THE LYMAN ALPHA REFERENCE SAMPLE: EXTENDED LYMAN ALPHA HALOS PRODUCED AT LOW DUST CONTENT*

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ABSTRACT

We report on new imaging observations of the Lyman alpha emission line (Lyα), performed with the Hubble Space Telescope, that comprise the backbone of the Lyman alpha Reference Sample. We present images of 14 starburst galaxies at redshifts 0.028 < z < 0.18 in continuum-subtracted Lyα, Hα, and the far ultraviolet continuum. We show that Lyα is emitted on scales that systematically exceed those of the massive stellar population and recombination nebulae: as measured by the Petrosian 20% radius, R20, Lyα radii are larger than those of Hα by factors ranging from 1 to 3.6, with an average of 2.4. The average ratio of Lyα-to-FUV radii is 2.9. This suggests that much of the Lyα light is pushed to large radii by resonance scattering. Defining the Relative Petrosian Extension of Lyα compared to Hα, ξ Lyα = R20 Lyα / Hα, we find ξ Lyα to be uncorrelated with total Lyα luminosity. However, ξ Lyα is strongly correlated with quantities that scale with dust content, in the sense that a low dust abundance is a necessary requirement (although not the only one) in order to spread Lyα photons throughout the interstellar medium and drive a large extended Lyα halo.

Key words: cosmology; observations – galaxies: evolution – galaxies: formation – galaxies: starburst – radiative transfer

Online-only material: color figures

1. INTRODUCTION

The Lyman alpha emission line (Lyα), emitted by the spontaneous de-excitation over the n = 2 → 1 electronic transition in neutral hydrogen (H i), is now an established observational probe of evolving galaxies in the high-z universe (Cowie & Hu 1998; Rhoads et al. 2000). Exploitation of Lyα has resulted in significant galaxy surveys (Ouchi et al. 2008; Nilsson et al. 2009; Guaita et al. 2010; Adams et al. 2011), the next generations of which will recover vast numbers of galaxies. However, the H i abundance in most galaxies, combined with the large Lyα absorption cross section of ground-state hydrogen, suggests that most Lyα will be absorbed and re-scattered by the same transition that created it. Thus most Lyα photons are thought to be subject to multiple scattering events as they encounter neutral gas, resulting in a complicated radiative transport (Neufeld 1990; Verhamme et al. 2006; Laursen et al. 2009).

Because H i is often found at distances that exceed the size of stellar disks and star-forming regions (Yun et al. 1994; Meurer et al. 1996; Cannon et al. 2004), characteristic Lyα scale lengths may be expected to be substantially larger than those of, for example, the FUV continuum or Hα. Indeed this has been well observed at high-z (e.g., Fynbo et al. 2001; Rauch et al. 2008; Steidel et al. 2011, although see also Feldmeier et al. 2013) and low-z (Mas-Hesse et al. 2003; Östlin et al. 2009), and studied extensively by simulation (Laursen et al. 2009; Barnes & Haehnelt 2010; Zheng et al. 2011; Verhamme et al. 2012).

In this Letter we present images from the Lyman alpha Reference Sample (LARS). The LARS program (G. Östlin et al., in preparation; M. Hayes et al., in preparation) is targeting 14 UV-selected star-forming galaxies in the nearby universe, all of which have been imaged in Lyα, Hα, Hβ, and five UV/optical continuum bands. Many other observables, both in hand and ongoing, are providing gas covering fractions and kinematics, and measuring the H i mass and extent directly.

Hubble Space Telescope (HST) imaging allows us to probe spatial scales down to 28 pc in individual galaxies, quantify the extent of Lyα, and compare it with other wavelengths and derived properties. This Letter discusses the extension of Lyα radiation. In Section 2 we briefly summarize the data and show the new images. In Section 3 we quantify the sizes of the galaxies in Lyα, FUV, and Hα, and discuss them with reference to high-z
measurements in Section 4. In Section 5 we show how a low dust content seems to be a necessary prerequisite in order to produce this extended emission. We assume a cosmology of \( \Omega_M = 0.2, \Omega_{\Lambda} = 0.8 \).

### 2. LARS IMAGES

LARS consists of 14 star-forming galaxies selected by FUV luminosity from the GALEX all-sky surveys, and imaged with \textit{HST} cameras ACS/Solar Blind Channel (SBC), ACS/WFC, and WFC3/UVIS. The sample selection, observations, and data processing are described in detail in G. Östlin et al. (in preparation). FUV luminosities range between \( \log(L_{\text{FUV}}/L_{\odot}) = 9.2 \) and 10.7, overlapping much of the luminosity range of Lyman break galaxy (LBG) surveys, and are listed in Table 1.

We use the Lyman alpha eXtraction software (Hayes et al. 2009) to produce continuum-subtracted Ly\( \alpha \) and H\( \alpha \) images, corrected for underlying stellar absorption and contamination from [N\( \text{II} \)]. In 1 arcsec square boxes away from the targets we measure rms background noise of \( 5.7 \times 10^{-10} \text{erg s}^{-1} \text{cm}^{-2} \) in Ly\( \alpha \), \( 2.1 \times 10^{-21} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \) in the FUV, and \( 6.8 \times 10^{-19} \text{erg s}^{-1} \text{cm}^{-2} \) in H\( \alpha \). Total Ly\( \alpha \) luminosities range from 0 (non-detection) and \( 2 \times 10^{13} \text{erg s}^{-1} \) with a median of \( 8.1 \times 10^{14} \text{erg s}^{-1} \); roughly seven of the objects would be recovered by the deepest Ly\( \alpha \) surveys (M. Hayes et al., in preparation).

We present our first imaging results in this Letter as a series of RGB composite images in Figures 1 and 2. In green we encode the far-UV continuum, which traces the unobscured massive stars, and roughly incorporates the sites that produce the ionizing photons. In red we show continuum-subtracted H\( \alpha \), which traces the nebulae where the aforementioned ionizing photons are reprocessed into the recombination line spectrum. The continuum-subtracted Ly\( \alpha \) observation is encoded in blue. The images have been adaptively smoothed using a variable Gaussian kernel (FILTER/ADAPTIVE in ESO/MIDAS), in order to enhance positive regions of low surface brightness emission. The intensity scaling of all the images is logarithmic, and the levels are set to show the maximum of structure and the level at which the faintest features fade into the background.

Immediately, it can be seen that Ly\( \alpha \) morphologies bear limited resemblance to those of the FUV and H\( \alpha \). In some cases, Ly\( \alpha \) appears to be almost completely absent: LARS 04 and 06 in particular show only small hints of Ly\( \alpha \) emission that contribute negligibly toward filling in the global absorption, and the composites are dominated by UV and H\( \alpha \) light. Ly\( \alpha \) is strongly absorbed, particularly in the central regions of these objects. Others show copious Ly\( \alpha \) emission and reveal morphological structures that are not seen at other wavelengths. Most obviously, LARS 01, 02, 05, 07, 12, and 14 show large-scale halos of Ly\( \alpha \) emission that completely encompass the star-forming regions, although the same phenomenon is visible to some extent in all the objects, even the absorbers.

We have discussed this extended Ly\( \alpha \) emission in depth in the past (Hayes et al. 2005, 2007; Atek et al. 2008; Östlin et al. 2009). However, now, with an observational setup that is more sensitive to faint levels of Ly\( \alpha \) and a larger and UV-selected sample (G. Östlin et al., in preparation), we are able to robustly quantify and contrast these sizes and the relative extension of Ly\( \alpha \).

### 3. APERTURES, SIZES, AND GLOBAL QUANTITIES

In order to quantify the sizes of the galaxies at various wavelengths, we adopt the Petrosian radius (Petrosian 1976) with index \( \eta = 0.2 \); i.e., the radius, \( R \), at which the local surface brightness is 20% the average surface brightness inside of \( R \). In M. Hayes et al. (in preparation), we will show the Ly\( \alpha \) extent of some objects to be so large that ACS/SBC cannot capture the full flux, and hence measurements like 50% light radius are not robust. Indeed Petrosian radii were developed to be depth-independent measures of size. We note from experimentation, however, that very similar conclusions are reached using other definitions. The choice of \( \eta = 0.2 \) gives a size for every Ly\( \alpha \)-emitting galaxy in the sample except LARS 09, for which even at the full extent of the SBC we do not come close to crossing the \( \eta = 0.2 \) threshold. We reach the edge of the detector at...
Figure 1. False-color images of the LARS galaxies 01–08. Red encodes continuum-subtracted Hα, green the FUV continuum, and blue shows continuum-subtracted Lyα. Images have been adaptively filtered to show detail. Scales in kiloparsec are given on the side. Intensity scales are logarithmic, with intensity cut levels set to show detail.

(A color version of this figure is available in the online journal.)

Figure 2. Same as Figure 1 except for LARS galaxies 09–14. The black square in LARS 09 masks a UV-bright field star.

(A color version of this figure is available in the online journal.)

η ∼ 1 (R > 12 kpc) and can expect the true extent of Lyα to be much larger. For the 11 galaxies in which $R_{\text{Ly}\alpha}$ is well measured, its determination is robust, and would not change were the observations deeper or the field-of-view larger. $R_{\text{P20}}$ is computed for Lyα, Hα, and the FUV continuum, and listed in Table 1. Based upon aperture-matched Hα and Hβ imaging and standard Case B assumptions, we recover up to 60% of the intrinsic Lyα flux, although the median value is just ∼3% (M. Hayes et al., in preparation).

We compare the light radii graphically in Figure 3. The plots show $R_{\text{P20}}^{\text{Ly}\alpha}$ versus $R_{\text{P20}}^{\text{FUV}}$, a comparison that could be made at high-z, and $R_{\text{P20}}^{\text{Ly}\alpha}$ versus $R_{\text{P20}}^{\text{H}\alpha}$, a comparison that more directly conveys the difference between the observed and intrinsic Lyα sizes. Clearly, though, there is little difference in the result: Lyα radii are, on average, substantially larger than corresponding FUV or Hα radii. In Table 1 we also report the Relative Petrosian Extension of Lyα compared to Hα, $\xi_{\text{Ly}\alpha}$, which is simply defined as $R_{\text{P20}}^{\text{Ly}\alpha}/R_{\text{P20}}^{\text{H}\alpha}$. Twelve galaxies show net emission of Lyα, where all except for one (LARS 03) has $\xi_{\text{Ly}\alpha} > 1$. The galaxy with the largest extension is LARS 14, for which we measure $\xi_{\text{Ly}\alpha} = 3.6$. It is not clear whether the globally absorbing galaxies LARS 04 and 06 become emitters on larger scales, but if so their
$R_{20}^{Ly\alpha}$ must be larger than the radius of the SBC chip, implying that $\xi_{Ly\alpha}$ must exceed 5.3 and 13.4, respectively. That would make them the most extended objects in the sample. Excluding these two galaxies, and also LARS 09 for which we can only provide a lower limit, the sample mean (median) is computed as 2.43 (2.28).

4. RELEVANCE FOR HIGH-REDSHIFT STUDIES

It is important to note that FUV radii imply that all the galaxies would be effectively unresolved by ground-based observations if they were at $z \geq 2$. The largest is 8 kpc, which corresponds to the 1 arcsec resolution that could be expected from the seeing. However, one of the objects has a Ly$\alpha$ radius of 15.5 kpc; recovering this total flux at $z \sim 2$ would require an aperture of at least 2 arcsec. Some objects are also highly elongated and were pushed to the high-$z$ universe, much of their Ly$\alpha$ could also be unmeasured if circular apertures are used.

Ly$\alpha$ emission more extended than the FUV has been reported in numerous high-$z$ samples. Fynbo et al. (2003) remarked upon a few such objects at the brighter end of the luminosity distribution of the 27 narrowband-selected galaxies, and the extremely deep spectroscopic observations of Rauch et al. (2008) uncovered 28 Ly$\alpha$ galaxies, 10 of which were classified as extended. Samples of Ly$\alpha$ blobs (e.g., Matsuda et al. 2012; Prescott et al. 2012) may be many times the size of their counterpart galaxies, if indeed counterparts are identified at all. Here we report that every galaxy in the sample that emits Ly$\alpha$ does so by producing a halo; on average the halo is over twice the linear size of H$\alpha$ and the FUV.

By stacking narrowband images of LBGs at $<z> = 2.65$, Steidel et al. (2011) reported Ly$\alpha$ halos that extend many tens of kiloparsec, probably probing the neutral circumgalactic medium out to the virial radius. Subdividing the full sample by Ly$\alpha$ properties, the halos at radii larger than 20–30 physical kpc show very similar scale lengths in all subsamples (although different central surface brightnesses), even when central Ly$\alpha$ absorption is found. At small radii the subsamples exhibit profiles that differ markedly, dropping rapidly to $\sim 0$ for the Ly$\alpha$-absorbing sample but steepening by varying degrees in all others. Even the steepest central profiles, however, still run much flatter than those of the stellar continuum, and this change likely marks the onset of higher density gaseous disks or similar.

From the various $z \approx 2.7$ Ly$\alpha$ profiles of Steidel et al. (2011) we calculate $R_{20}^{Ly\alpha}$ using the same method as for our sample, and dividing by $R_{20}^{Ly\alpha}$ from the continuum profile we obtain $\xi_{Ly\alpha}$ (now relative to the UV). These raw values range between $\xi_{Ly\alpha} = 3.8$ for the non-Lyman-alpha Emitters (LAEs), and 5.9 for the LAE-only sample, and are notably bigger than our largest $\xi_{Ly\alpha}$. However, under the assumption that the inner and outer profiles mark physically different regimes that may not be the same in low-$z$ galaxies, we also subtract the exponential halo fits of Steidel et al. (2011) and repeat the exercise; this yields a range of $\xi_{Ly\alpha} = 0.84$–2.0. This is now smaller than many of our values, although close to the average and the dispersion of the high-$z$ sample is obviously lost in the stacking process. On the other hand, the UV continuum profile of Steidel et al. (2011) is dominated by atmospheric seeing. If we instead use the continuum effective radius of BM/UX galaxies and LBGs from HST imaging (Mosleh et al. 2011) we compute $R_{20}^{Ly\alpha} \approx 5$ kpc, which would increase all the $\xi_{Ly\alpha}$ quoted above by a factor of 2.5. $\xi_{Ly\alpha}$ from the raw data would then become much larger than what we measure in the local universe (up to 15), and $\xi_{Ly\alpha}$ in halo-subtracted profiles that are roughly consistent (2.1–4.8).

LARS observations probe scales far below the tens of kiloparsec sampled at high-$z$ on a case-by-case basis. The galaxies likely include the range between, or roughly bracketing, the averaged subsamples of Steidel et al. (2011). Our imaging also suggests this extension to be a very common property of Ly$\alpha$-emitting galaxies, and its onset begins almost immediately in the inner few kiloparsec: we find seven galaxies with FUV Petrosian radii below 2 kpc, five of which have corresponding Ly$\alpha$ radii three times larger.

It is also noteworthy that Steidel et al. (2011) find different median dust attenuations for the Ly$\alpha$-emitting and non-emitting subsamples, almost precisely as we did in Hayes et al. (2010). LAEs, which show extended central peaks, were determined to have stellar $E_{B-V} = 0.09$ mag (cf. 0.085 in Hayes et al. 2010) while absorbers show $E_{B-V} = 0.19$ (cf. 0.23 for our H$\alpha$-selected sample). Adopting the prescription of Meurer et al. (1999) the stellar $E_{B-V}$ measurements for the Steidel et al. samples correspond to $\beta$ slopes$^{15}$ of $-1.77$ (LAEs) and $-1.27$

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$R_{20}^{Ly\alpha}$, $\xi_{Ly\alpha}$, and $f_{\lambda}$ are parameters used in astronomical observations. FUV refers to ultraviolet continuum flux density.
Similarly, the Hα/β objects have similar UV slopes to the vast majority of those used in studies of low-reddening (i.e., that which is to zeroth order expected for Lyα F390W) filters. With colors between β (SBC ξi trend of P20) and the total Lyα luminosity. In Figure 4 we show how ξi,α compares with both the UV continuum slope β and the Hα/β ratio. We note that the Sloan Digital Sky Survey (SDSS) fibers are on average smaller than the Lyα radii, but do capture the bulk of the nebular emission, and fluxes can easily be measured without contamination of [N ii] and stellar absorption. Since Meurer et al. (1999) β has been used almost ubiquitously as a proxy of stellar attenuation in high-z galaxies; here we measure β from aperture-matched HST imaging using the FUV (SBC/F140LP or F150LP) and the U-band (UVIS/F336W or F390W) filters. With colors between β ~ -2.2 and -0.6 our objects have similar UV slopes to the vast majority of those found in z = 2–4 Lyα-emitting galaxies (Blanc et al. 2011). Similarly, the Hα/β ratio is the canonical probe of nebular reddening (i.e., that which is to zeroth order expected for Lyα) used in studies of low-z and Galactic nebulae. β and Hα/β are listed in Table 1.

Both measures of dust content strongly anti-correlate with ξi,α although the sample is small (N = 12 defined sizes in Lyα). To assess its significance we compute the Spearman rank correlation coefficient, ρ, which yields ρ = -0.73 and -0.61 for the anti-correlation of ξi,α with β and Hα/β, respectively. This corresponds to likelihoods of the null hypothesis—that this correlation arises purely by chance—amounting to 0.7% (UV slope), and 3.6% (Hα/β).

The halo–dust phenomenon appears not to be a direct effect of radiative transfer. We have performed new test simulations with the MClya code (Verhamme et al. 2006), by tuning the gas-to-dust ratio in the synthetic galaxy of Verhamme et al. (2012). Indeed, the surface brightness does scale with dust abundance but the light profile (therefore P20) does not, and the ξi,α–dust trend must be a secondary correlation. A scenario is needed in which galaxies decrease the relative size of their H i envelopes as the absolute dust content increases. A sequence in which neutral gas settles into the galaxy (reducing ξi,α) and subsequently forms stars (creating more dust) would explain the trend, but without yet having obtained spatially resolved H i data this is conjecture.

Scattering also has the potential to spread Lyα over such an area that its surface brightness decreases greatly. In such a case, scattered radiation measured at large radii may not be sufficient to recover flux from a broad central absorption, making ξi,α observationally undefined when it is actually very large. The trend of ξi,α increasing in bluer galaxies, then, is also able to explain the undefined sizes of LARS 04 and 06, at their measured dust abundance. Similar considerations would also explain the non-detection of Lyα in local gas-rich but metal- and dust-poor dwarf starbursts such as i Zw 18 and SBS 0335–052 (Kunth et al. 1994; Mas-Hesse et al. 2003; Östlin et al. 2009), as discussed in Atek et al. (2009b).

We have empirically shown before (Atek et al. 2009a; Hayes et al. 2010) that the global escape fraction of Lyα photons correlates strongly with attenuation (also Kornei et al. 2010 in LBGs). We now demonstrate that at lower E_B–V, the more strongly emitting galaxies are likely to also spread their Lyα over larger surfaces. Thus while they do transmit more of their Lyα, it may be that more of the transferred Lyα is observationally lost outside photometric apertures. This may also explain the lack of correlation between Lyα/β and E_B–V observed by Giavalisco et al. (1996), compared to trends seen in other samples: the aperture of the IUE probed just 3 kpc at z = 0.01 and if more Lyα is lost in bluer galaxies the Lyα/Balmer ratios would be artificially lowered in such systems. This could in part mask an underlying correlation, and similar aperture effects may also be expected in the study of Wofford et al. (2013), which uses a smaller aperture still. By a similar token, galaxies that can very efficiently scatter Lyα photons may not be recovered at all,
despite frequently showing very blue UV colors. Determining precisely how Ly$\alpha$ profiles are modified for a given set of host properties will provide a cornerstone for interpreting future large high-$z$ surveys.

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