFC capital grants ST/P002293/1, ST/R002371/1 and ST/S002502/1, Durham University and STFC operations grant ST/R000832/1. Some of this work was performed using the DiRAC Data Intensive service at Leicester, operated by the University of Leicester IT Services, which forms part of the STFC DiRAC HPC Facility (www.dirac.ac.uk). The equipment was funded by BEIS capital funding via STFC capital grants ST/K000373/1 and ST/R002363/1 and STFC DiRAC Operations grant ST/R001014/1. DiRAC is part of the National e-Infrastructure.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Abel T., Bryan G. L., Norman M. L., 2002, Science, 295, 93
Agertz O., Kravtsov A. V., Leitner S. N., Gnedin N. Y., 2013, ApJ, 770, 25
Beers T. C., Christlieb N., 2005, ARA&A, 43, 531
Blondin J. M., Wright E. B., Borkowski K. J., Reynolds S. P., 1998, ApJ, 500, 342
Bromm V., Coppi P. S., Larson R. B., 2002, ApJ, 564, 23
Bryan G. L., Norman M. L., 1998, ApJ, 495, 80
Carilli C. L., Murphy E. J., Ferrara A., Dayal P., 2018, arXiv e-prints, p. arXiv:1810.07536
Erb D. K., Pettini M., Shapley A. E., Steidel C. C., Law D. R., Reddy N. A., 2010, ApJ, 719, 1168
Federrath C., Klessen R. S., 2012, ApJ, 761, 156
Ferland G. J., et al., 2017, Rev. Mex. Astron. Astrofis., 53, 385
Freyberg A., Johnson J. L., Bromm V., 2007, MNRAS, 380, L40
Gardner J. P., et al., 2006, Space Sci. Rev., 123, 485
Gill S. P. D., Knebe A., Gibson B. K., 2004, MNRAS, 351, 399
Greif T. H., Springel V., White S. D. M., Glover S. C. O., Smith R. J., Klessen R. S., Bromm V., 2011, ApJ, 737, 75
Grissdale K., Thatte N., Devriendt J., Pereira-Santaella M., Slyz A., Kimm T., Dubois Y., Yi S. K., 2021, MNRAS, 501, 5517
Gunn J. E., Peterson B. A., 1965, ApJ, 142, 1633
Hahn O., Abel T., 2011, MNRAS, 415, 2101
Population III Stars in the Early Universe

Heger A., Woosley S. E., 2002, ApJ, 567, 532
Hirano S., Hosokawa T., Yoshida N., Umeda H., Omukai K., Chiaki G., Yorke H. W., 2014, ApJ, 781, 60
Hosokawa T., Hirano S., Kuiper R., Yorke H. W., Omukai K., Yoshida N., 2016, ApJ, 824, 119
Inoue A. K., 2011, MNRAS, 415, 2920
Inoue A. K., Shimizu I., Iwata I., Tanaka M., 2014, MNRAS, 442, 1805
Izotov Y. I., Guseva N. G., Fricke K. J., Henkel C., 2019, A&A, 623, A40
Jeon M., Bromm V., 2019, MNRAS, 485, 5939
Karlsson T., Bromm V., Bland-Hawthorn J., 2013, Reviews of Modern Physics, 85, 809
Katz H., 2022, MNRAS, 512, 348
Katz H., Kimm T., Sijacki D., Haehnelt M. G., 2017, MNRAS, 468, 4831
Katz H., et al., 2022, MNRAS,
Kimm T., Cen R., Devriendt J., Dubois Y., Slyz A., 2015, MNRAS, 451, 2900
Kimm T., Katz H., Haehnelt M., Rosdahl J., Devriendt J., Slyz A., 2017, MNRAS, 466, 4826
Knollmann S. R., Knebe A., 2009, ApJS, 182, 608
Kroupa P., 2001, MNRAS, 322, 231
Lazar A., Bromm V., 2022, MNRAS, 511, 2505
Levermore C. D., 1984, J. Quant. Spectrosc. Radiative Transfer, 31, 149
Lintott C. J., et al., 2009, MNRAS, 399, 129
Luridiana V., Morisset C., Shaw R. A., 2015, A&A, 573, A42
Maiolino R., Mannucci F., 2019, A&ARv, 27, 3
Nakajima K., Maiolino R., 2022, arXiv e-prints, p. arXiv:2204.11870
Nomoto K., Tominaga N., Umeda H., Kobayashi C., Maeda K., 2006, Nuclear Phys. A, 777, 424
Oh S. P., Haiman Z., Rees M. J., 2001, ApJ, 553, 73
Oppenheimer B. D., Schaye J., 2013, MNRAS, 434, 1043
Padoan P., Nordlund Å., 2011, ApJ, 730, 40
Pawlik A. H., Milosavljević M., Bromm V., 2011, ApJ, 731, 54
Pignatari M., et al., 2016, ApJS, 225, 24
Planck Collaboration et al., 2020, A&A, 641, A6
Portinari L., Chiosi C., Bressan A., 1998, A&A, 334, 505
Raiter A., Schaerer D., Fosbury R. A. E., 2010, A&A, 523, A64
Raiteri C. M., Villata M., Navarro J. F., 1996, A&A, 315, 105
Rosdahl J., Teyssier R., 2015, MNRAS, 449, 4380
Rosdahl J., Blaizot J., Aubert D., Stranex T., Teyssier R., 2013, MNRAS, 436, 2188
Rydberg C.-E., Zackrisson E., Lundqvist P., Scott P., 2013, MNRAS, 429, 3658
Schaerer D., 2002, A&A, 382, 28
Schaerer D., 2003, A&A, 397, 527
Schaerer D., Fragos T., Izotov Y. I., 2019, A&A, 622, L10
Schauer A. T. P., Drory N., Bromm V., 2020, ApJ, 904, 145
Schmidt M., 1959, ApJ, 129, 243
Seitenzahl I. R., et al., 2013, MNRAS, 429, 1156
Sobral D., Matthee J., Darvish B., Schaerer D., Mobasher B., Röttgering H. J. A., Santos S., Hemmati S., 2015, ApJ, 808, 139
Stacy A., Greif T. H., Bromm V., 2010, MNRAS, 403, 45
Stacy A., Bromm V., Lee A. T., 2016, MNRAS, 462, 1307
Stanway E. R., Eldridge J. I., 2018, MNRAS, 479, 75
Stiavelli M., Trenti M., 2010, ApJ, 716, L190
Teyssier R., 2002, A&A, 385, 337
Thorstensen J., Steidel C. C., 2019, ApJ, 873, 75
Thornton K., Gaudlitz M., Janka H. T., Steinmetz M., 1998, ApJ, 500, 95
Tumlinson J., Giroux M. L., Shull J. M., 2001, ApJ, 550, L1
Vanzella E., et al., 2020, MNRAS, 494, L81
Vikaeus A., Zackrisson E., Schaerer D., Visbal E., Fransson E., Malhotra S., Rhoads J., Sahlén M., 2022, MNRAS, 512, 3030
Welch B., et al., 2022, Nature, 603, 815
Wise J. H., Abel T., Turk M. J., Norman M. L., Smith B. D., 2012a, MNRAS, 427, 311
Wise J. H., Turk M. J., Norman M. L., Abel T., 2012b, ApJ, 745, 50
Woosley S. E., Weaver T. A., 1995, ApJS, 101, 181
Yang H., et al., 2017a, ApJ, 844, 171
Yang H., Malhotra S., Rhoads J. E., Wang J., 2017b, ApJ, 847, 38
Zackrisson E., Rydberg C.-E., Schaerer D., Ostlin G., Tuli M., 2011, ApJ, 740, 13
Zackrisson E., et al., 2012, MNRAS, 427, 2212
This paper has been typeset from a TeX/LaTeX file prepared by the author.