A SUCCESSFUL BROADBAND SURVEY FOR GIANT Lyα NEBULAE. II. SPECTROSCOPIC CONFIRMATION

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ABSTRACT

Using a systematic broadband search technique, we have carried out a survey for large Lyα nebulae (or Lyα “blobs”) at 2 < z < 3 within 8.5 deg2 of the NOAO Deep Wide-Field Survey Boötes field, corresponding to a total survey comoving volume of \( \approx 10^8 h_{70}^{-3} \) Mpc3. Here, we present our spectroscopic observations of candidate giant Lyα nebulae. Of 26 candidates targeted, 5 were confirmed to have Lyα emission at 1.7 < z < 2.7, 4 of which were new discoveries. The confirmed Lyα nebulae span a range of Lyα equivalent widths, colors, sizes, and line ratios, and most show spatially extended continuum emission. The remaining candidates did not reveal any strong emission lines, but instead exhibit featureless, diffuse, blue continuum spectra. Their nature remains mysterious, but we speculate that some of these might be Lyα nebulae lying within the redshift desert (i.e., 1.2 < z < 1.6). Our spectroscopic follow-up confirms the power of using deep broadband imaging to search for the bright end of the Lyα nebula population across enormous comoving volumes.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – surveys

Online-only material: color figures

1. INTRODUCTION

Giant radio-quiet Lyα nebulae (also known as “Lyα blobs”) provide a window into the physics of ongoing massive galaxy formation (e.g., Francis et al. 1996; Ivison et al. 1998; Steidel et al. 2000; Palunas et al. 2004; Matsuda et al. 2004; Dey et al. 2005; Saito et al. 2006; Nilsson et al. 2006; Smith & Jarvis 2007; Prescott et al. 2009; Yang et al. 2009). Rare systems found primarily in overdense regions (Prescott et al. 2008; Matsuda et al. 2004, 2005, 2011; Saito et al. 2006; Yang et al. 2009, 2010), Lyα nebulae are extremely luminous (\( L_{Ly\alpha} \approx 10^{44} \text{ erg s}^{-1} \)) and are frequently associated with young, star-forming galaxy populations or obscured active galactic nuclei (AGNs; e.g., Basu-Zych & Scharf 2004; Matsuda et al. 2004; Dey et al. 2005; Geach et al. 2007, 2009; Prescott et al. 2012a). Theoretical and observational investigations into the power source behind Lyα nebulae have painted a varied picture, presenting arguments for AGN powering (Chapman et al. 2004; Basu-Zych & Scharf 2004; Geach et al. 2007, 2009), starburst-driven winds (Tanguchi & Shioya 2000; Tanguchi et al. 2001; Matsuda et al. 2004), spatially extended star formation (Matsuda et al. 2007; Prescott et al. 2012b), cold accretion (Nilsson et al. 2006; Smith et al. 2008; Goerdt et al. 2010; Faucher-Giguère et al. 2010; Rosdahl & Blaizot 2012), or some combination thereof (Dey et al. 2005; Prescott et al. 2009, 2012b; Webb et al. 2009; Colbert et al. 2011). Larger samples of giant radio-quiet Lyα nebulae drawn from unbiased surveys are needed in order to accurately measure the space density of these sources, to determine the emission mechanisms primarily responsible for the Lyα nebula class as a whole, and to understand their relationship to the more well-studied Lyα halos found around many high-redshift radio galaxies (e.g., McCarthy 1993, and references therein; van Ojik et al. 1996; Weidinger et al. 2005; Miley et al. 2006; Barrio et al. 2008; Smith et al. 2009; Zirm et al. 2009).

Increasing the sample of such a rare class of objects requires surveying large comoving volumes, but the standard approach relying on narrowband imaging is limited by observational expense. Our complementary approach was to design a new search technique using deep broadband imaging (Prescott 2009). We employed this method to select a sample of Lyα nebula candidates from the Boötes Field of the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey 1999). A full presentation of our survey algorithm as well as the selection function of this approach and the implications for the space density of Lyα nebulae can be found in companion papers (Prescott et al. 2012a; M. K. M. Prescott et al. 2013, in preparation; hereafter, Papers I and III, respectively).

In this work (Paper II), we focus on the spectroscopic follow-up of Lyα nebula candidates drawn from deep archival broadband imaging of the NDWFS Boötes field. In Section 2, we give a brief outline of the survey design and candidate sample. In Section 3, we discuss our spectroscopic observations and reductions. Section 4 presents the five Lyα nebulae discovered within this 8.5 deg2 survey and discusses our primary contaminant sources, potentially an interesting population in their own right. Section 5 discusses the implications of this sample, and we conclude in Section 6.

We assume the standard ΛCDM cosmology (\( \Omega_M = 0.3, \Omega_\Lambda = 0.7, h = 0.7 \)); 1" corresponds to physical scales of 8.3–7.8 kpc for redshifts of z = 1.2–2.9. All magnitudes are in the AB system (Oke 1974).

2. SEARCH DESIGN

We have designed an innovative search for Lyα nebulae in deep broadband imaging and applied it to the NDWFS Boötes field (Paper I). Our search is most sensitive to the largest and brightest Lyα nebulae because it leverages the deep blue (\( B_W \)) imaging of NDWFS to look for sources where bright Lyα emission boosts the broadband flux relative to the very dark sky. Thanks to the wide area (\( \approx 9 \text{ deg}^2 \)) of the NDWFS and the large...
3. SPECTROSCOPIC FOLLOW-UP

In this section, we describe the spectroscopic follow-up of the \( \text{Ly}\alpha \) nebula candidate sample.

3.1. Observations and Reductions

We targeted a total of 26 \( \text{Ly}\alpha \) nebula candidates (15 first priority, 5 second priority, and all 6 third priority candidates). Long-slit spectroscopic observations were obtained using the MMT and the Blue Channel Spectrograph during 2007 May, 2008 April and June (Table 1). The observations used the 300 \( \text{l mm}^{-1} \) grating with 1.0’/1.5’ wide slits resulting in a resolution FWHM of 2.6/3.4 Å and a wavelength range of \( \Delta \lambda \approx 3100–8320 \) Å.

During our 2007 run, we chose slit orientations based primarily on the morphology of the candidate (i.e., aligned with the major axis of the emission as estimated from the \( B_W \)-band morphology), and as a secondary criterion attempted to intersect a nearby bright reference object if possible. In practice, however, we found that the faintness of our candidates and the short duration of our spectroscopic exposures necessitated a positional reference. As a result, slit orientations during the 2008 runs were chosen to always include a positional reference object, and consequently do not always trace the major axis of the \( B_W \) morphology. During these later runs, we dithered the target along the slit by \( \approx 5'' \) between exposures to minimize the effect of any bad pixels. The full list of targeted candidates and the results of the spectroscopic observations are given in Table 2.

We reduced the spectroscopic data using IRAF.\(^5\) We subtracted the overscan and bias, and applied a flat-field correction using normalized observations of the internal quartz flat-field lamps. Twilight flats were used to determine the illumination correction for the science frames. We removed cosmic rays from the two-dimensional sky-subtracted data using the task apall\(^6\) and optimal variance-weighted extraction (Valdes 1992); the spectral trace was determined using bright unresolved sources on the slit. We determined the wavelength solution to an rms precision of \( \approx 0.08–0.18 \) Å using HeArNe and HgCd comparison lamps, and then corrected the data for any slight systematic offset using the night sky lines as a reference. The final wavelength calibration is accurate to \( \pm 0.42 \) Å. The relative flux calibration was based on observations of the standard stars BD+33 2642, BD+26 2606, BD+28 4211, Feige 34, and Wolf 1346.\(^7\) For each night, we applied a gray shift to compensate for any variable gray (i.e., independent of wavelength) extinction that may have affected a given standard star observation relative to one taken under better conditions. The sensitivity functions derived from individual standard star exposures were consistent to within \( \lesssim 0.1 \) mag.

Due to the faintness of the candidates and the fact that we are searching for luminous \( \text{Ly}\alpha \) nebulae at \( z \approx 2–3 \), the aim of our follow-up spectroscopic program was to look for strong, high equivalent width line emission. A single strong line in the blue can be identified as \( \text{Ly}\alpha \) rather than an unresolved [O \( \text{II} \)]\( \lambda\lambda 3726,3729 \) doublet (the only other possibility at these wavelengths) due to the fact that a detection of [O \( \text{II} \)] would be accompanied by stronger detections of [O \( \text{II} \)]\( \lambda\lambda 4959,5007 \) and H\( \alpha \) as well. Candidates with strong \( \text{Ly}\alpha \) emission at \( z \approx 2–3 \) in the \( B_W \) band are easily detectable with the MMT/Blue Channel down to a \( \sigma \) limit of \( \approx 1–7 \times 10^{-17} \) in 30 minutes (assuming a \( \text{Ly}\alpha \) line with FWHM\(_{\text{obs}} \) = 12 Å). This corresponds to limiting widths of the \( B_W \) filter (\( \approx 1275 \) Å, corresponding to \( \Delta \lambda \approx 1 \)), our survey is able to probe an enormous comoving volume (\( \approx 10^{9} h_{70}^{-3} \) Mpc\(^3 \)) with archival data and significantly reduce the required observational overhead. Our survey is therefore complementary to smaller volume surveys for \( \text{Ly}\alpha \) nebulae that rely on sensitive narrowband imaging (e.g., Matsuda et al. 2004; Saito et al. 2006; Smith & Jarvis 2007; Yang et al. 2009, 2010; Matsuda et al. 2011).

The search algorithm and candidate sample are discussed in detail in Paper I. In brief, we selected giant \( \text{Ly}\alpha \) nebula candidates using wavelet analysis of the compact-source-subtracted \( B_W \) images. We selected a set of first and second priority candidates (Figure 1) based on their \( B_W - R \) color, as measured using large 30 pixel diameter apertures, and wavelet size, as determined using SourceExtractor (Bertin & Arnouts 1996) on the wavelet-deconvolved images. The final candidate sample consisted of 39 first priority and 40 second priority sources over a search area of 8.5 deg\(^2\). Both first and second priority candidates consisted of diffuse morphologies (morphological category \textsc{diffuse}) as well as those that appear to be tight groupings of compact sources (morphological category \textsc{group}), as discussed in Paper I. In addition, we flagged six sources from outside these selection regions that showed promising morphologies (third priority).

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line luminosities of ≈0.3–5 × 10^{32} \text{ erg s}^{-1}, which are below the typical luminosities of giant Ly\alpha nebulae. However, continuum-only sources are much fainter and require longer integration to yield high signal-to-noise ratio spectra, more than was available during our spectroscopic campaign. To allow us to target the largest number of candidates, we therefore carried out a quick reduction of the data in real time and continued integrating on each of the 26 targeted candidates up until the point where we could either confirm the presence of a line or confirm the presence of continuum with no strong lines. The deeper we could either confirm the presence of a line or confirm each of the 26 targeted candidates up until the point where reduction of the data in real time and continued integrating on largest number of candidates, we therefore carried out a quick during our spectroscopic campaign. To allow us to target the yield high signal-to-noise ratio spectra, more than was available only sources are much fainter and require longer integration to

### Table 1

| UT Date       | Instrumental Resolution (arcsec) | Unvignetted Slit (∆Å) | Spatial Binning (arcsec pixel$^{-1}$) | Seeing (arcsec) | Conditions          |
|---------------|---------------------------------|-----------------------|----------------------------------------|-----------------|---------------------|
| 2007 May 20   | 2.6                             | 1.0 × 120             | 0.56                                   | 1.0–1.2         | Clear, high winds   |
| 2007 May 21   | 2.6                             | 1.0 × 120             | 0.56                                   | 1.0–1.2         | Clear, high winds   |
| 2007 May 22   | 3.4                             | 1.5 × 120             | 0.56                                   | 1.3–1.7         | Clear, high winds   |
| 2008 Apr 3    | 3.4                             | 1.5 × 120             | 0.28                                   | 1.0             | Mostly clear        |
| 2008 Apr 30   | 3.4                             | 1.5 × 120             | 0.28                                   | 1.2–1.9         | Clear, high winds   |
| 2008 Jun 8    | 3.4                             | 1.5 × 120             | 0.28                                   | 1.0             | Clear               |
| 2008 Jun 9    | 3.4                             | 1.5 × 120             | 0.28                                   | 1.1–2.0         | Clear, high winds   |

#### Notes
- Quoted instrumental resolution is the average of measurements of the Hg\i\lambda4047, Hg\i\lambda4358, Hg\i\lambda5461, and O\i\lambda5577 sky lines.

### Table 2

| Observing Log |
|---------------|
| UT Date | Instrumental Resolution (arcsec) | Unvignetted Slit (∆Å) | Spatial Binning (arcsec pixel$^{-1}$) | Seeing (arcsec) | Conditions          |
| 2007 May 20   | 2.6                             | 1.0 × 120             | 0.56                                   | 1.0–1.2         | Clear, high winds   |
| 2007 May 21   | 2.6                             | 1.0 × 120             | 0.56                                   | 1.0–1.2         | Clear, high winds   |
| 2007 May 22   | 3.4                             | 1.5 × 120             | 0.56                                   | 1.3–1.7         | Clear, high winds   |
| 2008 Apr 3    | 3.4                             | 1.5 × 120             | 0.28                                   | 1.0             | Mostly clear        |
| 2008 Apr 30   | 3.4                             | 1.5 × 120             | 0.28                                   | 1.2–1.9         | Clear, high winds   |
| 2008 Jun 8    | 3.4                             | 1.5 × 120             | 0.28                                   | 1.0             | Clear               |
| 2008 Jun 9    | 3.4                             | 1.5 × 120             | 0.28                                   | 1.1–2.0         | Clear, high winds   |

#### Notes
- Candidate ID numbers in the first column are the same as in Paper I.
- Spectroscopic targets were classified as either showing “Ly\alpha” or “Continuum” emission.

4. RESULTS

Of the 15 first priority and 5 second priority candidates targeted for spectroscopic follow-up, 4 first priority sources and 1 second-priority source had confirmed Ly\alpha emission: we easily recovered the previously discovered large Ly\alpha nebula at $z \approx 2.67$ (LABd05; Dey et al. 2005) and discovered new, spatially extended Ly\alpha nebulae at $z \approx 1.67$, $z \approx 1.88$, $z \approx 2.14$, and $z \approx 2.27$. In addition, we also targeted six third priority candidates that showed promising diffuse morphologies upon visual inspection. However, no Ly\alpha or [O\ii] line emission was confirmed in any of the third priority candidates. In this section, we describe each of the confirmed sources in turn and then discuss the primary contaminants to our survey.
4.1. Confirmed Lyα Sources

Figures 2–6 show the postage stamps, two-dimensional spectra, and one-dimensional spectra of the Lyα sources; the measured properties are listed in Table 3. The spectral extraction apertures were chosen to maximize the signal-to-noise ratio of Lyα. Redshifts were determined from the centroid of a Gaussian fit to the observed Lyα line. No correction was included for Lyα absorption, a potential source of bias in our redshift estimates. The $B_W$ sizes, isophotal areas, and sur-

Figure 2. Imaging and MMT spectroscopic observations of PRG1, a Lyα nebula at $z \approx 1.67$. The top row shows the optical $B_W$, $R$, and $I$ imaging along with the slit used for follow-up spectroscopy. The central panel contains the two-dimensional spectrum vs. observed wavelength, and the bottom panel presents the one-dimensional spectrum extracted from a 1′′5 × 5′′04 aperture. The error spectrum (red line) and $B_W$ bandpass (blue line) are shown, and the positions of common emission lines are indicated. The one-dimensional Lyα emission line profile is shown in the inset panel. Spectroscopic data presented are from the second night of observations only (UT 2008 June 9; for details see Prescott et al. 2009).

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

Figure 3. Imaging and MMT spectroscopic observations of PRG2, a Lyα nebula at $z \approx 2.27$. The top row shows the optical $B_W$, $R$, and $I$ imaging along with the slit used for follow-up spectroscopy. The central panel contains the two-dimensional spectrum vs. observed wavelength, and the bottom panel presents the one-dimensional spectrum extracted from a 1′′5 × 7′′84 aperture. The error spectrum (red line) and $B_W$ and $R$ bandpasses (blue lines) are shown, and the positions of common emission lines are indicated. The one-dimensional Lyα emission line profile is shown in the small inset panel. (A color version of this figure is available in the online journal.)

Figure 4. Imaging and MMT spectroscopic observations of PRG3, a Lyα nebula at $z \approx 2.14$. The top row shows the optical $B_W$, $R$, and $I$ imaging along with the slit used for follow-up spectroscopy. The central panel contains the two-dimensional spectrum vs. observed wavelength, and the bottom panel presents the one-dimensional spectrum extracted from a 1′0×5′′6 aperture. The error spectrum (red line) and $B_W$ and $R$ bandpasses (blue lines) are shown, and the positions of common emission lines are indicated. The one-dimensional Lyα emission line profile is shown in the small inset panel.

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

Figure 5. Imaging and MMT spectroscopic observations of PRG4, a Lyα nebula at $z \approx 1.89$. The top row shows the optical $B_W$, $R$, and $I$ imaging along with the slit used for follow-up spectroscopy. The central panel contains the two-dimensional spectrum vs. observed wavelength, and the bottom panel presents the one-dimensional spectrum extracted from a 1′′5 × 1′′68 aperture. The error spectrum (red line) and $B_W$ and $R$ bandpasses (blue lines) are shown, and the positions of common emission lines are indicated. The one-dimensional Lyα emission line profile is shown in the small inset panel. The size of PRG4 is unknown; the source is very compact along the spectroscopic slit, but additional diffuse emission that may or may not be Lyα is visible to the south in the $B_W$ imaging.

(A color version of this figure is available in the online journal.)
Table 3
Lyα Nebula Measurements

| Parameter | PRG1 | PRG2 | PRG3 | PRG4 | LABd05 |
|-----------|------|------|------|------|--------|
| Aperture (arcsec) | 1.5 × 5.04 | 1.5 × 7.84 | 1.0 × 5.60 | 1.5 × 1.68 | 1.0 × 4.48 |
| λLyα,obs (Å) | 3249.61 ± 0.39 | 3971.41 ± 0.13 | 3813.28 ± 0.90 | 3511.23 ± 0.67 | 4444.99 ± 0.31 |
| Redshift | 1.6731 ± 0.0003 | 2.2668 ± 0.0001 | 2.1368 ± 0.0007 | 1.8883 ± 0.0005 | 2.6564 ± 0.0003 |
| fLυα (10^{-17} erg s^{-1} cm^{-2}) | 44.1 ± 4.0 | 49.2 ± 1.1 | 10.2 ± 1.2 | 10.3 ± 1.2 | 19.0 ± 0.9 |
| fLυα (10^{-20} erg s^{-1}) | 8.2 ± 0.7 | 19.3 ± 0.4 | 3.5 ± 0.4 | 2.6 ± 0.3 | 10.9 ± 0.5 |
| Lyα EW_{3895} (Å) | 257.1 ± 9.1 | 207.3 ± 6.3 | 47.1 ± 6.4 | 88.7 ± 11.8 | 115.5 ± 9.5 |
| Lyα FWHM_{3895} (Å) | 9.19 ± 0.60 | 8.52 ± 0.19 | 23.36 ± 7.90 | 6.51 ± 0.89 | 15.44 ± 0.70 |
| Lyα σ_{A} (km s^{-1}) | 361.2 ± 23.7 | 273.9 ± 6.1 | 782.1 ± 264.3 | 236.8 ± 32.2 | 443.3 ± 20.0 |
| f_{FUV,1550} (10^{-17} erg s^{-1} cm^{-2})_{A} | 2.1 ± 1.1 | 3.5 ± 0.8 | <0.8 | <0.8 | <5.4 |
| f_{HeII,1640} (10^{-17} erg s^{-1} cm^{-2})_{A} | 5.8 ± 1.0 | 1.8 ± 0.9 | <0.9 | 0.7 ± 0.5 | 1.4 ± 1.3 |
| f_{HeII,1609} (10^{-17} erg s^{-1} cm^{-2})_{A} | 4.8 ± 0.9 | 2.4 ± 1.1 | <1.5 | <1.4 | <1.8 |
| BW diameter along slit^a (arcsec) | 8.96 | 10.12 | 6.72 | 6.75 | 9.32 |
| BW isophotal area^a (arcsec^2) | 40.9 | 72.3 | 45.3 | 38.7 | 54.4 |
| BW surface brightness^b (mag arcsec^{-2}) | 27.2 | 27.0 | 26.8 | 27.0 | 27.0 |
| Lyα diameter along slit^c (arcsec) | 9.24 | 12.04 | 8.96 | 3.92 | 8.96 |
| Lyα diameter along slit^c (kpc) | 78.3 | 99.0 | 74.4 | 33.0 | 71.3 |
| Approximate Lyα isophotal area^c (arcsec^2) | 43.4 | 103.7 | 80.4 | >5.9^e | 50.3 |
| Approximate total L_{Lyα} (10^{42} erg s^{-1}) | 47.2 ± 4.3 | 170.2 ± 3.7 | 49.6 ± 6.1 | >2.6^e | 122.8 ± 6.0 |

Notes.

^a Line flux upper limits are 2σ values.

^b BW sizes, isophotal areas, and surface brightnesses measured from the NDWFS imaging using SourceExtractor with a detection threshold of 28.9 mag arcsec^{-2}, the median 1σ BW surface brightness limit of NDWFS.

^c Lyα sizes measured from the two-dimensional spectra using SourceExtractor with detection thresholds of [2.5, 1.0, 0.8, 2.1, 1.5]×10^{-18} erg s^{-1} cm^{-2} Å^{-1} arcsec^{-2}, the respective 1σ line surface brightness limits at the position of Lyα.

^d Approximate Lyα isophotal area computed by correcting the BW isophotal area A_{BW} by a factor of ν^2, where ν is the ratio of the Lyα and BW diameters measured along the slit.

^e As the BW emission is not an accurate tracer of the Lyα emission in PRG4, approximate luminosity and area estimates have been replaced with lower limits derived from the spectroscopic data alone.

^f Approximate total Lyα luminosity computed by scaling the Lyα luminosity measured within the spectroscopic aperture by a geometric correction factor of f_{geo} = A_{geo} × v^2/(ω × d), where A_{geo} is the isophotal area of the source on the BW image, ν is the ratio of the Lyα and BW diameters measured along the slit, ω is the slit width, and d is the spatial extent of the spectral extraction aperture.

Figure 6. Imaging and MMT spectroscopic observations of LABd05, a previously-known Lyα nebula at z ≈ 2.656 (Dey et al. 2005). The top row shows the optical BW, R, and I imaging along with the slit used for follow-up spectroscopy. The central panel contains the two-dimensional spectrum vs. observed wavelength and the bottom panel presents the one-dimensional spectrum extracted from a 1′0 × 4.48 aperture. The error spectrum (red line) and BW and R bandpasses (blue lines) are shown, and the positions of common emission lines are indicated. The one-dimensional Lyα emission line profile is shown in the small inset panel. The emission line at 5081 Å from a background galaxy at z ≈ 3.2 is labeled for reference (Dey et al. 2005).

(A color version of this figure is available in the online journal.)
categorized as having a diffuse morphology while one (PRG4) was categorized as having a group morphology (see Paper I).

4.1.1. PRG1

PRG1 is a remarkable Lyα nebula (Figure 2). As discussed in Prescott et al. (2009), it is the first example of a Lyα nebula with strong, spatially extended He ii emission and weak metal lines, suggestive of a hard ionizing continuum and potentially low metallicity gas. The $B_W$ imaging shows a diffuse nebula and several compact sources, the brightest of which is located at the northwest edge of the nebula. Despite the strong Lyα emission and large size ($\gtrsim 78$ kpc), PRG1 was selected as a second priority candidate because, at $z \approx 1.67$, Lyα is at the edge of the optical window and not contained within the $B_W$ band, giving the source a relatively red $B_W - R$ color. Thanks to its diffuse blue continuum (95%) and He II emission (5%), however, this source was still selected by our survey. When first discovered, this source was the lowest redshift Lyα nebula confirmed by deep Keck/LRIS spectroscopy in progress (M. K. M. Prescott et al. 2013, in preparation).

4.1.2. PRG2

PRG2 is a large Lyα nebula at $z \approx 2.27$ with a roughly diamond-shaped morphology in the $B_W$ image (Figure 3). The identification of the strong line in the spectrum as Lyα is secure based on the fact that no other lines are well-detected in the discovery spectrum and corroborated by weak detections at the positions of C iv λ1548, 1550, He ii λ1640, and C iii λ1909. In the case of [O II] at lower redshift, we would have easily detected [O III] and Hα instead. The Lyα nebula spans almost 100 kpc, and at the southwestern corner there is a very blue compact source that appears to be a Lyα-emitting galaxy from the spectrum. The redshift of this source is ideal for follow-up NIR spectroscopy as the rest-frame optical emission lines ([O II], [O III], Hβ, and Hα) will be observable in the $J$, $H$, and $K$ bands. Continuum emission is observed from two compact knots located at either end and from spatially extended emission at fainter levels in between them.

4.1.3. PRG3

PRG3 is a Lyα nebula at $z \approx 2.14$ (Figure 4). It has a rather clumpy horseshoe-shaped morphology in the $B_W$ imaging and spans $\approx 74$ kpc. The single strong line is identified as Lyα rather than [O II] based on the fact that we do not see corresponding detections of [O III] and Hα. The spectrum shows spatially extended continuum, but no other strong emission lines.

4.1.4. PRG4

PRG4 appears to be a candidate that was selected due to a close grouping of compact blue sources (Figure 5). Due to the very blue color, it was flagged as a high-priority target. At these wavelengths (blueward of the rest-frame wavelength of [O II]), Lyα is the only possible strong line. In addition, no other strong lines are seen in the spectrum. Although the $B_W$ size of the full grouping is roughly $7''$, the observed Lyα at $z \approx 1.89$ is only marginally extended along the direction of the spectroscopic slit ($3''9$, 33 kpc). The source may be larger in Lyα: there is additional diffuse emission outside the slit that is visible to the southwest in the $B_W$ imaging, but without further spectroscopy, we cannot determine if it is associated with coincident Lyα emission.

4.1.5. LABd05

LABd05 is the source that was the inspiration for our broadband Lyα nebula search (Figure 6; Dey et al. 2005). One of the largest Lyα nebulae known ($\gtrsim 100$ kpc; Dey et al. 2005), it is located at $z \approx 2.656$. Our shallow MMT spectrum was taken at a slightly different position than the existing deeper spectroscopy from Keck but shows a hint of He II emission and an emission line at 5081 Å, both seen previously in the system (Dey et al. 2005). The emission line at 5081 Å is thought to be Lyα from a background interloper galaxy at $z \approx 3.2$, the compact source that is visible in the ground-based imaging and located at the western edge of the slit for this observation. Detailed study of ground-based data as well as high-resolution imaging from Hubble Space Telescope (HST) showed that there are numerous compact galaxies, including a spectroscopically confirmed Lyman break galaxy, within the system that are offset spatially from the Lyα nebula itself (Dey et al. 2005; Prescott et al. 2012b). The HST imaging demonstrated that the nebula contains diffuse rest-frame UV continuum emission, that the Lyα emission itself is smooth with a relatively round and disk-like morphology, and that the He II emission is spatially extended by $\approx 0''6 - 1''$ ($\approx 5$–8 kpc; Prescott et al. 2012b).

4.2. Survey Contaminants

The dominant contaminants in both the first- and second-priority spectroscopic samples are sources with spatially resolved blue continuum emission but no visible emission lines. Despite the lack of strong line emission in the $B_W$ band, our morphological broadband search selected these sources either due to sufficiently extended, blue continuum emission or due to a close projected grouping of blue galaxies. A few examples of these continuum-only sources are shown in Figure 7.

Without deeper spectroscopy, we can only speculate as to the nature of these continuum-only sources. The largest cases within the candidate sample (sources 1+2 and 3; Paper I) are so spatially extended ($\approx 15'' - 66''$, which at $z \approx 1.2 - 2.9$ would imply physical sizes of $\approx 130 - 710$ kpc in the continuum) and irregular in morphology that they are almost certainly located within the Galaxy, perhaps low surface brightness Galactic reflection nebulae. Since low-redshift ($z \lesssim 1.2$) blue star-forming populations or low surface brightness galaxies (LSBs) would be expected to show [O II], [O III], or Hα emission lines in our spectra, some fraction of the remaining continuum-only contaminants may in fact be galaxies or Lyα nebulae in the redshift desert ($1.2 \lesssim z \lesssim 1.6$), for which Lyα is blueward of the atmospheric cutoff ($\lambda_{\text{obs}} \lesssim 3100$ Å) but for which [O II] has been redshifted past the red end of our MMT/Blue Channel spectra ($\lambda_{\text{obs}} \gtrsim 8320$ Å). One of the Lyα nebulae confirmed by our survey (PRG1, at $z \approx 1.67$) is in fact below the redshift where Lyα is covered by the $B_W$ band. Instead, this source was selected by our survey primarily due to blue continuum emission, and it was only thanks to the excellent blue sensitivity of MMT/Blue Channel that we were still able to detect the Lyα emission at $\approx 3250$ Å. The case of PRG1 lends credence to the hypothesis that at least a fraction of the continuum-only “contaminant” sources are in fact Lyα nebulae at $1.2 \lesssim z \lesssim 1.6$.

At the same time, however, our expectation from Paper I was that Lyα nebulae in the redshift desert should make up
roughly 25% of the candidate sample, under the optimistic assumption that the Ly\(\alpha\) nebula number density does not evolve significantly with redshift. In practice, we found continuum-only detections represented a much larger fraction (75%) of the target spectroscopic sample, suggesting that this explanation may not be the full story. While the presence of continuum emission in the spectra does confirm that these continuum-only sources are indeed real astrophysical objects and not artifacts within the NDWFS imaging, deeper ground-based optical spectroscopy or UV spectroscopy from space will be required to confirm their origin on a case by case basis. At this stage, their nature remains mysterious.

5. DISCUSSION

5.1. A Successful Broadband Ly\(\alpha\) Nebula Survey

This work is the first demonstration of the feasibility of conducting systematic surveys for large Ly\(\alpha\) nebulae using deep broadband imaging data sets. The primary advantage of our unusual survey approach is the enormous comoving volume that can be surveyed using deep archival data sets. In addition, since this search technique is best used in the blue where the sky is dark, the resulting Ly\(\alpha\) nebula sample is weighted to lower redshifts \((z < 3)\) where we have the opportunity to undertake detailed studies of their properties. The obvious tradeoff is that our approach is not as sensitive to Ly\(\alpha\) nebulae that are intrinsically faint, low surface brightness, or compact in morphology, as discussed in Papers I and III. Our search, therefore, provides a measurement of the bright end of the Ly\(\alpha\) nebula luminosity function, nicely complementing standard narrowband surveys that probe to fainter luminosities.

The success rate for finding sources with Ly\(\alpha\) emission was \(\approx 27%\) for first priority and \(\approx 20\%\) for second priority candidates. Therefore, if we were able to target all the Ly\(\alpha\) nebula candidates in our sample, we would expect to find a total of \(\approx 18\) Ly\(\alpha\) nebulae (\(\approx 10\) and \(\approx 8\) from the first and second priority sets, respectively). While one of the goals of our broadband survey for Ly\(\alpha\) nebulae is to place constraints on the space density of these rare objects, a robust estimate of the space density requires a detailed analysis of the selection function and is beyond the scope of the present paper. Here, we briefly discuss our detection rate in the context of traditional narrowband Ly\(\alpha\) nebula surveys.

Based on the results of the narrowband survey carried out at \(z \approx 2.3\) by Yang et al. (2009), in Paper I we estimated the expected number of Ly\(\alpha\) nebulae in our survey volume to be \(\approx 60–400\), assuming a 100% detection rate, the same detection limit as Yang et al. (2009), and a constant volume density as a function of redshift. Instead, we have confirmed 5 Ly\(\alpha\) nebulae, and scaling these results to the unobserved candidates, we expect to find only 18. While this estimate is extremely crude, it does suggest that the space density of the detected Ly\(\alpha\) nebulae in our sample is lower than that of the Yang et al. (2009) sample. Possible reasons for this difference are that (1) the Yang et al. (2009) narrowband survey is more sensitive to fainter, and therefore less luminous, Ly\(\alpha\) nebulae than our broadband survey; (2) the Yang et al. (2009) survey does not exclude Ly\(\alpha\) nebulae with bright central sources whereas our survey does due to the nature of the morphological search algorithm; and/or (3) the Yang et al. (2009) survey is more sensitive to cosmic variance than our larger volume survey. We defer a more detailed discussion of the space density of Ly\(\alpha\) nebulae implied by our survey to Paper III.
5.2. Dispersion within the Lyα Nebula Class

The power of a systematic survey is the opportunity it provides to find out what is common among a class of objects and also what the dispersion in properties is among members of that class. The four large cases in our sample (PRG1, PRG2, PRG3, and LABd05) span nearly an order of magnitude in total Lyα luminosity (50–170 × 10^42 erg s^{-1}), show a range of Lyα equivalent widths (∼50–260 Å), and are at least 70–100 kpc in diameter. Morphologically, the four large Lyα nebulae all show clumps and knots of emission in the broadband imaging. The brightest compact knot in PRG1 is very red while that in PRG2 is remarkably blue. In addition, all four show what appears to be diffuse continuum emission in the ground-based spectroscopy. This could either be due to many unresolved clumps or due to a continuum component that is truly spatially extended. Analysis of HST imaging of one system (LABd05) lends support to the latter hypothesis, revealing that most of the continuum in this one source is unresolved even at high resolution (0.1′; Prescott et al. 2012b). In three cases (PRG1, PRG2, and LABd05) there is evidence for emission in other lines (e.g., C iv, He ii, or C iii).

Given that diffuse continuum emission will have a larger impact on the observed broadband color than line emission, one might ask if our survey is biased toward finding lower equivalent width sources than narrowband surveys. In fact, however, Figure 8 shows that our survey uncovered Lyα nebulae with rest-frame equivalent widths comparable to those of luminous Lyα nebulae found using standard narrowband surveys but over a much larger redshift range.

6. CONCLUSIONS

We have carried out an innovative and economical systematic search for large Lyα nebulae using archival deep broadband data. While our technique is only sensitive to the largest and brightest Lyα nebulae, it is able to probe enormous comoving volumes (∼10^8 h_70^{-2} Mpc^3) using existing deep broadband data sets. The details of our search algorithm, the selection function, and implied space density are discussed in Papers I and III of this series. In this paper (Paper II), we presented details of our spectroscopic follow-up of Lyα nebula candidates. Within our ∼8.5 deg^2 survey area and a redshift range of z ≈ 1.6–2.9, we confirmed four new Lyα nebulae and recovered one previously known case. The brightest four Lyα nebulae have Lyα luminosities of ∼5–17 × 10^42 erg s^{-1} and sizes of >70 kpc. Our broadband search found Lyα nebulae with large Lyα luminosities and equivalent widths comparable to those found with narrowband surveys, but revealed a new common theme: at least some large Lyα nebulae show diffuse, spatially extended continuum emission. The primary contaminants in our survey are sources that show nothing but blue continuum in the optical range, some of which we suspect may be galaxies or Lyα nebulae located in the redshift desert. Deep continuum spectroscopy and comparisons to GALEX photometry will be required to confirm this claim. This work uncovered the first example of a giant Lyα nebula at z < 2 and has demonstrated the feasibility of using deep broadband data sets to efficiently locate luminous Lyα nebulae within enormous comoving volumes.

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