

The physical properties of Ly α emitting galaxies: not just primeval galaxies?

L. Pentericci¹, A. Grazian¹, A. Fontana¹, M. Castellano², E. Giallongo¹, S. Salimbeni^{1,3}, and P. Santini¹

¹ INAF – Osservatorio Astronomico di Roma, via Frascati 33, 00040, Monte Porzio Catone, Italy
e-mail: penteric@mporzio.astro.it

² Dipartimento di Fisica, Università di Roma “La Sapienza”, P.le A. Moro 2, 00185, Roma, Italy

³ University of Massachusetts, Department of Astronomy, 710 North Pleasant Street, Amherst, MA 01003, USA

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ABSTRACT

Aims. We have analyzed a sample of Lyman break galaxies from $z \sim 3.5$ to $z \sim 6$ selected from the GOODS-S field as B , V , and i -dropouts, and with spectroscopic observations showing that they have the Ly α line in emission. Our main aim is to investigate their physical properties and their dependence on the emission line characteristic and to shed light on the relation between galaxies with Ly α emission and the general LBG population.

Methods. The objects were selected from their optical continuum colors and then spectroscopically confirmed by the GOODS collaboration and other campaigns. From the public spectra we derived the main properties of the Ly α emission such as total flux and rest frame EW . We then used complete photometry, from U band to mid-infrared from the GOODS-MUSIC database, and through standard spectro-photometric techniques we derived the physical properties of the galaxies, such as total stellar mass, stellar ages, star formation rates, and dust content. Finally we investigated the relation between emission line and physical properties.

Results. Although most galaxies are fit by young stellar populations, a small but non negligible fraction has SEDs that cannot be represented well by young models and require considerably older stellar component, up to ~ 1 Gyr. There is no apparent relation between age and EW : some of the oldest galaxies have high line EW , and should be also selected in narrow-band surveys. Therefore not all Ly α emitting galaxies are primeval galaxies in the very early stages of formation, as is commonly assumed.

We also find a range of stellar populations, with masses from $5 \times 10^8 M_{\odot}$ to $5 \times 10^{10} M_{\odot}$ and SFR from few to $60 M_{\odot} \text{ yr}^{-1}$. Although there is no net correlation between mass and EW , we find a significant lack of massive galaxies with high EW , which could be explained if the most massive galaxies were either dustier and/or if they contained more neutral gas than less massive objects.

Finally we find that more than half of the galaxies contain small but non negligible amounts of dust: the mean $E(B - V)$ derived from the SED fit and the EW are well-correlated, although with a large scatter, as already found at lower redshift.

Key words. galaxies: evolution – galaxies: high-redshift – galaxies: fundamental parameters

1. Introduction

In the past few years large samples of high-redshift star-forming galaxies have been found at increasingly greater distances (e.g. Bouwens et al. 2006; Iye et al. 2006). Their photometric and physical properties as well as spatial distribution have been extensively studied. The majority of these galaxies are detected on the bases of their typical broad band colors, given by the characteristic breaks (Lyman break, Lyman limit) that fall at different redshift into the different bands (the Lyman break galaxies LBGs e.g. Steidel et al. 1996). Alternatively, many galaxies have been found by means of their bright Ly α emission, in particular at redshift >3 : Ly α emitters (LAEs) are selected through ultra-deep narrow-band (NB) and by contrast to a nearby broad band image, as initially proposed by Cowie & Hu (1998) and then used by many others (e.g. Iye et al. 2006; Ouchi et al. 2005; Fujita et al. 2003). This technique tends to select galaxies with relatively faint continuum emission and large line equivalent width (EW).

Each of the two methods suffers from a different selection bias, the two resulting populations of galaxies overlap partially and the relationship between them is not clear. Most authors have shown that LAEs are, on average, smaller and younger galaxies than in the LBGs population (e.g. Finkelstein et al. 2007;

Gawiser et al. 2007; Pentericci et al. 2007, hereafter P07). Because the Ly α line is easily suppressed by dust, Ly α emitters are often characterized as extremely young galaxies, experiencing their initial phase of star formation in essentially dust-free environments (e.g. Gawiser et al. 2007). However, the different behavior of Ly α and continuum photons in interacting with dust makes it possible also for older galaxies to exhibit Ly α in emission, as predicted e.g. in the models of Haiman & Spaans (1999). Therefore LAEs (or a fraction of them) could also represent an older population with active star-forming regions, where the gas kinematics can favor the escape of Ly α emission. This scenario is partially supported by the results of Shapley et al. (2003). In addition Lai et al. (2007) found that some high-redshift Ly α galaxies could be consistent with hosting relatively old stellar population.

The fraction of Lyman break galaxies that are also LAEs is also still under debate. Some authors have recently claimed a deficiency of bright galaxies with large EW in deep samples of Lyman break galaxies, indicating that the fraction of Ly α emitters amongst LBGs might change abruptly with UV luminosity (Ando et al. 2006). On the other hand, Shimasaku et al. (2006) argue that at redshift 6 the fraction of LBGs with $EW > 100 \text{ \AA}$ is 80%. They claim that the fraction of Ly α emitters amongst

LBGs is a strong function of redshift. This is at variance with the results of Dow-Hygelund et al. (2007; see also Stanway et al. 2007), who find that the fraction of Ly α emitters in galaxies at $z = 6$ is $\sim 30\%$, in total accordance with what found by Shapley et al. (2003) for $z = 3$ Lyman break galaxies, indicating that there is no strong evolution between $z \sim 3$ and $z \sim 6$.

Clearly, it is worthwhile understanding these trends and the real relation between galaxies with Ly α emission and the general LBG population, so that properties of the overall high-redshift galaxy population, such as the total stellar mass density, can be better constrained.

An important limitation of the LAE technique is that it tends to select galaxies with extremely faint continuum: therefore most of the LAEs are not detected, or just barely detected, in the broad bands. Thus the analysis of all physical properties that are usually derived from a modeling of the multi-band spectral energy distributions, such as stellar masses and ages is extremely difficult. In most cases the determination of these properties for the individual objects is not possible and one has to rely on the analysis of stacked data (e.g. Lai et al. 2008). In other cases, the analysis is limited to very small sub-sample of LAEs that are detected in the continuum (e.g. Finkelstein et al. 2007). For example, it has been shown that to reliably estimate the masses at redshift larger than $z \sim 2.5$, the inclusion of near and mid IR bands is essential (e.g. Fontana et al. 2006, hereafter F06) to constrain the values and reduce the uncertainties. In this context, Lai et al. (2008) attempted to constrain the stellar population of $z = 3.1$ LAEs selected from the Extended CDFS, using Spitzer data. However of their initial sample of 162 LAEs, only 18 galaxies were detected in the IRAC 3.6 μ channel, and therefore had reliable individual mass estimates. For the rest of the sample, a limit in mass was determined from a stacking analysis, obtaining only information on the average properties. This makes it hard to analyze the correlation and trends between the various properties.

For the reasons detailed above and to ensure that we can derive the physical properties of Ly α emitting galaxies, we chose to analyze galaxies exhibiting Ly α in emission starting from a sample of LBGs. Thanks to the large area coverage of GOODS, in this way we can assemble a sample with a large enough number of galaxies, and a wide range of Ly α properties, from bright emission lines to absorption. We then selected only those exhibiting Ly α in emission. We do not include in this analysis those LBGs showing the Ly α line in absorption, since our main aim is to compare the physical properties of our galaxies to those of NB selected samples. Furthermore the fraction of LBGs with Ly α in absorption decreases with redshift, since it becomes progressively harder to identify Ly α absorbers. Therefore to keep the sample complete for Ly α absorbers we should have stopped at a lower redshift (as in P07) and the sample would have been smaller.

The paper is organized as follows: in Sect. 2 we outline the sample selection and in Sect. 3 we describe how the physical properties were derived from the multiwavelength observation and the properties of the Ly α emission from the spectroscopic observations. In Sect. 4 we analyze the various trend of physical properties with the characteristics of the line emission, and finally in Sect. 5 we discuss our results in the context of various proposed scenarios.

All magnitudes are in the AB system (except where otherwise stated) and we adopt the Λ -CDM concordance cosmological model ($H_0 = 70$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$).

2. Sample selection

We used a revised version of the GOODS-MUSIC z -selected sample of galaxies that will be presented in Santini et al. (2008, submitted). The limiting magnitude z varies for different areas of the field (see Grazian et al. 2006a, for more details) but is typically around $z \sim 26$ (AB scale). The color-color selection criteria have been presented by Giavalisco et al. (2004) and were used for the ESO spectroscopic campaign of the GOODS south field. We adopt the B , V and i dropout selections, which give samples of galaxies at redshift approximately between 3.5 and 4.5 (B dropouts) between 4.5 and 5.5 (V dropouts) and above 5.5 (i dropouts). All known AGNs have been removed by identifying the objects that have either broad line emission or X-ray detections (see Santini et al. 2008, for more details). This way we assembled a sample of several hundreds LBGs: we then selected those that were observed spectroscopically. Most of the spectra were taken within the GOODS-FORS2 spectroscopic campaign (Vanzella et al. 2005, 2006, 2008) and the 1D spectra were retrieved directly from the public GOODS database. The GOODS team has classified galaxies according to the presence of Ly α in emission or absorption. We further checked their classification and we retained only those galaxies with Ly α in emission (few spectra present the line both in emission and absorption and were also included in the final sample). We included galaxies with spectroscopic classification A and B (respectively secure and probable redshift determination); we also retained those galaxies with spectroscopic classification C (tentative redshift determination) if our independently determined photometric redshift (from 14 bands photometry, see G06 for more details) is in agreement with the spectroscopic one.

Few further spectra were retrieved from the GOODS-VIMOS database (Popesso et al. 2008). For these spectra we followed the same procedure as above, but we checked all of them for consistency with our photometric redshift, regardless of the spectral quality.

Finally few galaxies had published HST/ACS grism spectroscopy either from the GRAPES observing program (Malhotra et al.) or from preliminary PEARS results (Pirzkal et al. 2007). For these galaxies the spectra in electronic format are not public, but we retrieved all relevant information on the emission lines directly from the papers.

The final sample consists of 68 spectroscopically confirmed LBGs: in Fig. 1 we present the redshift distribution for B , V and i dropouts.

3. Physical and spectral properties

The main physical properties of the galaxies such as total stellar mass, continuum-based star formation rate, stellar age, dust extinction $E(B - V)$ and so on, were obtained through a spectral fitting technique which has been developed in previous papers (Fontana et al. 2003, F06), and is similar to those adopted by other groups in the literature (e.g. Dickinson et al. 2003; Drory et al. 2004). Briefly, it is based on a comparison between the observed multicolor distribution of each object and a set of templates, computed with standard spectral synthesis models. We used both the Bruzual & Charlot (2003) models for a consistent comparison with previous work, and the new Charlot & Bruzual (2007) models that include more recent calculations of evolutionary tracks of TP-AGB stars of different mass and metallicity.

The models were chosen to broadly encompass the variety of star-formation histories, metallicity and extinction of real galaxies. For purposes of comparison with previous research, we used

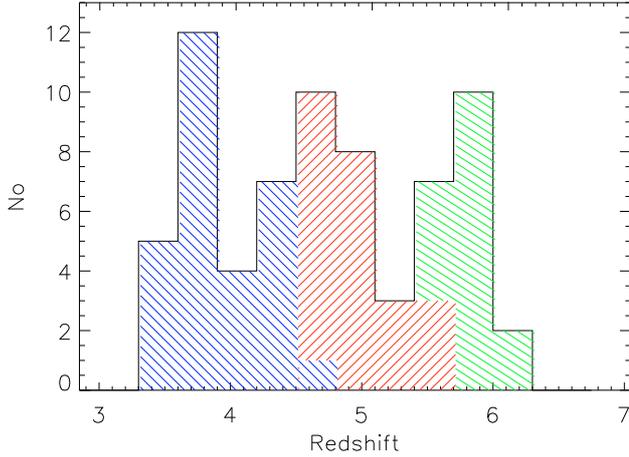


Fig. 1. The redshift distribution of LBG galaxies in our sample: blue are the B dropouts, red are the V dropouts and green are the i -dropouts (see text for details).

the Salpeter IMF, ranging over a set of metallicities (from $Z = 0.02 Z_{\odot}$ to $Z = 2.5 Z_{\odot}$) and dust extinctions ($0 < E(B-V) < 1.1$, with a Calzetti or a Small Magellanic Cloud extinction curve). Details are given in Table 1 of Fontana et al. (2004). For each model of this grid, we computed the expected magnitudes in our filter set, and found the best-fitting template with a standard χ^2 minimization. The stellar mass and other best-fit parameters of the galaxy, such as SFR estimated from the UV luminosity and corrected for dust obscuration (with a typical correction factor of $A_V \sim 0.4$), age, τ (the star formation e-folding timescale), metallicity and dust extinction, are fitted simultaneously to the actual SED of the observed galaxy. The derivation of these parameters is explained in detail in the above paper and in F06, where the uncertainties are also discussed. In particular the stellar mass generally turns out to be the least sensitive to variations in input model assumptions; the extension of the SEDs to the IRAC mid-IR data tends to reduce considerably the formal uncertainties on the derived stellar masses. On the other hand, the physical parameter with highest associated uncertainty is the metallicity, given that the models are strongly degenerate when fitting broad-band SEDs.

To characterize the Ly α emission we determined the following properties: the line equivalent width (EW), the width at half maximum (FWHM) and the total line flux. Where possible we used the flux and wavelength calibrated spectra provided by the GOODS team. For details on the reduction and calibration process and the involved uncertainties of the FORS2 spectra we refer to Vanzella et al. (2005, 2006, 2008).

The total line flux and the equivalent width were measured from the spectra using as reference continuum a measure from the region immediately red-ward of the line. In some case when this was particularly noisy the uncertainties (especially on the EW) are quite high. When no continuum is observed in the spectrum, the EW are lower limits. The measured EW were then divided by $(1+z)$ to determine the rest-frame values. In Fig. 2 we show the histogram of the EW s for all galaxies: the distribution is peaked at small values and spans the range from 0 to about 100 \AA , with few objects having EW above 100 \AA . In the plot, we also show the distribution of other galaxy samples already discussed in the introduction: the red histogram represents the 22 LAEs from Finkelstein et al. (2007) for which masses were determined in a reliable way. The green histogram represents the sample of 14 LBGs by Tapken et al. (2007), selected with similar

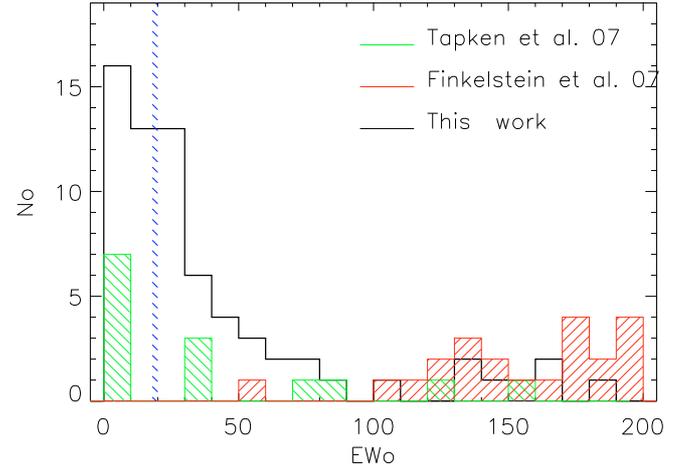


Fig. 2. The distribution of Ly α EW (rest-frame) as determined from the 1d spectra (values are not corrected for IGM absorption). The black histogram is the sample of LBGs presented in this work, the red dashed area is the sample of LAEs by Finkelstein et al. (2007) and the green dashed area represents the sample of LBGs by Tapken et al. (2007). The vertical blue line at 20 \AA indicates the limit for NB selected LAEs.

criteria from the FORS deep field, which spans a similar range of redshifts and has an EW distribution comparable to our sample.

In the plot we also indicated the 20 \AA rest-frame EW that is used by most authors to select LAEs from deep narrow-band surveys. In our sample, 38 of 68 galaxies have EW larger than this value. This is consistent with the statistics of LBGs at $z \sim 3$ of Shapley et al. (2003), who show that of all LBGs, 50% have Ly α in emission and half of those (i.e. $\sim 25\%$ of the total) have rest-frame EW exceeding 20 \AA . In the rest of the paper we will refer to the 38 galaxies with $EW > 20 \text{\AA}$ as the NB subsample.

To determine the intrinsic emission line flux we corrected the values measured from the spectra for IGM absorption. Ly α sits right at a step function in the Madau (1995) IGM treatment, so the amount of attenuation applied to Ly α depends strongly on the exact wavelength position of the Ly α line. The accepted interpretation is that the internal kinematics of a given galaxy will result in half of the Ly α flux coming out slightly blue of the rest wavelength, and half slightly red. This results in the characteristic asymmetric profile of the Ly α observed in many spectra, where the blue side is truncated. We therefore applied the Madau (1995) prescription assuming that only a half of the flux is attenuated, and we derived the intrinsic flux. As pointed by several authors (e.g. Santos 2004; Dijkstra et al. 2007) this is a simplistic approach. In particular the IGM around a galaxy is probably overdense and has peculiar velocities: these models predict that the fraction of Ly α flux that is transmitted might be lower than 0.5, and/or might fluctuate between galaxies.

Finally we measured the line FWHM from the spectra by fitting a Gaussian to the red part of the spectra (that should be unabsorbed). Given that the spectra were not taken with high resolution set-up, this is probably a simplistic approach. The measured FWHM were then deconvolved by the resolution of the spectroscopic set-up ($R = 660$).

For the small sample of objects that were observed by GRAPES, the EW s were determined from the values of narrow-band Ly α and continuum flux given in the relevant papers (Pirzkal et al. 2007). In these cases no value for the FWHM is available. No significant correlations were found between FWHM and other physical quantities, probably because the

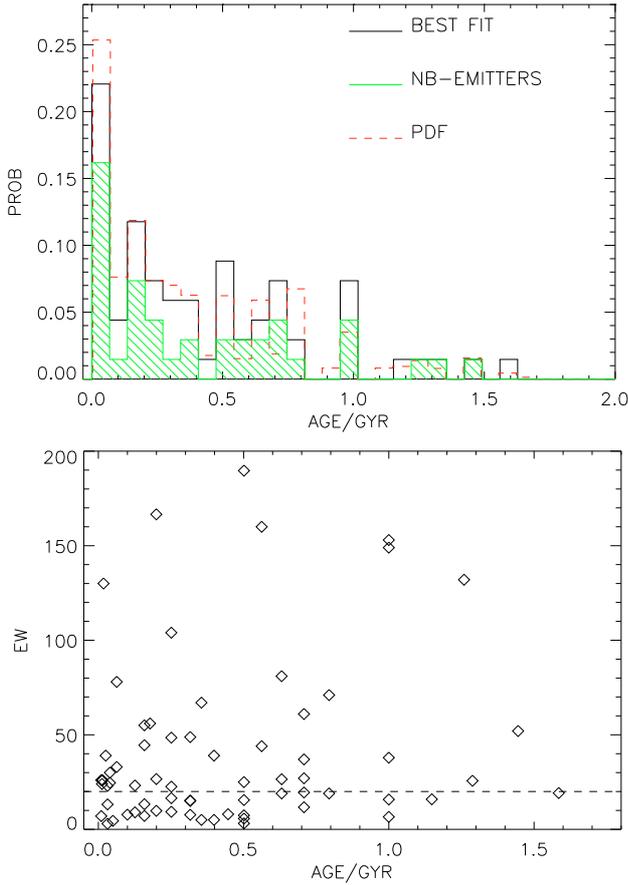


Fig. 3. *Upper panel:* the distribution of stellar ages for the LBGs in our sample. The full line refers to the best fit values, while the dashed line is the sum of the probability distribution function of all galaxies. *Lower panel:* the dependence of stellar ages (best fit values) from the Ly α EW. The dashed line is the 20 Å value that is normally used for the narrow-band selection of Ly α emitters.

resolution is not adequate for line shape analysis (see also Tapken et al. 2004). Therefore we will not discuss them further in the paper.

4. Results

4.1. Old Ly α emitters?

In Fig. 3 (upper panel), we show the derived stellar ages for our galaxies: the black histogram represents the distribution of best fit values from the SED fit for the entire sample, while the hatched green region refers to the NB subsample. In the lower panel we show how the age correlates with the Ly α EW. The age distribution presents a peak at small values, with ages of a few tens of Myr. The distribution drops quite quickly: about half of the entire sample has ages shorter than 300 Myr. The histogram then shows the presence of a group of relatively old galaxies, peaked around $T = 700$ Myr and extending up to ~ 1.5 Gyr. From the lower panel we see no dependence of age on the EW. The median ages are 350 Myr for the entire sample and 300 Myr for the NB subsample, but the difference is not statistically significant.

A comparison to values found in the literature is not straightforward, also because in many studies the 4000 Å/Balmer break is not well sampled and therefore the usual dust/age degeneracy cannot be resolved. Age estimates for LBGs at $z \sim 5$ and ~ 6 are

of the same order as those found in this study (e.g. Verma et al. 2007; Yan et al. 2007). For LAEs, most authors estimate younger ages, of at most few million year (Pirzkal et al. 2007; Finkelstein et al. 2007; Malhotra & Rhoads 2002) giving support to the idea that LAEs are primitive objects. However in some cases much older stellar populations give equally good fit to the SEDs (Lai et al. 2007; Nilsson et al. 2007; Gawiser et al. 2006). Recently Finkelstein et al. (2008b) reported that 2 out of their 15 LAEs have ages of several hundreds Myr.

Since usually the Ly α emission, and in particular the bright emission, with $EW > 100$ Å is related to very young stellar ages (e.g. Charlot & Fall, see also discussion in Sect. 4), we have further checked the reliability of our results, in particular the validity of the fits giving old ages. We have therefore derived the distribution of stellar ages, using for each object the probability distribution function (PDF) instead of the best fit value. In practise for each object we scan the parameter space and determine the probability of each particular model from the χ^2 of the fit, as $e^{-\chi^2}$. The redshift of each galaxy is of course fixed to the spectroscopic one. For each galaxy, we then compute the PDF for all the physical parameters by scanning the χ^2 levels obtained during the fitting process. The probabilities of all models are normalized, so that the sum is unity. Then the range of values of the physical parameter analyzed (age, in our case) are scanned from a minimum value till a maximum and we sum the probabilities for all objects that fall within each particular interval, ending up with the PDF of the physical parameter for the entire sample.

In this way we have derived the overall age distribution using the sum of the PDFs for each galaxy, for our full sample of 68 objects: in Fig. 3 this is shown as a red dashed line. We see that the probability distribution is in general agreement with the best fit one, but is slightly shifted towards smaller ages. We further checked the origin of this difference and we found that while the PDFs for all young galaxies (best fit age $T_{BF} < 200$ Myr) are peaked around the best fit values with little dispersion, for some of the old galaxies (with $T_{BF} > 500$ Myr) the PDF extends also to much lower ages: in practise the SEDs of these galaxies could be fit almost equally well by models with much younger stellar populations and the age is not well constrained.

To create a robust sample of “old” galaxies, we therefore selected galaxies with best fit ages $T_{BF} \geq 500$ Myr, and minimum age for a reasonable fit of $T_{min} \geq 350$ Myr. In total there are 13 such galaxies in the entire sample. Any reasonable model that fits their SEDs must have a stellar population with age of at least few hundreds Myrs. Therefore these galaxies are most certainly *not primeval galaxies* even if they show Ly α in emission. Interestingly these old galaxies have values of Ly α EW that span the entire range from 3 Å to 150 Å as can be seen in Fig. 3. Of the 13 old galaxies, 7 have $EW > 20$ Å and therefore they are part of the NB subsample. In Fig. 4 we show the SED of one of these bright emission line galaxies with old age, a galaxy at redshift 4.1: the best fit model is shown with a black line (best fit age 1.1 Gyr). The relative best fit models with younger ages (with age set equal to 10, 100, 200 and 600 Myr respectively) are also shown with different colors. They clearly give a much poorer representation of the observed SED, especially in the mid-IR range. Another object, from our sample of old galaxies with bright Ly α emission, was already recognized by Wiklind et al. (2007) as an evolved and massive high-redshift galaxy (object number 5197 of their Table 4), since it has a prominent Balmer break. Although they did not have the spectroscopic redshift ($z = 5.56$), their best fit model with a z_{phot} of 5.2 gives results that are entirely consistent with our fit: in particular their

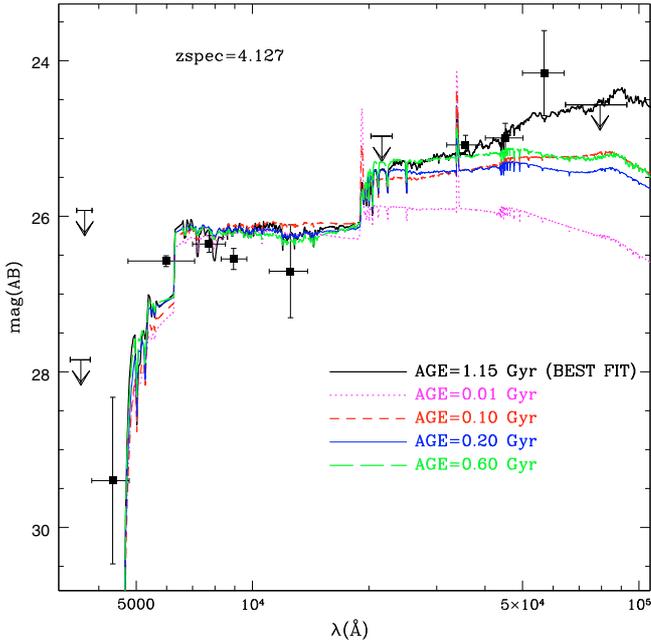


Fig. 4. The SED of galaxy with ID8073 at $z = 4.127$: the black line is the best fit with age = 1.1 Gyr. The other lines with different colors and types represent the best-fit models with varying ages.

best fit age and mass agree very well with ours. The nature of these old Ly α emitters will be further discussed in Sect. 5.

4.2. Lack of massive LBGs with high EW Ly α emission

In the upper panel of Fig. 5 we show the distribution of the total stellar masses: the black line represents the best fit values while the red dashed line is the sum of the PDFs for each individual galaxy, computed as in the previous section. The two agree very well with each other.

The total masses range from $10^9 M_{\odot}$ to as large as $10^{11} M_{\odot}$ with a median value of $6 \times 10^9 M_{\odot}$. The median mass for the NB subsample is $5 \times 10^9 M_{\odot}$. Similar values for $z \sim 5$ V-dropouts were obtained by Verma et al. (2007), and for $z \sim 6$ i -dropouts in GOODS survey by Yan et al. (2007); these last authors used also deep SPITZER-IRAC data to constrain the masses. LAEs have in general much smaller masses: Finkelstein et al. (2007) find masses between $2 \times 10^7 - 2 \times 10^9 M_{\odot}$ for a sample of 98 LALA galaxies at redshift ~ 4.5 . Gawiser et al. (2006) found an average mass per object of $\sim 5 \times 10^8 M_{\odot}$ for a numerous sample of LAEs although at smaller redshift $z \sim 3.1$ (see also Gawiser et al. 2007). Pirzkal et al. (2007) find masses between $6 \times 10^6 - 3 \times 10^9 M_{\odot}$ for $z \sim 5$ LAEs from PEARS. Finally the most recent estimate comes from Finkelstein et al. (2008b) which show a larger mass range, from $10^8 M_{\odot}$ to as high as $6 \times 10^9 M_{\odot}$.

More similar masses come from Lai et al. (2007) who find $M = 10^9 - 10^{10} M_{\odot}$ for three Spitzer detected LAEs at $z = 5.7$ in the GOODS north field. The same authors in another study at redshift 3.1 of LAEs in the ECDF south, find that the median mass of LAEs is low, $3 \times 10^8 M_{\odot}$, but the IRAC-detected LAEs (which make up 30% of the sample) have masses of the order of $\sim 10^{10} M_{\odot}$.

Clearly most (but not all) of the NB emitters have somewhat fainter continuum than our LBGs: we are studying objects that are, on average, intrinsically brighter and thus more massive.

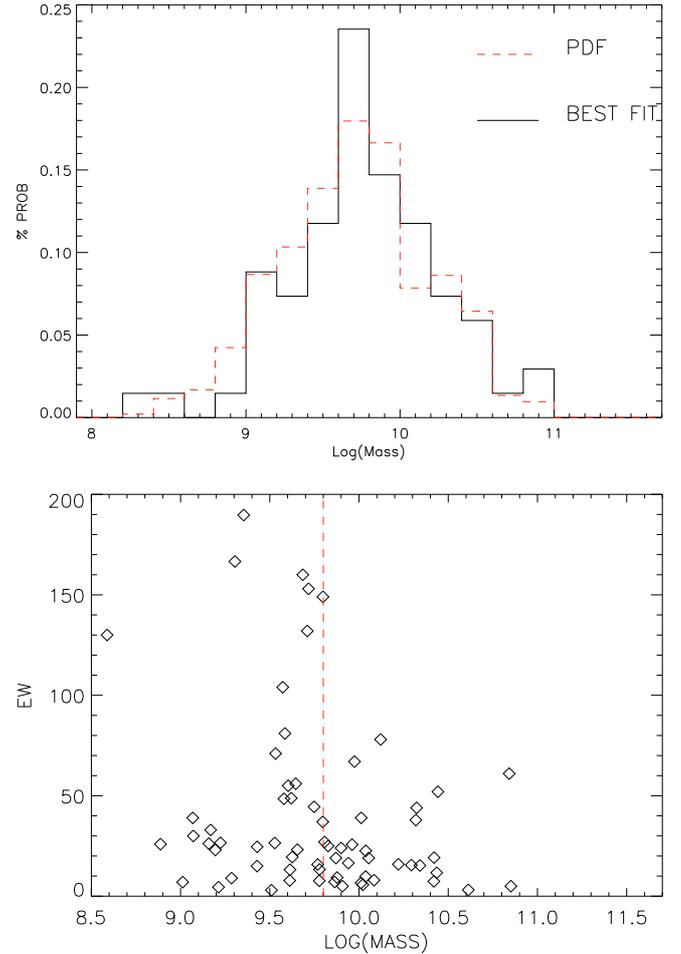


Fig. 5. Upper panel: the distribution of stellar masses for the LBGs in our sample (best fit values). Lower panel: the dependence of stellar masses (best fit values) on Ly α EW . The dashed line indicates the median mass.

However the difference in mass is larger than expected: our sample comprises also galaxies with similarly faint broad-band magnitudes, thanks to the very deep GOODS observations. For example the NB emitters of Finkelstein et al. (2007) at $z \sim 4.5$ have typical i -band brighter than 26(AB), while several of our V-dropouts, at a similar redshift, are even fainter than this limit, in i -band. We also point out that most of the previously reported mass values, either lacked good IR data (which are of extreme importance for a reliable mass estimate) or were performed on stacked photometry.

The difference could be due, in part, to the observed lack of massive galaxies with bright EW which is clearly seen in the lower panel of Fig. 5. Here we show how the stellar mass and Ly α EW s are related. The dashed line indicates the median mass of the entire sample, derived above. Although we see no definite correlation between total stellar mass and EW , we notice that while lower mass objects span the whole range of EW from 0 to 200 \AA , more massive objects have in general smaller EW s. In particular if we take those galaxies with $EW > 80 \text{\AA}$ (9 in our samples) they all have masses that are equal or below the median mass.

This effect is similar to the deficiency of bright galaxies with high EW s that was initially noted by Ajiki et al. (2004) and recently confirmed by Ando et al. (2007) in a smaller sample of

LBGs at redshift $z \sim 5-6$: they found that luminous LBGs (with absolute magnitudes $M_{1400} = -21.5$) generally show weak emission lines, while fainter LBGs show a wide range of Ly α EW . We also checked our EW as a function of absolute luminosity at 1400 Å and confirmed the results of Ando et al. in terms of continuum luminosity, with a much larger sample of galaxies and spanning a slightly wider redshift range. This same result is confirmed by Vanzella et al. (in preparation) for all LBGs in the GOODS sample.

This effect cannot be due to selection biases, since bright/massive objects with high EW would not be missed in a spectroscopic survey (on the other hand observations could miss faint-small galaxies with low EW). Moreover it cannot be due to statistics given the size of the sample: the total absence of such strong emitters in the more massive half of the sample would be an implausibly large fluctuation. We will discuss the possible origin of this effect in Sect. 5. Here we point out that this observational trend could partially explain the difference in mass between our sample and the sample of LAEs. As already noted previously, NB surveys tend to select galaxies with extremely high EW . Although nominally the limit is 20 Å, most objects have much larger EW , of the order of 100 Å or higher (see for example Fig. 1 of Finkelstein et al. 2007). Thus they would naturally tend to select less massive galaxies than the LBG selection criteria, even in samples with similar broad band detection limits (e.g. see Fig. 6 of Dijkstra & Wyithe 2007).

4.3. Star formation rates

There are different ways of estimating the SFR in line emitting galaxies.

- The first and most obvious is from the Ly α emission, using the calibration from Kennicutt (1998) for the H α emission line $SFR = 7.9 \times 10^{-42} L_{H\alpha} M_{\odot} \text{ yr}^{-1}$, and assuming case B recombination which gives $L_{Ly\alpha} = 8.7 \times L_{H\alpha}$ where all luminosities are expressed in units of ergs/s. This SF estimator is sensitive to instantaneous star formation, since the flux depends mostly on very massive stars ($M > 20 M_{\odot}$).
- The SFR can also be estimated from the UV continuum using the Kennicutt conversion: $SFR_{UV} = 1.4 \times 10^{-28} L_{\nu} M_{\odot} \text{ yr}^{-1}$, where L_{ν} is the luminosity at rest-frame 1400 Å in units of ergs per second per hertz. This relation assumes a 10^8 years timescale for a galaxy to reach the full UV luminosity, so for the youngest objects the conversion could underestimate the SFR. In any case the line-derived SFR is a more instantaneous measure than the UV-derived one. Both the Ly α and UV continuum photons are highly sensitive to the presence of dust although in a different way (see next section). Moreover both SFR estimators are highly dependent on the IMF. Note that our UV continuum luminosity at 1400 Å comes out of the SED fit so it depends also on the model.
- Finally we have the SFR value derived from the fit. This is not independent of the UV derivation, but it depends more heavily on the model assumed for the star formation history, in our case the exponentially declining star formation rate with e -folding time τ .

The values derived are between few and few tens of $M_{\odot} \text{ yr}^{-1}$ for $SFR_{Ly\alpha}$ and SFR_{UV} , in broad agreement with the range found e.g. by Tapken et al. (2007) for LBGs with Ly α in emission and by Ajiki et al. (2003) for Ly α emitters at $z = 5.7$.

Like these authors we then examined how SFR_{UV} and $SFR_{Ly\alpha}$ compare to each other. In principle the ratio

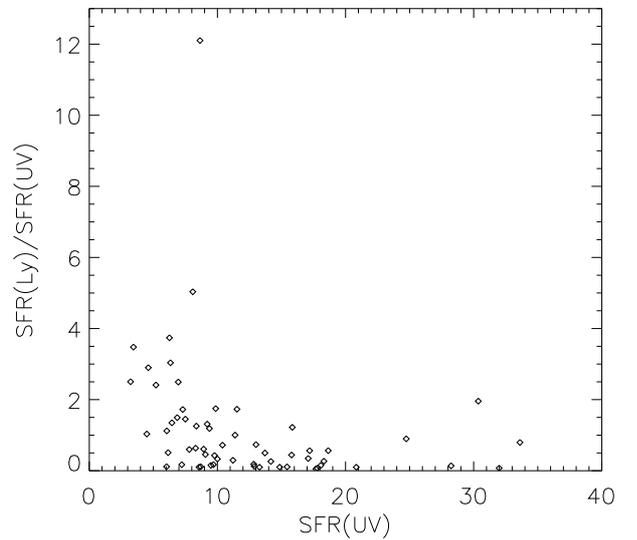
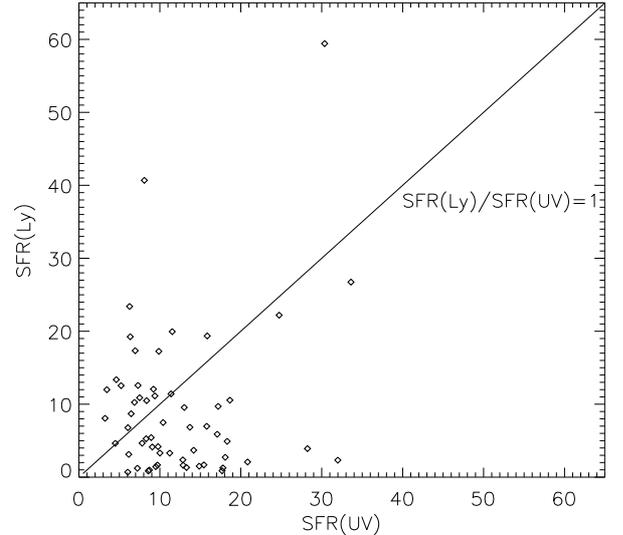


Fig. 6. Upper panel: the star formation rate derived from the UV continuum at 1400 Å versus the SFR derived from the Ly α line emission (uncorrected for dust extinction, see text for details). Both values are in $M_{\odot} \text{ yr}^{-1}$. Lower panel: the ratio $SFR_{Ly\alpha}/SFR_{UV}$ versus the total SFR_{UV} .

$SFR_{Ly\alpha}/SFR_{UV}$ is directly related to the EW value. However for the present work we point out that EW and Ly α total flux are measured directly from the spectra, with the reference continuum taken at ~ 1200 Å; the UV continuum that goes into the SFR_{UV} determination is derived from a fit to the broad band photometry and at 1400 Å rest-frame. Therefore the line EW and flux come from a region of width $1''$ centered on the galaxy, corresponding to the slit width used in the spectroscopic observations. The UV continuum (and the SED fit) refers to aperture photometry flux, and can be assumed to be the “total flux”. This should not be a big problem since the Ly α emitters are in general very compact galaxies, as shown by Lai et al. (2007). Moreover LBGs with Ly α in emission are in general smaller than those with the line in absorption, as recently shown by Vanzella et al. (2008, in preparation). Their typical half light radius is ~ 5 ACS pixels i.e just $0.25''$. Therefore most of the flux should come from the inner region, well within the slit-width used for

spectroscopy. Clearly this refers to the continuum morphology but a comparison of NB and continuum images for Ly α emitters around several high-redshift radio galaxies shows that the two are very well correlated (Venemans et al. 2007).

We therefore estimated the correction factor: we assumed that the line emission is distributed as the continuum, smoothed the high resolution continuum image (closest to the Ly α λ), to the ground based spectroscopic resolution and then estimated the flux inside the slit aperture. We repeated this for all galaxies and found that the fraction of flux that falls inside the slit is $\sim 80\%$ of the total.

The results are presented in Fig. 6. Note that all these values are uncorrected for dust extinction, so the true star formation rates are likely to be higher.

The values are comparable to what is found for LBGs at similar redshifts by e.g. Tapken et al. (2007), Stanway et al. (2007) and Verma et al. (2007) and for LAEs at $z = 3-6$ (Ajiki et al. 2003; Venemans et al. 2005).

The median ratio $SFR_{Ly\alpha}/SFR_{UV}$ is ~ 0.7 , so in general the SFR_{UV} is larger than the $SFR_{Ly\alpha}$ but the scatter is very large. Similar results although with large variations were found both for LAEs and for LBGs with Ly α emission. For continuum selected high-redshift galaxies, Tapken et al. (2007) find a median ratio of 0.2 with values ranging from 0.1 to 20 while at higher redshift Dow-Hygelund et al. (2007) find values between 0.27 and 1.2 with a large scatter for i -dropouts. For Ly α emitters Ajiki et al. (2003) find a median $SFR_{Ly\alpha}/SFR_{UV} \sim 0.5$; whereas Venemans et al. (2006) find a mean of 0.6–0.7 for galaxies in a protocluster around a radio-galaxy at redshift 3.1

The lower average value of $SFR_{Ly\alpha}$ are therefore ubiquitous and can in general be attributed to the effect of dust extinction and scattering by the intergalactic medium. However, some of our galaxies have $SFR_{Ly\alpha}/SFR_{UV}$ larger than 1. These galaxies could be in the very early phases of star formation activity, in which SFR_{UV} values are underestimated (Schaerer 2000; see also Nagao et al. 2004, 2005). Indeed by checking the best fit ages estimated from the multiwavelength SED, we see that most of these galaxies having $SFR_{Ly\alpha}/SFR_{UV} > 1$ are extremely young, with ages of a few tens of Myr. As illustrated in Fig. 6 (bottom panel), objects with small SFR_{UV} have higher $SFR_{Ly\alpha}/SFR_{UV}$ ratios, i.e. these very young galaxies tend to have also relatively modest SFR values.

The wide variety of $SFR_{Ly\alpha}/SFR_{UV}$ could also be the effect of the different way in which dust suppress Ly α photons and continuum photons, which will be discussed in the next subsection.

4.4. Dust

While in general Ly α emitters are regarded as a dust-free population (e.g. Lai et al. 2008; Gawiser et al. 2006), we find that the presence of a modest but non-zero amount of dust is required by the SED fit of many galaxies. The fitted $E(B-V)$ parameter is not zero in about 2/3 of the galaxies, with individual galaxies showing values as high as $A_V \sim 1$. However the mean extinction of the whole sample is very low, corresponding to $A_V \sim 0.25$ (roughly $A_{1200} \sim 1$). This fits in the trend recently noticed by Finkelstein et al. (2008b): studies that analyze objects separately seem to detect dust extinction (at least in some galaxies), while those that stack fluxes do not.

In our previous paper (P07) we found that LBGs with Ly α in absorption are actually dustier than the LBGs with Ly α in emission: they had redder slope β , as determined directly from the

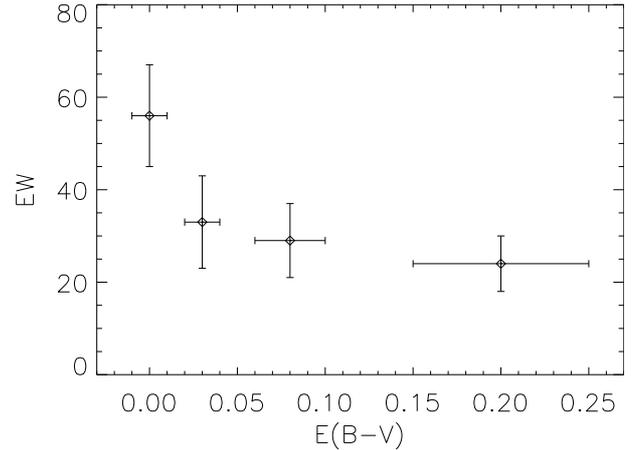


Fig. 7. The average EW of galaxies divided by values of $E(B-V)$. Error bars for EW are the standard error of the mean, error bars in $E(B-V)$ correspond to the range of values in each subsample.

observed colors $i-z$ and consequently had, on average, a higher $E(B-V)$ parameter, as derived from the spectral fitting. However, the differences we found were not very large, possibly due the small size of our sample. With our enlarged sample we checked if there is any dependence on the $E(B-V)$ parameter on the Ly α equivalent width, by dividing our sample into 4 sub-groups according to the value of $E(B-V)$, respectively $E(B-V) = 0, 0.03, 0.06-0.1, 0.15-0.4$. For each group we determined the mean EW , and we plot them in Fig. 7 (error bars for EW indicate the standard error of the mean, while the bars in $E(B-V)$ correspond to the range of values in each subsample). As we can see there is a net trend of Ly α EW with dust extinction, with unextincted galaxies showing on average higher Ly α EW , similar to what found by Shapley et al. (2003). The number of objects is approximately equal in each subgroups, therefore the larger error bars for the objects with less extinction reflect a larger dispersion of the values around the mean.

Previously Shapley et al. (2003) also found similar trend between $E(B-V)$ and EW , for LBGs at $z \sim 3$. From composite spectra they found considerable difference between the LBGs with and without Ly α emission, with the former having a steeper slope. They also found a significant positive dependence of slope on the Ly α equivalent width. Finally Vanzella et al. (2008, in preparation) analysed composite spectra of B , V and i -dropouts from GOODS: in particular for the $z \sim 4$ sample the composite spectrum of the absorbers has a spectral slope considerably redder than the emitters, in accordance with our results.

Finkelstein et al. (2007, 2008a) proposed an interesting scenario in which dust effects could enhance the Ly α EW by allowing the Ly α photons to escape, even if the continuum is extinguished. In other words dust can selectively suppress the continuum emission but not the Ly α : this is possible in a clumpy medium where dust is primarily in cold neutral clouds, whereas the inter-cloud medium is hot and mainly ionized (e.g. Hansen & Oh 2006). Since we find that in general EW and $E(B-V)$ are well correlated, and the larger the $E(B-V)$ inferred from the continuum, the smaller the Ly α EW , we can conclude that on average dust suppresses in a similar way both the continuum and the Ly α photons. Therefore the clumpy scenario is not needed. However we cannot exclude that it can work for some individual galaxies. We have not attempted a full SED modeling of our galaxies to include the clumpiness q parameter *à la* Finkelstein et al., but

we can search our sample for galaxies with non negligible dust content, and at the same time a relatively bright Ly α emission.

We find one galaxy at redshift 5.5 which shows a bright Ly α line, with $EW \sim 80 \text{ \AA}$ (rest-frame) and a relatively large value of $E(B - V) = 0.4$. We checked the SED and it is indeed a quite red and massive galaxy ($M \sim 10^{10} M_{\odot}$). Its slope in the near-IR rest-frame is well constrained by detections in the four IRAC bands. The observed SFR_{UV} is also about 3.5 higher than the $SFR_{Ly\alpha}$. It is therefore possible that in this galaxy a clumpy dusty ISM could enhance the EW . Actually Finkelstein et al. argue that this mechanism could be at work also in galaxies with smaller amounts of dust: they find few objects that require values of $A_{1200} = 1$ (corresponding to $A_v = 0.25$ approximately) but where the dust enhancement is necessary. A full modeling of our galaxies within this scenario is beyond the scope of this paper and is deferred to future work.

4.5. New Charlot and Bruzual models

All previous results have been obtained with the Bruzual & Charlot models (BC03), since these are the most used models in the community, and we wanted to make a direct comparison to previously published work. In this subsection we briefly summarize the results obtained with the more recent CB07 models. The obtained masses are on average 20% lower than those obtained with the BC03 models and the ages are younger also by an average 20%, while the continuum derived star formation rates are more similar. Moreover the differences are systematic and do not present a large scatter; this implies that qualitatively the main results (i.e. the presence of old and massive Ly α emitters) do not change even using the new libraries, but are only mildly rescaled. As an example if we consider the “solid” old galaxies with the same requirement as in Sect. 3 (i.e. best fit age larger than 500 Myr and minimum age for a good fit ≥ 300 Myr) we find 11 (instead of 13) galaxies with only two objects dropping out of the group. All correlations between properties that we have presented, namely the age vs. EW , total mass vs. EW and $E(B - V)$ vs. median EW , do not change with the new models.

Note that the differences in mass and age that we find are somewhat smaller than those reported in the literature, e.g. a 50% mass difference reported by Bruzual (2007). This is not surprising since our sample is at high-redshift. In the new models (as well as those of Maraston 2005) the most notable change is the inclusion of the TP-AGB phase of stellar evolution: its contribution, in the 0.2–2 Gyr age range, is at a maximum in the near-IR (K band) rest-frame which we do not sample even for the lower redshift galaxies in our sample.

5. Discussion and conclusions

We have analyzed a sample of 68 Ly α emitting LBGs analyzing their physical and spectral properties. Here we summarize the main results and discuss them:

Although most galaxies are fit by young stellar populations, a small but non negligible fraction has SEDs that cannot be well represented by young models and require considerably older stellar component up to ~ 1 Gyr. Age and EW do not show a strong correlation. Some of the robust “old” galaxies have EW as high as 100 \AA and therefore in principle they should be present also in narrow-band selected samples of LAEs.

The presence of these old galaxies with strong Ly α emission is also important for modeling the entire LAE population. For example most authors that have modeled the Ly α population to reproduce the LF and clustering properties of LAEs and of LBGs (e.g. Mao et al. 2007; Mori & Umemura 2006; Thommes & Meisenheimer 2005) assume in general much shorter timescale for Ly α emission of the order of ~ 1 –200 Myr at most.

Recently Finkelstein et al. (2008b) found 2 out of 15 LAEs to be consistent with evolved galaxies with ages around 0.5 Gyr, with the rest confined to ages below few tens of Myr. They suggested a possible bi-modality in the age distribution of LAEs. They also suggested that the clumpy dusty ISM scenario (already discussed above) could cause old galaxies to still have Ly α in emission.

Similarly Thommes & Meisenheimer (2005) presented model calculations on the Ly α emitting primeval galaxies. They suggested the possibility of a double phase activity for the Ly α emission, i.e. that the Ly α had a initial bright phase with a short timescales, due to primeval gas in almost dust-free galaxies, and a secondary phase at much later time.

As a possible test to this model, they predict that in the galaxies undergoing the second bright phase of emission, the dust has been swept away by gas outflows, so the Ly α lines should be shifted by the velocity of the outflowing wind relative to the metal absorption lines and should show a P-Cygni profile. Furthermore the relative contribution of the second generation of these bright Ly α emitters should increase with cosmic epoch, i.e. while at redshift ~ 5 –6 most of the Ly α emitters should be primeval galaxies, at redshift 3, i.e. a Gyr after, there should be also a lot in this second bright phase.

Both this effects could be tested. In a forthcoming paper we will present results on a sample of LBGs with Ly α emission at $z \sim 2.5$ –3 from the GOODS-south field, to see if the age distribution of these galaxies is significantly different from the present sample.

We then found a lack of galaxies with large stellar masses and high EW , which cannot be due to a selection effect or a statistical fluctuation. There could be several possible causes for this trend: a first possibility is that the brightest/most massive galaxies might reside in more dusty environment compared to less massive galaxies. We do not find significant differences in the $E(B - V)$ values between massive galaxies and the rest of the sample, but we cannot exclude this possibility.

The amount of HI gas in and surrounding the galaxies could also affect the Ly α EW s: the most massive galaxies probably reside in more massive DM halos, and they could be surrounded by a larger amount of HI gas that selectively extinguish the Ly α emission, resulting in smaller EW s. This also fits in the biased galaxy formation scenario. Finally as argued by Shapley et al. (2003), LBGs with smaller EW have in general also stronger LIS absorption and large velocity offset of the Ly α emission: it could therefore be that these galaxies (which are most massive) contain more outflowing neutral gas with a large velocity dispersion that would depress partially the Ly α emission resulting in a smaller EW . This would result in more asymmetric line profiles, which could be observed in higher resolution spectra (such as those by Tapken et al. 2007).

The presence of dust, although in small amounts, is required by the SED fit of many galaxies. Therefore Ly α emitters are not completely dust-free galaxies. The amount of dust and the EW are well correlated, at least on average. This was already observed at redshift ~ 3 by Shapley et al. (2003) and at redshift ~ 4 in our previous work (P07). In a recent paper Schaerer & Verhamme (2008) present the results of the application of their

radiative transfer model (Verhamme et al. 2006) on the well studied LBG 1512-cB58 at $z \sim 3$. From this analysis they derive the interesting implications that even to model the spectra of LBGs where Ly α is present in absorption, an intrinsic relatively high EW ($>60\text{--}80 \text{ \AA}$) Ly α line is required. They propose that the vast majority of LBGs have intrinsically high EW (60 or larger) and that the main physical parameter responsible for the observed variety of line profiles and strengths in LBGs is the HI column density N_{H} , and the accompanying variation of the dust content. This model explains naturally the trend of EW with $E(B - V)$ parameter found in Fig. 7. It also explains the difference in the UV slope parameter between the LBGs with and without Ly α emission, that we found in P07 for $z \sim 4$ galaxies and the analogous results by Shapley et al. (2004) at $z \sim 3$. Given the observed mass metallicity relation, it is natural to speculate that the most massive galaxies are in general also dustier: this could easily explain the lack of massive galaxies with very large Ly α EW that we show in Fig. 1, but as already noted above we do not recover any net correlation between mass and $E(B - V)$, possibly due to the large scatter.

Finally we found that the SFR_{UV} and $SFR_{\text{Ly}\alpha}$ are similar, with the $SFR_{\text{Ly}\alpha}$ on average somewhat lower than the other values, in agreement with previous results. There is a large scatter in the values of $SFR_{\text{Ly}\alpha}/SFR_{\text{UV}}$ for individual galaxies which could be due to the different effect of dust on the continuum and Ly α photons or to other effects, such as the variations in the gas metallicity or fluctuations in the opacity of the IGM.

In conclusion, there seems to be a continuity of properties between LBGs with faint Ly α emission, and those with brighter Ly α , such that they would be selected also by NB searches. Not all Ly α emitting galaxies are small, young dust-free galaxies. A non negligible fraction shows older stellar populations, with ages up to ~ 1 Gyr and masses in excess of $10^{10} M_{\odot}$. The lack of massive objects in NB selected samples can be partly explained by the observational trend presented in Fig. 5. On the other hand, relatively old galaxies should be present also in NB selected samples. This difference could be in part ascribed to two effects: first, most of the NB studies do not have a wavelength range as wide as GOODS to effectively determine the physical properties, and/or lack data in the fundamental region around 4000 \AA break which are essential to reduce model degeneracies (although they cannot be solved completely). Second, and most important, we find that there is a large diversity of properties amongst Ly α emitting galaxies. Therefore, those studies that rely on stacked photometry to derive the average physical properties might miss to represent the galaxies with the most extreme characteristics: e.g. the presence of a 20% old galaxies could be missed if “diluted” in a more numerous, much younger population.

The present study shows that the simple picture LAEs equal young galaxies, LBGs equal older galaxies cannot explain all the observed properties and trends. A more complex scenario is probably needed, including variables such as the dust content, the ISM clumpiness, the amount and kinematics of neutral gas, and perhaps the viewing angle of galaxies as recently suggested by Laursen et al. (2008).

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