LYα-EMITTING GALAXIES AT REDSHIFT z ∼ 4.5 IN THE LALA CETUS FIELD*

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ABSTRACT

We present a large sample of Lyα-emitting galaxies (LAEs) spectroscopically confirmed at redshift z ∼ 4.5, based on Inamori-Magellan Areal Camera and Spectrograph spectroscopic observations of candidate z ∼ 4.5 Lyα-emitting galaxies in the large area Lyman alpha (LALA) narrowband imaging survey Cetus field. We identify 110 of them as z ∼ 4.5 Lyα emitters based on single-line detections with no continuum emission blueward of the line. Six foreground galaxies are identified, either based on multiple lines or blueward continuum emission. The Lyα confirmation rate varies from <50% to 76% for candidates selected in different narrowband filters at slightly different redshifts. We find a drop in the LAE density at redshift 4.50 ± 0.03 from redshift 4.39 to 4.47 by a factor of 66%, which could be a large-scale void in the distribution of star-forming galaxies (~18 Mpc along the line of sight and ~80 Mpc across). The sample includes many objects with equivalent widths (EWs) 200 Å. These large EW candidates are spectroscopically confirmed at the same rate as candidates with more modest EWs. A composite spectrum of all 110 confirmed LAEs shows the characteristic asymmetry of the Lyα line. It also places new and stringent upper limits on the Cα line ratios, providing a new upper limit on the fraction of active galactic nuclei in Lyα selected galaxy samples, and on the contribution of Pop III populations. Finally, we calculate the Lyα luminosity function for our z ∼ 4.5 sample, which is consistent with those at other redshifts, showing that there is no evolution in Lyα luminosity function from z = 3.1 to 6.6.

Key words: cosmology: observations – early universe – galaxies: evolution – galaxies: formation – galaxies: high-redshift

Online-only material: color figures

1 INTRODUCTION

The number of known high-redshift galaxies has grown rapidly in the past decade, thanks to efficient wide field cameras and effective selection techniques (i.e., the dropout technique and Lyα-line search technique). Narrowband imaging surveys have become the most efficient approach for finding high-redshift Lyα-emission lines galaxies. Great successes have been achieved recently in detecting high-redshift Lyα emitters using this technique (e.g., from z = 3 to z = 6.96; see Iye et al. 2006; Rhoads et al. 2000, 2003, 2004; Wang et al. 2005; Tappenden et al. 2006; Westra et al. 2006; Shimasaku et al. 2004, 2006; Kashikawa et al. 2006; Ajiki et al. 2006; Ouchi et al. 2005, 2006; Hu et al. 2002, 2004; Dawson et al. 2004, 2007; and references therein). Large well-defined samples of high-redshift Lyα-emitting galaxies are essential to study the nature of these galaxies, including their stellar populations (age and stellar mass; e.g., Lai et al. 2008; Pirzkal et al. 2007; Finkelstein et al. 2007, 2009a), the mechanism of Lyα production (Malhotra & Rhoads 2002) and escape (Finkelstein et al. 2008), the luminosity function and its evolution (Dawson et al. 2007; Malhotra & Rhoads 2004, 2006; Ouchi et al. 2008), and spatial clustering of star-forming galaxies in the early universe (Wang et al. 2005; Ouchi et al. 2005; Malhotra et al. 2005; Kovač et al. 2007).

The Large Area Lyman Alpha (LALA) survey (e.g., Rhoads et al. 2000) has obtained deep narrowband images in several fields, yielding a large sample of Lyα emitters at z ∼ 4.5 (Malhotra & Rhoads 2002; Dawson et al. 2004, 2007), and z ∼ 5.7 (Rhoads & Malhotra 2001; Rhoads et al. 2003; Wang et al. 2005), plus a smaller sample at z ∼ 6.5 (Rhoads et al. 2004). In this paper, we present the spectra of 110 Lyα emitters at z ∼ 4.5 in LALA Cetus field, confirmed using the Inamori-Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2006; A. Dressler et al. 2009, in preparation) on the 6.5 m Magellan I Baade Telescope. Together with our previously confirmed sources from Keck observations (Dawson et al. 2004, 2007), we now have an overall sample of 171 spectroscopically confirmed Lyα emitters at z ∼ 4.5.

2 OBSERVATIONS

2.1 Candidate Selection through Narrowband Imaging

We obtained the narrowband images used to select z ∼ 4.5 Lyα galaxy candidates for this work using the 8192 × 8192 pixel Mosaic CCD cameras at the National Optical Astronomy Observatory’s 4 m telescopes (the Mayall Telescope at Kitt Peak National Observatory, and the Blanco Telescope at Cerro Tololo Inter-American Observatory). We observed the LALA Cetus field (02:05:20 –04:55; J2000.0). In total, we obtained deep narrowband stacks over a 36′ × 36′ field in five distinct but overlapping filters, each with full width at half-maximum (FWHM) ∼ 80 Å (see Figure 1 of Dawson et al. 2004). The central wavelengths are 6559, 6611, 6650, 6692,
and 6730 Å for narrowband filters Hα0, Hα4, Hα8, Hα12, and Hα16, respectively. The filters thus cover a total redshift range of 4.36 < z < 4.57 for Lyα, with approximately 50% overlap in bandpass between adjacent filters. The average seeing in the final stacked narrowband images are 1′′.00, 1′′.26, 1′′.12, 1′′.27 and 0′′.99, and the 5 σ (2′′.4 diameter aperture) limiting magnitudes are 24.7, 24.8, 24.8, 24.7 and 24.1 (Vega), respectively. The zero points of the narrowband images were obtained by matching the narrowband photometry to that of the underlying broadband (R) image.

To study the continuum emission properties of our candidates, we used deep broadband images in B$_W$, R, I from the NOAO Deep Wide Field Survey (NDWFS; Jannuzi & Dey 1999). We followed reasonably standard practices in our narrowband imaging data reduction and our Lyα galaxy candidate selection, which are described in detail elsewhere (Rhoads et al. 2000; Rhoads & Malhotra 2001; Wang et al. 2005). Briefly, our selection criteria are: (1) >5σ detection in a narrowband filter; (2) a narrowband excess of >0.75 mag, so that >50% of the narrowband flux comes from an emission line; (3) significance of the narrowband excess >4σ; and (4) <2σ detection in B$_W$ band.

We identified a total of 226 candidate Lyα emitters at z ≈ 4.5 in our primary sample. The numbers of candidates selected in each narrowband filter are presented in Table 1. Additionally, we performed an extended catalog selection using the spectral overlap of adjacent filters to go to fainter flux levels by combining data from filters that overlap in wavelength.

### Table 1

| Filter | Average Seeing | Limiting mag$^a$ | Candidates | Targeted | Confirmed |
|--------|----------------|-----------------|------------|----------|-----------|
| Hα0    | 1′′.00         | 24.7            | 57         | 48       | 35        |
| Hα4    | 1′′.26         | 24.8            | 64         | 45       | 34        |
| Hα8    | 1′′.12         | 24.8            | 80         | 56       | 36        |
| Hα12   | 1′′.27         | 24.7            | 38         | 22       | 9         |
| Hα16   | 0′′.99         | 24.1            | 31         | 23       | 8         |
| ext    |                | 38              | 27         | 12       |           |

$^a$ 5 σ (2′′.4 diameter aperture) limiting magnitudes (Vega).

We note that none of our subsequent scientific results rely on the continuum level measured in the spectroscopic data. We note that none of our subsequent scientific results rely on the continuum level measured in the spectroscopic data.

To control for possible spatial shifts along the slits between individual exposures of a mask, we measured the trace locations of the 30 brightest continuum sources in the mask. We corrected for any measured shifts while stacking the exposures for each mask to increase the quality of the stacked two-dimensional spectra. We also identified and removed cosmic ray hits while stacking the multiple exposures of each mask. Finally, we extracted the one-dimensional spectra (2 Å per bin) using a weighted extraction assuming a Gaussian spatial profile.

### Table 2

| Mask | Exp Time (ks) | Targeted | Confirmed |
|------|---------------|----------|-----------|
| 1    | 11.3          | 52       | 35        |
| 2    | 8.9           | 58       | 33        |
| 3    | 10.8          | 44       | 21        |
| 4    | 9.9           | 58       | 26        |
| 6    | 9.0           | 46       | 17        |

The data were reduced using the IMACS version of the Carnegie Observatories System for MultiObject Spectroscopy (COSMOS) data reduction package. We first determined two-dimensional wavelength solutions for each science exposure using arc lamp exposures taken immediately before or after. We found relatively large wavelength residuals (~6 pixels) in the course of this calibration, perhaps pointing to inaccuracies in the geometric coefficients describing the layout of the detector chips in the focal plane. Regardless of their origin, these residuals are repeatable from exposure to exposure. They therefore do not significantly affect our search for Lyα-emission lines, though they do lead to extra uncertainties in the line wavelengths we determine (see below for details) and sky subtraction.

To wavelength calibration, each frame was first bias-subtracted and flat-fielded. We then performed sky subtraction following the algorithm described by Kelson (2003), and extracted one-dimensional spectra from the two-dimensional spectra using the task “extract-2dspec” for each slit. Frequently, this procedure produced an apparently “negative” blue continuum in the one-dimensional spectra of our confirmed Lyα emitters, indicating small systematic errors in the software’s measured sky level. In these cases, we checked that the continuum level appears to be zero in the two-dimensional spectra, and then applied an additive correction to the one-dimensional spectrum. We note that none of our subsequent scientific results rely on the continuum level measured in the spectroscopic data.

3. SPECTROSCOPIC RESULTS

3.1. Line Identification

We identified 110 single emission lines as Lyα at z ≈ 4.5, among our 194 observed candidates. Of these, 97 are new spectroscopic confirmations. We present a catalog of the 110 confirmed Lyα-emitting galaxies (LAEs) at z ≈ 4.5 in LALA Cetus field in Table 3. In Figure 1, we present the narrowband flux distributions of the targeted and confirmed LAEs in different narrowbands, and in Figure 2 we present a set of sample IMACS spectra of confirmed LAEs.

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Notes. The “ext” line represents candidates in the extended sample, which goes to a fainter flux level by combining data from filters that overlap in wavelength.

6 http://lama.lco.cl/~aoemler/COSMOS.html
Table 3
IMACS Spectroscopically Confirmed Lyα Emitters at $z \approx 4.5$ in the LALA Cetus Field

| Target     | \(z\) | Lyα flux \((\text{erg cm}^{-2} \text{s}^{-1})\) | \(\delta z \) |
|------------|-------|---------------------------------|------------|
| J020631.1–044851 | 4.431 | 2.584 ± 0.335 | >105 |
| J020616.5–045457 | 4.378 | 3.795 ± 0.410 | 124±158 |
| J020616.2–050315 | 4.428 | 2.399 ± 0.435 | 70±113 |
| J020615.9–050555 | 4.380 | 2.389 ± 0.353 | >82 |
| J020614.4–050523 | 4.380 | 7.448 ± 0.376 | 275±1287 |
| J020613.1–045101 | 4.372 | 2.648 ± 0.401 | >83 |
| J020612.4–045463 | 4.385 | 3.029 ± 0.361 | >118 |
| J020556.7–048584 | 4.421 | 2.850 ± 0.359 | 107±52 |
| J020556.5–050917 | 4.388 | 2.817 ± 0.408 | 30±49 |
| J020544.7–045921 | 4.382 | 2.117 ± 0.380 | >78 |
| J020542.1–050520 | 4.382 | 1.993 ± 0.377 | >77 |
| J020536.3–044822 | 4.414 | 5.660 ± 0.399 | >179 |
| J020533.0–050042 | 4.395 | 2.844 ± 0.408 | >125 |
| J020526.2–050724 | 4.390 | 2.576 ± 0.377 | >67 |
| J020525.2–050048 | 4.400 | 2.476 ± 0.431 | 186±1599 |
| J020524.5–045241 | 4.390 | 3.221 ± 0.420 | >135 |
| J020518.1–045615 | 4.406 | 0.747 ± 0.417 | >161 |
| J020513.9–044638 | 4.395 | 2.628 ± 0.431 | >87 |
| J020510.5–044456 | 4.406 | 3.513 ± 0.434 | >70 |
| J020509.7–044005 | 4.410 | 5.030 ± 0.372 | 134±292 |
| J020501.0–050731 | 4.388 | 7.290 ± 0.413 | 83±113 |
| J020457.3–051157 | 4.398 | 5.928 ± 0.414 | >100 |
| J020451.6–045737 | 4.365 | 2.221 ± 0.386 | >85 |
| J020450.6–050107 | 4.378 | 2.526 ± 0.399 | >87 |
| J020450.9–044323 | 4.401 | 2.124 ± 0.414 | >296 |
| J020446.9–050116 | 4.354 | 2.208 ± 0.387 | >92 |
| J020436.8–044437 | 4.398 | 3.233 ± 0.428 | 43±67 |
| J020436.4–051016 | 4.378 | 2.813 ± 0.410 | 99±111 |
| J020434.5–050516 | 4.401 | 6.029 ± 0.452 | 202±140 |
| J020423.2–045519 | 4.360 | 2.740 ± 0.413 | >97 |
| J020428.5–045924 | 4.391 | 2.766 ± 0.393 | 96±138 |
| J020427.4–050045 | 4.390 | 2.486 ± 0.411 | >100 |
| J020425.7–045810 | 4.383 | 2.788 ± 0.400 | >68 |
| J020414.3–051201 | 4.401 | 4.139 ± 0.453 | >119 |
| J020413.8–044703 | 4.385 | 2.928 ± 0.422 | >72 |
| J020428.0–045307 | 4.462 | 2.011 ± 0.376 | >69 |
| J020428.3–044221 | 4.444 | 3.859 ± 0.366 | >169 |
| J020603.5–050019 | 4.441 | 2.297 ± 0.357 | >79 |
| J020601.7–050258 | 4.433 | 3.134 ± 0.373 | >126 |
| J020553.4–044147 | 4.428 | 2.761 ± 0.346 | >77 |
| J020506.5–050055 | 4.429 | 2.005 ± 0.350 | 69±282 |
| J020536.6–045520 | 4.418 | 2.689 ± 0.393 | 99±65 |
| J020531.4–044053 | 4.459 | 2.115 ± 0.360 | 53±59 |
| J020527.7–043944 | 4.436 | 3.848 ± 0.374 | 54±36 |
| J020519.2–044902 | 4.421 | 2.531 ± 0.380 | >95 |
| J020517.5–044537 | 4.436 | 2.420 ± 0.396 | >99 |
| J020513.8–043833 | 4.419 | 2.723 ± 0.376 | >117 |
| J020507.2–050636 | 4.465 | 2.861 ± 0.362 | >119 |
| J020506.8–043858 | 4.429 | 3.873 ± 0.355 | 87±34 |
| J020458.0–050140 | 4.452 | 2.155 ± 0.377 | 82±42 |
| J020457.3–043847 | 4.431 | 2.086 ± 0.366 | >47 |
| J020452.1–043802 | 4.431 | 3.346 ± 0.361 | >88 |
| J020450.2–045828 | 4.423 | 2.510 ± 0.360 | >94 |
| J020448.0–044257 | 4.426 | 2.871 ± 0.374 | 79±30 |
| J020445.5–050008 | 4.416 | 2.297 ± 0.383 | 57±29 |
| J020439.0–045233 | 4.421 | 2.387 ± 0.398 | >70 |
| J020438.9–044401 | 4.414 | 2.151 ± 0.376 | >54 |
| J020438.9–051116 | 4.447 | 9.920 ± 0.366 | >247 |
| J020434.9–045703 | 4.433 | 2.422 ± 0.363 | 48±18 |

Notes.

- The redshift was measured from the wavelength of the peak pixel in the line profile from one-dimensional spectra. Due to the uncertainties in the wavelength calibration (see the text for details), we expect the error in the measurement to be $\delta z \sim 0.005$.
- The line flux was measured based on narrowband and broadband photometry, in units of $10^{-17}$ erg cm$^{-2}$ s$^{-1}$.
- The EW were obtained based on broadband and narrowband photometry. See Section 3.3 for details.
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Figure 1. Narrowband flux distributions of IMACS targeted candidates (solid) and confirmed Ly$\alpha$ emitters (dashed). Different panels plot the distributions of candidates selected in different narrow bands. (A color version of this figure is available in the online journal.)

Figure 2. Sample IMACS spectra for Ly$\alpha$ lines from the set of 110 confirmed LAEs at $z \approx 4.5$ in LALA Cetus field.

Figure 3. Plot of two measurements of the line asymmetry for 110 Ly$\alpha$ emitters (see the text for definitions of $a_\lambda$ and $a_f$). Due to the low resolution of our IMACS spectra, both measurements suffer large uncertainties. Considering the large error bars, all but one of the sources satisfy (within 1$\sigma$) $a_\lambda > 1$ or $a_f > 1$, and all but three sources satisfy both.

We also identify six foreground sources which either show multiple identified emission lines or blue continuum. The remaining 78 targets were classified as nondetections. Among the nondetections, there are 10 whose expected emission-line wavelength range (based on the narrowband data) falls (entirely or partially) within one of the $\sim 80$ Å gaps between the IMACS CCD detectors. These 10 include one source previously confirmed as a Ly$\alpha$ emitter with Keck LRIS spectrum by Dawson et al. (2004).

Following Rhoads et al. (2003, 2004), we perform two measurements of the line asymmetry. For both measurements, we first determine the wavelength of the emission-line peak ($\lambda_p$), and the wavelengths where the line flux equals 10% of the peak on the blue side ($\lambda_{10,b}$) and the red side ($\lambda_{10,r}$). The “wavelength ratio” is defined as $a_\lambda = (\lambda_{10,r} - \lambda_p) / (\lambda_p - \lambda_{10,b})$, and the “flux ratio” $a_f$ as the ratio of the accumulated line flux between $\lambda_{10,r}$ and $\lambda_p$ to that of between $\lambda_p$ and $\lambda_{10,b}$. In Figure 3, we plot $a_\lambda$ versus $a_f$ for the 110 single lines emitters. The error bars are obtained through 1000 Monte Carlo simulations in which we added random noise to each data bin. Both asymmetry measures are expected to be $> 1$ for the characteristic profile of high-redshift Ly$\alpha$ lines, which show an extended wing on the red side but a sharper falloff on the blue side (generally attributed to absorption and/or scattering by neutral hydrogen, either in outflows from the Ly$\alpha$ galaxy itself or in the surrounding intergalactic gas).

Given the relatively modest spectral resolution and signal-to-noise ratio of our IMACS spectra, there are few for which we can definitively show $a_f > 1$ and $a_\lambda > 1$. This can be seen from the large error bars of $a_\lambda$ and $a_f$ in Figure 3. On the other hand, the formally measured asymmetry parameters do exceed 1 in a majority of cases. Moreover, all but one of our sources statistically satisfy (within 1$\sigma$) $a_\lambda > 1$ or $a_f > 1$, and all but three sources satisfy both. Overall, then we cannot securely identify emission lines as Ly$\alpha$ in individual object spectra based on line asymmetry measurements alone. We will revisit line asymmetry measurements for a stacked spectrum of our entire sample in Section 3.4.
Possible contaminants to our identifications of Lyα lines include [O ii] λ3727 and [O iii] λ5007. Such objects can be identified spectroscopically by looking for other expected emission lines. [O ii] λ5007 can be typically identified by the neighboring [O iii] λλ4959 and Hβ lines, while [O ii] λ3727 is best identified by looking for [O iii]λ4959,5007 and Hβ at longer wavelengths (roughly 8500–9030 Å). We have looked for such lines in more than 90% of our confirmed Lyα spectra. For the remaining few percent, the search for Hβ and [O ii] λ5007 is not possible because of limited spectral coverage. (The spectral coverage in multislit data differs from object to object, depending on where each falls in the field of view.) For the sources without good red coverage, secure identification of [O ii] λ3727 would require new observations with either improved red coverage or higher spectral resolution than our present data set affords. Luckily, most of the foreground [O ii] λ3727 emission-line galaxies have been excluded from our candidate list by excluding sources detected in broadband photometry blueward of the narrowband filter. Residual contamination of Lyα candidate lists by [O ii] λ3727 is generally not a major problem. For instance, using line profiles from Keck DEIMOS spectra of Lyα candidates from the LALA Boötes field, Dawson et al. (2007) identified only two [O ii] λ3727 sources, compared to 59 Lyα lines. In this paper, we identify all the 110 single lines as Lyα lines.

3.2. Comparison with Dawson et al.

With previous Keck observations, Dawson et al. (2004, 2007) have confirmed a total of 17 LAEs at z ∼ 4.5 in LALA Cetus field. In designing our IMACS masks, we gave lower priorities to these previously confirmed LAEs, in order to maximize the total number of LAE candidates with spectroscopic coverage. Thanks to the large field of view of IMACS, we still have 13 of previously confirmed LAEs covered by IMACS observations. Twelve of these 13 sources are confirmed at z ∼ 4.5 independently with the IMACS observations. In the remaining overlap object, the line wavelength as measured with Keck fell in an IMACS chip gap, making confirmation impossible. In Figure 4, we plot the observed Keck redshifts versus IMACS redshifts for these 12 sources, which demonstrates the uncertainties in the IMACS wavelength calibration (Δz/σz = 0.005 at z ∼ 4.5). Our IMACS exposures also covered seven candidates in Cetus field which were previously reported as non-detections based on Keck spectra.

3.3. Equivalent Width Distribution

Several previous studies have found that large fractions of Lyα-selected galaxies show high equivalent widths (e.g., Malhotra & Rhoads 2002; Dawson et al. 2004, 2007; Kudritzki et al. 2000), frequently exceeding 240 Å (rest frame). Such equivalent widths are too large to be produced by normal stellar populations, unless they have a top-heavy initial mass function (IMF), zero (or very low) metallicity, and/or extreme youth (age < 10^6 yr). Significant contributions of type 2 active galactic nuclei (AGNs) to the large line EW have been ruled out (see Section 4.2 below). The large line EWs might also be due to a clumpy and dusty interstellar medium in the galaxy. If the medium consists of an ionized, low-density medium, with embedded clouds of neutral hydrogen and dust, the UV continuum photons may be attenuated to a much greater degree than line photons. This requires that there be substantial gaps between the neutral clouds, but that the clouds have a large covering factor. (That is, the clouds are isolated in three-dimensional space, but overlap in projection.) Under these circumstances, the resonantly scattered line photons can scatter off neutral hydrogen near cloud surfaces, escaping the galaxy through the ionized medium, while the continuum photons are not scattered by neutral hydrogen and must penetrate a dust cloud to be observed. Such an effect could increase the observed EW substantially (Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2007, 2008, 2009).

Could the candidate LAEs with highest photometrically determined equivalent widths (i.e., those with no continuum detection) be contamination due to noise spikes, or spurious features? Our large spectroscopic sample enables us to perform a statistical test on this issue. In Figure 5, we plot the distributions of the broadband to narrowband flux density ratio for our confirmed z ∼ 4.5 LAEs, foreground sources, and spectroscopically undetected sources. (The broadband to narrowband flux density ratio serves as a surrogate for the equivalent width. The two quantities are monotonically related, but the ratio we plot has a much better behaved error distribution.) The figure shows that the spectroscopically confirmed LAEs and the undetected sources have a consistent distributions of broadband to narrowband flux density ratio. A Kolmogorov–Smirnov test shows that two distributions are indistinguishable (p = 85%). This demonstrates that high EW candidates are confirmed at the same rate.

In Table 3, we also present the line equivalent width for all the spectroscopically confirmed z ∼ 4.5 galaxies. Due to the large uncertainty in estimating the continuum level...
and $R$ the widths of the line from optical spectra, we utilize narrowband and broadband photometry to derive the line equivalent width. Following Malhotra & Rhoads (2002), we calculate the equivalent widths as $\text{EW}_{\text{obs}} = F_{\lambda \gamma}/f_\lambda = (W_N - W_R)/(R - N)$, where $F_{\lambda \gamma}$ is the Ly$\alpha$ line flux, $f_\lambda$ the continuum flux density, $W_N$ and $W_R$ the widths of the $R$ band (1568 Å) and the narrowband (80 Å), and $R$ and $N$ the integrated fluxes in the $R$ band and narrowband respectively. The rest-frame equivalent width is then given by $\text{EW}_{\text{rest}} = \text{EW}_{\text{obs}}/(1 + z)$. Consistent with Malhotra & Rhoads (2002), we find that only 50% of the confirmed LAEs show $\text{EW}_{\text{rest}} < 240$ Å. The remainder either shows larger EW, or no detection of continuum at all. It is clear that the uncertainty in line EW mainly comes from that of the continuum, especially for high EW sources. We therefore calculate the uncertainties of the line EWs by applying the $1\sigma$ error bar to each object’s measured $R$-band flux. In many cases, the upper limits of the line EW cannot be constrained, and lower limits are given.

The line EW distributions of differentially selected samples are sensitive to the selection criteria adopted. For example, requiring a broad band detection (e.g., Hu et al. 2004) would exclude very high EW sources. As an illustrative example, only one out of seven LAEs at redshift 3.7 selected by Fujita et al. (2003) in Subaru/XMM-Newton Deep Field show rest-frame line EW above 200 Å (based on narrow and broadband photometry). However, this is after they excluded candidates with no broadband detection. Including objects without broadband detections would add another seven LAEs, among which six would have rest-frame equivalent widths $\geq 200$ Å. The EW distribution is also likely sensitive to the relative depths of the broad and narrowband images. Because we require that the difference between narrowband and broadband flux density be significant at some particular level (4σ in the present work), reducing the uncertainty in broad band fluxes will bring additional sources into the emission-line sample, and these will be sources with lower typical EW.

While most of the sources with high EWs have no broadband detection at all, if we sum the broad and narrowband fluxes for all the confirmed LAEs, we obtain an average EW of 182$^{+26}_{-20}$ Å. If we sum the broad and narrowband fluxes for the confirmed LAEs with $< 3\sigma$ continuum detection (100 out of 110), we do obtain a significant detection of the composite broad band flux, allowing us to derive an average EW of 316$^{+102}_{-62}$ Å. This again demonstrates that a large population of these individual LAEs have high EW.

One final concern about the highest EW sources is whether their equivalent widths are overestimates caused by a statistical selection bias (akin to Malmquist bias). That is, did the selection favor the sources whose broadband fluxes were underestimated due to photon noise? If this were an important effect, there should be one immediate consequence: these high EW sources would be systematically brighter in an independent broadband image. We adopted the independent broadband images obtained with MMT (Finkelstein et al. 2007; Wang et al. 2007) to test this possibility. In Figure 6, we plot Cerro Tololo Inter-American Observatory (CTIO) R-band flux versus scaled MMT $r$-band flux for 44 confirmed LAEs with $r$-band coverage. The MMT $r'$-band “scaled flux” was scaled by a factor which was derived by requiring that the clipped average $R - r'$ color be zero for the full list of sources well detected in both images. We note that the bandpass of MMT $r'$-band is not identical to that of the CTIO band. However, considering that MMT $r'$-band has much better efficiency between 6500 Å and 7200 Å than CTIO $R$ band, while CTIO $R$ band extends to 8000 Å with transmission below 40%, the fluxes from two bands are comparable for our purpose. From the figure, we can see that these LAEs have scaled $r'$-band fluxes consistent with their $R$ fluxes. This suggests that the possible selection bias we mentioned above, if there is any, is.
underestimated due to photon noise) mostly have a composite spectrum. In the co-added spectrum, neither C\textsc{iv} nor He\textsc{ii} line could be detected in the vicinity of expected wavelengths, and 2σ detection limits were given in the text.

The clearest exception is that fluxes that appear negative in the R-band image (and whose R fluxes are therefore surely underestimated due to photon noise) mostly have r'-fluxes that are zero or slightly positive. EW calculations show that 24 out of 44 confirmed LAEs with r'-band flux measurements have EW above 240 Å based on old R-band measurements, while 21 of the 44 show EW above 240 Å based on r'-band fluxes. The EW calculations based on r'-band fluxes have been adjusted to the r'-band transmission curve. We conclude that the high EWs we have obtained are physically real, and cannot be fully ascribed to selection bias.

3.4. The Stacked Spectrum

Stacking a large number of spectra could further help us understand the nature of the line emitters, especially for those with low signal to noise ratio. In Figure 7, we present the stacked spectrum of all 110 confirmed Ly\(\alpha\) emitters at \(z \approx 4.5\) in the LALA Cetus field. Dashed lines show the 1σ uncertainty in the composite spectrum. In the co-added spectrum, neither C\textsc{iv} λ1549 nor He\textsc{ii} λ1640 line could be detected in the vicinity of expected wavelengths, and 2σ detection limits were given in the text.

Figure 7. Co-added spectrum of the 110 IMACS confirmed Ly\(\alpha\) emitters at \(z \approx 4.5\) in the LALA Cetus field. Dashed lines show the 1σ uncertainty in the composite spectrum. In the co-added spectrum, neither C\textsc{iv} λ1549 nor He\textsc{ii} λ1640 line could be detected in the vicinity of expected wavelengths, and 2σ detection limits were given in the text.

4. DISCUSSION

4.1. Large-scale Structures

We find significantly different success rates and total numbers of candidates obtained in images from different narrowband filters (see Table 1). The small number of candidates in the Ha16 filter can be ascribed to the shallower depth in the Ha16 narrowband image. The lower spectroscopic success rate in Ha16 could be due to a higher percentage of contamination from noise spikes (assuming the total number of spurious detections due to noise spikes per image remains constant) and asteroids (with a small number of frames, asteroids could leave more spurious features in the stacked image).

The Ha12 narrowband image has the same depth as Ha0, Ha4, and Ha8 bands, yet has many fewer candidates detected. This indicates that the source density probed by the Ha12 filter, at the redshift 4.50 ± 0.03, is much smaller than that in the redshift range of 4.39–4.47 (covered by the Ha0, Ha4, and Ha8 filters). The success rates and number of candidates in Ha0, Ha4, and Ha8 filters are similar, with Ha8 having marginally more candidates, and a marginally lower confirmation rate.

In Figure 8, we plot the spatial distributions of the candidates selected in each narrowband image. Similar large-scale structure has been reported at various redshifts elsewhere (e.g., see Ouchi et al. 2005; Wang et al. 2005; Palunas et al. 2004; Kovac et al. 2007, and more). Quantitative analysis on the large-scale structures presented in Figure 8 requires careful analysis of the candidate selection effects, the regions covered by each slit mask, and the success rate of each mask in each narrowband. Such analysis is beyond the scope of this paper. However, we note that the source density at redshift 4.50 ± 0.03 is 66% of the source density in the bluer narrowband filters, and that this drop is consistent with a cosmic variance calculation (Trenti & Stiavelli 2008), which gives a 40% cosmic variance (1σ) for the volume of our survey.

4.2. Active Galactic Nucleus Fraction

Significant contributions of AGNs to the large EW emission-line population have been ruled out using deep X-ray images and optical spectra (e.g., see Malhotra et al. 2003; Wang et al. 2004; Dawson et al. 2004; Gawiser et al. 2006). Deep X-ray images can be used to test whether these LAEs are AGNs, since such AGN should be strong X-ray emitters based on their Ly\(\alpha\)-line fluxes. We have applied this test, using two deep Chandra ACIS exposures (~180 ks each) in the LALA Boötes and Cetus fields. We were unable to detect individually any of 101 LAE candidates covered by these X-ray images (Malhotra et al. 2003; Wang et al. 2004). By stacking the X-ray images of all the Ly\(\alpha\) sources in these data sets, we established a strong constraint (3σ)

\[ f(\text{C\textsc{iv}} \lambda 1549)/f(Ly\alpha) < 3.7\% \text{ and } f(\text{He\textsc{ii}} \lambda 1640)/f(Ly\alpha) < 7.4\% \]

These constraints are significantly stronger than we previously obtained based on 11 LAEs spectra with Keck (8% and 13% respectively; Dawson et al. 2004).

\[ \text{EW} = \frac{f(\text{C\textsc{iv}} \lambda 1549)}{f(Ly\alpha)} \text{ and } \text{EW} = \frac{f(\text{He\textsc{ii}} \lambda 1640)}{f(Ly\alpha)} \]

We first calculated the expected numbers of LAEs in Ha0, Ha4, Ha8, and Ha12 bands, respectively, by multiplying the total number of candidates with the spectroscopic success rate in each band. The fraction 66% was obtained by comparing the expected number of LAEs in Ha12 band with the average value in Ha0, Ha4, and Ha8 bands.
on the average X-ray luminosity, $L_{2-8keV} < 2.8 \times 10^{42}$ erg s$^{-1}$, and estimated that <4.8% of the LAEs in LALA Boötes and Cetus field could be possible AGNs (Wang et al. 2004). No AGN lines have been identified in our individual or composite optical spectra, either (Dawson et al. 2004 and this paper). Dawson et al. (2004) have presented an upper limit of C iv to Lyα-line flux ratio of 8% (2σ) based on the composite spectrum of 11 LAEs at $z \approx 4.5$.

In Section 3.4, we have presented the composite spectra of 110 Lyα emitters at $z \approx 4.5$. Even in the composite spectrum, C iv line is invisible. A much stronger upper limit to the C iv line flux is derived, which is < 3.7% (2σ) of the Lyα flux. For comparison, the typical ratio of C iv to Lyα line in type II AGNs is 22% (Ferland & Osterbrock 1986). This confirms previous results that the AGN contribution to individual or composite optical spectra is rather small. The formal upper limit from the C iv line is $\lesssim 3.7/22 = 17\%$. This is somewhat weaker than our earlier X-ray-based limits (Malhotra et al. 2003; Wang et al. 2004), but is an entirely independent constraint. Interestingly, this limit is below the AGN detection fraction for nearby (redshift $z \sim 0.3$) LAEs, reinforcing the observation of AGN fraction evolution by Finkelstein et al. (2009b).

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The search for the first generation (or Pop III stars) is one of the major targets in observational studies. However, until now there is no strong evidence for the detection of Pop III stars, and the search for such objects remains a major observational challenge (Schaerer 2008). Because stellar surface temperatures rise with decreasing metallicity, very low-metallicity stellar populations have strong Lyman continuum emission, and can produce Lyα lines with maximum EW $> 400$–$850$ Å for $Z < 10^{-5} Z_\odot$ (e.g., Schaerer 2003; Tumlinson et al. 2003). Stellar populations of extremely low metallicity can also produce sufficient luminosity at photon energies $> 54.4$ eV that the He ii $\lambda 1640$ line (the Balmer $\alpha$ transition of singly ionized helium) becomes strong. This makes the He ii $\lambda 1640$ line a prominent tool in searching for Pop III stars, and several studies have been performed to search for strong He ii $\lambda 1640$ emission line in the spectra of high-redshift LAEs. However, no positive detection has been obtained yet.

In our redshift $z = 4.5$ sample, we have found a large population of spectroscopically confirmed LAEs with rest-frame Lyα-line EW above 240 Å, consistent with Malhotra & Rhoads (2002) and Ouchi et al. (2008). This contrasts with the lower EWs reported at $z \approx 3.1$ and 2.2 (Gronwall et al. 2007; Nilsson et al. 2009). It is not clear if this difference in EW is primarily due to cosmic evolution or to different selection criteria in different studies. We have ruled out a substantial AGN contribution to this large EW Lyα-emitting population (Section 4.2).

Our measured upper limit of $f(\text{He} \> ii \lambda 1640)/f(\text{Ly} - \alpha) < 7.4\%$ in the composite Lyα galaxy spectrum can be translated into constraints on Pop III galaxy contributions to the Lyα population. The upper limit can be converted to $\log(Q_{\text{He} ii}/Q_{\alpha}) < -1.4$, where $Q_{\text{He} ii}$ and $Q_{\alpha}$ are ionizing fluxes for He ii and H, respectively (Schaerer 2003). This upper limit is close to the maximum predicted values for metal-free populations with IMFs including very massive stars (up to 500 $M_\odot$; see Figure 5 of Schaerer 2003). Thus, although He ii $\lambda 1640$ is not detected in our composite spectrum, and our upper limit is the most stringent to date, it remains insufficient to rule out the existence of Pop III (or very metal-poor) stars in our LAEs at $z \approx 4.5$. Considering that the fraction of Pop III galaxies among LAE sample at $z \approx 4.5$ could be rather small (such as a few percent, e.g., Scannapieco et al. 2003), the composite spectrum can not even rule out some model which predict comparable He ii $\lambda 1640$ and Lyα-line fluxes for Pop III populations (e.g., Tumlinson et al. 2003), although a flux ratio $f(\text{He} \> ii \lambda 1640)/f(\text{Ly} - \alpha) \gtrsim 1$ would be readily detected in individual object spectra and can therefore be ruled out.

4.4. Lyα Luminosity Function

We have presented a large spectroscopically confirmed LAE sample at $z \approx 4.5$. In this section, we present the Lyα luminosity function based on this sample. Due to the large uncertainty in flux calibration in spectroscopic observations, we adopt photometric measurements to calculate the Lyα fluxes. The Lyα fluxes were derived from narrowband and broadband photometry, where $f_{\text{Ly} \alpha} = f_{\text{nb}} - f_{\text{continuum}} * w_{\text{nb}}$ and $f_{\text{continuum}} = (f_R - f_{\text{nb}})/(w_R - w_{\text{nb}})$. The line luminosities of the confirmed LAEs were calculated assuming a cosmology model of $H_0 = 71$ km/s/Mpc, $\Omega_m = 0.27$, and $\Omega_k = 0.73$.

For each confirmed LAE, we first calculated the comoving volume $V_{\text{max}}$ over which the source could be selected by our

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8 Type 1 AGN could be ruled out in most (if not all) LAEs because of the lack of broad emission lines in the spectra.
survey, from $z_{\text{min}} = 4.36$ (Ha0 filter) to $z_{\text{max}} = 4.65$ (Ha16 filter). The survey area is $35' \times 35'$. Effects of different flux limits in narrow bands were also taken into account. We show the incompleteness of our spectroscopic observations in Figure 9. In the figure, we plot the fraction of spectroscopically observed LAEs as a function of Ly$\alpha$-line flux. Such incompleteness was taken into account while calculating the luminosity function. To be conservative, if a source that was observed but not detected in our spectroscopic data, we assume it is not a Ly$\alpha$ galaxy.

The derived Ly$\alpha$ luminosity function of LAEs at $z \approx 4.5$ is plotted in Figure 10. Following Malhotra & Rhoads (2004), we fit the luminosity function with a Schechter function

$$\Phi(L) dL = \frac{\Phi^*}{L^*} \left( \frac{L}{L^*} \right)^\alpha \exp \left( -\frac{L}{L^*} \right) dL. \quad (1)$$

In fitting, we fixed the slope $\alpha = -1.5$ since our data are insufficient to have constrain $\alpha$. The best-fit parameters are $L^* = 6.3 \pm 1.5 \times 10^{42}$ erg s$^{-1}$ and $\Phi^* = 3.5 \pm 1.3 \times 10^{-4}$ Mpc$^{-3}$. Considering the still-substantial statistical uncertainties on the Schechter function parameters, plus systematic differences in the selection criteria used by different groups to identify different Ly$\alpha$ samples, the best-fitted $L^*$ and $\Phi^*$ are consistent with the range of values found in various surveys at $3 \lesssim z \lesssim 6.5$ (see the lower panel in Figure 10).

5. SUMMARY

We have presented the largest spectroscopic sample of $z \approx 4.5$ Ly$\alpha$-emitting galaxies yet studied. Examining the properties of this sample, we reach several conclusions.

1. Large equivalent width Ly$\alpha$ emitters, which we have earlier reported as a common feature of narrowband-selected samples (Malhotra & Rhoads 2002), are spectroscopically confirmed at the same rate as less spectacular line emitters. Thus, the high equivalent width sample is not dominated by noise spikes. Nor can the large equivalent widths be solely a byproduct of calculating the EW using the same broad band data employed in candidate selection, because our large EW subsample changes little when we calculate EW using an independent broad band image completely independent of object selection.

2. The C$\ IV$ 1549 Å line is (on average) $\lesssim 3.7\%$ of the Ly$\alpha$ line strength, placing an upper limit of $\lesssim 17\%$ on the AGN fraction in the Ly$\alpha$-selected sample. This limit is independent of the X-ray to Ly$\alpha$ ratio in AGNs and therefore complements earlier limits on the AGN fraction based on X-ray photometry.

3. The He$\ II$ 1640 Å line is $\lesssim 7\%$ of the Ly$\alpha$-line strength. This is the most stringent limit to date on the He$\ II$ emission from these objects. Though it does not strongly rule out many Population III models yet, it is nearly deep enough to do so and could be combined with a few similarly sized samples in future.

4. We present a new Ly$\alpha$ luminosity function, based on a large spectroscopic data set at $z \approx 4.5$. Allowing for differences in Ly$\alpha$ galaxy selection criteria among different research groups, this luminosity function remains broadly consistent with others over the range $3 \lesssim z \lesssim 6.5$.

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