**EVIDENCE FOR SPATIALLY COMPACT Lyα EMISSION IN z = 3.1 Lyα-EMITTING GALAXIES**

**Nicholas A. Bond**1, John J. Feldmeier2, Ana Matković3, Caryl Gronwall3, Robin Ciardullo3, and Eric Gawiser3

1 Physics and Astronomy Department, Rutgers University, Piscataway, NJ 08854-8019, USA; nbond@physics.rutgers.edu, gawiser@physics.rutgers.edu
2 Department of Physics and Astronomy, Youngstown State University, Youngstown, OH 44555, USA; jfelfmeier@ysu.edu
3 Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA; matkovic@astro.psu.edu, caryl@astro.psu.edu

Received 2010 February 4; accepted 2010 May 15; published 2010 June 4

**ABSTRACT**

We present the results of a high spatial resolution study of the line emission in a sample of z = 3.1 Lyα-emitting galaxies (LAEs) in the Extended Chandra Deep Field-South. Of the eight objects with coverage in our HST/WFPC2 narrowband imaging, two have clear detections and two are barely detected (~2σ). The clear detections are within ~0.5 kpc of the centroid of the corresponding rest-UV continuum source, suggesting that the line-emitting gas and young stars in LAEs are spatially coincident. The brightest object exhibits extended emission with an half-light radius of ~1.5 kpc, but a stack of the remaining LAE surface brightness profiles is consistent with the WFPC2 point-spread function. This suggests that the Lyα emission in these objects originates from a compact (~2 kpc) region and cannot be significantly more extended than the far-UV continuum emission (~1 kpc). Comparing our WFPC2 photometry to previous ground-based measurements of their monochromatic fluxes, we find at 95% (99.7%) confidence that we cannot be missing more than 22% (32%) of the Lyα emission.

**Key words:** cosmology; observations – galaxies: formation – galaxies: high-redshift – galaxies: structure

**Online-only material:** color figure

1. INTRODUCTION

Lyα-emitting galaxies (LAEs) at z ~ 2–4 are thought to be actively star forming (e.g., Cowie & Hu 1998), with low stellar masses (~10^9 M☉), high mass-specific star-formation rates, and very little dust (Venemans et al. 2005; Gawiser et al. 2007). Morphological studies of their rest-frame ultraviolet light using the Hubble Space Telescope (HST) reveal small (r_e ~ 1 kpc), compact (C > 2.5) galaxies that are often clumpy or irregular (Venemans et al. 2005; Pirzkal et al. 2007; Overzier et al. 2008; Taniguchi et al. 2009; Bond et al. 2009; Gronwall et al. 2010). Although the objects known as Lyα blobs often exhibit extended diffuse morphologies (e.g., Fynbo et al. 1999; Nilsson et al. 2006; Smith & Jarvis 2007) that could be explained by cold accretion onto a dark matter halo (Dijkstra et al. 2006) or AGN/stellar feedback (Geach et al. 2009), to date there has been no published study of the morphology of the line-emitting regions of the lower-mass LAEs. In the local universe, HST observations by Ostlin et al. (2008) reveal that much of the Lyα emission of six star-forming galaxies originates in a diffuse halo surrounding the galaxy. These “Lyα halos” are likely caused by resonant scattering of the Lyα line off of cold, diffuse gas surrounding the galaxy. If the same process occurs at high redshift, then we would expect LAEs to exhibit extended Lyα emission and, since the majority of LAEs are resolved in the rest-UV continuum at HST resolution (Bond et al. 2009), the extended Lyα halos should be detectable. In a study of LAEs at z = 2.25, Nilsson et al. (2009) report that the majority of their sample “are significantly more extended than point sources” in narrowband images with 1′′ seeing. If true, this would suggest an order-of-magnitude difference between the extent of the UV continuum emission and the line emission.

The Multiwavelength Survey by Yale-Chile (MUSYC; Gawiser et al. 2006a) is a broad-based collaboration dedicated to obtaining multiwavelength imaging and spectroscopy of 1.2 deg^2 of sky and includes coverage of the Great Observatories Origins Deep Survey South (GOODS–S) region within the Extended Chandra Deep Field-South (ECDF–S). As part of this survey, Gronwall et al. (2007) discovered an unbiased sample of 162 LAEs at z = 3.1 using broadband and 4990 Å narrowband imaging. In a previous paper, we presented an analysis of the rest-frame ultraviolet light of 97 of these LAEs (Bond et al. 2009) and found that the majority were small (<1 kpc), single-component objects. Gronwall et al. (2010) extend this analysis to higher-order morphological diagnostics, finding that LAEs possess a wide range of Sérsic indices and ellipticities, with (e) ~ 0.5.

In this Letter, we present the results of a high spatial resolution study of the line emission in eight LAEs drawn from the Gronwall et al. (2007) sample. Throughout we will assume a concordance cosmology with H⊙ = 71 km s^{-1} Mpc^{-1}, Ω_m = 0.27, and Ω_Λ = 0.73 (Spergel et al. 2007). With these values, 1″ = 7.75 physical kpc at z = 3.1.

2. DATA

Minor modifications to the Gronwall et al. (2007) sample were published in Bond et al. (2009). In both of these studies, LAEs were selected to have F > 1.5 × 10^{-17} erg cm^{-2} s^{-1} in a 4990 Å narrowband filter and an observed-frame Lyα equivalent width > 80 Å. As shown in Figure 1, the filter used to create the Gronwall et al. (2007) sample only overlaps with the HST narrowband filter over a ~20 Å wavelength range, so our two HST/WFPC2 pointings targeted LAEs with Lyα lines identified spectrocopically within this region (which corresponds to 3.11 < z < 3.13; see Table 1). The fields were observed as program GO-11177 (PI: C. Gronwall) on July 28–30 and 2008 August 13–14. Each was observed with 12 exposures of 2600 s each through the F502N filter applying a standard four-point dither pattern. Once the data were taken, we generated stacked images and weight images from our pipeline-reduced exposures using the MultiDrizzle task within PyRAF.
We found that the parameters \( \text{PIXFRAC} = 0.8 \) and \( \text{PIXSCALE} = 0'05 \) optimized a combination of image quality and cosmic-ray rejection efficiency. Other input parameters to MultiDrizzle were set to their standard values (see Fruchter & Hook 2002; Fruchter & Sosey 2009).

The two \( \text{HST}/\text{WFPC2} \) pointings lie within the southern GOODS field, which covers \( \sim 160 \) arcmin\(^2 \) of sky and includes \( \text{HST}/\text{ACS} \) observations in the \( B_{75}, V_{606}, I_{775}, \text{and} z_{850} \) filters. In Bond et al. (2009), the \( V_{606} \)-band images were used to identify the rest-frame ultraviolet centroids and sizes of each LAE component, so we use these measurements for comparison to the emission-line centroids and morphologies measured with \( \text{HST}/\text{WFPC2} \). All GOODS broadband images were multidrizzled to a pixel scale of \( 0'03 \) and the typical 5 \( \sigma \) detection limit in \( V_{606} \) is \( m_{AB} = 28.8 \).

In order to make a robust comparison between the centroids of the rest-frame ultraviolet continuum emission and the Ly\( \alpha \) emission, we must ensure that the world coordinate system of the \( \text{HST}/\text{WFPC2} \) images is matched to that of the GOODS \( V_{606} \)-band images. Using a sample of five stars in field 1, we estimate \( \Delta \alpha_0 = +0'19 \) and \( \Delta \delta_0 = +0'18 \). For field 2, we found \( \Delta \alpha_0 = -0'15 \) and \( \Delta \delta_0 = -0'11 \). Each of these corrections is uncertain by \( \sim 0'03 \) and individual stars were found to deviate by as much as \( 0'05 \) in a single direction.

A single photometric calibration was performed for both WFPC2 images using a sample of three bright stars with well-behaved curves of growth. We performed 1'' aperture photometry on each star and calibrated their magnitudes to the MUSYC NB4990 image of the ECDF-S (Gawiser et al. 2006b). Using the mean calibration to these stars, we found an AB zero point of \( m_{AB} = 19.87 \) and a scatter of 0.05 mag.

3. METHODOLOGY

We extracted 8'' \( \times \) 8'' pixel (62 \( \times \) 62 kpc) cutouts from the \( \text{HST}/\text{WFPC2} \) images (see the left panels of Figures 2 and 3), each centered at the GOODS \( V_{606} \)-band centroid of the LAE. Of the eight objects with coverage, two (LAEs 11 and 16) have clear detections near the cutout centers. There is evidence for a possible detection in LAE 107, but it lies near the edge of a WFPC2 pointing and vignetting makes this difficult to verify. We exclude this LAE from subsequent analysis due to poor data quality.

Following Bond et al. (2009), we used SExtractor (Bertin & Arnouts 1996) to identify components within the WFPC2 images, fitting a constant sky to the cutout and defining detections as 15 contiguous pixels above a 1.65 \( \sigma \) threshold. This procedure confirmed single detections in LAEs 11 and 16, but no others within 0''5 of the \( V_{606} \)-band LAE centroids.

We used the IRAF routine PHOT to perform aperture photometry on each object in our sample, in each case using the minimum aperture that enclosed the total emission line flux seen within 0''5. The mean aperture size used for the sample was 0''34. For the two LAEs with clear detections, the aperture center was set to their SExtractor position, while the centers for
the remaining LAEs were set to their $V_{606}$-band centroids (see Bond et al. 2009; and the right panels of Figures 2 and 3). Following Gronwall et al. (2007), we obtain monochromatic fluxes,

$$F_{Ly\alpha} = 3.63 \times 10^{-20} \times 10^{-m_{AB}/2.5} \frac{c}{\lambda^2} \frac{\int T(\lambda) d\lambda}{\langle T_{Ly\alpha} \rangle},$$

where $F_{Ly\alpha}$ is in erg cm$^{-2}$ s$^{-1}$, $T(\lambda)$ is the filter transmission function, and $\langle T_{Ly\alpha} \rangle$ is the mean value of the transmission function when convolved with the Ly$\alpha$ line profile (Jacoby et al. 1987). When computing $\langle T_{Ly\alpha} \rangle$, we have approximated the Ly$\alpha$ line as a Gaussian with FWHM = 500 km s$^{-1}$ and centered at its spectroscopic redshift. The resulting monochromatic fluxes are given in Column 5 of Table 1. As expected, LAEs 11 and 16 are $>2\sigma$ detected using PHOT. LAEs 90 and 94 also prove to be $>2\sigma$ detections. In all LAEs, the rest-UV continuum will make a small contribution to the total narrowband flux, but its impact on the observed morphology is negligible. Of the LAEs with PHOT detections, the object with the largest relative continuum contribution (LAE 11) has an expected flux that is 7.5 times smaller than the measured narrowband flux.

We also report the half-light radius of each source, interpolated individually from the curves of growth. For the LAEs without SExtractor detections, these half-light radii will be biased high due to uncertainty in the source centers (see Bond et al. 2009).

4. RESULTS

The offsets between the emission-line and rest-UV continuum centroids of the two LAEs with SExtractor detections are given in Column 6 of Table 1. In LAE 11, the emission-line centroid...
Although the separation is too great ($\sim$), the line-emitting region in the majority of LAEs is compact ($\lesssim 1$ kpc) and cannot be significantly more extended than the far-UV continuum emission ($\lesssim 2$ kpc) and cannot be significantly more extended than the far-UV continuum emission.

The exceptions are LAE 11, which exhibits extended line emission out to $\sim 0.02$ ($\sim 1.5$ kpc) from the source center. Although the $V$-band (UV continuum) image suggests the presence of at least two components in the system, the line emission is centered on the northwest component and their separation is too great ($\sim 0.07$) for the second object to be the dominant source of the extended emission. The narrowband image also shows evidence for two distinct clumps of emission, but at a much smaller separation ($\sim 0.15$). This could indicate the presence of multiple star-forming regions, a dust lane, or perhaps Ly$\alpha$ photons from a single star-forming region scattering from multiple clumps of gas. Even considering this substructure, however, the line-emitting region is still compact ($\lesssim 1.5$ kpc) and should be indistinguishable from a point source in ground-based imaging.

Analysis of the surface brightness profiles can miss an extended diffuse component if the mean surface brightness is below the sky noise. To explore this possibility, we compare the monochromatic fluxes of our LAEs as measured in the WFPC2 frames to those measured from the ground by Gronwall et al. (2007; see Column 6 of Table 1). In all cases, the fluxes measured from the ground exceed $1.5\sigma$ of those measured from the ground. To explore this possibility, we compare the monochromatic fluxes of our LAEs as measured in the WFPC2 frames to those measured from the ground by Gronwall et al. (2007; see Column 6 of Table 1). In all cases, the fluxes measured from the ground exceed $1.5\sigma$ of those measured from the ground. To explore this possibility, we compare the monochromatic fluxes of our LAEs as measured in the WFPC2 frames to those measured from the ground by Gronwall et al. (2007; see Column 6 of Table 1). In all cases, the fluxes measured from the ground exceed $1.5\sigma$ of those measured from the ground.

### Table 1

| ID $^a$ | $\alpha^b$ | $\delta^b$ | z | $\log F_{\lambda 334}$ (erg s$^{-1}$ cm$^{-2}$) | $\log F_{\lambda 334}^{G2}$ (erg s$^{-1}$ cm$^{-2}$) | $d_z$ (arcsec) | $r_{\text{phot}}$ (arcsec) |
|-------|-----------|-----------|---|-------------------------------|-------------------------------|--------------|--------------|
| 11    | 3:32:26.922 | $-$27:41:28.174 | 3.113 | $-$16.03 $\pm$ 0.12 | $-$16.11 $\pm$ 0.02 | 0.51 | 0.17 |
| 16    | 3:32:13.274 | $-$27:43:29.933 | 3.117 | $-$16.28 $\pm$ 0.14 | $-$16.22 $\pm$ 0.03 | 0.06 | 0.14 |
| 44    | 3:32:15.783 | $-$27:44:10.228 | 3.119 | $-$17.32 $\pm$ 1.52 | $-$16.43 $\pm$ 0.04 | ... | 0.22 |
| 90    | 3:32:14.560 | $-$27:45:52.634 | 3.118 | $-$16.34 $\pm$ 0.22 | $-$16.64 $\pm$ 0.05 | ... | 0.24 |
| 94    | 3:32:09.32 | $-$27:43:54.427 | 3.113 | $-$16.41 $\pm$ 0.29 | $-$16.65 $\pm$ 0.05 | ... | 0.29 |
| 107   | 3:32:10.143 | $-$27:44:28.558 | ... | ... | $-$16.68 $\pm$ 0.06 | ... | ... |
| 117   | 3:32:12.936 | $-$27:44:51.590 | 3.117 | $-$16.58 $\pm$ 0.35 | $-$16.70 $\pm$ 0.06 | ... | 0.18 |
| 136   | 3:32:24.315 | $-$27:41:52.125 | 3.111 | $-$17.13 $\pm$ 1.54 | $-$16.76 $\pm$ 0.07 | ... | 0.24 |

**Notes.**

$^a$ Index from Table 2 of Gronwall et al. 2007.

$^b$ Position of WFPC2 narrowband centroid (set to the V-band centroid when there are no SExtractor detections).

$^c$ Distance between WFPC2 and ACS V-band centroids; LAE 11 is 0.04 from the position of the northwest component in the V-band image.

$^d$ Half-light radius computed by PHOT.

---

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

Figure 4. Normalized F502N surface brightness profiles for LAE 11 (short dashed curve), LAE 16 (dot-dashed curve), a stack of the other five LAEs (solid curve), and five stars in the WFPC2 images (dot curve). In addition, we plot the surface brightness profiles for Gaussian models with $\sigma = 0.2 (1.5 \text{ kpc})$ and $\sigma = 0.4 (3 \text{ kpc})$ as thin solid lines. Each curve is normalized to the total light from the source.

(No. 2, 2010 SPATIALLY COMPACT Ly$\alpha$ EMISSION IN LAEs AT $z = 3.1$ L203)
5. DISCUSSION

The results presented in Section 4 suggest that the Lyα emission in the majority of LAEs originates from a small ($\lesssim 2$ kpc) region that coincides very closely (within $\sim 0.5$ kpc) with the young stars producing the rest-frame UV continuum emission. One object in our sample (LAE 11) exhibits extended line emission out to $\sim 1.5$ kpc, but this is still comparable in extent to the rest-UV continuum ($r_e \simeq 1.3$ kpc; Bond et al. 2009).

Unlike the LAEs in our sample, low-redshift star-forming galaxies typically exhibit extended Lyα halos (Ostlin et al. 2008) out to many half-light radii from the rest-frame UV emission. These galaxies are not direct analogs of the objects in our sample, as both their Lyα luminosities and specific star formation rates are far smaller than those of the typical LAE. However, their Lyα halos suggest the presence of a reservoir of gas at large radii that is either not present in $z = 3.1$ LAEs or is only scattering a small fraction of the Lyα photons created by star formation.

Although this paper represents the first published search for extended Lyα emission in LAEs using HST imaging, Nilsson et al. (2009) report that $z = 2.25$ LAEs are "significantly more extended than point sources" in narrowband images with 1″ seeing. There may be a modest amount of size evolution in LAEs between $z = 3.1$ and $z = 2.25$, but their result would seem to contradict our finding that even the most extended LAEs have emission-line half-light radii $< 0.2"$. It is possible that we have failed to account for a component of highly diffuse line emission extending to large radii, but we find it must be $< 22\%$ of the total line emission in the present sample.

It is important that we continue to explore the wavelength dependence of high-redshift galaxy morphologies, as different regions of the spectrum probe different physical components of the host galaxy. The sample presented here could certainly be improved, both with greater sky coverage and deeper observations. It would also be interesting to target a sample of Lyα-emitting Lyman break galaxies to determine how the spatial distribution of their Lyα emission differs from that of a typical LAE, if at all.

We thank Patrick Durrell for helpful discussions about HST/WFPC2 data reduction. We also thank the referee for their helpful comments. Support for this work was provided by NASA through grant numbers HST-GO-11177.01, HST-AR-11253.01-A, and HST-AR-10324.01 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555 and by the National Science Foundation under grants AST-0807570 and NSF AST-0807885.

REFERENCES

Altmann, M., Méndez, R. A., van Altena, W., Korchargin, V., & Ruiz, M. T. 2006, RevMexAA Conf. Ser., 26, 64
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bond, N. A., Gawiser, E., Gronwall, C., Ciardullo, R., Altmann, M., & Schawinski, K. 2009, ApJ, 705, 639
Cowie, L. L., & Hu, E. M. 1998, AJ, 115, 1319
Dijkstra, M., Haiman, Z., & Spaans, M. 2006, ApJ, 649, 14
Fruchter, A. S., & Hook, R. N. 2002, PASP, 114, 144
Fruchter, A. S., & Sosey, M. 2009, MultiDrizzle Handbook, version 3.0 (Baltimore, MD: STScI)
Fynbo, J. U., Møller, P., & Warren, S. J. 1999, MNRAS, 305, 849
Gawiser, E., et al. 2006a, ApJS, 162, 1
Gawiser, E., et al. 2006b, ApJ, 642, L13
Gawiser, E., et al. 2007, ApJ, 671, 278
Geach, J. E., et al. 2009, ApJ, 700, 1
Gronwall, C., Bond, N. A., Ciardullo, R., Gawiser, E., Altmann, M., Blanc, G. A., & Feldmeier, J. J. 2010, arXiv:1005.3006
Gronwall, C., et al. 2007, ApJ, 667, 79
Jacoby, G. H., Africanu, J. L., & Quigley, R. J. 1987, PASP, 99, 672
Nilsson, K. K., Fynbo, J. P. U., Möller, P., Sommets-Larsen, J., & Ledoux, C. 2006, A&A, 452, L23
Nilsson, K. K., et al. 2009, A&A, 498, 13
Ostlin, G., Hayes, M., Kunth, D., Mas-Hesse, J. M., Leitherer, C., Petrovina, A., & Atek, H. 2008, AJ, 138, 923
Overzier, R. A., et al. 2008, ApJ, 673, 143
Pirzkal, N., Malhotra, S., Rhoads, J. E., & Xu, C. 2007, ApJ, 667, 49
Smith, D. J. B., & Jarvis, M. J. 2007, MNRAS, 378, L49
Spergel, D. N., et al. 2007, ApJS, 170, 377
Taniguchi, Y., et al. 2009, ApJ, 701, 915
Venemans, B. P., et al. 2005, A&A, 431, 793