SIZING UP Lyα AND LYMAN BREAK GALAXIES

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Received 2010 November 22; accepted 2012 March 29; published 2012 April 23

ABSTRACT

We measure the sizes for a sample of 174 Lyα-selected galaxies with broadband imaging with the Hubble Space Telescope. Over the redshift range 2.25 < z < 6, Lyα-selected galaxies have a characteristic, constant, small size in rest-frame ultraviolet (UV) light. Coupled with a characteristic star formation intensity (i.e., UV luminosity per unit area), this can explain their non-evolving ultraviolet continuum luminosity function. This is in contrast to Lyman break galaxies (LBGs) over the same redshift range, which have been previously shown to increase in linear size as H(z)−1. The compact physical size seems to be a critical determining factor in whether a galaxy will show Lyα emission or not. The Lα of LBGs and its evolution with redshift can be derived from a simple model where the star formation intensity has an upper limit set by feedback processes, independent of redshift. The increase in Lα of LBGs is mainly driven by the increase in linear size over redshifts for z = 2–7. Since Lyα galaxies do not grow in linear size, they do not show an increase in Lα.

Key word: galaxies: high-redshift

1. INTRODUCTION

The two major ways of finding galaxies at high redshift using optical data are the Lyman break method (e.g., Steidel et al. 1996) and the Lyα method (e.g., Hu et al. 1998; Rhoads et al. 2000). While both selection methods identify actively star-forming galaxies, there are clear quantitative differences. The Lyα-selected objects are seen in most cases to be young, relatively less massive, and less evolved chemically than Lyman break galaxies (LBGs; Gawiser et al. 2007; Pirzkal et al. 2007; Finkielstein et al. 2009, 2010).

What makes a galaxy an Lyα emitter (LAE)? We investigate the sizes and surface brightnesses of Lyα-selected galaxy samples over a wide range of redshift, and compare our result to previous studies of both size evolution and surface brightness evolution in LBGs.

The sizes of typical LBGs increase from redshift 6 to redshift 1.5 (Ferguson et al. 2004; Bouwens et al. 2004; Hathi et al. 2008). “Typical LBGs” here means those galaxies with luminosities about Lα or brighter. The observed size evolution of LBGs is well described by R ∝ H−1(z), as expected for samples of disk galaxies selected by fixed circular speed.

High-redshift LBGs are similar to low-redshift (z ≈ 0) starbursts in that their star formation intensity (SFI), measured in UV luminosity per unit area, shows a distinct upper limit that does not change from redshift 0 to 6.5 (Meurer et al. 1997; Hathi et al. 2008). The upper limit of SFI corresponds to the maximum pressure, beyond which galaxy-scale winds become prevalent and inhibit further star formation by heating cold interstellar medium (ISM) and/or removing cold ISM with winds (Meurer et al. 1997; Heckman et al. 1990; Thompson et al. 2005; Murray et al. 2005).

In Section 2, we describe the Lyα samples that we use, together with the size measurements. We present new size measurements for 174 galaxies with redshifts between z = 2.25 and z = 6.7, combined with previously published size measurements from the literature (Venemans et al. 2005; Overzier et al. 2006, 2008; Taniguchi et al. 2009; Bond et al. 2009; Dow-Hygelund et al. 2007). In Section 3, we describe the calculations of the SFI in the full sample. We discuss our results in Section 4. Finally, in Section 5 we summarize the implications of our findings for galaxy formation and evolution.

2. SAMPLES AND SIZE MEASUREMENTS

We measured the sizes of known LAEs from several surveys spanning the redshift range 2 < z < 6. (see Table 1). We select surveys in fields where images from the Hubble Space Telescope (HST) exist, since Lyα galaxies are unresolved in ground-based imaging.7 We measure the sizes of the Lyα galaxies from broadband imaging around the wavelength 1500 Å, to facilitate comparison with the sizes measured for LBGs.

The most common measure of size is the half-light radius r25, defined as radius of a circle enclosing half the total projected light of the galaxy, and is calculated using the program SExtractor (Bertin & Arnouts 1996) in most cases. We measured the half-light radii of LAEs at z = 2.25 (a sample from Nilsson et al. 2009), 3.1 (sample from McLinden et al. 2011), and 4.45 (sample from Finkielstein et al. 2009), after excluding sources identified as active galactic nuclei. We used the SExtractor half-light radius parameter, based on publicly available HST images. In the z = 2.25 and z = 3.1 samples, the HST images are from the COSMOS survey (Capak et al. 2007), using the Advanced Camera for Surveys (ACS)/Wide Field Camera with the F814W filter. In the z = 4.45 sample, the HST images are from the GOODS survey (Giavalisco et al. 2004; F775W

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7 Here we exclude the Lyα blobs (e.g., Steidel et al. 2000; Matsuda et al. 2004; Yang et al. 2009, 2010), which come in a variety of sizes, appear to be associated with only the most overdense regions, and may be powered by some mechanism besides star formation.
In images provide a rest wavelength of 1420 Å at z = 4.45. In addition, we compile other size measurements made using HST images for other Lyα galaxies up to redshift z ~ 6 (Pirzkal et al. 2007; Bond et al. 2009; Overzier et al. 2006, 2008; Venemans et al. 2005; Taniguchi et al. 2009). The parameters used to generate catalogs are described by Leauthaud et al. (2007) for COSMOS, and Caldwell et al. (2008) for GEMS.8

Table 1 summarizes the different samples of Lyα galaxies, including the sample size, redshift, and the continuum rest wavelength used for size measurements. The measured sizes of galaxies are not sensitive to the wavelength, given the modest wavelength differences among the samples. This Letter uses a sample of 343 galaxies, among which we are reporting the first size measurements for 174. About 15%–20% of Lyα galaxies are also reported to be “clumpy,” or have more than one candidate association among the broadband sources (Pirzkal et al. 2007; Rhoads et al. 2005; Taniguchi et al. 2009; Bond et al. 2009). Being a minority, they do not affect the median size greatly; but these objects have been excised from the size estimates.

### 2.1. Possible Biases, Incompletenesses, and Errors due to Inhomogeneous Samples

At low signal-to-noise ratios (S/Ns), the half-light radius measured with SExtractor may be biased. Venemans et al. (2005), Overzier et al. (2006, 2008), and Taniguchi et al. (2009) all added simulated galaxies of known half-light radius to their images and measured their half-light radii with SExtractor. They found that SExtractor underestimates the half-light radius slightly at low S/N. Venemans et al. (2005) and Overzier et al. (2006, 2008) found that for signal-to-noise ratios S/N ≥ 10 (corresponding to a continuum magnitude of I_{lim} = 27 AB) and sizes ≤0.13, the correction remains below 15% of the measured size. The median LAE size in the Taniguchi et al. (2009) sample is the same (0′.15) for both the direct SExtractor measurements and for their simulation results, while the mean size increases from 0′.16 to 0′.19. Bond et al. (2009) estimated r_{hl} using SExtractor and using a curve of growth from aperture fluxes measured with the IRAF “phot” task, and find that SExtractor half-light radii are underestimates, especially when S/N is low. Finally, the Pirzkal et al. (2007) half-light radii were measured using GALFIT (Peng et al. 2002). To summarize, a 15% underestimate of size is typical for the sizes and brightnesses seen in these samples.

The completeness of the sample can potentially be an issue if the HST imaging is not deep enough. For all but one sample, more than 80% of these sources are detected in the HST imaging. The exception is the sample of Taniguchi et al. (2009) at z = 5.7 which is covered by the comparatively shallow COSMOS survey. The remaining z > 4 samples all had a 100% HST detection rate (9 objects from Pirzkal et al. 2007, 4 from Overzier et al. 2006, 14 from Finkelstein et al. 2009, and 12 from Overzier et al. 2008). The size distributions at any redshift are skewed, with a preponderance of compact sources and tail of larger ones comprising a modest fraction of the total. We have based our size evolution analysis on the median size distribution, which is robust to outliers. The median size also seems to be independent of the Lyα line flux. For example, the McLinden et al. sample has a line flux cutoff six times brighter than that of Venemans et al. (2005) and Bond et al. (2009) at the same redshift of z = 3.1, yet the median size is the same within the errors.

### 3. STAR FORMATION INTENSITY MEASUREMENTS

The SFI is calculated following Hathi et al. 2008. We assume that the UV continuum is well represented by a power law of the form f_{\lambda} \propto \lambda^{\alpha}, where f_{\lambda} is the flux density per unit wavelength (erg s^{-1} cm^{-2} Å^{-1}). The UV spectral slope (\beta) is then derived from a power-law fit to the UV colors using two filters. In cases where we did not have the color information, we assume that the UV slope \beta = -2, which is a typical slope among well-studied Lyα galaxies (Pirzkal et al. 2007; Gawiser et al. 2007; Rhoads et al. 2009).

A dust-free stellar population is expected to have a slope of \beta \approx -2 for a wide range of young stellar populations, so observed deviations from this slope give us an estimate

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8 In particular, the MIN AREA is 18 and 37 for COSMOS and GEMS, respectively.
of reddening by dust. This reddening estimate is then used along with the Calzetti extinction law (Calzetti et al. 1994) to correct for dust extinction. We next k-correct the UV flux at the observed wavelength to that at rest-frame 2300 Å. Finally, we apply a correction factor to convert the extinction-corrected UV luminosity into a bolometric luminosity: \( L_{\text{UV}} / L_{\text{bol}} \approx 0.33 \) (Hathi et al. 2008).

The SFI \( S \) is then defined using the luminosity and size,

\[
S = \frac{L_{\text{bol}}}{2\pi r^2} \left( \frac{L_{\odot}}{\text{kpc}^2} \right).
\]

The SFI versus redshift is plotted in Figure 1, for LBGs (Hathi et al. 2008) as well as LAEs.

4. RESULTS

1. Star formation intensity. Hathi et al. (2008) showed that the upper limit for SFI seems to hold for LBGs up to redshifts \( z > 6.5 \). In Figure 1 we see that the SFI for the LAEs also stays within that upper envelope. The lower envelope of the SFI distribution is of course set by incompleteness, so we concentrate on the upper envelope.

The typical SFI for Ly\( \alpha \) galaxies is smaller than that of LBGs by about a factor of 2.5, but above the threshold required to drive galaxy-scale winds (Lehnert & Heckman 1996), and such winds may play a significant role in Ly\( \alpha \) photon escape. The SFI could be underestimated if we have overestimated the size of LAEs. With the measured size of the Ly\( \alpha \) galaxies 0.15, and the point spread function (PSF) for ACS at 0.09, subtracting the PSF in quadrature would yield a 0.12 size and an underestimate of 0.2 dex in SFI. In Figure 1, we plot SFI for Ly\( \alpha \) and LBGs, with the size correction applied. The SFI for Ly\( \alpha \) galaxies shows no evolution with redshift between \( z = 3–7 \). The average SFI at \( z = 2.1 \) is lower than the average SFI at \( z > 3 \). It is not clear whether this can be explained by selection effects.

2. Sizes. Figure 2 shows the half-light radii of Ly\( \alpha \) galaxies and LBGs. The median size of Ly\( \alpha \) galaxies is small and does not change significantly with redshift \( z \) over the range 3.1 < \( z \) < 6.6. A formal straight line fit to median linear sizes versus redshift results in a slope of 5% and an average size change of 23% going from \( z = 2.25 \) to 6.5, much of which occurs between \( z = 3.1 \) and 2.1 for Ly\( \alpha \) galaxies (Bond et al. 2011). This is to be contrasted to the 250% size evolution between \( z = 2.0–6.0 \) for LBGs. The average size of LBGs follows closely the relation \( r_{\text{hl}} \propto 1/H(z) \), where \( H(z) \) is the Hubble parameter at redshift \( z \).

Given that nearly all of the Ly\( \alpha \) galaxies studied here were identified in ground-based surveys with typical seeing of \( \gtrsim 1'' \), it seems unlikely that the typical observed size of \( \sim 0.15 '' \) is due to observational selection against larger objects. This is not to say that it is the same set of Ly\( \alpha \) galaxies that stays unevolved from redshift 2 to 6. It just means that whenever we identify galaxies by means of strong Ly\( \alpha \) emission, we find them to be compact in size, independent of the redshift. It may be that the Ly\( \alpha \) emitting phase in a galaxy is short with a duty cycle of about 10%–15%, a conclusion that has been arrived at by studying their stellar populations, correlation functions among other properties (e.g., Malhotra & Rhoads 2002; Kovač et al. 2007; Tilvi et al. 2009; Nagamine et al. 2010).
The observed absolute magnitudes $M_*$, which are related to the characteristic UV luminosity $L_*$ by $L_*(\text{UV}) \propto 10^{-0.4 M_*}$. This model is represented by the line. The open points represent the observed absolute magnitudes $M_*$ of Lyman break galaxies at different redshift bins (Bouwens et al. 2007), and the solid points show extinction-corrected values.

**3. Luminosity.** Putting together the evolution in size and the constancy of surface luminosity for both the LBGs and LAEs, we can reproduce the observed evolution of $L_*$ in LBGs and LAEs. The UV luminosity function of Ly$\alpha$ galaxies does not evolve measurably for redshifts $3 < z < 6.0$ (Ouchi et al. 2008). On the other hand, the luminosity function of LBGs does evolve, with $L_*$ getting brighter at lower redshifts (e.g., Bouwens et al. 2007). In Figure 3, we plot our prediction for the redshift evolution of $L_*$—based on the observed size evolution and constant characteristic surface brightness of LBGs—and plot for comparison the observed evolution in $L_*$. We see that the observed evolution is reproduced well by our model. Correction for extinction has been applied to the $L_*$ points for each redshift bin.

A full calculation of the luminosity function would depend on the bivariate probability distribution of galaxy size and galaxy surface brightness. However, by restricting our attention to $L_*$, we avoid much of this complexity. Since $L_*$ is a “knee” in the luminosity function, above which the number of galaxies drops exponentially, we expect that $L_*$ galaxies will correspond roughly to the upper envelope of SFR.

**5. DISCUSSION**

At this point the alert reader will note that of the three quantities, radius, luminosity, and surface luminosity, at most two are independent. So once we have determined the size evolution with redshift and know that the upper envelope of the surface brightness stays constant, we can then predict the redshift evolution of $L_*$ (Figure 3). The relevant question then becomes: of these three properties, which two are the independent variables, and which one is the dependent property? For that, we will rely on which two quantities seem more physically fundamental.

The upper limit to the surface luminosity is a natural candidate. The upper limit for LBGs and low-redshift starbursts observed by Meurer et al. (1997), by Hathi et al. (2008), and here corresponds to the maximum pressure measured in starburst galaxies driving winds (Heckman et al. 1999) and to Eddington luminosity via momentum-driven winds (Murray et al. 2005). The LBGs also show evidence for strong winds in the line profiles and relative velocities between absorption and emission lines (e.g., Steidel et al. 2010).

The observed size evolution of LBGs can be understood in terms of growth of disks. If LBG selection identifies galaxies with a particular rotation speed at all redshifts, we should expect their typical size to grow with redshift as $H(z)^{-1}$ (Fall & Efstathiou 1980). It is not entirely clear that the LBGs, or Ly$\alpha$ galaxies, are disks in formation. Ravindranath et al. (2006) find that only 40% of LBGs at $z \approx 3$ have exponential profiles. Similar results are seen for Ly$\alpha$ galaxies at $z = 3.1$ (Gronwall et al. 2011).

It could well be that Ly$\alpha$ galaxies show us a very early stage of galaxy formation, as initially suggested by Partridge & Peebles (1967). This is supported by the small physical sizes, smaller dust extinction, younger stellar ages, and lower stellar masses seen for most (though not all) Ly$\alpha$ galaxies (Pizgalk et al. 2007; Gawiser et al. 2007; Finkelstein et al. 2007, 2008, 2009; Pentericci et al. 2007). The first observational demonstration of the youth of the stellar populations in these galaxies came from the high equivalent widths of the Ly$\alpha$ line, which arises most naturally from stellar populations younger than 30 Myr (Malhotra & Rhoads 2002). Studies of correlation functions of Ly$\alpha$ galaxies also indicate that the duty cycle of Ly$\alpha$ emitting phase is about 15% (e.g., Kovač et al. 2007). The bias inferred from the correlation function matches expectations for the progenitors of low-redshift $L_*$ galaxies based on models of bias evolution, further supporting the idea that LAEs may be building blocks of typical present-day galaxies (e.g., Gawiser et al. 2007). There is some controversy whether the LBGs showing Ly$\alpha$ line emission are older or younger than their counterparts without line emission (Pentericci et al. 2007; Kornei et al. 2010). Perhaps size is the crucial property that determines whether or not a galaxy shows Ly$\alpha$ emission.

So far, we have discussed the sizes of galaxies as seen in the UV continuum. This allows us to compare the LBGs and Ly$\alpha$ galaxies on an equal basis. The Ly$\alpha$ galaxies may show a different size in line emission: larger, if the resonant scattering of Ly$\alpha$ photons to escape from the galaxy is important; and smaller if the Ly$\alpha$ comes from an active nucleus.

**6. CONCLUSIONS**

We have shown that the growth in characteristic luminosity of high-redshift star-forming galaxies proceeds in step with their growth in size, due to their observed maximum surface brightness (which in turn may be explained by galactic wind feedback).

We have also shown that a compact physical size is likely to be a key factor in whether or not a galaxy is an LAE. This is true for all redshifts in the range $2 \lesssim z \lesssim 6$, and Ly$\alpha$ galaxies are faint at these redshifts because of their small sizes. The
more fundamental question, then, is why do we see the same size for galaxies with Lyα emission across the redshift range 2–7? The Lyα line is resonantly scattered, which increases its path length in neutral gas and therefore the chance of its being absorbed by dust—although in a clumpy medium it can escape (Neufeld 1990; Finkelstein et al. 2008, 2009). Galactic winds also help in the escape of Lyα photons by shifting the photons away from the resonant frequency (Santos 2004; Verhamme et al. 2006; McLinden et al. 2010). The optical depth to Lyα resonant scattering increases with size. It could also be that larger galaxies contain multiple starbursting regions, resulting in incoherent flows on a galaxy-wide scale. This in turn could hamper Lyα escape, since any particular line of sight would be likely to sample gas at a wide range of velocities. Larger, more massive galaxies also have higher metallicity, leading to more dust and fewer Lyα photons escaping. While we do not completely understand the relative importance of all the mechanisms that aid in Lyα escape, the small sizes of these galaxies give us a crucial clue to their nature.

We thank the referee for advice that improved this Letter. We also thank Evan Scannapieco, Gerhardt Meurer, and Mike Fall for useful discussions, and DArk Cosmology Centre in Copenhagen, Denmark, for hospitality. We also acknowledge financial support from the US National Science Foundation through NSF grant AST-0808165.

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