Local Group progenitors: Lyman Alpha bright?

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ABSTRACT

We present a novel approach of identifying the Milky Way (MW) and Andromeda (M31) progenitors that could be visible as Lyman Alpha emitters (LAEs) at \( z \approx 6 \): we couple a snapshot from the Constrained Local UniversE Simulations (CLUES) project, which successfully reproduces the MW and M31 galaxies situated in their correct environment, to a LAE model. Exploring intergalactic medium (IGM) ionization states ranging from an almost neutral to a fully ionized one, we find that including (excluding) the effects of clustered sources the first Local Group progenitor appears as a LAE for a neutral hydrogen fraction \( \chi_{H_1} = 0.4 \) \( (\chi_{H_1} = 0.1) \). This number increases to five progenitors each of the MW and M31 being visible as LAEs for \( \chi_{H_1} = 10^{-5} \); the contribution from clustered sources is crucial in making many of the progenitors visible in the Ly\( \alpha \) for all the ionization states considered. The stellar mass of the Local Group LAEs ranges between \( 10^{7.2} \) and \( 10^{8} \) \( M_\odot \), the dust mass is between \( 10^{4.6} \) and \( 10^{5.1} M_\odot \) and the colour excess \( E(B-V) = 0.03–0.048 \). We find that the number density of these LAEs is higher than that of general field LAEs (observed in cosmological volumes) by about two (one) orders of magnitude for \( \chi_{H_1} = 10^{-5} \) (0.4). Detections of such high LAE number densities at \( z \approx 6 \) would be a clear signature of an overdense region that could evolve and resemble the Local Group volume at \( z = 0 \).

Key words: galaxy: evolution – galaxies: high redshift – intergalactic medium – cosmology: theory.

1 INTRODUCTION

The search for high-redshift Lyman Alpha emitters has advanced tremendously since the days of their first successful detections (e.g. Lowenthal et al. 1991). Advances in instrument sensitivity, refined selection techniques and specific LAE spectral signatures have led to the confirmed detections of hundreds of LAEs in a wide redshift range, between \( z \sim 2.2 \) and 6.6 (e.g. Cowie & Hu 1998; Steidel et al. 2000; Malhotra et al. 2005; Kashikawa et al. 2006; Shimakawa et al. 2006; Hu et al. 2010).

Over the past few years, LAEs have been used extensively as probes of re-ionization, high-redshift galaxy evolution and the dust content of early galaxies (Dijkstra, Wyithe & Haiman 2007; Kobayashi, Totani & Nagashima 2007; Dayal et al. 2009; Finkelstein et al. 2009; Dayal, Ferrara & Saro 2010; Dayal, Maselli & Ferrara 2011). However, scant effort has been devoted to establishing a link between such high-redshift observations \( (z \sim 6) \) and those at \( z = 0 \), especially in the context of the Local Group.

The first such attempt was made by Salvadori, Dayal & Ferrara (2010), who coupled the semi-analytic code, \textsc{gamaete} (Salvadori, Schneider & Ferrara 2007; Salvadori & Ferrara 2009), which successfully reproduces most of the observed Milky Way (MW) and dwarf satellite properties at \( z = 0 \), to a LAE model developed in Dayal et al. (2009, 2010). Though a powerful statistical tool, the semi-analytic nature of \textsc{gamaete} meant that the effects of clustered sources on the visibility of LAEs could not be properly considered; to alleviate such a problem to some extent, all the calculations presented therein were carried out assuming the intergalactic medium to be completely ionized.

In this work, we extend the calculations presented in Salvadori et al. (2010). We use a \( z \approx 6 \) snapshot from the CLUES runs, which are state-of-the-art constrained simulations that build up one of the possible merger histories of the Local Group, including the MW and M31 galaxies. This snapshot is coupled to a LAE model presented in Dayal et al. (2010, 2011) that reproduces a number of data sets accumulated for high-\( z \) LAEs. The main advantage of using these simulations lies in the fact that they provide information on both the physical properties and the spatial positions of all the progenitors of the Local Group at any given redshift. This allows us to calculate the effects of clustered sources on the visibility of such progenitors in the Ly\( \alpha \) for IGM ionization states ranging from a completely neutral \( (\chi_{H_1} = 0.99) \) to a fully ionized \( (\chi_{H_1} = 10^{-5}) \) one.

The main questions we aim to answer with such an approach are the following. (a) How re-ionized does the volume containing the Local Group have to be at \( z \approx 6 \) for any of its progenitors to be visible as a LAE? (b) Where do such LAEs lie with respect to the underlying dark matter (DM) distribution? (c) What are the physical properties of the progenitors that are visible as LAEs, and how do
the CLUES simulations

For the calculations presented in this Letter, we use the CLUES simulations (http://www.clues-project.org). We briefly summarize the simulations here, and the interested reader is referred to Libeskind et al. (2010, 2011) and Knabe et al. (2010, 2011) for complete details on the central galaxies, their discs and the properties of their z = 0 substructure population, as well as details regarding the simulation initial conditions, gas dynamics and star formation.

The simulations used in this study were run with the PMTree-SPH MPI code GADGET2 (Springel 2005) in a cosmological box of size 64 h$^{-1}$ comoving Mpc (cMpc). The runs used standard ΛCDM initial conditions and WMAP3 parameters (Spergel et al. 2007) such that Ω_m = 0.24, Ω_b = 0.042, Ω_L = 0.76, h = 0.73, σ_8 = 0.73 and n = 0.95. The initial conditions were constrained using observations of peculiar velocities and the positions of objects in the local volume (Hoffman & Ribak 1991). Since this method only constrains large (i.e. linear) scale structures, a Local Group (defined in terms of the mass, relative distance and number of members) was selected from a number of constrained low-resolution simulations.

The Local Group, of volume 2 h$^{-1}$ cMpc at z = 0, was resimulated at a much higher resolution using the prescriptions given by Klypin et al. (2001) to produce two objects resembling the MW and M31, each of which contains about 10$^6$ particles within their virial radii. Outside of this region, the simulation box was populated with lower resolution (i.e. higher mass) particles to mimic the correct surrounding environment. In the resimulated region, the DM and gas particle masses were taken to be 2.1 $\times$ 10$^5$ and 4.4 $\times$ 10$^4$ h$^{-1}$ M$_\odot$, respectively. The initial mass function used is Salpeter between 0.1 and 100 M$_\odot$. We used the star formation rules of GADGET2 with minor modifications (see Libeskind et al. 2010, for details); each gas particle was allowed to undergo two episodes of star formation, each time spawning a star particle of half the original mass (i.e. 2.2 $\times$ 10$^5$ h$^{-1}$ M$_\odot$). After the simulation was run to z = 0, we identified cosmological structures using the MPI-OpenMP Amiga halo finder (AHF; Knollmann & Knbe 2009) in each snapshot.

In order to find the Local Group LAEs at z $\sim$ 6, we identify all the particles within the virial radius of MW and M31 at z = 0. These particles are then followed back in time and located at z $\sim$ 6 in the simulation box. If bound to a structure, we identify the corresponding halo: each of these haloes was then considered a progenitor of the Local Group at z $\sim$ 6 and used in the LAE calculations, as explained in what follows.

3 Lyα VISIBILITY

We start the calculations by obtaining the mass, metallicity and redshift of formation of each star particle in each of the MW/M31 progenitors, in addition to the global physical properties (total halo/stellar/gas mass) of each progenitor; the age for each star particle is calculated as the time difference between its formation redshift, z_fom and z $\sim$ 6. We find 234 and 240 star-forming progenitor haloes of the MW and M31, respectively. Considering that stars form in a burst after which they evolve passively, we use the population synthesis code STARBURST99 (Leitherer et al. 1999) to obtain the intrinsic spectrum for each star particle depending on its age, mass and metallicity; the latter two values refer to the mass and metallicity of the star particle at the time of its formation. The total intrinsic Lyα/continuum luminosity (1216 and 1375 Å in the galaxy rest frame, respectively) produced by stellar sources for each progenitor is then the sum of the Lyα/continuum luminosity produced by all its star particles. The intrinsic Lyα luminosity can be translated into the observed luminosity such that L_α = L_α^int f_α T_α, while the observed continuum luminosity, L_c, is expressed as L_c = L_α^obs f_c.

Here, f_α (f_c) are the fractions of Lyα (continuum) photons escaping the galactic environment and T_α is the fraction of the Lyα photons that are transmitted through the IGM.

We start by summarizing the calculation of f_α: for each progenitor, the dust enrichment is calculated assuming Type II supernovae (SNII) to be the primary dust factories (Todini & Ferrara 2001). We assume each SNII produces about 0.5 M$_\odot$ of dust (Todini & Ferrara 2001), each SNII destroys dust with an efficiency of about 40 per cent the region it shocks to speeds $\geq$ 100 km s$^{-1}$ (e.g. Seab & Shull 1983), a homogeneous mixture of gas and dust is astirated into star formation and that dust is lost in SNII-powered outflows. We assume a slab-like dust distribution such that the dust distribution scale r_d = 0.5 r_g, where the gas distribution radius is calculated as r_g = 4.5 x 10$^4$; the spin parameter is taken to be λ = ν = 0.05 (Ferrara, Pettini & Shchekinov 2000) and r_g is the virial radius. We then use f_α = 1.5 f_c, as inferred for LAEs at z $\approx$ 6 (see Dayal et al. 2010, for complete details of this calculation).

Lyα photons are further attenuated by the H I present in the IGM and only a fraction 0 < T_α < 1 reach the observer. Since the IGM ionization state is largely unconstrained at z $\sim$ 6, we explore 14 different values ranging from an almost neutral to completely ionized IGM such that $\chi$/H_I = 0.99, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 10$^{-2}$, 10$^{-3}$, 10$^{-4}$ and 10$^{-5}$ for each such initial value of $\chi$/H_I (i.e. the value before the effects of the ionization regions built by each progenitor are considered), we start by computing the radius of the H I region each progenitor ionizes around itself; we use an H I ionizing photon escape fraction of 2 per cent, following the results obtained by Gnedin, Kravtsov & Chen (2008). However, in reality, multiple galaxies generally contribute ionizing photons to the same ionized region due to source clustering, which is then characterized by an effective radius. Then, within the effective ionized region each galaxy is embedded in, the total photoionization rate seen by it includes the direct radiation from the galaxy itself, from the galaxies clustered around it and from the ultraviolet (UV) background. This procedure is carried out for each galaxy in the simulated volume. Assuming photoionization equilibrium within the effective ionized region of each galaxy and forcing $\chi$/H_I to attain the assigned global value at the edge of this region, we use the Voigt profile to calculate the optical depth, and hence T_α for Lyα photons along the line of sight. Complete details of this calculation can be found in Dayal & Ferrara (2011).

Progenitors of the Local Group are then identified as LAEs based on the currently used observational criterion: $L_\alpha \geq 10^{42}$ erg s$^{-1}$ and the observed equivalent width $L_\alpha/L_\alpha > 20$ Å. Progenitors visible as LAEs for any IGM ionization state are then referred to as LAE_LG.

4 RESULTS

We now answer the first question we posed: how re-ionized does the Local Group volume have to be at z $\sim$ 6 for any of its progenitors to be visible as LAEs? We find that including the effects of clustered sources, the first LAE_LG (which is a progenitor of the MW) appears when the average H I fraction is $\chi$/H_I = 0.4; if clustering is not considered, the first LAE_LG appears as late as $\chi$/H_I = 0.1. Progressively lower values of $\chi$/H_I lead to more progenitors becoming visible in the Lyα as expected: one progenitor each of the MW/M31 is visible for complete details of this calculation).
for $\chi_{HI} = 0.3$, one (four) progenitor of the MW (M31) is visible as LAE$_{LG}$ for $\chi_{HI} = 0.1$, while the number rises to five each for the MW and M31 for $\chi_{HI} = 10^{-5}$, as seen from the leftmost to rightmost projections for the MW (M31) in the top (bottom) panels of Fig. 1. These results can be explained as follows: for a given stellar mass [or star formation rate (SFR)] and age, the size of the H II region that any progenitor can ionize around itself increases with decreasing values of $\chi_{HI}$; a lower value of $\chi_{HI}$ in the IGM also results in a larger number of clusters. Both these effects lead to a lower value of $\chi_{HI}$ at each point within the H II region, which itself is now larger. As a result, the Ly$\alpha$ photons face a lower optical depth at each point within this ionized region and are more redshifted when they reach the edge of such a region; these two effects then boost $T_{\alpha}$. As expected, all the LAEs become progressively brighter in the Ly$\alpha$ as the value of $\chi_{HI}$ decreases, as seen from a comparison of the observed Ly$\alpha$ luminosity plotted (left- to right-hand panels), for decreasing $\chi_{HI}$ for both the MW and M31, as shown in Fig. 1. As for the distribution of the LAE$_{LG}$ with respect to the underlying DM density field, we find that for any value of $\chi_{HI}$, LAEs lie in dense DM filaments where the halo masses are large enough so that the gas in them can cool and form stars, as shown in Fig. 1.

As for the physical properties of the LAE$_{LG}$, we start with the total stellar mass, which is possibly the best constrained physical quantity, when far-infrared (FIR) data are available (e.g. from Spitzer at 3.6 and 4.5 $\mu$m). The LAE$_{LG}$ are amongst the most massive progenitors and have stellar mass $M_\star \sim 10^{9.2} - 10^{10}$ M$_\odot$; for progenitors with lower masses, a combination of dust and IGM transmission reduces $L_\alpha$ to below $10^{42}$ erg s$^{-1}$. As expected in a hierarchical structure formation scenario, LAE$_{LG}$ with the largest stellar mass have taken the longest to assemble and have stellar mass weighted ages $t_\star \sim 150-250$ Myr as shown in panel (a) of Fig. 2, implying that many of these progenitors started forming stars at $z \geq 7.6$. However, we stress that it is the young stars that formed over the last $\sim 30$ Myr that dominate the stellar luminosity in the entire wavelength range from the rest-frame UV to the near-IR.

As star formation is the main source of metals, progenitors that are able to build up the largest stellar mass are also the most metal rich, as seen from panel (b) of Fig. 2, where the mass weighted stellar metallicity for the LAE$_{LG}$ ranges between $Z_\star = 0.04$ and $0.1 Z_\odot$. Since the dust mass is calculated using the SFR averaged over the entire star formation history of each progenitor ($=M_\star/\tau_\star$), and since all the LAE$_{LG}$ have ages between $t_\star = 150$ and 250 Myr as mentioned, progenitors with the largest stellar mass are also the most dust rich with dust mass $M_{dust} \sim 10^{46} - 10^{47}$ M$_\odot$, as seen from panel (c) of Fig. 2. To translate the dust mass into the colour excess, we use the SN extinction curve (Bianchi & Schneider 2007).

The colour excess is then related to the escape fraction of continuum photons as $E(B - V) = -2.5 \log 10(f_{\alpha})/11.08$, using which $E(B - V) = 0.03 - 0.048$ for the LAE$_{LG}$; as shown in panel (d) of Fig. 2; the results quoted here do not change using the Calzetti extinction curve where $E(B - V) = -2.5 \log 10(f_{\alpha})/10.9$.

As for the IGM transmission for LAE$_{LG}$, it shows a scatter between $T_{\alpha} \sim 0.35$ and 0.65 due to the varying contributions to the photoionization rates of the LAE$_{LG}$ from clustered sources. This clearly highlights the importance of such sources even for values of $\chi_{HI}$ as low as $10^{-5}$, as seen from panel (e) of Fig. 2; it is not necessarily the largest galaxies that have the largest contribution from clustering, as seen from the same panel. Finally, we show the observed Ly$\alpha$ luminosity for the LAE$_{LG}$ for $\chi_{HI} = 10^{-5}$: the scatter in $T_\alpha$ translates into a scatter in the observed Ly$\alpha$ luminosity, which ranges between $10^{42}$ and $10^{43}$ erg s$^{-1}$ as shown in panel (f) of the same figure. As the value of $\chi_{HI}$ increases, the values of both $T_\alpha$ and $L_\alpha$ decrease. Therefore, the values shown in panels (e) and (f)
represent the upper limits on the quantities shown. We can now compare the properties of the LAE$_{LG}$ to those of the field LAEs in cosmological volumes ($\sim 10^6$ cMpc$^3$). The LAE$_{LG}$ lie at the lower mass end of the general LAE population, which have stellar masses $\sim 10^6$--$10^{10.5}$ M$_\odot$ (panel a1 of fig. 6 in Dayal et al. 2009), stellar metallicity between 0.01 and 0.5 Z$_\odot$ (panel a3 of fig. 6 in Dayal et al. 2009), dust mass between $10^4$ and $10^{7.2}$ M$_\odot$ (panel a of fig. 5 in Dayal et al. 2010) and an average colour excess $E(B-V) \sim 0.14$ (Dayal et al. 2010).

Finally, we find that in our resimulated volume ($\sim 86$ cMpc$^3$), the number density of LAE$_{LG}$ is $10^{-0.93}$ cMpc$^{-3}$ for $X_{HI} = 10^{-5}$. For a similar value of $X_{HI}$, we sample a cosmological simulation snapshot at $z \sim 6$ (described in Dayal et al. 2010, which has a volume of $10^6$ cMpc$^3$) about 10,000 times by randomly placing the resimulated volume within it. We find that the number density of field LAEs is about two orders of magnitude lower. $10^{-2.86}$ cMpc$^{-3}$. Even for $X_{HI} = 0.4$, the number density of LAE$_{LG}$ ($10^{-1.93}$ cMpc$^{-3}$) is higher than that of the field LAEs by about one order of magnitude. Detection of such a large overdensity of LAEs in a volume similar to the resimulated one could be an excellent signature of a region that could evolve to resemble the Local Group volume at $z \sim 0$. However, we caution the reader that to what extent such a result depends on the different resolutions of these two simulations still needs to be explored in full detail.

5 CONCLUSIONS AND DISCUSSION

We present the first work at $z \sim 6$ that couples state-of-the-art high-resolution gas-dynamical simulations of the Local Group run within the CLUES framework with a LAE model to identify the Local Group progenitors (designated LAE$_{LG}$) that could be visible as LAEs at a time when the Universe was only about 1 Gyr old. The main results from this study are now summarized.

(i) The first LAE$_{LG}$, which is a progenitor of the MW, appears at an average IGM neutral hydrogen fraction of $X_{HI} = 0.4$ (0.1 including (neglecting) the effects of clustered sources. As $X_{HI}$ decreases to $10^{-5}$, five progenitors each of the MW and M31 become visible as LAE$_{LG}$.

(ii) $T_a$ shows a large scatter, ranging between 0.35 and 0.65 at $X_{HI} = 10^{-5}$, due to the varying photoionization rate contributions from the clustered sources of the LAE$_{LG}$; clustering is imperative in making many progenitors visible in the Ly$\alpha$ even for a fully ionized IGM.

(iii) The LAE$_{LG}$ lie at the low-mass end of the field LAEs: they have $M_* \sim 10^{7.2}$--$10^{8}$ M$_\odot$, $M_{dust} \sim 10^{4.6}$--$10^{5.1}$ M$_\odot$ and $E(B-V) \sim 0.03$--0.048. On the other hand, field LAEs are much larger and have $M_* \sim 10^6$--$10^{10.3}$ M$_\odot$, $M_{dust} \sim 10^{7.6}$--$10^{7.2}$ M$_\odot$ and an average $E(B-V) = 0.14$.

(iv) Finally, our results suggest an observable imprint of such high-$z$ LAE$_{LG}$: the number density of LAE$_{LG}$ is about two (one) orders of magnitude higher than that of field LAEs for $X_{HI} = 10^{-5}$ ($X_{HI} = 0.4$). Such high number densities at $z \sim 6$ would be excellent signatures of a region that could resemble the Local Group volume at $z \sim 0$. However, the extent to which such a result depends on the varying simulation resolutions still needs to be explored in more detail.

The main caveats involved in this study are with regards to the distribution of dust (homogeneous/clumpy) in the interstellar medium of these high-$z$ progenitors (e.g. Finkelstein et al. 2009; Dayal et al. 2010).
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2010, 2011) and the effects of peculiar velocities (inflows/outflows into/from the galaxies) that can have enormous impact on $T_\alpha$ (Verhamme, Schaerer & Maselli 2006; Dayal et al. 2011). Uncertainties also remain on the value of the escape fraction of H\textsc{i} ionizing photons used. As discussed in the above-mentioned works, it is unclear to what extent these effects can modify the observed Ly\textalpha luminosity. It is hoped that a combination of the expected data from upcoming missions such as ALMA, Multi Unit Spectroscopic Explorer (MUSE) and JWST will be fundamental in resolving such issues.

ACKNOWLEDGMENTS

PD thanks SISSA for their generous allocation of cluster time. NIL is supported through a grant from the Deutsche Forschungsgemeinschaft. The simulations were performed and analysed at the Leibniz Rechenzentrum Munich (LRZ), the Neumann Institute for Computing (NIC) Juelich and at the Barcelona Supercomputing Centre (BSC). The authors thank A. Ferrara, S. Gottlöber, S. Nuza, S. Salvadori and the referee for positive comments.

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