The physical properties and evolution of Ly$\alpha$ emitting galaxies

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Abstract. A significant fraction of high redshift starburst galaxies presents strong Ly$\alpha$ emission. Understanding the nature of these galaxies is important to assess the role they played in the early Universe and to shed light on the relation between the narrow band selected Ly$\alpha$ emitters and the Lyman break galaxies: are the Ly$\alpha$ emitters a subset of the general LBG population? or do they represent the youngest galaxies in their early phases of formation? We studied a sample of UV continuum selected galaxies from $z \sim 2.5$ to $z \sim 6$ (U, B, V and i-dropouts) from the GOODS-South survey, that have been observed spectroscopically. Using the GOODS-MUSIC catalog we investigated their physical properties, such as total masses, ages, SFRs, extinction etc as determined from a spectrophotometric fit to the multi-wavelength (U band to mid-IR) SEDs, and their dependence on the emission line characteristics. In particular we determined the nature of the LBGs with Ly$\alpha$ in emission and compared them to the properties of narrow band selected Ly$\alpha$ emitters. For U and B-dropouts we also compared the properties of LBGs with and without the Ly$\alpha$ emission line.

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THE RELATION BETWEEN LY$\alpha$ EMITTERS AND LYMAN BREAK GALAXIES

Over the past few years large samples of galaxies of up to the highest redshifts have been found (Iye et al. 2006, Kashikawa et al. 2006) using techniques that rely on color-selection criteria. Among the various methods, one of the more efficient is the Lyman break technique (Steidel & Hamilton 1993), which is sensitive to the presence of the 912 Å break and is effective in finding star-forming galaxies. This method requires a blue spectrum, implying low to moderate dust absorption. An alternative technique is to search for Ly$\alpha$ emission, through very deep, narrow-band imaging in selected redshift windows, as first shown by Cowie & Hu (1998). Ly$\alpha$ emitters (LAEs) are generally selected to have high restframe Ly$\alpha$ equivalent width, typically $EW > 20\AA$, with no constraint on the continuum. Consequently, this method tends to select much fainter galaxies, compared to the general LBGs population. Many Ly$\alpha$ emitters have now been found (e.g. Ouchi et al. 2004, Gawiser et al. 2007) and several distant large-scale structures or protoclusters have been discovered (e.g. Venemans et al. 2007).

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. Various scenarios have been proposed to explain the properties of Ly$\alpha$ emitters. Because the Ly$\alpha$ line is easily suppressed by dust, Ly$\alpha$ emitters are often identified 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$\alpha$ and
continuum photons in interacting with dust makes it possible also for older galaxies to exhibit Ly$\alpha$ 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$\alpha$ emission. This scenario is partially supported by the results of Shapley et al. (2003): based on rest-frame optical photometry, they concluded that LBGs with Ly$\alpha$ in emission are "old" (ages greater than a few $\times 10^8$ yr), while "young" (ages less than $\sim 100$ Myrs) LBGs exhibit Ly$\alpha$ in absorption. In addition Lai et al. (2007) found that some high-redshift Ly$\alpha$ galaxies could be consistent with hosting relatively old stellar population. Finally, some authors have suggested that galaxies could have more than one Ly$\alpha$ bright emission phase (e.g. Thommes & Meisenheimer 2005). An initial - primeval - phase in which dust is virtually non-existent, and a later, secondary phase in which strong galactic winds, as observed in some Lyman break galaxies, facilitate the escape of Ly-$\alpha$ photons after dust has already been formed. Clearly, it is worthwhile understanding the real relation between galaxies with Ly$\alpha$ 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.

**THE GOODS-MUSIC SAMPLE**

To shed light on this issue, we analyzed a sample of LBGs selected as U-B-V- and i-dropouts from the GOODS-MUSIC sample (Grazian et al. 2006), and with VLT spectroscopic confirmation (Vanzella et al. 2006, Vanzella et al. 2008, Popesso et al. 2008). For the color cut adopted see Giavalisco et al. (2004). Given the good quality of the spectra, it was possible to assess whether the galaxies exhibit Ly$\alpha$ emission or the line is absent and/or appears as an absorption feature. In the following we define $LBG_L$ the LBGs with line emission and $LBG_N$ the LBGs with no line. For the lower redshift sets (U and B dropouts), the spectroscopic confirmation of LBGs is effective, regardless of the presence or absence of the Ly$\alpha$ line. At higher redshift ($z > 4.8$) the spectroscopic confirmations are almost exclusively based on the presence of the Ly$\alpha$ line in emission, while the objects with possible Ly$\alpha$ in absorption (or absent) become progressively more difficult to identify. Therefore for V and I-dropouts it is not possible to make a comparison of the properties of $LBG_N$ and $LBG_L$, since the first set is not complete. We will therefore compare the properties of $LBG_L$ and $LBG_N$ for galaxies at redshift $\sim 2.5$ to $\sim 4.8$. At all redshifts, ($\sim 2.5$ to $\sim 6$), we will study the properties of $LBG_L$ and compare them to the properties of the narrow band selected LAEs.

For all galaxies the physical properties, such as total stellar mass and age, star formation rate metallicity and so on, were derived from a spectrophotometric fit of the multi-wavelength (U band to mid-IR) SEDs, using the templates of Bruzual & Charlot (2007) (an example is shown in Figure 1). A full description of this procedure with a discussion of the uncertainties involved can be found in Fontana et al. (2006).
2. PROPERTIES OF LINE EMITTING LBGS AT HIGH REDSHIFT: NOT JUST PRIMEVAL GALAXIES?

We first analyzed the properties of all LBGs that show the Ly$\alpha$ line in emission. In about half of the galaxies, the rest-frame EW of the line is high enough (EW > 20 Å) that they would be selected also in a narrow band survey. In the rest of the galaxies the EW is weaker than this limit. Our main results are the following:

• 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 $\sim 1$ Gyr. In Figure 1 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 Myrs respectively) are also shown with different colors. They clearly give a much poorer representation of the observed SED, especially in the mid-IR range. 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$\alpha$ emitting galaxies are primeval galaxies in the very early stages of formation, as is commonly assumed.

• We 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 $60 M_\odot yr^{-1}$. These values are higher than those derived in general for narrow band selected LAEs. Clearly most (but not all) of the NB emitters
FIGURE 2. The dependence of stellar masses (best fit values) on Lyα EW. The left figure refers to the U-dropout sample, while the right figure contains B-V- and i-dropouts. The dashed lines indicate in each case the median masses.

have somewhat fainter continuum than our LBGs: we are studying objects that are, on average, intrinsically brighter and thus more massive. 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. The difference could be due, in part, to a trend that we observe in Figure 2. Here we show how the stellar mass and Lyα EWs are related. The dashed lines indicate the median mass of each sample. 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.

The results presented here are extensively discussed in Pentericci et al. 2008

2. COMPARISON BETWEEN LBGS WITH AND WITHOUT EMISSION LINE

We then compared the properties of $LBG_L$ to those of $LBG_N$. As already detailed in the introduction, this is only possible (in an unbiased way) for the lower redshift part of the sample. In particular our analysis of the B-dropouts was presented in Pentericci et al. (2007), while the analog study for the U-dropouts will be reported in Pentericci et al. 2009 (in preparation).

Our main results are the following:

- Both the total stellar masses and the median ages are considerably lower for the $LBG_L$ compared to the $LBG_N$. For B dropouts the average mass is $(5.0 \pm 1) \times 10^9 M_\odot$ for the $LBG_L$ and $(2.3 \pm 0.8) \times 10^{10} M_\odot$ for the others, i.e. a factor of almost
The physical properties of B and V-dropouts. Top left: distribution of total stellar mass; top right the extinction parameter E(B-V) derived from the spectral fitting; middle left the total star formation rate derived from the spectral fitting; middle right: stellar ages; bottom left: $\tau$ the star formation e-folding time-scale; bottom right: the metalicity. Solid black and dashed light histograms denote LBG$_L$ and LBG$_N$ respectively. The black and light arrows indicate the mean values of each sample.

The K-S test gives a very low value, implying that the two populations are different from each other with $> 99.8\%$ probability. We can therefore conclude that the LBG$_L$ are less massive than the LBG$_N$ by a factor of almost 5. The median ages are also quite different, with an average of $200 \pm 50$ Myr for the LBG$_L$, an age distribution that is very peaked towards low age values and is basically confined to values below 300 Myr. The LBG$_N$ on the other hand have an average age of $410 \pm 70$ Myr (older by a factor of more than 2) and there are several galaxies with ages exceeding 1 Gyr, which is a considerable fraction of the cosmic time at redshift $\sim 4$. Again performing a K-S test, the two populations are different with a probability $> 98\%$. We conclude that the LBG$_L$ are significantly younger galaxies than the LBG$_N$.

As at redshift 4, also at redshift 3 for U dropouts the masses of LBG$_N$ are larger than the masses of LBG$_L$ and the galaxies without emission line are older. The average values differ considerably (the same holds true if one derives the median value instead of the average). The K-S test gives a significance of more than 99% in both cases (P=0.0003 for age and P=0.000 for mass). However we notice that the
difference between the samples is less pronounced than at higher redshift: the mass
difference is less than a factor of 2, and the age difference is only a 50% factor.
Especially for the age, we find that although the two distributions are different, the
range spanned by \( LBG_L \) and \( LBG_N \) is basically equal. In other words LBGs seem
to be a more uniform population at lower redshift and the properties vary less with
the presence or absence of \( Ly\alpha \) emission.

- \( LBG_L \) are less dusty than \( LBG_N \) although the difference is not large. This can
  be also observed from the UV slope of the stacked spectra that we derived for the
  \( z \sim 3 \) \( LBG_L \) and \( LBG_N \) separately (Pentericci et al. 2009). In general, as a natural
  consequence of the initial color selection, all galaxies contain small amounts of
dust.

- Both populations are forming stars very actively and the average star formation
  rates similar. However for U-dropouts we find that, while in \( LBG_L \) the current SFR
  is approximately equal to the past average SFR (derived as the total assembled mass
divided by the galaxy age), for \( LBG_N \) this is not true. For many \( LBG_N \) the past
  average SFR is much larger than the current value, indicating that in the past they
  have formed stars much more vigorously than at present.

- The morphological properties are also somewhat different: \( LBG_L \) tend to be more
  nucleated than those without line emission. Most of the absorbers have a very
diffuse and/or clumpy morphology; this could be due either to the presence of more
dust or to intrinsic morphological differences.

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