THE OVERDENSE ENVIRONMENT OF A LARGE Lyα NEBULA AT $z \approx 2.7^{1,2}$

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Received 2008 February 26; accepted 2008 March 27; published 2008 April 10

ABSTRACT

Large nebulae ($\geq 50$ kpc) emitting strongly in Lyα (also known as Lyα “blobs”) are likely signposts of ongoing massive galaxy formation. The relative rarity of these sources and their discovery in well-studied galaxy overdensities suggest that they may be associated with regions of high galaxy density. One of the largest Lyα nebulae, discovered at a redshift of $z \approx 2.7$ via its strong mid-infrared-emission, provides an unbiased test of this association. We have carried out a deep intermediate-band imaging survey for Lyα-emitting galaxies (LAEs) within a 30’ × 26’ field of view around this Lyα nebula. This is the first study of the environment of a Lyα nebula found without a priori knowledge of its surroundings. We find that the nebula is located in an overdense region, at least $20 \times 50$ h$_{70}^{-1}$ comoving Mpc in size, showing a factor of $\sim 3$ LAE number density enhancement relative to the edge of the field. Given the predicted number of such overdensities, we rule out the possibility of a chance coincidence at the $\leq 1\%$ level. This study, in conjunction with previous work, provides strong confirmation of the association between the largest Lyα nebulae and overdense regions of the universe.

Subject headings: galaxies: formation — galaxies: high-redshift — large-scale structure of universe

1. INTRODUCTION

Studies of massive galaxy populations show that the most massive galaxies are in place and in possession of the majority of their stellar mass by $z \sim 1–2$ (McCarthy et al. 2004; van Dokkum et al. 2004; Daddi et al. 2005; Bundy et al. 2005; Brown et al. 2007). Thus, while dark matter halos in a $\Lambda$CDM cosmology build up hierarchically with the gradual accretion and merging of smaller halos, the most massive galaxies within that context likely have more dramatic origins. The details of this process are uncertain, and ideally we would like to study sites of ongoing massive galaxy formation. Lyα nebulae or Lyα “blobs” (LABs)—large ($\geq 50$ kpc) clouds of gas emitting strongly in Lyα ($\sim 10^4$ erg s$^{-1}$)—provide such an opportunity. The large Lyα equivalent widths and the association with galaxy populations such as Lyman break galaxies (LBGs) and submillimeter galaxies (SMGs) strongly suggest that LABs are sites of ongoing galaxy formation. They have been found in small numbers (only 16 $\geq 50$ kpc LABs are known) around $z \sim 2–3$, a key epoch of black hole and galaxy growth (Steidel et al. 2000, hereafter S00; Francis et al. 2001; Palunas et al. 2004; Matsuda et al. 2004; Dey et al. 2005; Nilsson et al. 2006; Smith & Jarvis 2007; Greve et al. 2007). LABs span a range in size and surface brightness from the scales of Lyα-emitting galaxies (LAEs) to the largest LABs known ($\sim 150$ kpc, $\sim 27$ mag arcsec$^{-2}$; e.g., Matsuda et al. 2004). LABs are similar to the large Lyα halos observed in the overdensities around higher redshift radio galaxies (e.g., Venemans et al. 2007; Overzier et al. 2008) but are found in radio-quiet environments. The dominant power source in LABs is difficult to determine; among the limited sample of large LABs, there is evidence for embedded AGNs, starburst-driven superwinds, gravitational cooling radiation, and spatially extended star formation, all of which may play a role in powering the Lyα emission (M. K. M. Prescott et al. 2008, in preparation; S00; Chapman et al. 2004; Nilsson et al. 2006; Taniguchi & Shioya 2000; Matsuda et al. 2004; Dey et al. 2005; Matsuda et al. 2007).

Most known LABs, including two of the largest cases, have been discovered via narrowband surveys, often by targeting known galaxy overdensities (S00; Francis et al. 2001; Palunas et al. 2004; Matsuda et al. 2004). Follow-up narrowband imaging of the SSA22 region surrounding the S00 LABs revealed fainter LABs associated with the same overdensity traced by the LAEs (Matsuda et al. 2004). This suggests that LABs may be confined to overdense regions, as would be expected for sites of massive galaxy formation. A blank-field survey by Saito et al. (2006) supported this claim, finding no LABs with sizes greater than $\sim 30$ kpc and an order of magnitude lower number density of LABs relative to that found within the SSA22 galaxy overdensity. However, the association between LABs and galaxy overdensities may be misleading, as a truly systematic wide-area search has yet to be completed. A thorough environmental study has only been done for the S00 LABs, which were found by targeting a known galaxy overdensity.

In contrast, one of the largest LABs uncovered recently was found by entirely different means. While conducting a study of mid-infrared (24 $\mu$m) sources detected by the Spitzer Space Telescope, Dey et al. (2005) discovered a LAB at $z = 2.656$ within the NOAO Deep Wide-Field Survey Boötes field (NDWFS;7 Jannuzi & Dey 1999). Follow-up observations revealed complexity typical of the LAB class: the region hosts a buried AGN, many young galaxies, an LBG, and diffuse H$\alpha$ and continuum emission suggestive of spatially extended star formation (M. K. M. Prescott et al. 2008, in preparation). One of the largest and most luminous LABs known, and found without any a priori knowledge of its surroundings, this source

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1 Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.
2 Based on part in observations obtained at Kitt Peak National Observatory, a division of the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
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represents a unique opportunity to perform an unbiased, complementary test of the association between LABs and overdense regions.

In this work, we present the first results from an ongoing deep intermediate-band Lyα imaging survey of the environment of the Dey et al. (2005) LAB (hereafter, LABd05) and report on the spatial distribution of the LAEs in the immediate vicinity. A detailed analysis of the multiwavelength properties of LABd05 and the properties and clustering of the LAEs in the region will be presented by M. K. M. Prescott et al. (2008, in preparation). We assume the standard ΛCDM cosmology ($\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = 0.7$); the angular scale at $z = 2.656$ is 7.96 kpc arcsec$^{-1}$. All magnitudes are in the AB system.

2. OBSERVATIONS AND REDUCTIONS

We obtained deep imaging of the field around LABd05 using the Subaru telescope and the SuprimeCam imager (Miyazaki et al. 2002) on UT 2007 May 10–14 and June 17. The survey covers 0.22 deg$^2$ in an intermediate-band filter, IA445 ($\lambda \approx 4458$ Å, $\Delta \lambda_{\text{FWHM}} \approx 201$ Å), centered on the Lyα line at the redshift of the nebula; this corresponds to a convolving volume of $4.27 \times 10^7 h_{70}^{-3}$ Mpc$^3$ ($52 \times 45 \times 180 h_{70}^{-1}$ Mpc). Conditions during the May observations were variable (clouds, variable seeing 0.7″–1.2″) and good in June (clear with 0.7″ seeing). We obtained a total of 3 hours of observations.

We reduced the data using the SDFRED software (Yagi et al. 2002; Ouchi et al. 2004). The data were overscan-subtracted and corrected for geometric and atmospheric distortions. We generated the sky flat using object frames that were free of bright stars in combination with other images taken in the same intermediate-band filter (Y. Taniguchi 2007, private communication). Small portions of the SuprimeCam field of view are vignette by the autoguider probe; the affected areas were masked, as were bad columns, bright star ghosts, and satellite trails. Images were aligned and scaled using common stars and then combined using a clipped mean algorithm, which successfully removed cosmic rays. Of the SuprimeCam field of view (0.26 deg$^2$), 73% was usable (the remainder being of lower signal-to-noise ratio along the edge of the field or in the vicinity of bright stars).

The limiting magnitude of the stacked image is 28.3 AB mag (1 $\sigma$, 2″ diameter aperture), calculated using 10,000 random apertures. An approximate magnitude zero point was calculated from observations of the standard stars BD +25 4655 and Feige 34. For the NDWFS broadband imaging, the limiting magnitudes are $B_{\text{w,lim}} = 27.9$ mag, $R_{\text{lim}} = 27.1$ mag, and $I_{\text{lim}} = 26.0$ mag (1 $\sigma$, 2″ diameter aperture).

A portion of the field was observed in a custom U-band filter ($U_d; \lambda \approx 3590$ Å, $\Delta \lambda_{\text{FWHM}} \approx 116$ Å) using the Mayall 4 m Telescope over 6 nights (UT 2007 June 8–13). These data will be described elsewhere (M. K. M. Prescott et al. 2008, in preparation) but here provide a useful check on interlopers in our $z \approx 2.7$ LAE sample.

3. CANDIDATE SELECTION

We used Source Extractor (Bertin & Arnouts 1996) to select a sample of $\approx$38,600 sources detected in the IA445 band down to the 5 $\sigma$ limit of IA445 = 26.5 mag (2″ diameter aperture; $L_{\text{IA445}}(z = 2.656) = 1.5 \times 10^{42}$ ergs s$^{-1}$) with the following search parameters: at least 5 contiguous pixels, a threshold of 2 $\sigma$ per pixel, and a Gaussian filter matched to the seeing ($\text{FWHM} \approx 0.8$″). We measured matched aperture photometry using 2″ diameter apertures from the IA445, $B_w$, $R$, and $I$ imaging data sets, which were registered and resampled to match the $B_w$ astrometry and pixel scale (0.258″ pixel$^{-1}$). Aperture corrections were neglected ($\approx 0.08$ for an unresolved source). Line-emitting sources are strongly detected in IA445 relative to $B_w$, i.e., they have large negative IA445 $- B_w$ colors relative to the normal galaxy locus (see Fig. 1). We removed bright stars (IA445 $\leq$ 25.0) using the CLASS_STAR parameter in Source Extractor (>0.91) and employed a cut of IA445 $- B_w \leq -0.85$ mag yielding 1500 candidates. Shifting the IA445 $- B_w$ cut by ±0.2 mag causes no significant change to the main results presented in § 4. For $F_r \propto \nu^p$ continuum source, this corresponds to an observed equivalent width (EW) cut of $W_{\text{ew}} \geq 148$ Å. LAEs are known to be young, with estimated ages of 4–200 Myr (Finkelman et al. 2007; Gawiser et al. 2007; Lai et al. 2008). For the case of a young galaxy (25 Myr old simple stellar population, solar metallicity, Chabrier IMF; Bruzual & Charlot 2003; Tremonti et al. 2004) at $z = 2.7$ with standard intergalactic absorption (Madau 1995), this is equivalent to a rest-frame EW cut of $W_{\text{ew}} \geq 50$ Å.

We expect our LAE candidate sample to be contaminated by high-EW, low-redshift, $[\text{O} \text{II}]$ emission galaxies at $z \approx 0.2$. Since the IA445 bandpass lies on the red side of the $B_w$ filter (Fig. 1, inset), we also expect contamination from higher redshift galaxies ($z \approx 2.9–4.0$) for which the Lyman limit has entered the $B_w$ filter, thus depressing the $B_w$ flux relative to the IA445 flux. Using the publicly available NDWFS imaging (Jannuzi & Dey 1999), we employ a cut of $B_w - R \leq 0.8$ to remove both contaminant populations (see Fig. 2). The final sample of 785 LAE candidates corresponds to a mean LAE surface density of $\approx 4200$ deg$^{-2}$. The properties and sizes of the LAE sample will be discussed in an upcoming paper (M. K. M. Prescott et al. 2008, in preparation). There are no other large ($\geq$50 kpc) LABs in the vicinity of LABd05.

Sources at these redshifts should show very little flux in the $U_d$ band, which straddles the Lyman limit ($\lambda_{\text{rest}} \approx 970–1000$ Å).
Fig. 2.—$B_w - R$ vs. $R - I$ color-color diagram of the 1500 line-emitting candidates (open and filled circles). A typical error bar is shown. Expected color tracks for low-redshift galaxy templates are shown for 0.1 < $z$ < 0.3 (Leitherer et al. 1996); the color track for high-redshift LAE/LBG contaminants is based on a young galaxy template at 2.9 < $z$ < 4.0 (25 Myr old simple stellar population, solar metallicity, Chabrier IMF; Bruzual & Charlot 2003) with standard intergalactic absorption (Madau 1995). To remove both low- and high-redshift interlopers, candidates were required to have $B_w - R < 0.8$. The final sample of 785 LAE candidates is shown (filled circles).

\[ \Delta z \approx 2.656 \]

At $z \approx 2.656$, using the 25 Myr old model above to represent the typical LAE continuum shape, the $z = 3$ galaxy luminosity function from Reddy et al. (2008), and standard intergalactic absorption (Madau 1995), we predict that $\sim 1\%$–$2\%$ of the LAE sample should have $U_j$ detected at the 5σ level ($U_j = 25.3$). Only one LAE candidate is detected with $U_j \leq 25.3$, giving us confidence that we have selected a clean sample of LAEs. More sophisticated interloper rejection would require deeper $U_j$ imaging over the entire field.

4. RESULTS AND DISCUSSION

Figure 3 shows the spatial distribution of LAEs in the vicinity of LABd05. We find an overabundance of LAEs in the immediate vicinity of the LAB and clear evidence of an elongated overdense structure, with what appears to be a $\sim 10 h^{-1}_{70}$ Mpc underdensity at [218.36, 33.07]. In Figure 4, we plot the surface density of LAEs versus distance from LABd05. This shows a peak overdensity of a factor of 3.0 relative to the edge of the field, or a factor of 2.6 when averaged over the central 10 $h^{-1}_{70}$ Mpc radius. For comparison, the dashed line shows the expected LAE surface density estimated from the $z \approx 3.1$ luminosity functions of Gronwall et al. (2007) and Ouchi et al. (2008) assuming a uniform redshift distribution across our bandpass and no evolution. The overdensity spans at least $17 \times 47 h^{-1}_{70}$ Mpc (comoving). A study of the LAE population around the two S00 LABs, which are of comparable size and luminosity to LABd05, also found a factor of $\sim 3$ overdensity relative to the field that was $\sim 60$ Mpc across (Hayashino et al. 2004). Thus, although it was found without any a priori knowledge of its surroundings, LABd05 appears to reside in a similarly overdense environment.

Without follow-up spectroscopy, we cannot know the true redshift distribution of the sample within the intermediate-band filter. Assuming a uniform distribution across the filter ($\Delta z \approx 0.17, 180 h^{-1}_{70}$ Mpc, comoving, along the line of sight), our survey yields a mean number density of $\rho \approx 2.1 \times 10^{-3} h^{-3}$ Mpc$^{-3}$ for LAEs with $L_{5102} > 1.5 \times 10^{42}$ s$^{-1}$ cm$^{-2}$. The inner contour in Figure 3 corresponds to $\rho \approx 2.8 \times 10^{-3} h^{-3}$ Mpc$^{-3}$ while at the edge of the field $\rho \approx 1.2 \times 10^{-3} h^{-3}$ Mpc$^{-3}$. Given the presence of an overdensity, we expect the true redshift distribution to be significantly narrower. If we assume the overdensity resembles that hosting the S00 LABs, the overdensity would require a mean number density at $z \approx 3$ of $\sim 2.5 \times 10^{-3} h^{-3}$ Mpc$^{-3}$.

Fig. 3.—Spatial distribution of LAE candidates (filled circles). After smoothing on $3.2' \times 2.8'$ scales, isodensity contours were laid down at 0.7, 1.0, 1.8, and 2.3 times the average LAE density at the edge of the field. The four circle sizes represent four bins in $1500$ luminosity: $L_{5102} \leq 2.5 \times 10^{41}$, $2.5 \times 10^{41} < L_{5102} \leq 5 \times 10^{41}$, $5.0 \times 10^{41} < L_{5102} \leq 1.0 \times 10^{42}$, and $L_{5102} > 1.0 \times 10^{42}$. The position of LABd05 is indicated with a star. Regions masked along the edge and due to bright stars are shown in gray. There is evidence for an extended structure stretching from SE to NW and a $\sim 10 h^{-1}_{70}$ Mpc void at [218.36, 33.07].

Fig. 4.—Radial density profile measured in circular annuli centered on LABd05. The LAB lies in an overdense region that is a factor of $\sim 3$ times the density at the edge of the field of view. The dashed line represent the predicted number density at $z \approx 3$ if we assume a uniform redshift distribution and no evolution (Gronwall et al. 2007; Ouchi et al. 2008). The shaded areas correspond to the range covered by 1σ error bars; all three parameters ($\alpha$, $L\*$, $\phi$) from Gronwall et al. (2007) were allowed to vary in turn (light shading), while in the comparison to Ouchi et al. (2008) the faint-end slope $\alpha$ is fixed at $-1.5$ (dark shading). The predicted LAE number density is consistent with what we measured at the edge of the field. Since the redshift distribution of our sample can only be narrower than assumed, the overdensity measured within the structure is likely a lower limit.
which extends $40 \, h^{-3}_{70} \, \text{Mpc}$ comoving (22% of the filter width) along the line of sight (Matsuda et al. 2005, and that it is centered within the IA445 filter, the inner contour corresponds to a number density of $\rho \approx 12 \times 10^{-3} \, h^{-3}_{70} \, \text{Mpc}^{-3}$. Alternatively, if the structure is cylindrical in shape with a radius of $10 \, h^{-1}_{70} \, \text{Mpc}$, the corresponding number density at the inner contour is $\rho \approx 25 \times 10^{-3} \, h^{-3}_{70} \, \text{Mpc}^{-3}$.

We estimate the expected frequency of such overdense structures using the galaxy catalog of Bower et al. (2006) which is based on the Millennium Simulation (Springel et al. 2005). We approximate our observational setup by sampling the simulation volume randomly with cylinders that are $10 \, h^{-1}_{70} \, \text{Mpc}$ in radius (the size of the overdensity peak) and $180 \, h^{-1}_{70} \, \text{Mpc}$ in depth (the full span of the filter). We assumed a Ly$\alpha$/H$\alpha$ ratio of 10 (Osterbrock 1989) and scaled from the predicted H$\alpha$ luminosity to select model LAE galaxies down to the Ly$\alpha$ limit of our observations (under the assumption that Ly$\alpha$ dominates the measured IA445 flux) at a redshift of $z \approx 2.7$. The number density of model LAEs in this case is $10.8 \times 10^{-3} \, h^{-3}_{70} \, \text{Mpc}^{-3}$, which is a factor of $\sim 5$ higher than the mean density we observe. Taken at face value, this could imply that LAEs have a duty cycle of $\sim 20\%$ or that they are a younger, less massive subset of this population. If we restrict the model galaxies to be younger than the sample’s median age ($\approx 172\, \text{Myr}$) and less massive than the median stellar mass ($\approx 9 \times 10^{8} \, M_{\odot}$), the number density of model LAEs is $3.5 \times 10^{-3} \, h^{-3}_{70} \, \text{Mpc}^{-3}$. In either case, we uncover overdensities of greater than a factor of 2 at a rate of $\approx 0.3\%$. Therefore, within the large span of our filter, which will tend to average out inhomogeneities and reduce the signal, our imaging survey had only a $\approx 0.3\%$ chance of randomly uncovering such an overdense region if LABs and overdensities are independent phenomena. The space density of large Ly$\alpha$ nebulae is very uncertain, but at the high end is the range quoted for the S00 Ly$\alpha$ nebula: $(3–400) \times 10^{-6} \, \text{Mpc}^{-3}$ (Saito et al. 2006). Taking these values (equivalent to a $\sim 17%–100\%$ chance of finding one large LAB within the peak of the overdensity), the likelihood of a chance coincidence between a factor of $\approx 2$ overdensity and a large Ly$\alpha$ nebulae would be $\leq 0.05%–0.3\%$. Preliminary results from more recent systematic Ly$\alpha$ nebulae surveys hint that their true space density may be orders of magnitude lower (e.g., M. K. M. Prescott et al. 2008, in preparation), making the likelihood of chance coincidence vanishingly small.

In terms of the relevant emission mechanisms the Ly$\alpha$ nebula class appears to be a highly heterogeneous mix, and this diversity could in principle derive from environmental differences. The largest Ly$\alpha$ nebulae ($\approx 100\, \text{kpc}$), including the case studied here, often show evidence for obscured AGNs and extended star formation (e.g., Matsuda et al. 2007; Basu-Zych & Scharf 2004; M. K. M. Prescott et al. 2008, in preparation) and have received the most scrutiny in terms of their properties and environments. Presumably, the somewhat smaller “cooling” LABs (e.g., Nilsson et al. 2006; Smith & Jarvis 2007) must also reside in dense regions with sufficient gas supply, but thorough environmental studies of these sources have, to our knowledge, not yet been completed.

5. CONCLUSIONS

The discovery of a large Ly$\alpha$ nebula at $z \approx 2.7$ via its strong mid-infrared emission has provided an unbiased test of the association between these rare sources and galaxy overdensities. Using deep Ly$\alpha$ imaging of the environment surrounding this LAB, we identify 785 LAE candidates and find evidence for a factor of $\approx 3$ LAE overdensity which spans $20 \times 50 \, \text{Mpc}$ (comoving). This is comparable to what is found in the vicinity of the well-known S00 Ly$\alpha$ nebulae. We rule out a chance coincidence at the $\approx 1\%$ level. In conjunction with previous work, these results point conclusively to a strong association between the largest Ly$\alpha$ nebulae and overdense regions of the universe.

We are grateful to Masafumi Yagi and Yoshiaki Taniguchi for data reduction advice and assistance. We thank Naveen Reddy for the use of data from an ongoing $U_{\text{iso}}$ imaging program and the referee for constructive comments on the manuscript. M. P. was supported by an NSF Graduate Research Fellowship. Support for this work was provided by NASA (HST-GO10591) and the National Science Foundation (grant 0714311).

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