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Detecting Lyman alpha emitters in the submillimetre

Pratika Dayal,1,2 Hiroyuki Hirashita2 and Andrea Ferrara3

1SISSA/International School for Advanced Studies, Via Beirut 2-4, Trieste 34014, Italy
2Institute of Astronomy and Astrophysics, Academia Sinica, PO Box 23-141, Taipei 10617, Taiwan
3Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy

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ABSTRACT

Using the results from a previously developed Lyman α/continuum production/transmission and dust enrichment model for Lyman alpha emitters (LAEs), based on cosmological smoothed particle hydrodynamics simulations, we assess the detectability of their dust-reprocessed submillimetre (submm) radiation. As supernovae (rather than evolved stars) control dust formation and destruction processes, LAEs are relatively dust-poor with respect to local galaxies: they have low dust-to-gas ratios (0.05 times the dust-to-gas ratio of the Milky Way) in spite of their relatively high metallicity, Z ≈ 0.1–0.5Z⊙. Using the derived escape fraction of ultraviolet (UV) continuum photons, we compute the UV luminosity absorbed by dust and re-emitted in the far-infrared. The LAE submm fluxes correlate with their Lyman α luminosity: about (3, 1 per cent) at z = (5.7, 6.6) of the LAEs in our simulated sample (those with log Lα > 43.1) would have fluxes at 850 μm (the optimal band for detection) in excess of 0.12 mJy and will be therefore detectable at 5σ with ALMA with an integration time of only 1 h. Such detections would open a new window on the physical conditions prevailing in these most distant galaxies.

Key words: radiation mechanisms: general – methods: numerical – galaxies: high-redshift – cosmology: theory.

1 INTRODUCTION

Lyman alpha emitters (LAEs) are galaxies identified by means of their strong Lyman α emission. Unambiguous characteristics of this line including the strength, width and bluewards cutoff have enabled recent detections of LAEs out to z ~ 7.7 (Hibon et al. 2009), adding to the already existing data at z ~ 7 (Iye et al. 2006), z ~ 6.5 (Kashikawa et al. 2006) and lower redshifts. Since LAEs are among the most distant objects known, in addition to being superb probes of reionization, they serve as laboratories to study early galaxy evolution and clarify fundamental but poorly understood aspects of high-z galaxies such as their dust content and extinction law.

Although a number of studies have been conducted, the extent and sources of the dust enrichment of LAEs remains a much debated issue. Using cosmological smoothed particle hydrodynamics (SPH) simulations, Dayal et al. (2009a) and Nagamine et al. (2008) have shown that at z ~ 5.7, the colour excess of LAEs, E(B − V) ~ 0.15. These theoretical estimates are not inconsistent with recent experimental determinations: by fitting the spectral energy distributions (SEDs) of three LAEs at z = 5.7, Lai et al. (2007) have inferred E(B − V) < 0.225–0.425; in a sample of 12 LAEs at z ~ 4.5, Finkelstein et al. (2009a) have found A1200 = 0.5–4.5; finally, Pirzkal et al. (2007) have found AV = 0.05–0.6 for three galaxies at z = 4–5.76. The latter two values, when translated into the colour excess (using a supernova dust extinction curve, e.g. Bianchi & Schneider 2007) are found to be E(B − V) = 0.035–0.316 and 0.025–0.3. These values therefore result in a coherent picture. However, Gronwall et al. (2007) and Ouchi et al. (2008) find much lower values of the colour excess, E(B − V) ≤ 0.05 for z = 3.1 LAEs.

The main uncertainty in using the SEDs to infer the dust content lies in the fact that the observed spectra depend on: (i) stellar population properties such as the age, metallicity, initial mass function (IMF) and (ii) the amount and distribution of dust in the interstellar medium (ISM). These two effects are not easily disentangled from each other and this might be the source of the disparity in the dust extinction inferred by different works. These difficulties can be overcome if one can exploit the fact that the dust absorbs ultraviolet (UV) radiation and re-emits it at far-infrared (FIR) wavelengths; thus, if LAEs could be observed in the submillimetre (submm; FIR in the LAE’s rest frame), a new window on the study of LAE properties would open, allowing the precise determination of their dust content and a far better determination of their stellar populations and star formation history. Work has already begun in this direction with two LAEs at z ~ 6.6 having been studied in the submm by Webb et al. (2007).

Clumped dust has also been invoked by many authors (Dawson et al. 2004; Kobayashi, Totani & Nagashima 2007, 2010; Dayal, Ferrara & Gallerani 2008; Finkelstein et al. 2008, 2009a,b; Dayal

*E-mail: dayal@sissa.it (PD)
The adopted cosmological model for the simulation corresponds to the cold dark matter universe with $\Omega_m = 0.26, \Omega_{\Lambda} = 0.74, \Omega_b = 0.0413, n_s = 0.95, H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\sigma_8 = 0.8$, consistent with the 5 yr analysis of the Wilkinson Microwave Anisotropy Probe data (Komatsu et al. 2009).
(corresponding to a wavelength of 100 μm), which is an arbitrary frequency in FIR used for normalization.

Since we assume all the dust grains to be spherical with a single size \( a = 0.05 \mu m \) (appropriate for a SN-produced dust, see Todini & Ferrara 2001; Nozawa et al. 2003, 2007) and material density \( s \), the mass absorption coefficient \( \kappa_\nu \) can be written as \( \kappa_\nu = 3Q_\nu [4\pi a]^{-1} \), where \( Q_\nu \) is the optical absorption cross-section normalized to the geometrical cross-section \( (4\pi a^2) \). For graphite/ carbonaceous grains, \( Q_\nu a^{-1} = 1.57 \times 10^5 \text{ cm}^{-1} \) at a wavelength of 100 μm, \( s = 2.25 \text{ g cm}^{-3} \) and \( \beta = 2 \) (Draine & Lee 1984). This results in \( \kappa_\nu = 52.2 (\nu/\nu_\nu)^{0.6} \text{ cm}^2\text{ g}^{-1} \). Even though, in this work, we assume the dust grains to be graphites, the flux is insensitive to the specific grain material for a given value of L_{FIR} since a small \( \kappa_\nu \) is compensated by a high \( T_{dust} \) and vice versa. Then, equation (5) can be simplified to the following expression:

\[
T_{dust} = 6.73 \left( \frac{L_{FIR}/L_\nu}{M_{dust}/M_\odot} \right)^{1/6} \text{ K}. \tag{6}
\]

This temperature is put in equation (4) to obtain \( L_\nu \) and hence the dust emission flux detectable in the submm bands in the observer’s frame.

\section{RESULTS}

\subsection{Dust abundance}

The relation between dust-to-gas ratio \( (D) \) and gas metallicity is useful to discuss the dust enrichment scenario in the low-metallicity phase as shown by Lisenfeld & Ferrara (1998) for nearby blue compact dwarf galaxies. We calculate this ratio as \( D = M_{dust}/M_g \), where the dust mass, \( M_{dust} \), is calculated as shown in Dayal et al. (2009b). The gas mass, \( M_g \), and the mass-weighted gas metallicity, \( Z_g \), are both obtained from the simulation as mentioned before. We normalize the dust-to-gas ratio to the one measured in the solar neighbourhood, \( D_\odot = 1/150 = 6 \times 10^{-3} \) (Hirashta & Ferrara 2002). The relation between \( D \) and \( Z_g \) has been investigated by several authors. In particular, Lisenfeld & Ferrara (1998) have shown that for nearby dwarf galaxies the following relation holds: \( Z_g \propto D^p \), with \( p = 0.52 \pm 0.25 \). In principle, there is no reason to expect that such low-redshift determination applies equally well to LAEs, due to the very different physical conditions and shorter evolutionary time-scales allowed by the Hubble time at \( z \approx 6 \). Using the above relation for a gas metallicity value equal to 0.2Z_\odot, appropriate for our calculation of LAEs, yields \( D = 0.003-0.12D_\odot \); from our result, we get a mean value in reasonable agreement with this expectation, \( D = 0.001-0.045D_\odot \) for \( Z_g = 0.27Z_\odot \).

However, although we confirm a correlation between dust abundance and metallicity, the \( D-Z_g \) relation we find, shown in Fig. 1, shows considerable deviations from the above power law. First, the slope of the relation is considerably steeper (i.e. \( p > 1 \)); secondly, in spite of the relatively high metallicity of LAES (about 0.1–0.5Z_\odot), the dust abundance is relatively depressed with essentially all objects having \( D < 0.05D_\odot \). Taken together, these two points imply that LAEs are relatively poorly efficient dust producers with respect to local galaxies. The physical explanation of this fact is straightforward. Because of their young ages (<500 Myr), LAEs can only have their dust produced by SNII rather than by evolved stars, which dominate the dust production in local galaxies. However, since dust

\[ Q_\nu a^{-1} = 1.45 \times 10^5 \text{ cm}^{-1}, \]
\[ s = 3.3 \text{ g cm}^{-3} \]
\[ \beta = 2, \]
\[ \kappa_\nu = 32.9 (\nu/\nu_\nu)^{0.6} \text{ cm}^2\text{ g}^{-1}. \]

\[ L_{\alpha} = L_{\alpha}^\text{int} f_a T_a, \tag{7} \]

where \( f_a \) is the fraction of Lyman β luminosity which emerges from the galaxy, undamped by dust and \( T_a \) is the fraction of Lyman α luminosity transmitted through the IGM. Now, the largest galaxies have the largest SFRs (Dayal et al. 2009a) and hence the largest values of \( L_{\alpha}^\text{int} \) since this scales with the SFR. As shown in Dayal et al. (2009b), their \( T_a \) is also the largest. Further, the largest galaxies
Correlations between Lyman $\alpha$ luminosity and submm flux for $z = 5.7$ (left) and 6.6 (right). The horizontal solid, dotted and dashed lines show the 5$\sigma$ detection limit of ALMA with 1 h integration for the bands corresponding to 100 GHz (3 mm), 220 GHz (1.4 mm) and 353 GHz (850 $\mu$m), respectively. Symbols (squares, triangles, circles) in both panels show the results obtained from this work for the same bands (100, 220, 353 GHz).

are also the most dust-enriched by SNII since the SNII rate scales with the SFR. However, due to large radii of dust distribution (which scales with the SFR), the largest galaxies do not have the smallest $f_\alpha$ as expected. This implies that the largest galaxies show both the largest $L_\alpha$ and $f_\alpha$, hence the trend seen. Fig. 2 shows that the 850 $\mu$m band is the optimum one to look for submm emission; (32, 5) LAEs at $z = (5.7, 6.6)$ in our simulation volume have an 850 $\mu$m flux larger than the 5$\sigma$ 1 h integration limit of ALMA which is 0.12 mJy (Morita & Holdaway 2005). This corresponds to about (3, 1 per cent) of the LAEs in our simulated samples at these redshifts.

In Fig. 3, we show the FIR luminosity and submm flux LFs for our LAE sample at 850 $\mu$m since this seems to be the most optimum band to look for FIR emission, as mentioned above. We see that selecting LAEs with $L_\alpha \geq 10^{42.2}$ erg s$^{-1}$ can efficiently detect galaxies whose submm fluxes are bright enough to be detected by ALMA with an integration time of only 1 h. A longer integration time drastically increases the number of LAEs detected by ALMA because of the steep rise of distribution function towards faint submm fluxes as shown in Fig. 3.

Thus, we show that we can simply point ALMA towards bright LAEs that have already been identified at high-$z$ to detect LAEs in the submm band at 5$\sigma$ with an integration time of only 1 h.

4 SUMMARY AND CONCLUSIONS

This work is based on the results obtained in Dayal et al. (2009b), where we coupled a cosmological SPH simulation with a Lyman $\alpha$/continuum production/transmission model and a dust model. This enabled us to calculate the observed Lyman $\alpha$/continuum luminosities and the dust mass evolution for each galaxy. We thus obtained the escape fraction of continuum photons for each galaxy based on its intrinsic properties including the SFR, age, metallicity, IMF and gas mass. The only free parameter, the escape fraction of Lyman $\alpha$ photons was obtained by comparing the model results to the observations at $z \sim (5.7, 6.6)$.

Though we find that the dust to gas ratio values as a function of gas metallicity obtained from our model are broadly consistent with those predicted by Lisenfeld & Ferrara (1998) at $Z = 0.2Z_\odot$, the slopes predicted by the two works are different. The reason for this disagreement arises because we assume SNII to be the only sources of dust. While this leads to a progressive metal enrichment of the ISM and hence a high value of the gas metallicity, since SNII also destroy the dust that they produce, the dust to gas ratio remains very small ($<0.05$ of that in the solar neighbourhood). On the other hand, in dwarf galaxies, both SNII and evolved stars produce dust; the supernovae shocks, however, are not capable of destroying the huge amounts of dust produced by evolved stars and this leads to much larger values of the dust to gas ratio.
For each galaxy identified as a LAE as these redshifts, we assume that the UV luminosity between 912–4000 Å that is absorbed inside the galaxy heats up the dust, leading to reradiation in the submm band in the observer’s frame. This allows us to calculate the emitted flux at 3000, 1363 and 850 μm.

We then present a very efficient strategy to look for dust emission from LAEs. We find that the observed Lyman α luminosity and the FIR fluxes are correlated for LAEs in all the three ALMA bands (3000, 1363 and 850 μm); the LAEs with the largest observed Lyman α luminosity also show the largest fluxes. This means that pointing surveys of the brightest LAEs already identified would yield large fluxes in ALMA. We find that the 850 μm band seems to be the optimum one for detecting the FIR emission from high-z LAEs. Although a few tens of objects would be detectable with a 1 h integration, the number density of objects detectable would rise steeply with the integration time.

Finkelstein et al. (2009b) have used the measurements of the UV spectral slopes to derive FIR flux predictions for a sample of 23 LAEs (Pirzkal et al. 2007; Finkelstein et al. 2009a) at $z \geq 4$. It is interesting to compare to what extent the results obtained using their approach match with those from our model. We first compare the colour excess obtained from these works where we find that the average value, $E(B-V) \sim 0.15$ obtained from our work (Dayal et al. 2009a,b) is very consistent with $E(B-V) = 0.035 \pm 0.316$ and 0.025–0.3, found by Finkelstein et al. (2009a) and Pirzkal et al. (2007), respectively. However, while Finkelstein et al. (2009b) find that 39 ± 22 per cent of their LAEs would be visible with ALMA with an integration time of 4 h, we find only $\sim (3, 1 \text{ per cent})$ of the LAEs in our simulation would be visible with a 5–$\sigma$, 1 h integration limit at $z \sim (5.7, 6.6)$. Although these results may seem discrepant at the first glance, they can be explained quite easily considering the redshifts of the LAEs modelled by Finkelstein et al. (2009b). In their sample, 20 of the LAEs are at $4 \leq z \leq 5$, of which, nine (i.e. 45 per cent) would be visible with ALMA with a 4 h integration time. However, none of the three LAEs with $z \geq 5.2$ would be detectable in the submm. This is highly consistent with our results, where only 3 per cent of the LAEs would be visible with ALMA at $z \sim 5.7$ for a 5–$\sigma$, 1 h integration time; hence, in a sample of three LAEs, none would be visible. This is also a confirmation of our dust model, where SNII are the primary dust factories at $z \geq 5.7$, with evolved stars dominating at lower redshifts. Since SNII both produce and destroy dust, the dust enrichment levels at high redshifts are very small as compared to that at lower redshifts ($z \leq 5.7$). Hence, the detectability of LAEs in the submm decreases with increasing redshift.

The main uncertainty in this work lies in the fact that we assume SNII to be the primary sources of dust production/destruction at the redshifts considered. While this is justified for ages ≤ 1 Gyr, we cannot completely rule out the contribution from evolved stars as shown by Valiante et al. (2009). Further, the dust yield per SNII and the dust destruction efficiency due to supernova shocks are only known well enough to within a factor of a few. Also, since the scalelength of dust distribution is not well known at these redshifts, we have to resort to the data to guide us. We plan to deal with these uncertainties in future works.

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REFERENCES

Iye M. et al., 2006, Nat, 443, 186
Morita K.-I., Holdaway M., 2005, ALMA Memo 538 (http://www.alma.nrao.edu)

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