Physical and morphological properties of z~3 LBGs: dependence on Lyα line emission

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ABSTRACT

Aims. We investigate the physical and morphological properties of LBGs at redshift ~2.5 to ~3.5, to determine if and how they depend on the nature and strength of the Lyα emission.

Methods. We selected U-dropout galaxies from the z-detected GOODS-MUSIC catalog, by adapting the classical Lyman Break criteria on the GOODS filter set. We kept only those galaxies with spectroscopic confirmation, mainly from VIMOS and FORS public observations. Using the full multi-wavelength 14-bands information (U to IRAC), we determined the physical properties of the galaxies, through a standard spectral energy distribution fitting procedure with the updated Charlot & Bruzual (2009) templates. We also added other relevant observations of the GOODS field, i.e. the 24μm observations from Spitzer/MIPS and the 2 MSec Chandra X-ray observations. Finally, using non parametric diagnostics (Gini, Concentration, Asymmetry, M bb and ellipticity), we characterized the rest-frame UV morphologies of the galaxies. We then analyzed how these physical and morphological properties correlate with the presence of the Lyα emission line in the optical spectra.

Results. We find that, unlike at higher redshift, the dependence of physical properties on the Lyα emission tends to be more massive and duster than the rest of the sample, but all other parameters, ages, star formation rates (SFR), X-ray emission as well as UV morphology do not depend strongly on the presence of the Lyα emission. A simple scenario where all LBGs have intrinsically high Lyα emission, but where dust and neutral hydrogen content (which shape the final appearance of the Lyα) depend on the mass of the galaxies, is able to reproduce the majority of the observed properties at z~3. Some modification might be needed to account for the observed evolution of these properties with cosmic epoch, which is also discussed.

Key words. Galaxies: distances and redshift - Galaxies: evolution - Galaxies: high redshift - Galaxies: fundamental parameters -

1. Introduction

A long debated issue concerns the relation between Lyman break galaxies (LBGs), i.e. star-forming galaxies selected from the presence of the Lyman break in their spectral energy distribution (e.g. Steidel et al. 1996), and Lyα emitters (LAEs), i.e star-forming galaxies selected via the presence of a strong Lyα emission line, through deep narrow-band observations (e.g Cowie & Hu 1998, Hu et al. 1998, Rhoads & Malhotra 2001). Both these techniques have led to the discovery of large number of galaxies at increasingly high redshift (e.g. Ouchi et al. 2005, Venemans et al. 2007, Stanway et al. 2007, Ota et al. 2008), with the current record holder being a LAE at z=6.96 (Iye et al. 2006). The nature of the high redshift galaxies selected through the Lyα emission line and the link with the star-forming population selected via the Lyman–Break is still not clear (e.g. Gawiser 2009). This relation has an important implication in our interpretation of the very high redshift Universe where, due to current instrumental limitations, it becomes progressively easier to spectroscopically confirm only the Lyα emitters (e.g. Dow-Hygeldun et al. 2007).

On one hand the Lyα bright phase could represent a stochastic event in the life of any galaxy (as in the duty cycle model e.g. Nagamine et al. 2008); alternatively it could be related to some specific physical property of the galaxies, such as the (young) age, the dust or gas content.

In principle, the Lyα line can be used to probe star-formation rates, clustering properties (Kovac et al. 2007), and even for cosmological applications such as re-ionization studies (e.g. Dijkstra et al. 2007, Dayal et al. 2008). In practice, this effort is far from trivial because of the above stated complications. Understanding what determines the presence of the Lyα emission line is therefore fundamental to interpret the bias introduced by the observational selection techniques.

A comparison between the physical and morphological properties of LBGs and LAEs is necessary but not straightforward. Because of the different selection techniques, LAEs tend to be much fainter than LBGs and therefore modelling their spectral energy distributions (SEDs) to constrain the relevant physical properties has always been a difficult task (see Gawiser 2009 for a review). Most studies rely on stacked photometry and are able to derive only average properties (e.g. Finkelstein et al. 2007, Nilsson et al. 2007, Lai et al. 2008). Furthermore until recently, most LAEs samples, lacked (deep) data in the mid-IR range which are crucial to constrain stellar mass at redshift > 4, where the 4000 Å break is shifted beyond the K-band. A good coverage of the near-IR was also often missing, and this is important to reduce the model degeneracies (e.g old/dust-free vs young/dusty population). For this reason, we took a slightly different approach and decided to study the properties of Lyα emitting galaxies selected as LBGs. In this way, we select galaxies that are bright enough in the continuum to be detected at other wavelengths (so their SEDs can be modelled) and show Lyα in emission: we can then study the dependence of phys-
ical properties on the emission line strength and characteristics, on individual galaxies, rather than relying on the stacking technique. Clearly this is only possible with a survey that has both deep multi-band data on a relatively large area, as well as excellent spectroscopic coverage. The GOODS survey (e.g., Dickinson et al. 2004, Giavalisco et al. 2004) has all these properties: in particular we took advantage of the excellent observations in the near-IR, which cover the rest-frame region around the 4000 Å Balmer break, reducing some of the model degeneracies. Furthermore, the deep IRAC data allow the determination of stellar masses with great accuracy (e.g. Fontana et al. 2006). In previous works, we have compared the properties of LBGs with and without line emission for a relatively small sample of z~ 4 galaxies (Pentericci et al. 2007, hereafter P07), and then studied the properties of a more numerous sample of Lyα emitting LBGs in the redshift range 3 to 6 (Pentericci et al. 2009, hereafter P09). In this paper we study the properties of LBGs at redshift ∼2.5-3.5, the so-called U–dropouts, initially selected from their continuum and color properties and with follow-up spectroscopic confirmation: the lower redshift allows us to assemble a sample much larger than in our previous work and study the trends in a statistically more significant way. At the same time thanks to the brighter average magnitude of the galaxies we can also attempt a morphological analysis, which was not possible at higher z. As in previous work, we use the GOODS–MUSIC catalog (Grazian et al. 2006) in its revised and updated version (Santini et al. 2009). In particular the new cataloger contains 24 micron data from Spitzer/MIPS observations and a revised and more accurate IRAC photometry. New spectra from public surveys (Vanzella et al. 2009; Popesso et al. 2009) were also added. We also include an analysis of the deep X-ray data available for the field i.e. the 2 Ms Chandra exposure (Luo et al. 2008) that allows us to study the star formation and/or AGN content in an independent way. All magnitudes are in the AB system (except where otherwise stated) and we adopt the Λ–CDM concordance cosmological model (H₀ = 70, Ωₘ = 0.3 and Ωₐ = 0.7).

2. The sample

To select z~ 3 galaxies we have adapted the usual Lyman break technique to the filters adopted in the GOODS survey, which is different from the classical UGR set used by Steidel et al. 2003 (see also Giavalisco et al. 2004). The redshift ∼ 3 objects are selected as U–dropouts according to the following cuts:

\[ -0.2 \leq V - I \leq 0.35 \]
\[ U - V \geq 0.75(V - I) + 1.15 \]

which are effective at 2.4 ≤ z ≤ 3.5. These cuts were determined by Grazian et al. (2007) using our multicolor GOODS–MUSIC database, and from a comparison to the photometric redshift distribution were adjusted to maximize the completeness and minimize the number of interlopers at redshift outside the above range. In that work, we also verified that these criteria are almost (although not entirely) equivalent to the original LBG criteria, by reproducing the synthetic UGR magnitudes for the galaxies. However several differences remain, beside the difference in the filter set and the color selection: first of all the LBGs were traditionally selected in the R–band, which is lacking in the GOODS survey, and not in the z–band, as in this work; furthermore LBGs were originally relatively bright galaxies, since the historical criterion used was R ≤ 25.5, while in this work the selection is pushed till the nominal completeness of the GOODS–MUSIC sample (z–band magnitude limit of 26.0). All these result in some differences in the final sample properties, mainly a redshift distribution of galaxies that is slightly wider than in Steidel et al. (2003) sample and possibly a slightly bluer average color (see also Section 4.1 for this point). Objects flagged as AGNs (on the basis of their X-ray emission, and/or mid-IR excess and/or spectral properties) in the GOODS–MUSIC catalog were not included in the analysis. We found about 450 U–dropouts in the entire GOODS–South. We then cross correlated this list with the spectroscopic observations available in the area. Spectra of galaxies in the GOODS–South field were obtained by several different observational campaigns: the two largest ones were conducted by ESO, with FORS2 (Vanzella et al. 2006, 2008, 2009) and VIMOS (Popesso et al. 2009). Other redshifts were obtained with the VLT by GMASS (Kurk et al. 2009), by the HST/ACS/G880L grism survey PEARLS (Straughn et al. 2008) and the similar GRAPES project (Pizzol et al. 2004, Malhotra et al. 2005). In total there are 130 U–dropout galaxies with confirmed redshift.

As in P07 we define LBG₁ the Lyman break galaxies that show the Lyα line in emission, regardless of its strength. We measured the equivalent width (EW) of the Lyα line from the 1D spectra, using the IRAF task spex, by marking two continuum points around the line to be measured. The linear continuum is subtracted and the flux is determined by simply summing over the pixels (no fitting of the line profile is performed). The sample of LBG₁ contains 66 galaxies of which 24 have rest-frame Lyα Equivalent Width EW > 20 Å and, therefore, would be selected as LAEs in a narrow band survey. The rest of the LBG₁ have a line emission too faint to pass that selection. Lyman break galaxies with no sign of emission or with a clear absorption are called LBGᵥ and are also 66 (note that two galaxies show both a clear emission line and an absorption and are included in both samples). The two sub-samples are not biased in terms of V-band magnitude, or absolute rest-frame luminosity at 1400 Å (see first entry of Table 1). This indicates that, for this sample, the redshift confirmation of LBGs does not depend sensibly on the presence of emission lines (see also Popesso et al. 2009). In Figure 1 we plot the redshift distribution of our final sample of galaxies, as well as for the two sub-samples separately. The overall redshift distribution of the GOODS survey is shown in black. The LBG₁ sub-sample is shown in green, and the LBGᵥ sub-sample in red.

Fig. 1. Distribution of spectroscopic redshifts for the entire sample (black line), the LBG₁ sub-sample (green line) and LBGᵥ sub-sample (red line).
distribution of our LBGs, and in particular the partial lack of objects around $z \sim 3$, is shaped by the spectroscopic completeness level of the GOODS catalog (plotted in Figure 6 of Popesso et al. 2009). This spectroscopic catalog is actually formed by a compilation of many different spectroscopic surveys (as discussed earlier), each with its own selection criteria and efficiency: the completeness level is therefore a complicated function of redshift and it has a local minimum around $z \sim 3$. For the purpose of the present work, we just note that the two sub-samples have a consistent redshift distribution.

3. SED fitting

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; Dory et al. 2004). Briefly, a grid of spectral templates is computed from standard spectral synthesis models, and the expected magnitudes in our filter set are calculated. The derived template library is compared with the available photometry and the best-fit model template is adopted according to a $\chi^2$ minimization. During the fitting process, the redshift is fixed to its spectroscopic value. The physical parameters associated with each galaxy are obtained from the best-fit template up to 5.5 $\mu$m rest-frame. This analysis assumes that the overall galaxy SED can be represented as a purely stellar SED, extincted by a single attenuation law, and that the relevant $E(B-V)$ and basic stellar parameters (mostly age and star formation history, but also metallicity) can be simultaneously recovered with a multi-wavelength fit. We note that parameter degeneracies cannot be completely removed, especially at high redshift, even if our filter sets samples quite evenly the overall wavelength range involved. Previous studies (Shapley et al. 2003, 2001; Papovich et al. 2001) demonstrated that stellar masses are well constrained, while for other parameters the uncertainties become larger, especially at high redshifts, due to the SFR-age-metallicity degeneracies.

In our analysis, we estimated SFR, AGE Mass, $E(B-V)$ and metallicity using Charlot & Bruzual (2009 in preparation, hereafter CB09) synthetic models, fitting the whole 14 bands of photometry (namely $U_{33}$ and $U_{8}$ from the WFI on the ESO 2.2m telescope, $UVIMOS$, ACS/HST B, V, i and z, VLT/ISAAC J, H and K, SPITZER/IRAC 3.5, 4.5, 5.8 and $8\mu m$). Note that the catalog was produced using a specific software for the accurate “PSF-matching” of space and ground based images of different resolution and depth, named ConvPhot (De Santis et al. 2007). We assumed a Salpeter IMF and we parametrize the star formation histories with a variety of exponentially declining laws (of timescales ranging from 0.1 to 15 Gyr), metallicities (from $Z = 0.02Z_{\odot}$ to $Z = 2.5Z_{\odot}$) and dust extinctions ($0 < E(B-V) < 1.1$, using a Calzetti extinction curve). Details are given in Table 1 of Fontana et al. (2004), in Fontana et al. (2006) and in Grazian et al. (2006). The age of each object is constrained to be less than the age of the Universe at the relevant redshift. We also adopted a minimum age of 10 Myrs. We are aware that exponential star formation histories may not be the correct choice in some cases, but allowing $\tau$ to vary we can actually reproduce both an instantaneous burst (when $\tau$ is very small) and a constant star formation rate (when $\tau$ is $>>$ than the age of the galaxy.) At variance with our previous works (P07, P09) we use here the new version of the stellar population model described in detail in Charlot & Bruzual (2009). The main improvement over the previous Bruzual & Charlot (2003, BC03) model is an updated treatment of the emission from the stars that are in the thermally-pulsing asymptotic giant branch (TP-AGB) phase of stellar evolution from the models of Marigo & Girardi (2007). As shown first by Maraston (2005, M05) and Maraston et al. (2006), TP-AGB stars are especially important in galaxies whose spectra are dominated by emission from these intermediate age stars. As already shown by several authors (e.g. Marchesini et al. 2009, Eminian et al. 2008, Lamareille et al. 2008) the CB09 models give masses that are, on average, lower than the BC03 ones. In particular, the recent study by Salimbeni et al. (2009) on a sample that partially overlaps with the present one showed that the average mass difference in their highest redshift bin (which includes the range $z \sim 2.5-3.5$, see their figure 4) is around $\sim 30\%$, with a slight dependence on mass.

Examples of SED fitting for some of the galaxies, spanning the entire redshift range, are shown in Figure 2. While $[OII]$ and H$\alpha$ emission are included in the models, with strength proportional to the SFR, according to the Kennicutt (1998) relations, the Ly$\alpha$ and $[OIII]$ emission line are more difficult to model. In particular the Ly$\alpha$ line could contaminate the photometry of the B or V-band (depending on the redshift) and therefore change the result of the SED fitting. To check this, we have performed a second fit, excluding the band that contains the emission line. Alternatively we estimate the Ly$\alpha$ line contribution to the corresponding broad band flux (B-band for $z < 2.9$ and V-band for the rest) following eq. (2) of Papovich et al. (2001) and perform a third fit including the full set of 14 bands. This method is actually somewhat more uncertain, since the EW are estimated from the 1-dimensional spectra, while the broad band magnitudes are measured from aperture photometry, and we have no information on the relative spatial distribution of the line emitting gas and the stars in each individual object. In any case both fits give results that are entirely consistent with the initial one: this indicates that the Ly$\alpha$ line does not influence significantly the SED-fitting outcome, also because none of the LBG is a strong emitter/absorber. It also confirms the solidity of the fit: the results do not depend on the individual band, thanks to the large number of bands that we are using in the fits. Finally we also checked if the $[OIII]5007$ line contribution could somehow change the results of the SED-fit: the $[OIII]$ line is harder to model, since its strength is known to vary considerably for a given H$\alpha$ flux (e.g. Moustakas et al. 2006), and this precludes its suitability as a SF indicator: If we include it in the SED fitting assuming a mean $[OIII]$ flux as inferred in local star-burst galaxies corresponding to a ratio f([OIII])/f([OII])=0.32, the output of the fit do not change.

4. Physical properties: results

We present here the main results for stellar masses and ages of our sample. The values are those obtained with the CB09 models. For reference and comparison to previous work we also report the relative values obtained with the BC03 (between parenthesis). The total stellar masses that are found span a range $10^7 - 10^{11} M_{\odot}$, with a median value of $5.3(7.5) \times 10^8 M_{\odot}$. These values are similar to those found by Shapley et al. 2003 (which were obtained with the even older BC96 models). The median age of our sample is 320 (500) Myrs, very similar to the Shapley et al. value, while the E(B-V) best fit parameter is smaller 0.06(0.06) vs 0.15. The discrepancies in the best fit E(B-V) raise in part from the different model of star formation history adopted.
Fig. 2. Examples of the 14-bands SED fitting for some of the galaxies, in order of increasing redshift from $z \sim 2.4$ (upper left) to $z \sim 3.5$ (lower right). In each panel we plot the photometry in the 14 bands (U to 8 $\mu$m) in black with relative errors, and in red the best fit solution. The two emission lines that are visible in many SEDs are the $[\text{OII}]$ and $\text{H}$\,$\alpha$ emission respectively, which are proportional to the SFR. The best fit parameters for each galaxy and the spectroscopic redshift are also reported.

Following the approach used in P07 we compare the properties of $LBG_L$ to those of $LBG_N$. We find that the masses of $LBG_N$ are larger than the masses of $LBG_L$ and the galaxies without emission line are somewhat older. The median values with relative uncertainties, are reported in Table 1 and the distributions are shown in Figure 3. To assess the differences between the two samples in the physical parameters and their statistical significance, we perform a non-parametric Kolmogorov-Smirnov (K-S) test on the age and mass distributions. We find that the difference is indeed highly significant for the mass distribution ($P=0.000$), while only weakly significant for the age distributions ($P=0.136$).
The di masse are indeed all lower than the median mass. Therefore the value of $0.06$ E(B-V) derived from the SED fit are small, with a median than at higher redshift.

In the study of P09 we found that amongst the LBG, at redshift 3 to 6 there was a significant lack of massive galaxies with high EW. In other words, although there was no clear correlation between EW and stellar mass, all galaxies with $EW_0 > 80\AA$ (9 out of a sample of 70) had stellar masses equal or below the median mass. There are only 3 galaxies with $EW_0 > 80\AA$ in the present sample and their masses are indeed all lower that the median mass. Therefore the effect might be present, but is definitely much less pronounced than at higher redshift.

The E(B-V) derived from the SED fit are small, with a median value of $0.06 \pm 0.012$ and $0.03 \pm 0.009$ for $LBG_N$ and $LBG_L$, respectively. In accordance with previous results at higher redshift (P07) and with Shapley et al. (2003), we find that $LBG_L$ tend to show less dust extinction: the difference between the sub-sample is small but significant (PKS=0.012). To confirm this result, we also evaluated the continuum UV-slope from broad band V and I data assuming that the continuum can be represented by a simple power law, of the form $f_\nu \propto \nu^\beta$. The median values for the two sub-sample are $\beta = -1.15 \pm 0.11$ for $LBG_N$ and $-1.33 \pm 0.12$ for $LBG_L$. Again, this difference indicates that there is a scatter in dust extinction between the two sub-samples. We note that, although the trend is similar to that found by Shapley et al. (2003), they report slightly redder slopes for their LBGs for a given EW, ranging from -0.73 for the absorbers to -1.1 for the strongest emitters (but their beta values are evaluated from the G-R colors, while our slopes are from V and I band data). On the other hand our values are similar to that reported by Hathi et al. (2008) for $z \sim 3$ LBGs, which is $\beta = -1.1 \pm 0.2$ and by Adelberger & Steidel (2000), which is $\beta = -1.5 \pm 0.4$.

We finally report a significant, although very scattered correlation between the total stellar mass and the extinction, in the sense that the most massive galaxies tend to show more dust.

### 4.2. SFR from UV continuum and SED fitting

There are different ways of estimating the star formation rates (SFR) in LBGs. First the SFR can be estimated from the UV continuum luminosity using Kennicut (1998): $SFR_{UV} = 1.4 \times 10^{-28} L_\nu_{1400} \ M_\odot yr^{-1}$, where $L_\nu$ is the luminosity at rest-frame 1400 Å in units of ergs sec$^{-1}$ h$^{-1}$. 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 true SFR. The UV emission is very sensitive to the presence of dust and can be attenuated even by small amounts: we correct for this using the slope of the UV rest-frame continuum determined from the V and I band data and assuming a Calzetti law.

A second value is given by the SED fit output $SFR_{SED}$. This clearly depends on the model assumed for the star formation history, in our case the exponentially declining star formation rate with e-folding time $\tau$.

The median values for the 2 samples obtained for the SFRs in both ways are reported in Table 1. We find no significant differences between $LBG_L$ and $LBG_N$ in agreement with P07 for $z \sim 4$ sources.

A commonly used measure to assess the importance of the current episode of star formation to the buildup of the stellar mass in galaxies is the specific star formation rate (SSFR) i.e. the star formation rate per unit mass. It is well known that more massive galaxies have lower SSFR (e.g. Erb et al. 2006) and that at a fixed stellar mass, the SSFR declines with increasing redshift (e.g. Reddy et al. 2006, Feulner et al. 2005). In Figure 4 we plot the SSFR vs total stellar mass: the two quantities are anticorrelated with high probability (a Spearman Rank test gives a correlation coefficient of -0.6). In practice, galaxies with lower stellar mass are assembling a much higher fraction of their mass with the current star formation episode, compared to more massive objects.

### 4.3. MIPS detection and IR-determined SFR

At redshift $z \sim 2.4$ the mid-IR (5–8.5 $\mu$m) features associated with PAH emission, which are ubiquitous in local and $z \sim 1$ star-forming galaxies, are shifted into the MIPS 24$\mu$m filter. We searched for counterparts of our LBGs in the GOODS-MUSIC 24$\mu$m MIPS catalog (see Santini et al. 2009 for details). Note that
Table 1. Average properties of LBG$_{L}$ and LBG$_{N}$ derived from the SED fitting with the Charlot & Bruzual (2009) models

| Property         | LBG$_{L}$ | LBG$_{N}$ | P(K-S) |
|------------------|-----------|-----------|--------|
| $N_{gal}$        | 66        | 66        | 0.993  |
| L(1400) (cgs)    | 5.9 ± 0.6 x 10$^{26}$ | 6.0 ± 0.6 x 10$^{26}$ | 0.367  |
| SFR$_{SED}$ ($M_{\odot}$ yr$^{-1}$) | 13.2 ± 4.2 | 16.0 ± 11 | 0.367  |
| SFR$_{UV}$ ($M_{\odot}$ yr$^{-1}$) | 15.6 ± 1.9 | 12.9 ± 3.4 | 0.414  |
| Age (Myrs)       | 250 ± 35  | 316 ± 40  | 0.136  |
| E(B-V)           | 0.03 ± 0.009 | 0.06 ± 0.012 | 0.012  |
| Mass ($M_{\odot}$) | 3.4 ± 1.5 x 10$^{9}$ | 8.7 ± 1.2 x 10$^{9}$ | 0.000  |

Fig. 4. The SSFR vs stellar mass. The two dashed lines indicate constant values of SFR of 100 and 5 $M_{\odot}$ yr$^{-1}$. Red symbols are LBG$_{N}$ and black ones are LBG$_{L}$.

galaxies with mid-IR excess such that the MIPS flux is probably due to AGN activity rather than star formation (see also Fiore et al. 2008 for the proper definition) are flagged as AGNs in the revised version of the GOODS-MUSIC catalog that we are using and therefore were excluded from our initial sample selection (see also Section 2). Therefore we assume that the 24$\mu$m flux is due to star formation.

We found a total of 39 objects with clear detections. Of these, 12 are LBG$_{L}$ and 27 are LBG$_{N}$ indicating that the detection rate of LBG$_{N}$ is more than double, compared to the line emitters. As expected the subset of MIPS detected sources is on average brighter (in $z$-band) and at a slightly lower redshift than the entire sample. The MIPS detected sources all belong to the most massive end of the stellar mass distribution, while other properties such as age and morphology (see later) are in the average range. In particular the mean log(Mass) of MIPS detected galaxies is 0.48 dex higher than the rest of the sample, and this can explain the higher detection rate for LBG$_{N}$.

Reddy et al. (2006) found similar results for optically selected (UGR) star-forming galaxies at $z$~ 2: the age distributions of 24$\mu$m detected and non-detected galaxies are similar, while the mass distributions are offset such that undetected galaxies have an average log($M$) of 0.4 dex lower than for 24$\mu$m detected galaxies. The MIPS detected galaxies have weaker Ly$\alpha$ emission and stronger interstellar absorption lines, consistent with our results. Following the approach outlined in Santini et al. we derived the total IR luminosity and then the MIPS-Inferred total SFR. As noted by Reddy et al. 2006, the conversion from the 24$\mu$m flux to total IR luminosity and then to unobscured SFR is subject to many uncertainties. For our galaxies, accurate spectroscopic redshifts are known and this gives the advantage of knowing precisely the location of the PAH features and their contribution to the 24 micron flux. Nevertheless we point out that there are still many sources of uncertainties in the conversion from 24 micron flux to total IR luminosity, due to the modeling of the PAH features, which depend on the galaxy metallicity, galaxy environment, galaxy size, star formation history, and on the ionizing radiation field (Calzetti et al. 2007).

The derived SFR$_{MIPS}$ are on average higher than both SFR$_{SED}$ and SFR$_{UV}$. We also find a clear trend that the SFR$_{MIPS}$/SFR$_{SED}$ tend to be ~ 1 for objects with moderate star formation rates, while becoming >> 1 for objects with large SFR, as shown in Figure 5. Both LBG$_{L}$ and LBG$_{N}$ seem to follow this trend. One possibility is that, in objects showing SFR$_{MIPS} >> $ SFR$_{SED}$, the MIPS emission is not (entirely) due to star formation but might be still partially due to AGN contribution, even after the exclusion of the clear obscured AGNs. However since the trend extends also to values lower than unity and is present at all redshifts (see Santini et al. 2009), it is possible that it reflects a change in some intrinsic physical property of star-forming galaxies, such as metallicity. Galaxies with sub-solar metallicities have lower mid-IR emission (at least at 8$\mu$m, Calzetti et al. 2007) and higher UV luminosity than solar ones, for a given level of SFR. The observed trend could therefore be related to a metallicity trend. Unfortunately, a direct check of this is not feasible. Reliable metallicities cannot be inferred from broad-band SED fitting, and high resolution spectroscopy is necessary to properly distinguish between SEDs characterized by different lines and hence metallicities.

Finally the observed trend could also be due to a failure of the assumed modelling of star formation history for example in galaxies with very high star formation.
5. Spectral properties

The majority of the spectra were retrieved from the GOODS VIMOS database. Since relatively few spectra and redshifts were obtained from other programs, we decided to make a composite spectrum using only the VIMOS data. The homogeneity of the data set in terms of resolution, depth and calibration accuracy, makes it easier to add up the spectra, even if the number of sources is reduced.

The 1-D spectra are distributed in fits format from the GOODS database, they are calibrated both in flux and wavelength. For details on reduction and calibration see Popesso et al. (2009). The final redshift uncertainty quoted there is $\sigma_z = 0.0013$, obtained from a comparison between redshifts of the same objects obtained more than once with different set-ups.

The spectra were brought to rest-frame and co-addition was performed adopting a sigma-clipping procedure to eliminate sky-subtraction residuals, zero-count pixels due to CCD gaps, and other spectral blemishes. After several tests, the best results were obtained when a single 3σ clipping iteration was adopted. On average more than 90% of all galaxies in a given bin contribute to the stacked spectrum at any given wavelength.

In Figure 6 we present the composite spectrum of all LBGs and compare it to the LBG$_N$ spectrum, after normalizing the two spectra at 1280 Å. Besides the obvious difference of the presence of bright Lyα in the spectrum of LBG$_L$, we note that the spectrum of LBG$_N$ is flatter than the spectrum of LBG$_L$, in agreement with the higher value of E(B-V) derived from the SED fit and indicating in LBG$_N$ the presence of more dust than in the LBG$_L$. Furthermore, in the LBG$_L$ spectrum the interstellar absorption lines are more prominent than in the LBG$_L$ spectrum: this is more evident for the low ionization lines (SII1260, OI+SII1303, CI11334, SII1536) while for the high ionization lines the difference is not as marked. This was already observed in more details by Shapley et al. (2003), who found that the kinematic offset between the Lyα line and the interstellar absorption lines also depends on Lyα emission strength. A detailed analysis of the spectral stacks as Shapley et al. is not allowed by the S/N of our composite spectra. Our aim here was only to check the resulting spectral stacks for consistency with previous work.

6. X-ray emission

The field has been observed by Chandra in the 2Msec exposure (Luo et al. 2008). We therefore searched for signatures of X-ray emission from our sample of LBG$_1$ and LBG$_N$.

To start we remind that, in the initial sample selection, we had excluded spectroscopically confirmed broad line and narrow line AGNs (BLAGNs and NLAGNs respectively). The first (BLAGNs) are easily spotted since they usually show a broad Lyα line, with typical FWHM of several thousands km/s, clearly resolved even in our low resolution spectra. The NLAGNs are recognized by the presence of high excitation emission lines in the spectra such as NIV, CIV, HeII. Clearly in this case there could be more ambiguity, since the presence of these lines depends also on the s/n of the spectra, on the relative line ratio and on the spectral range observed. Therefore we cannot exclude that some NLAGNs might still be included in our sample.

Assuming that we have removed all AGNs, we search for possible X-ray flux associated to the LBGs, as due to star-burst emission. We cross correlated our catalogue with the 2 Msec Chandra point source list by Luo et al. (2008). The survey covers an area of $436 \text{arcmin}^2$ and reaches on-axis sensitivity limits of $1.9 \times 10^{-17} \text{ergs cm}^{-2} \text{s}^{-1}$ for the 0.5-2.0 and 2-8 keV bands, respectively. Two objects (both classified as LBG$_1$) are present in the Chandra 2 Msec catalog as individual detections: # 11006 and # 8543. They were observed spectroscopically by Mainieri et al. (2006) who list them as LEX (emission line galaxies). However from soft band fluxes (5.37 and 3.7 $\times 10^{−16} \text{ergs cm}^{-2}$ respectively) and optical magnitude, we derive ratios of X-ray to optical flux that fall within the region populated by AGNs (e.g. Hornschemeier et al. 2001).

The detection rate is comparable to Lemher et al. (2005) who find 7 individually detected objects out of 449 U-dropouts, while Laird et al. (2006) present a higher detection rate in the HDF-N area: in their spectroscopic sample of 89 LBGs they find X-ray emission from 4 galaxies, or 4.5%.

We stacked the X-ray undetected sources following the procedure adopted by Laird et al. (2006). The final stacked image corresponds to a total integration time of 0.26 Gs. As background we used the images produces by Luo et al. and available at the Chandra survey web site. The flux at each source position was summed using a box cell of 6x6 pixels, corresponding to approximately 3″ a side. This value was chosen following Laird et al., who determined that a radius of ~1.5″ maximizes the signal to noise in stacked detection of U-dropouts. The total counts were summed and the background was determined in an area of the same aperture. The result is a detection with S/N= 4.1, in the soft band (0.5-2KeV), and a non-detection in the hard and total bands. The total net source counts in the soft band is 76 for 128 sources, implying a mean source count of 0.59. This is basically equal to the result of Laird et al., who report an average 0.58 net counts for their sample of 277 HDF-N U dropouts in the 2 Msec observations, while Lemher et al. found an average 0.44 counts per source. Assuming the stacked X-ray flux is due to star formation activity we determine the average unobscured SFR implied by the X-ray. The flux corresponding to the average count rate is $2.3 \times 10^{-17} \text{ergs s}^{-1} \text{cm}^{-2}$. At the mean redshift of the sample ($z=2.85$) this corresponds to a luminosity in the 2-8 KeV rest-frame band of $1.62 \times 10^{41} \text{ergs s}^{-1}$. We apply the conversion from X-ray flux to SFR derived by Nandra et al. (2002), assuming a Salpeter IMF (as in our models). We derive an aver-

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1 http://www.eso.org/science/goods/spectroscopy/vimos.html
age unobscured \( SFR_X = 29.1 M_{\odot}/yr^{-1} \), slightly higher than both \( SFR_{UV} \) and \( SFR_{IR} \).

Most importantly, in the context of the present work, when we stack the fluxes of the \( LBG_L \) and \( LBG_N \) separately we do not find any significant difference. In particular, we find a total S/N of 2.1 for the \( LBG_L \) and S/N=2.6 for the \( LBG_N \). Again, we run a nonparametric K-S test on the individual counts for each group and find that the two distributions are perfectly compatible with each other (P=0.99). We further probe this by stacking only the strongest emitters, with an observed Ly\( \alpha \) EW $>$ 100\( \AA \) and we obtain a similar result. Therefore we conclude that the X-ray properties do not depend on the presence and strength of the Ly\( \alpha \) emission line or, at most, are only weakly correlated.

### 7. Morphological properties

Even for the lowest redshift objects in the sample, the ACS z-band samples the rest UV-emission ($\sim$ 3000\( \AA \) or shorter). The UV morphology tends to be patchy and irregular even for local galaxies (e.g. Gordon et al. 2004). However, high redshift galaxies have irregular morphologies not only in the UV, but also at longer rest-frame wavelengths (Papovich et al. 2005, Dickinson et al. 2005), indicating that light is always dominated by the young stellar component. The most popular explanation is that these irregular systems represent mergers (e.g., Conselice et al. 2003). Alternatively, it could be that the different components observed are just clumps of star formation rather than different merging systems. It is therefore interesting to determine if the morphology is connected to the other physical and spectral properties of the galaxies.

We have analyzed the high resolution ACS z-band morphologies of our galaxies. In Figure 8 we show the postage stamps of some of the galaxies in our sample, in order of increasing redshift. We performed a non parametric analysis as in Scarlata et al. (2007). The program initially determines the Petrosian radius and then uses it as semi-major axis of an elliptical aperture where it calculates the following parameters: asymmetry, concentration, Gini coefficient, and second-order moment of the brightest 20% of galaxy pixels. The Gini coefficient (G) describes how uniformly the flux is distributed among galaxy pixels. The Gini statistics assumes values from 0 (if the galaxy light is homogeneously distributed among galaxy pixels) up to 1 (if all the light is concentrated in 1 pixel, regardless of its position in the galaxy). The concentration \( C = 5log(r_{80}/r_{20}) \) with \( r_{80} \) and \( r_{20} \) the radii including 80% and 20% of the total galaxy light, respectively, quantifies the central density of the galaxy light distribution. \( M_{20} \) is the second-order moment of the brightest 20% of the galaxy flux (Lotz et al. 2004). For centrally concentrated objects, \( M_{20} \) correlates with the concentration \( C \); however, \( M_{20} \) is also sensitive to bright off-centered knots of light. The asymmetry (A) quantifies the degree of rotational symmetry of the light distribution. A is measured by calculating the normalized difference between the galaxy image and the image rotated by 180. A correction for background noise is also applied (as in Lotz et al. 2004). Finally we also use the ellipticity (\( \epsilon \)) of the light distribution, as measured by SExtractor (Bertin & Arnouts 1996).

As shown in Scarlata et al. (2007), this non-parametric method is very efficient in quantifying galaxy morphology. The quantities above provide complementary, but also redundant, information on galaxy structure. For a complete description and also the uncertainties on the parameters see Scarlata et al. (2007).

We only remark here that, using the Petrosian radius we are not affected by distance since surface brightness dimming does not change the shape of a galaxy light profile and therefore it does not affect the Petrosian index. For this reason we can compare the morphology of objects even if our sample spans a relatively large redshift range. We are aware that our method to calculate the Gini coefficient (inside a Petrosian aperture) might introduce some compression in its dynamic range and somewhat limit its discriminating power (as argued by Law et al. 2007). In addition to the above parameters, we have visually inspected the individual z-band thumbnails to check for multiple peaks of emission: clearly this is a more subjective and less precise analysis.

### Table 2. Average morphological properties of \( LBG_L \) and \( LBG_N \)

| Property | \( LBG_L \) | \( LBG_N \) | P(K-S) |
|----------|-----------|-----------|--------|
| Concentration | 2.55 | 2.57 | 0.52 |
| Gini | 0.47 | 0.46 | 0.54 |
| Asymmetry | 0.11 | 0.097 | 0.291 |
| \( M_{20} \) | -1.40 | -1.41 | 0.989 |
| Ellipticity | 0.258 | 0.323 | 0.203 |
| Size | 3.89 | 4.62 | 0.056 |
| Area | 154 | 207 | 0.020 |
| Clumpy obj. | 19/66 | 19/66 | – |

We find that the z$\sim 3$ LBGs have median values $G \sim 0.48$, \( M_{20} \) $\sim$ $-1.46$, \( C \sim 2.6 \) and A$\sim 0.12$. Comparison of the absolute values to those derived by other studies is not meaningful since they depend on the S/N ratio and on the choice of aperture within which they are measured (Lisker 2008). However our aim is a relative comparison between \( LBG_N \) and \( LBG_L \) : this is possible because the possible systematic errors are similar for both populations.

As for the physical parameters, a series of Kolmogorov-Smirnov tests was performed to assess the probability that in each case the \( LBG_L \) and \( LBG_N \) are drawn from different distributions for all the five parameters (A, G, C, \( M_{20} \) and \( \epsilon \)), plus area and size. The probability P for each test is also reported in Table 2. In almost all case (with the exception of size and area) there are no substantial differences in the morphology of galaxies. The morphological analysis was also repeated restricting the two subsamples, \( LBG_N \) and \( LBG_L \), to galaxies brighter than \( z_{850} \sim 25 \), and the results do not change.

This is at variance with what suggested by Vanzella et al. (2009) who found a higher concentration for z$\sim 4$ – 5 galaxies with Ly\( \alpha \) emission. Note however that their sample is smaller and the claimed difference has less than 2\( \sigma \) significance. Like Vanzella et al., we also find that galaxy size and area depend on line emission properties: however this might be a consequence of the lack of bright (massive) galaxies with large EW, rather than a real dependence on line emission. If we plot the size vs EW of our galaxies (analogous to Figure 19 of Vanzella et al.) we find that galaxies with small or negative EW span the whole range of sizes while large EW objects tend to be very small. This same trend was found by Law et al. (2007) in an analysis of combined u,v,i and z band data on LBGs at z$\sim 3$. They also find a possible correlation between Ly\( \alpha \) and Gini parameter, but they note that the correlation is not well defined.

In conclusion we do not find much evidence for a strong morphological dependence of the emission line properties, but we find that line emitters tend to be small galaxies, while amongst \( LBG_N \) there are both small and large galaxies.
8. Summary and discussion

We briefly summarize the main results of this work and then attempt to interpret them in the context of a simple scenario.

1. At $z \sim 3$, LBGs are significantly more massive than LBG$_L$.
2. The ages of LBG$_L$ and LBG$_N$ are comparable. The median age of LBG$_N$ is somewhat larger than the median age of LBG$_L$ but at least at 3σ level.
3. The current SFR (SFR$_{UV}$ or SFR$_{SED}$) is similar for both groups, as expected given the initial selection. This is further confirmed by the stacked X-ray flux, related to unobscured star formation: no relevant differences are observed between the two groups.
4. Given that ages and SFR are similar for both LBG$_N$ and LBG$_L$, the larger average masses of LBG$_N$ imply that these galaxies had higher star formation in the past. We remind that SFR$_{UV}$ is sensitive only to current star formation rate, on timescales of less than 100 Myrs, while many galaxies have ages larger than this.
5. The SSFR is a strong function of Mass, and is higher for low mass objects and therefore tends to be higher for LBG$_L$.
6. The MIPS detection rate of LBG$_N$ is 2.5 times higher than for LBG$_L$.
7. All LBGs have small dust extinction as expected: LBG$_N$ have relatively higher dust content, as inferred by the larger E(B-V) values derived from the SED-fitting and by the steepness of the stacked spectra.
8. We find no notable differences in the morphological parameters, with the exception of the smaller sizes and areas of LBG$_L$ compared to LBG$_N$.

8.1. A simple scenario

The continuity and almost substantial overlap of physical and morphological properties of LBGs, and the few trends we have found are in substantial agreement with the unification scheme between LBGs and LAEs proposed by Verhamme et al. (2008). In their model, most all LBGs have intrinsically high Lyα emission ($EW \sim 60 - 80\,\AA$) or larger), and the observed variety of Lyα strengths and profiles, and ultimately the fact that these galaxies are selected as LBGs or LAEs is due to variations in the content of dust and HI (see also Atek et al. 2009). The assumed geometry is that of an expanding, spherical, homogeneous, and isothermal shell of neutral hydrogen surrounding a central starburst emitting a UV continuum plus Lyα recombination line radiation from its associated H II region: dust is uniformly mixed to the HI gas and the variation of these two quantities shape the profile of the Lyα. Ultimately the main parameter responsible for these variations may be the galaxy mass. Indeed, if the most massive galaxies also contain more dust, as we observe given the correlation between E(B-V) and stellar mass (although with a large scatter), a natural consequence is that massive galaxies would show Lyα with smaller EW or Lyα in absorption. This would naturally produce the large mass segregation observed between LBG$_L$ and LBG$_N$, which is one of the strongest results of the present work. It would also explain the lack of massive galaxies with bright Lyα emission observed here and already pointed out in P09, and similarly the lack of luminous galaxies with bright Lyα emission observed by other authors (e.g. Ando et al. 2007).

Furthermore, in the Verhamme et al. model, no age constraints are derived from the presence of Lyα up to $EW \sim 100\,\AA$, as such equivalent widths can be obtained, especially in the case of a constant star formation history, even taking into account various degrees of dust suppression. This is at variance with other models that put strong limitation of the maximum age of Lyα emitting galaxies (e.g. Mao et al. 2007, Mori & Umemura 2006). Therefore our result that LBG$_L$ and LBG$_N$ have very similar ages, and the fact that we do find Lyα emitting galaxies with ages exceeding several hundred Myrs are also nicely in agreement with the Verhamme et al. model. They actually predict that objects with very bright Lyα (EW >> 100Å) should all be extremely young (less than 10-40 Myrs), but in our sample of LBG$_L$ we do not have any of these large EW galaxies. Last but not least, the lack of significant morphological differences between LBG$_L$ and LBG$_N$ is also in agreement with this scenario. Possible outlier in this unifying scheme would be objects that have Lyα absorption but at the same time show no indications for dust extinction, basically LBG$_N$ with $E(B-V) = 0$. Most of the LBG$_N$ indeed have $E(B-V) \neq 0$, and only 3 of them seem to be dust-free galaxies with no Lyα in emission. Clearly the E(B-V) we estimate is subject to errors, so it could still be that a little dust is present: alternatively in these cases the n$_{HI}$ could be playing a major role in suppressing the Lyα emission and/or there could be variations in the dust/HI ratio. Indeed Steidel (2008) argue that the Lyα emission strength and apparent redshift is strongly affected by the presence of gas near the systematic velocity of the galaxy, which is often absent in lower-mass objects. Therefore low mass objects naturally tend to show brighter Lyα emission than high mass ones.

To further test the above scenario, one would need to establish a solid relation between the total stellar mass of a galaxy and the neutral hydrogen content. Also the exact dependence between the amount of dust and the stellar mass, as well as the variation of dust/gas ratio must be still explored in details. Last but not least, dust geometry and the way dust and emitting sources are mixed might also influence the observed Lyα appearance. Recently Scarlata et al. (2009) considered various possibilities for the geometry of dust around emitting sources, and found that the uniform dust screen in not able to reproduce all the observations, while a clumpy dust distribution does a better job, with no need to invoke differential extinction of Lyα and continuum photons for most of the galaxies.

8.2. Redshift evolution?

Although the simple scenario described before seems to fit well the correlation found at $z \sim 3$, as well as the absence of trends in other properties, some modification might be needed to account for the evolution in some of these properties/trends with redshift. Indeed, there are strong indications that some of the correlation between Lyα strength and LBGs properties change considerably with cosmic epoch. First of all, as discussed in the introduction, the simple fraction of LBGs that are also LAEs, and ultimately the EW distribution of Lyα in LBGs at various cosmic epochs, is still subject to debate. Most authors claim that the distribution of Lyα strength found at $z \sim 3$ by Shapley et al. (2001) remains valid at all redshifts (e.g. P07, Stanway et al. 2007, Dow-Hygelund et al. 2007), although the $z \sim 6$ population has a tail of sources with high rest-frame equivalent widths (Stanway et al. 2007). Other authors claim instead that at very high redshift almost all LBGs strong Lyα emitters (e.g. Shimasaku et al. 2006). Finally, at lower redshift, Reddy et al. (2008) noted that, amongst UV selected star-forming galaxies, the redshift~3 (LBG) population has a higher incidence of Lyα in emission than the redshift~2 (the so called BX) population. In this work we found further indication of evolution for other properties: first of all at $z \sim 3$, we find no age segregation, while
at $z \sim 4$, we reported that $LBG_1$ were considerably much younger than $LBG_N$ (P07). The difference in total stellar mass was also much more pronounced at $z \sim 4$ (P07), compared to this study. At $z \sim 3$ we also find no significant evidence for morphological differences between $LBG_N$ and $LBG_{12}$, but at lower redshift Law et al. (2007), using a different set of morphological parameters, found possible although not well defined trends. On the other hand, at $z \sim 4$ Vanzella et al. (2009) reported a marked difference in the Gini and concentration indexes of the two groups, with the $LBG_{12}$ being more concentrated than the rest of the galaxies. Similarly at $z \sim 6$ the tentative results of Dow-Hygelund et al. (2007) showed that sources with Ly$\alpha$ emission are smaller, on average, than the i-dropout population in general. However at variance with this study, Taniguchi et al. (2009) recently claim that there is no difference in the morphological properties between the two populations, LAEs and LBGs at $z \sim 6$. These discrepant results indicate that disentangling the morphological properties of high-z galaxies and comparing different samples at different redshift is still far from trivial. In a forthcoming work we plan to analyse more in depth the morphologies of LBGs at various redshifts, using a unique set of parameters, so that a consistent comparison can be made between the various cosmic epochs.

In any case, the above results strongly suggest an evolution of some fundamental property of galaxies, be it the dust content (e.g. Nillson et al. 2009) or Ly$\alpha$ escape fraction (e.g. Nagamine et al. 2008), that shape the appearance of star-forming galaxies: it is therefore essential that they are taken into account by the models.

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Fig. 7. Relations between the nonparametric diagnostics (M20, G, A, C, and $\epsilon = 1 - b/a$). The main correlations among some of the parameters, such as M20, C, and G, are clearly visible in these diagrams. In each panel black + are $LBG_L$ and red triangles are $LBG_N$. 
Fig. 8. Postage stamps of some of our LBGs, in order of increasing redshift. Each image is taken in the z-band and is $4'' \times 4''$ in size.