Ancient giants: on the farthest galaxy at \( z = 8.6 \)

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ABSTRACT

The observational frontiers for the detection of high-redshift galaxies have recently been pushed to unimaginable distances with the record-holding Lyman Alpha Emitter (LAE) UDFy-38135539 discovered at redshift \( z = 8.6 \). However, the physical nature and the implications of this discovery have yet to be assessed. By selecting galaxies with observed luminosities similar to UDFy-38135539 in state-of-the-art cosmological simulations tuned to reproduce the large scale properties of LAEs, we bracket the physical nature of UDFy-38135539: it has a star formation rate \( \sim 2.7 - 3.7 M_{\odot} \text{yr}^{-1} \), it contains \( 10^{8.3-8.7} M_{\odot} \) of stars 50-80 Myr old, with stellar metallicity \( \sim 0.03 - 0.12 Z_{\odot} \). For any of the simulated galaxies to be visible as a LAE in the observed range, the intergalactic neutral hydrogen fraction at \( z = 8.6 \) must be \( \chi_{HI} \leq 0.2 \) and extra ionizing radiation from sources clustered around UDFy-38135539 is necessary. Finally, we predict that there is a 70% (15%) probability of detecting at least 1 such source from JWST (HST/WFC3) observations in a physical radius \( \sim 0.4 \text{Mpc} \) around UDFy-38135539.

Key words: cosmology: theory, galaxies: individual, galaxies: high redshift; galaxies: intergalactic medium

1 INTRODUCTION

The earliest galaxies which ushered in the era of the cosmic dawn changed the state of the intergalactic medium (IGM) out of which they formed in numerous ways: they polluted it with heavy elements, heated and (re)ionized it, thereby affecting the evolution of all subsequent generations of galaxies. We are now in the golden era for the search for such galaxies, made possible by the use of ingenious selection techniques. The first of these, the standard dropout technique (e.g. Steidel et al. 1996; Giavalisco et al. 2004) relies on broad band filters to detect the Lyman break at 912 Å in the galaxy rest frame. Although galaxy candidates have been detected up to \( z \sim 10 \) (Bouwens et al. 2009) using this method, it has the drawback that the exact source redshift cannot be determined with complete confidence. In this respect, searches for the Lyman Alpha (Ly\( \alpha \)) line at 1216 Å (in the galaxy rest frame) using narrow band filters have been far more successful in confirming the detection of high-redshift galaxies; specific spectral signatures including the strength, width and continuum bluewards of the Ly\( \alpha \) line make the detection of LAEs (galaxies showing a strong Ly\( \alpha \) line) rather unambiguous. Narrow band searches have enabled the confirmation of hundreds of LAEs in a wide high-redshift range, at \( z \approx 5.7 \) (Malhotra et al. 2005; Shimasaku et al. 2006), \( z \approx 6.6 \) (e.g. Kashikawa et al. 2006) and \( z \approx 7 \) (e.g. Vanzella et al. 2010). Using the same technique, recently, a LAE, designated UDFy-38135539, has been confirmed at \( z = 8.6 \) (Lehnert et al. 2010), making it the farthest astrophysical object known so far; it has overtaken the redshift record of \( z = 8.2 \) set by the Gamma Ray Burst GRB090423 (Salvaterra et al. 2009; Tanvir et al. 2009).

This object has already been observed by a number of groups: Lehnert et al. (2010) have observed both the Ly\( \alpha \) and ultraviolet (UV) luminosity for UDFy-38135539, and Finkelstein et al. (2010) have obtained broad band UV and Spitzer data points for this galaxy, designated ID 125 in their work. However, the physical nature of the galaxy and the cosmological implications of its discovery have yet to be assessed. In this work, we use state-of-the-art cosmological simulations coupled to a previously developed LAE model (Dayal, Ferrara & Gallerani 2008; Dayal et al. 2009; Dayal, Ferrara & Saro 2010), tuned to reproduce a number of observables of LAEs, to bracket the physical properties of UDFy-38135539. We use the observed Ly\( \alpha \) luminosity to get a hint on the ionization state of the IGM at \( z \approx 8.6 \), calculate how much this galaxy could have contributed to reionization and make predictions for the number of Lyman Break Galaxies (LBGs) that could be detected in its vicinity.
2 THEORETICAL MODEL

We start from the analysis of a z = 8.6 snapshot of a set of cosmological simulations carried out using the TreePM-SPH code GADGET-2 (Springel 2005) with the implementation of chemodynamics as described in Tornatore et al. (2007). The periodic simulation box has a comoving size of 75 h^{-1} Mpc and initially contains 512^3 particles each of dark matter (DM) and gas. The masses of the DM and gas particles are $n_{\text{DM}} \simeq 1.7 \times 10^8 \, h^{-1} M_{\odot}$ and $m_{\text{gas}} \simeq 4.1 \times 10^7 \, h^{-1} M_{\odot}$, respectively. For each “bona-fide” galaxy (which has at least 20 bound particles; see Saro et al. 2006 for details) in the simulated volume at $z = 8.6$, we compute the DM halo/stellar/gas mass, star formation rate (SFR), mass-weighted age, gas/stellar metallicity, and gas temperature.

The adopted cosmological model for this work corresponds to the ΛCDM Universe with $\Omega_m = 0.26$, $\Omega_\Lambda = 0.74$, $\Omega_b = 0.0413$, $n_s = 0.95$, $H_0 = (100 h) = 73$ km s^{-1} Mpc^{-1} and $\sigma_8 = 0.8$, thus consistent with the 5-year analysis of the WMAP data (Komatsu et al. 2009). Complete details of these simulation runs can be found in Dayal et al. (2009).

2.1 Intrinsic luminosities and dust

Star forming galaxies produce their intrinsic Lyα line and UV continuum luminosities ($L_{\text{Ly}α}^{\text{int}}$ and $L_{\text{UV}}^{\text{int}}$) at restframe wavelengths $\lambda_{\alpha} = 1216$ Å and $\lambda_c = 1700$ Å, respectively) both via stellar (and nebular) emission, and cooling radiation from collisionally excited neutral hydrogen (H I) in their interstellar medium (ISM). While the spectral energy distributions (SEDs) are obtained using the population synthesis code STARBURST99 (Leitherer et al. 1999) to calculate the stellar and nebular emission, the latter depends on the temperature distribution in the ISM gas. The interested reader is referred to previous work (Dayal, Ferrara & Saro 2010) for a comprehensive discussion.

As Lyα and continuum photons are efficiently absorbed by dust grains, we calculate the dust content of each galaxy by considering SNII to be the main dust producers; this is justified by the fact that the typical evolutionary timescale of evolved stars ($\geq 1$ Gyr) becomes longer than the age of the Universe above $z \gtrsim 5.7$ (Todini & Ferrara 2001). We further pose that: (i) 0.5 $M_{\odot}$ of dust is produced per SNII (Todini & Ferrara 2001; Nozawa et al. 2007), (ii) SNII destroy dust in forward shocks with an efficiency of about 40% (McKee 1998; Seab & Shull 1983), and (iii) a homogeneous mixture of gas and dust is assimilated into further star formation. To calculate the dust optical depth, $\tau$, to UV continuum photons, based on the results obtained at $z \sim 6.6$, we assume that dust is made up of carbonaceous grains and spatially distributed as the stars (Dayal, Ferrara & Saro 2010). The fraction of continuum photons escaping the galaxy undamped by dust is then $f_{\alpha} = (1-e^{-\tau})^{-1}$. The analogous quantity for Lyα photons is taken to be $f_{\alpha} = 1$ so as to obtain the maximum possible Lyα luminosity emerging from the galaxy itself.

2.2 IGM transmission and source clustering

After escaping out of the galactic environment, Lyα photons are further attenuated as they travel through the IGM. Depending on the intergalactic hydrogen ionization state, only a fraction $0 < T_\alpha < 1$ of the Lyα photons emerging out of a galaxy undamped by dust reaches the observer (continuum photons are instead unaffected by the IGM); $T_\alpha$ hence depends upon the IGM ionization state. Since this value is largely unconstrained, we explore 6 different values of the average IGM $H_I$ fraction at $z = 8.6$: $\chi_{HI} = 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$. For each value of $\chi_{HI}$, we compute the nominal radius, $R_I$, of the spherical, ionized HI region around each simulated galaxy. In reality, though, due to source clustering (i.e. when the separation between any two galaxies becomes smaller than either of their ionized region radii), multiple galaxies can contribute ionizing photons to the same ionized region, which will then be characterized by an effective radius, $R_I^{\text{eff}} > R_I$, calculated as follows. Suppose galaxies ‘A’ and ‘B’, and ‘B’ and ‘C’ have overlapping ionized regions. Then, the effective ionized volume ‘A’ is embedded in is the sum of the ionized volumes of ‘A’, ‘B’ and ‘C’; the same holds true for both ‘B’ and ‘C’.

Within this ionized volume, the total photoionization rate at distance $r$ from ‘A’, is

$$\Gamma_{\alpha}(r) \sim \int_{\nu_\alpha}^{\infty} \frac{L_{\alpha}^{\text{int}}}{4\pi} \sigma_{\alpha}(\nu) \left(\frac{\nu L}{\nu_\alpha}\right)^3 d\nu$$

$$+ \sum_{i=1, r \neq A}^{N} \int_{\nu_\alpha}^{\infty} \frac{L_{\alpha}^{\text{int}}}{4\pi} \sigma_{\alpha}(\nu) \left(\frac{\nu L}{\nu_\alpha}\right)^3 d\nu + \Gamma_B,$$

where the terms on the right hand side represent the photoionization rate from (i) the direct radiation from ‘A’, (ii) the galaxies clustered around ‘A’ and (iii) the ultraviolet background (UVB) from distant galaxies, respectively. The UVB photoionization rate is related to $\chi_{HI}$ by $\Gamma_B = (1 - \chi_{HI})^2 \chi_{HI} l_n H_{0} \sigma_B$, where $n_B$ is the mean IGM hydrogen number density and $\sigma_B$ is the case-B hydrogen recombination coefficient. Further, $L_{\text{Ly}α}^{\text{int}} = L_{\text{Ly}α}^{\text{int}} f_{\text{esc}}$, is the specific ionizing luminosity emerging from ‘A’ and $f_{\text{esc}} = 0.92$ is the escape fraction of H i ionizing photons (Gnedin et al. 2008), $L_{\alpha}^{\text{int}}$ is the ionizing luminosity emerging from the 10th galaxy of the total ‘N’ galaxies with which ‘A’ shares an ionized region, $\nu_{\alpha}$ is the frequency corresponding to the Lyman limit wavelength (912 Å), $\sigma_{\alpha}$ is the hydrogen photoionization cross-section and $r_{\alpha}$ is the distance between galaxies i and ‘A’. This procedure is carried out for each galaxy in the simulated volume. We then assume photoionization equilibrium to compute $\chi_{HI}$ within the effective ionized region of each galaxy. At the edge of this region, we force $\chi_{HI}$ to attain the assigned global value. We use the complete Voigt profile to calculate the optical depth of Lyα photons along the line of sight to compute $T_\alpha$. The observed Lyα and UV continuum luminosity are then simply $L_{\alpha} = L_{\alpha}^{\text{int}} f_{\alpha} T_{\alpha} = L_{\alpha}^{\text{int}} T_{\alpha}$ (the latter equality descends from our maximal assumption $f_{\alpha} = 1$), and $L_{\text{UV}} = L_{\text{UV}}^{\text{int}} f_{\text{esc}}$, respectively.

As a final step, we select galaxies that would be observable as LAEs according to the canonical criterion, $L_{\alpha} \geq 10^{42.2}$ erg s^{-1} and observed equivalent width $EW \geq 20$ Å. Among these, we further isolate those that fall within the $L_{\alpha}$ and continuum magnitude $M_{\text{UV}}$ range observed by Lehnert et al. (2010) and Finkelstein et al. (2010): using SINFONI, the former find $L_{\alpha} = (2.7 - 8.3) \times 10^{42}$ erg s^{-1}, $M_{\text{UV}} = -19.6$ to $-18.6$, while Finkelstein et al. (2010) find a tighter bound of $M_{\text{UV}} = -19.2$ to $-19.0$. To summarize, all simulated galaxies that have $L_{\alpha} = (2.7 - 8.3) \times 10^{42}$ erg s^{-1}
We find that, without requiring any tuning of the model parameters, no \( \text{LAE}_{UDF} \) are found in the simulated volume for \( \chi_{HI} > 0.2 \). For \( \chi_{HI} = 0.2 \), we find a total of 215 LAEs in the simulated volume, 7 of which are identified as \( \text{LAE}_{UDF} \) as shown in Fig. 1. From now on, \( \text{LAE}_{UDF} \) refer to the LAEs in the combined observed Ly\( \alpha \) and UV luminosity range of Lehner et al. (2010) and Finkelstein et al. (2010) for \( \chi_{HI} = 0.2 \).

We digress here to discuss the two main ingredients whose combined effects can change the slope of the \( L_{\alpha} - M_{UV} \) relation shown in Fig. 1. The first of these concerns the dust attenuation: for any given LAE, an increase (decrease) in \( f_{\alpha} \) leads to the galaxy becoming brighter (fainter) in the UV, shifting the position of the galaxy vertically upward (downward) on the plot; a decrease in the value of \( f_{\alpha} \) (recall that we have used \( f_{\alpha} = 1 \) in our model) due to dust attenuation of Ly\( \alpha \) photons leads to a corresponding decrease in \( L_{\alpha} \), moving the points horizontally leftward on the plot. The second effect is the change in \( T_{\alpha} \) due to peculiar velocities: inflows (outflows) of neutral gas into (from) the galaxy impart an extra blueshift (redshift) to the Ly\( \alpha \) photons, leading to a decrease (increase) in \( f_{\alpha} \) (Santos 2004; Verhamme et al. 2006; Dijkstra & Wyithe 2010; Dayal, Maselli & Ferrara 2011) moving the relation horizontally towards the left (right).

Further constraints on the \( \text{LAE}_{UDF} \) come from the SEDs which we have obtained from STARBURST99 including dust attenuation (\( f_{\alpha} \) ranges between 0.24-0.3 for the \( \text{LAE}_{UDF} \)) using the supernova extinction curve (Bianchi & Schneider 2007). As shown in Fig. 2, the model SEDs are in excellent agreement with the observed data points, including the two from Spitzer at 3.6 and 4.5\( \mu \)m obtained by Finkelstein et al. (2010). The SED is a crucial constraint on the physical properties of galaxies that could be identified as \( \text{LAE}_{UDF} \): although for values of \( \chi_{HI} < 0.2 \) (for the given dust model) a larger number of galaxies would fulfill the \( \text{LAE}_{UDF} \) selection criterion, their physical properties cannot vary too much without the SEDs becoming inconsistent with the observed one.

As the 7 \( \text{LAE}_{UDF} \) galaxies closely resemble the observed properties of UDFy-38135539, it is reasonable to conclude that their physical properties should also match those of that object, which are now discussed. \( \text{LAE}_{UDF} \) show SFRs in the range 2.7 - 3.7 \( M_{\odot} \) yr\(^{-1} \), as seen from Panel (a) of Fig. 3. These values are quite comparable to the ones inferred by Lehner et al. (2010) from the Ly\( \alpha \) luminosity of UDFy-38135539 (0.3 - 2.1 \( M_{\odot} \) yr\(^{-1} \)). \( \text{LAE}_{UDF} \) have stellar masses \( \sim 10^{9.3-8.7} M_{\odot} \) (Fig. 3, Panel (b)); this is highly consistent with the stellar mass of \( 10^{9.8} M_{\odot} \) found by Finkelstein et al. (2010) from best-fitting the observed SED. In terms of the halo mass, \( \text{LAE}_{UDF} \) correspond to rare, massive \( 3\sigma \) mass fluctuations at \( z = 8.6 \) and have halo masses \( \sim 10^{10.5} M_{\odot} \). The \( \text{LAE}_{UDF} \) have dust masses between \( 10^{7.7-6} M_{\odot} \) as seen from Panel (c) of Fig. 3. These lead to values of \( f_{\ell} = 0.24-0.3 \) for these galaxies, which translate

3 RESULTS

We now discuss the main results obtained from the above mentioned computations. We find that, without requiring any tuning of the model parameters, no \( \text{LAE}_{UDF} \) are found in the simulated volume for \( \chi_{HI} > 0.2 \). For \( \chi_{HI} = 0.2 \), we find a total of 215 LAEs in the simulated volume, 7 of which are identified as \( \text{LAE}_{UDF} \) as shown in Fig. 1. From now on, \( \text{LAE}_{UDF} \) refer to the LAEs in the combined observed Ly\( \alpha \) and UV luminosity range of Lehner et al. (2010) and Finkelstein et al. (2010) for \( \chi_{HI} = 0.2 \).

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Figure 3. Summary of the physical properties of LAEs at \( z = 8.6 \). In each Panel, points represent galaxies identified as LAEs in our simulation; the 7 LAE\( UD\) for \( \chi_{HI} = 0.2 \) (see text for details) are shown by colored symbols. For each LAE, as a function of the observed \( Ly\alpha \) luminosity, the Panels represent: (a) the SFR; (b) the stellar mass; (c) the dust mass; (e) the mass-weighted stellar age; (f) the mass-weighted stellar metallicity, and (g) the effective ionized region radius around each LAE.

As for the contribution of LAE\( UD\) to reionization, the photon rate density required to balance recombinations, \( q_{rec} \), can be expressed as (Madau, Haardt & Rees 1999)

\[
q_{rec} = 10^{51.09} C \left( \frac{1+z}{9.6} \right)^3 \left( \frac{\Omega_b h^2}{0.022} \right)^2 \text{s}^{-1} \text{Mpc}^{-3},
\]

where \( C \) is the IGM clumping factor. For the 2% HI ionizing photon escape fraction used in this work and assuming \( C = 5 \), the LAE\( UD\) have an HI ionizing photon output \( \sim 10^{47.2} \text{s}^{-1} \text{Mpc}^{-3} \); at most, such objects could have contributed \( \sim 0.01\% \) of the photons needed to balance recombinations at \( z = 8.6 \).

Finally, we estimate the probability of finding a LAE like UDFy-38135539 in the experimentally sampled volume \( (1 \times 10^4 \text{cm}^3) \). Our simulated volume \( (1.08 \times 10^6 \text{cm}^3) \) is about 100 times larger; therefore we sample the simulated
volume by randomly placing the observed volume within it. We find that only 7 of these sub-volumes contain 1 LAE similar to UDFy-38135539 for $\chi_{HI} = 0.2$. This translates into a detection probability of only about 7%, classifying the discovery as a relatively serendipitous one.

4 CONCLUSIONS AND DISCUSSION

We have constrained the IGM ionization state at $z = 8.6$. We find that without requiring any fine-tuning of the model parameters from $z = 6.6$ and for the maximum possible Ly$\alpha$ luminosity emerging from the galaxy itself, no LAE are found in the observed luminosity range of UDFy-38135539 for $\chi_{HI} > 0.2$. For $\chi_{HI} = 0.2$, we find 7 LAEs (designated LAE$_{UDF}$) whose observed Ly$\alpha$ and UV luminosity fall in the ranges of UDFy-38135539 (Lehnert et al. 2010) and ID 125 (Finkelstein et al. 2010). LAE$_{UDF}$ are observable in the Ly$\alpha$ only because an overlapping of their H II regions with those of their nearby galaxies make the effective H II radius $\sim 0.24 - 0.42 \text{ Mpc}$; averaged over the 7 LAE$_{UDF}$, there is a 70% (15%) probability of such a clustered source being found by JWST (HST/WFC3) observations.

We have also bracketed the physical properties of UDFy-38135539: the SFR range between $2.7 - 3.7 \text{ M}_\odot \text{ yr}^{-1}$, it has $10^{8.3-8.7} \text{ M}_\odot$ of stars with a mass weighted age of 50-80 Myr and a mass weighted stellar metallicity between $0.03 - 0.12 Z_\odot$. It is dust enriched with dust masses $\sim 10^{5.7-6} \text{ M}_\odot$ which translates into $A_V \sim 0.75 \text{ mag}$ and a color excess of $E(B-V) \sim 0.16 - 0.19$ using the supernova dust extinction curve.

We add three caveats. The first concerns uncertainties related to dust attenuation of Ly$\alpha$ photons. As has been shown by many works (Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2008; Dayal et al. 2009; Dayal, Ferrara & Saro 2010; Dayal, Maselli & Ferrara 2011), the relative escape fraction of Ly$\alpha$ and continuum photons depends on the distribution (smooth/clumpy) of dust in the ISM of high-$z$ galaxies. Lacking data at the cape fraction of Ly$\alpha$, a $\sim 50-80 \text{ Myr}$ and a mass weighted stellar metallicity between $3.7 - 4.0 Z_\odot$, it has a $70\%$ (15$\%$) probability of such a clustered source being found by JWST (HST/WFC3) observations.

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