THE CLUSTERING PROPERTIES OF THE FIRST GALAXIES

MASSIMO STIAVELLI\(^1\) AND MICHELE TRENTE\(^2\)

\(^1\) Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
\(^2\) University of Colorado, Center for Astrophysics and Space Astronomy, 389 UCB, Boulder, CO 80309, USA

Received 2009 September 11; accepted 2010 May 19; published 2010 June 3

ABSTRACT

We study the clustering properties of the first galaxies formed in the universe. We find that, due to chemical enrichment of the interstellar medium by isolated Population III stars formed in mini-halos at redshift \(z \gtrsim 30\), the (chronologically) first galaxies are composed of metal-poor Population II stars and are highly clustered on small scales. In contrast, chemically pristine galaxies in halos with mass \(M \sim 10^8 M_\odot\) may form at \(z < 20\) in relatively underdense regions of the universe. This occurs once self-enrichment by Population III stars in mini-halos is quenched by the buildup of an \(H_2\) photodissociating radiative background in the Lyman–Werner bands. We find that these chemically pristine galaxies are spatially uncorrelated. Thus, we expect that deep fields with the James Webb Space Telescope (JWST) may detect clusters of chemically enriched galaxies but individual chemically pristine objects. We predict that metal-free galaxies at \(10 \lesssim z \lesssim 15\) have surface densities of about 80 arcmin\(^{-2}\) and per unit redshift but most of them will be too faint even for JWST. However, the predicted density makes these objects interesting targets for searches behind lensing clusters.

Key words: cosmology: theory – early universe – galaxies: high-redshift

1. INTRODUCTION

The concept of the first galaxies is not as easy to define as that of the first stars and it is partly a matter of convention. A first, somewhat arbitrary, decision is the mass scale where an object becomes a galaxy. A common convention in the context of the first galaxies is describing galaxies as those objects that are forming in dark halos massive enough that their gaseous content can cool by atomic hydrogen (Ly\(\alpha\) cooling), i.e., characterized by a virial temperature greater than \(10^4\) K (Ricotti et al. 2008; Wise & Abel 2008; Greif et al. 2008). The advantage of this definition is that it is based on a physical process and makes galaxy formation relatively independent of the presence of a Lyman–Werner (LW) background that could hamper the formation of Population III stars in mini-halos by photodissociating molecular hydrogen (Lepp & Shull 1983; Tegmark et al. 1997; Haiman et al. 1997; Machacek et al. 2003; Trenti & Stiavelli 2009; Trenti et al. 2009).

Once we have defined “galaxy” we need to define “first.” The usual assumption is that “first” refers to a chronological sequence of events, so that the first galaxies are those that formed at the earliest redshifts. It is sometimes assumed that the chronologically “first” galaxies will also be the least chemically evolved ones. In fact, these objects are most likely to have formed in highly clustered areas, and they are also very likely to have been polluted by metals produced by Population III stars forming in mini-halos (Wise & Abel 2008; Greif et al. 2008). Thus, these chronologically first galaxies would not have a primordial chemical composition. However, we can imagine another class of galaxies that would form after an LW background is in place and would then not be polluted by stars in mini-halos (Jimenez & Haiman 2006; Trenti et al. 2009; Johnson et al. 2008). These objects could conceivably form stars out of pristine primordial gas and would then be galaxies made of Population III stars. Assuming that they can form Population III stars in significant numbers, these objects would be chemically less evolved (i.e., “younger”) despite forming later in a chronological sense.

This Letter is devoted to explore the validity of the two scenarios described above and to study the redshift distributions and clustering properties of these two classes of objects. These quantities are relevant for planning surveys to study the first galaxies with the James Webb Space Telescope (JWST) and other (future) facilities, such as 30 m class telescopes used for imaging behind lensing clusters.

The structure of this Letter is as follows. In Section 2, we discuss our model for galaxy formation during the Dark Ages; and in Section 3, we present our results on star formation rates and clustering. Section 4 concludes with prospects for future detections and speculates on the possibility that metal-free galaxies have already been observed behind a lensing cluster by Stark et al. (2007).

2. GALAXY FORMATION DURING THE REIONIZATION ERA

Our method is based on a combination of numerical simulations and analytical considerations developed by Trenti & Stiavelli (2007, 2009), Trenti et al. (2008, 2009), and Trenti & Shull (2010). Here, we briefly summarize the main properties of our model.

We determine the dark matter halo formation rate and merging history using either extended Press–Schechter modeling based on the Sheth & Tormen (1999) mass function (see Trenti & Stiavelli 2009) or high-resolution cosmological simulations (see Trenti et al. 2009). We populate metal-free halos with stars by taking into account the cooling timescales for atomic and molecular hydrogen, also including radiative feedback due to LW radiation (Trenti & Stiavelli 2009; also see Stiavelli 2009). The minimum halo mass required for metal-free star formation from our model is shown as a solid black line in the left panel of Figure 1. Metal-free star formation transitions from mini-halos with virial temperature \(T_{\text{vir}} \sim 10^3\) K, where molecular hydrogen cooling is efficient at \(z \gtrsim 30\), to more massive halos \((T_{\text{vir}} \gtrsim 10^4\) K) at \(z \lesssim 15\), where Ly-\(\alpha\) cooling is possibly independent of the radiation background. The minimum mass we require for
star formation is consistent with the results from detailed hydrodynamic simulations of metal-free star formation in the presence of a radiative LW background (O’Shea & Norman 2008), as discussed in detail in Trenti et al. (2009). If a halo is able to cool and if $T_{\text{vir}} \sim 10^5$ K (Abel et al. 2002; Yoshida et al. 2003; O’Shea & Norman 2007), we assume it forms a single, massive Population III star drawn from a Salpeter initial mass function (IMF) in the mass range $50–300 \, M_\odot$. When appropriate, the star explodes as a Pair Instability Supernova (PISN) (Heger & Woosley 2002; Scannapieco et al. 2003). A constant fraction of metal-free gas ($f_s \approx 5 \times 10^{-3}$) is converted into stars when Ly$\alpha$ cooling is possible in halos with $T_{\text{vir}} \gtrsim 10^4$ K at lower redshift. In this case, we assume a lower characteristic mass ($O(30) \, M_\odot$) for Population III stars (see Yoshida et al. 2006).

The transition from metal-free to metal-enriched star formation happens at a critical metallicity $Z_{\text{crit}} \sim 10^{-3.5} \, Z_\odot$ (Bromm & Larson 2004; Smith et al. 2009) and might be as low as $Z_{\text{crit}} \sim 10^{-6} \, Z_\odot$ in the presence of dust (Schneider et al. 2006). A single PISN provides enough metals to trigger the transition to metal-enriched star formation in halos with $T_{\text{vir}} \sim 10^4$ K (that is with mass $M \lesssim 3 \times 10^7$ at $z \gtrsim 10$—see the left panel of Figure 1). In fact, several studies show that these halos may even reach a metallicity well above $Z_{\text{crit}}$ as a result of PISN enrichment (Wise & Abel 2008; Karlsson et al. 2008; Greif et al. 2010).

For metal-enriched halos, we assume that a fraction $f_s \approx 5 \times 10^{-3}$ of gas is converted into stars with a Salpeter IMF in the mass range $1–100 \, M_\odot$. In the analytical model, metal enrichment is based on a statistical approach making use of the probability that progenitors of a halo will have formed a star before the halo collapses, as described in Trenti & Stiavelli (2007). In the numerical simulations, we regularly save full snapshots of the system and use them to construct a detailed halo tree to determine whether a halo is self-enriched. Through simply counting photons, we track the establishment of an average radiative background, i.e., our models do not include detailed radiative transfer.

The numerical simulations have been run using the Particle Mesh Tree Code Gadget-2 (Springel 2005). We adopt the fifth year Wilkinson Microwave Anisotropy Probe concordance cosmology with $\Omega_\Lambda = 0.72$, $\Omega_m = 0.28$, $\Omega_b = 0.0462$, $\sigma_8 = 0.817$, $n_s = 0.96$, and $h = 0.7$. We start our main simulation at redshift $z = 199$ using a box with edge $7 \, h^{-1}$ Mpc, $N = 1024^3$ dark matter particles, a mass resolution of $3.4 \times 10^4 \, M_\odot$, and a force resolution of $0.16 \, h^{-1}$ kpc. Halos are identified with a friend-of-friend halo finder (Davis et al. 1985) using a linking length equal to 0.2 times the mean particle separation. In addition to in situ enrichment by progenitor mini-halos, in the numerical simulations we also consider enrichment by winds which is not included in the analytical model. We assume an outflow speed of $60 \, h^{-1}$ km s$^{-1}$ from halos that contain metal-enriched galaxies, that is, with $T_{\text{vir}} \gtrsim 10^4$ K (see Trenti et al. 2009 for further details). The resulting wind enrichment is consistent with what is obtained using a non-cosmological Sedov–Taylor model (e.g., Equation (8) in Tumlinson et al. 2004), namely bubble sizes of $\lesssim 150 \, h^{-1}$ kpc at $z \gtrsim 6$. Gas polluted by winds in dark matter halos that have not been self-enriched is also likely to reach a metallicity $Z \sim 10^{-3.5} \, Z_\odot$, sufficient to trigger the transition to extremely metal-poor (EMP) star formation. In fact, the typical distance traveled by winds before they encounter a non-self-enriched halo is of the order of $\sim 50 \, h^{-1}$ kpc, sufficient to reach the critical level of metal pollution for metal outflows originating from a dwarf galaxy (see Section 2.1 and Figure 3 in Trenti et al. 2009).

3. RESULTS

3.1. Galaxy Formation Rate

In Figure 2, we show, as a function of redshift, the rate of protogalaxies forming per year and made of chemically enriched stars (marked as PopII, dashed red line) compared to that of protogalaxies made of Population III stars (solid blue line). The figure is derived from the analytical model for galaxies with virial temperature between $10^4$ and $2 \times 10^4$ K—roughly corresponding to $\lesssim 10^9 \, M_\odot$ (see the left panel of Figure 1)—and confirms our expectation that chemically enriched galaxies form at earlier redshifts than galaxies made of Population III stars. The analytical model does not include the effect of enrichment.
Figure 2. Formation rate of protogalaxies per comoving volume in halos with $10^4 \, \text{K} \leq \Tvir < 2 \times 10^4 \, \text{K}$ that are either chemically pristine (solid blue line) or with a low metallicity of the order of the critical one (red dashed line). The rate (rest frame and comoving) has been obtained from an analytical extended Press–Schechter model (see Trenti & Stiavelli 2009) considering self-enrichment only, thus galactic metal outflows are neglected. If these were to be considered, they would reduce the formation rate of Population III protogalaxies (see Trenti et al. 2009). The first galaxies to be formed at very high redshift are very likely to be made of Population II (metal-enriched) stars.

3.2. Clustering Properties

In Figure 1, we show an analytical estimate of the bias as a function of redshift for halos that can contain Population III stars. Clearly, the bias decreases rapidly with redshift as the Population III halos become more common. However, Figure 1 does not distinguish between halos that are polluted by winds and those that are truly metal-free (self-enrichment does not influence the bias). To address the expected clustering properties of the first galaxies, we need to resort to the numerical simulation results, which of course carry spatial information on the presence of neighboring galaxies capable of polluting pockets of metal-free stars. This effect is important only for redshift $z \lesssim 15$ because at higher redshift the metal outflows do not have enough time to propagate far from their host galaxies (see Trenti et al. 2009).

The cosmological simulation allows us to measure the bias for both the chemically enriched “first” galaxies population and the Population III galaxies. To quantify their clustering, we use the positions of galaxy-hosting dark matter halos to construct the three-dimensional two-point correlation function $\theta(r)$ in comoving space, defined as the excess number of pair counts at separation $r$ over those from a uniform random distribution. We generate a random uniform distribution of 40,000 points within the simulation box and adopt the Landy & Szalay (1993) estimator:

$$1 + \theta(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)},$$

where $DD(r)$ are the halo–halo pair counts with distance bound in an annulus centered on $r$. Similarly $DR(r)$ are the halo–random pair counts, and $RR(r)$ are the random–random counts within the same annulus.

In Figure 3, we show for redshift $z = 9.5$ the correlation function as a function of radius for chemically enriched protogalaxies, that is for all dark matter halos with $10^4 \, \text{K} \leq \Tvir \leq 2 \times 10^4 \, \text{K}$ by winds which will lead to $\sim 30\%$ lower numbers of pristine objects at $z \sim 10$ (see Figure 4 in Trenti et al. 2009).

In our model, chemically enriched galaxies peak at a redshift $z \simeq 15$, while galaxies made of Population III stars peak at a redshift $z \simeq 11$. This trend is in agreement with that shown in Figure 1 of Trenti & Stiavelli (2009) once one considers that Population II formation in that figure was for all halos regardless of their mass while here it is limited to halos of the prescribed virial temperature. The presence of a peak at $z \sim 15$ in the enriched galaxies is due to this mass constraint.
10^4 K that had past star formation bursts (θ_{popII} marked as “Pop II Gal”; solid red) and for galaxies containing Population III stars, that is dark matter halos with \( T_{\text{vir}} \geq 10^4 \) K that are chemically pristine with respect to both wind and self-enrichment (θ_{popIII}; blue line).\(^3\) We also show the correlation function for EMP protogalaxies, at or above the critical metallicity \( Z \sim 10^{-5} \) Z\(_\odot\), enriched by winds but otherwise not self-enriched, again hosted in halos with \( T_{\text{vir}} \leq 2 \times 10^4 \) K (green line). In the same figure, we also show the ratio of \( \theta(r)_{\text{popIII}}/\theta(r)_{\text{popII}} \) to quantify the relative bias of these two galaxy populations (Porciani et al. 1999; Sheth & Tormen 1999). Clearly for radii in excess of a few tens of kpc, the chemically enriched galaxies exhibit stronger clustering than the galaxies containing Population III stars. The low bias for Population III galaxies compared to their metal-enriched counterparts extends up to \( z \sim 15 \) (see Figure 4).

4. DISCUSSION AND CONCLUSIONS

Figure 3 predicts that galaxies containing Population III stars will be essentially uncorrelated on scales larger than <150 comoving kpc. At redshift \( z = 9.5 \), 1 arcsec corresponds to roughly 50 comoving kpc in the transverse direction. This implies that the typical arcmin scales of the imaging instruments on the JWST correspond to a few comoving Mpc and on those scales we should not detect any significant clustering for galaxies with primordial chemical composition. In contrast, enriched protogalaxies could be very clustered on small scales, as they live in high density regions. Thus, in an ultra-deep field with JWST, we expect to detect individual unevolved galaxies at \( z \simeq 10 \), but small clusters of chemically evolved objects. From Figure 2, we see that the rest-frame rate of galaxy formation per comoving volume at \( z \simeq 10 \) is \( \sim 2 \times 10^{-8} \) Mpc\(^{-3}\) yr\(^{-1}\) (estimating the halo formation rate from the simulations gives a similar number). Assuming that the burst of Population III stars is short lived, we expect that the galaxy will be visible as Population III galaxy only for a time of the order of the stellar lifetime (assumed to be \( 2 \times 10^6 \) yr). Considering that the comoving volume per unit redshift at \( z \sim 10 \) is \( \sim 2000 \) comoving Mpc\(^3\) over an area of 1 arcmin\(^2\), we predict a surface density of \( \sim \)80 galaxies arcmin\(^{-2}\) and per unit redshift. However, there are large uncertainties as to the luminosity such a galaxy would have. In a deep exposure, the JWST should be able to detect a young cluster with a stellar mass of \( 10^6 \) M\(_\odot\).\(^4\) Most of the pristine galaxies will have lower stellar masses. At a virial temperature \( T = 10^4 \) K at \( z \sim 10 \), a galaxy has a halo mass of \( \sim 3.7 \times 10^7 \) M\(_\odot\) and only \( \sim 6 \times 10^5 \) M\(_\odot\) in baryons. At this stage, it is unclear whether the Population III stellar burst in a protogalaxy would produce many stars and with what efficiency \( \epsilon \), but \( \epsilon \gtrsim 0.15 \) is unlikely in the first burst. Even if the majority of these objects would be too faint, their large number density and the expected lack of strong correlations are encouraging as they make it more likely that we could detect some of these objects through a lensing cluster. A Population III galaxy of \( 10^6 \) M\(_\odot\) of stars formed over a stellar lifetime forms stars at about \( 0.3 \) M\(_\odot\) yr\(^{-1}\) and would have an Ly\(\alpha\) luminosity of \( \sim 3 \times 10^{42} \) erg s\(^{-1}\) (Schaerer 2003) and an Ly\(\alpha\) line flux at \( z = 10 \) of \( \sim 1.9 \times 10^{-18} \) erg s\(^{-1}\) cm\(^{-2}\). These fluxes are close to what can be detected today in a lensing cluster after modest amplification and is in fact in agreement with some reports of detections (Stark et al. 2007). The (chronologically) first galaxies at the same redshift and the extremely poor galaxies are instead expected to be highly correlated at least on scales of a few arcsec. Thus, to first order our models predict that one should observe small clusters of chemically evolved galaxies but only isolated primordial galaxies.

We thank the anonymous referee for comments that have helped improve this Letter. M.S. acknowledges partial support from NASA JWST IDS grant NAG5-12458. M.T. acknowledges partial support from the University of Colorado Astrophysical Theory Program through grants from NASA (NNX07AG77G) and NSF (AST07-07474).
REFERENCES

Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Bromm, V., & Larson, R. B. 2004, ARA&A, 42, 79
Davis, M., Efstathiou, G., Frenk, C. S., & White, S. D. M. 1985, ApJ, 292, 371
Greif, T. H., Glover, S. C. O., Bromm, V., & Klessen, R. S. 2010, ApJ, 716, 510
Greif, T. H., Johnson, J. L., Klessen, R. S., & Bromm, V. 2008, MNRAS, 387, 1021
Haiman, Z., Rees, M. J., & Loeb, A. 1997, ApJ, 476, 458
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Jimenez, R., & Haiman, Z. 2006, Nature, 440, 501
Johnson, J. L., Greif, T. H., & Bromm, V. 2008, MNRAS, 388, 26
Karlsson, T., Johnson, J. L., & Bromm, V. 2008, ApJ, 679, 6
Labbé, I., et al. 2010, ApJ, 708, 26
Landy, S. D., & Szalay, A. S. 1993, ApJ, 412, 64
Lepp, S., & Shull, J. M. 1983, ApJ, 270, 578
Machacek, M. E., Bryan, G. L., & Abel, T. 2003, MNRAS, 338, 273
O’Shea, B. W., & Norman, M. L. 2008, ApJ, 673, 14
Porciani, C., Catelan, P., & Lacey, C. 1999, ApJ, 513, L99
Ricotti, M., Gnedin, N. Y., & Shull, J. M. 2008, ApJ, 685, 21
Scannapieco, E., Schneider, R., & Ferrara, A. 2003, ApJ, 589, 35
Schaefer, D. 2003, A&A, 397, 527
Schneider, R., Omukai, K., Inoue, A. K., & Ferrara, A. 2006, MNRAS, 369, 1437
Sheth, R. K., & Tormen, G. 1999, MNRAS, 308, 119
Smith, B. D., Turk, M. J., Sigurdsson, S., O’Shea, B. W., & Norman, M. L. 2009, ApJ, 691, 441
Springel, V. 2005, MNRAS, 364, 1105
Stark, D. P., Ellis, R. S., Richard, J., Kneib, J.-P., Smith, G. P., & Santos, M. R. 2007, ApJ, 663, 10
Stiavelli, M. 2009, From First Light to Reionization: The End of the Dark Ages (New York: Wiley-VCH)
Tegmark, M., Silk, J., Rees, M. J., Blanchard, A., Abel, T., & Palla, F. 1997, ApJ, 474, 1
Trenti, M., Santos, M. R., & Stiavelli, M. 2008, ApJ, 687, 1
Trenti, M., & Shull, J. M. 2010, ApJ, 712, 435
Trenti, M., & Stiavelli, M. 2007, ApJ, 667, 38
Trenti, M., & Stiavelli, M. 2009, ApJ, 694, 879
Trenti, M., Stiavelli, M., & Shull, M. J. 2009, ApJ, 700, 1672
Trenti, M., et al. 2010, ApJ, 714, 202
Tumlinson, J., Venkatesan, A., & Shull, J. M. 2004, ApJ, 612, 602
Wise, J. H., & Abel, T. 2008, ApJ, 685, 40
Yoshida, N., Abel, T., Hernquist, L., & Sugiyama, N. 2003, ApJ, 592, 645
Yoshida, N., Omukai, K., Hernquist, L., & Abel, T. 2006, ApJ, 652, 6