Lyα Emitters at redshift $z \sim 4.5$ in the Extended CDF-S region: I, Lyα Luminosity Function

Zhen-Ya Zheng$^{1,2}$, Steven L. Finkelstein$^{3,7}$, Keely Finkelstein$^3$, Vithal Tilvi$^4$, James E. Rhoads$^2$, Sangeeta Malhotra$^2$, Jun-Xian Wang$^1$, Neal Miller$^5$, Pascal Hibon$^6$, Lifang Xia$^2$

ABSTRACT

We present a spectroscopically confirmed Lyman alpha emitter sample at $z \sim 4.5$ in the Extended Chandra Deep Field South region. Starting with spectra of 68 candidate Lyα emitters, we identified 46 $z \sim 4.5$ Lyα emitters based on single-line detections with no continuum emission blueward of the line, and 5 Lyman break galaxies. The Lyα confirmation rate is $\sim 70\%$ for candidates selected in our two narrowband filters, and the remaining candidates including 5 Lyman Break Galaxies and one strange multi emission line object. We did not find any significant CIV emission line or HeII emission line in the optical spectra even with the coadded optical spectra. A majority of the LAEs show asymmetric Lyα line profile, and the coadded Lyα line has wavelength-based asymmetry of $a_\lambda = 1.49^{+0.26}_{-0.13}$ and flux-based asymmetry of $a_f = 1.45^{+0.06}_{-0.07}$. Deep X-ray, radio and the optical spectral data are also used to constrain the AGN contribution in our sample, only one detection (not targeted in spectroscopic observation) was found at $z=4.5$ in both X-ray and radio, while the other objects show non-detection even with a stacking method. Finally, the Lyα luminosity function for our $z \sim 4.5$ sample is consistent with others published in the literature for the redshift range

$^1$Center for Astrophysics, University of Science and Technology of China, Hefei, Anhui 230026, China; zhengzy@mail.ustc.edu.cn.

$^2$School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287

$^3$Department of Astronomy, The University of Texas, Austin, TX 78712

$^4$Department of Physics, Texas A&M University, College Station, TX 77843

$^5$Department of Astronomy, University of Maryland, College Park, MD 20742

$^6$Gemini Observatory, La Serena, Chile

$^7$Hubble Fellow
of $3 < z < 6$, while the Ly$\alpha$ luminosity functions in our two separate narrowband filters show a $\sim 2\sigma$ difference. This difference is comparable to the differences among $z = 5.7$ and $z = 6.5$ Ly$\alpha$ luminosity functions reported by Ouchi et al. (2010), which are thought to be an implication of cosmic re-ionization.

Subject headings: galaxies: active — galaxies: high-redshift — galaxies:starburst

1. INTRODUCTION

Thanks to efficient wide field cameras, the number of star-forming galaxies known in the early universe has grown rapidly in the past decade. These high-redshift star-forming galaxies are selected mainly through two techniques, the dropout technique and Ly$\alpha$-line search technique. The former is known as the Lyman-break technique applied on the deep broadband images (e.g., Steidel et al. 1996), whereby high-redshift galaxies are identified via a flux discontinuity caused by Lyman limit absorption, and the latter is designed to search for the strong Ly$\alpha$ line from the narrowband images as the Ly$\alpha$ line redshifted to the windows of low night-sky emission (e.g., from $z = 2.1$ to $z = 7.7$, Cowie & Hu 1998, Guaita et al 2010, Gawiser et al. 2007, Rhoads et al. 2000, 2003, Ouchi et al. 2008, Wang et al. 2005, Dawson et al. 2004, 2007, Iye et al. 2006, Finkelstein et al. 2008, 2009b,c and more). The Narrowband surveys of high-redshift Ly$\alpha$ emitter (LAE) galaxies can reach a successful fraction of $\gtrsim 70\%$ (Dawson et al. 2007, Wang et al. 2009). Ly$\alpha$ searches at corresponding redshift can identify galaxies with strong Ly$\alpha$ line emission, which might be too faint to be detected by the Lyman-break technique.

Although Narrowband Surveys have found thousands of Ly$\alpha$ emitters from $z = 2.1$–6.96, fewer than one thousand of them have been spectroscopically confirmed. It is very interesting that the Ly$\alpha$ luminosity functions of LAEs do not evolve from redshift $z \sim 3$ to $z \sim 6.5$ (e.g., Malhotra & Rhoads 2004, Dawson et al. 2007, Wang et al. 2009, Ouchi et al. 2008, Ono et al. 2011). Optical spectra of LAEs typically show asymmetric Ly$\alpha$ line profiles (Rhoads et al. 2003). No CIV emission line (indicating of active galactic nuclei [AGN] activity) or HeII emission line (indicating of the first generation stars, as well as some kind of AGNs) was reported in the previous LAEs’ spectra (Dawson et al. 2007, Wang et al. 2009). Deep X-ray images are the most effective ways to find AGNs. Previous 170ks and 180ks Chandra X-ray exposure in the Large Area Lyman Alpha (LALA, Rhoads et al. 2000) survey did not find any X-ray individual or average detections at $z \sim 4.5$ (Malhotra et al. 2003, Wang et al. 2004). However, in the 250ks Extended Chandra Deep Field South (ECDFS) region, where exist the deepest X-ray field of 4Ms Chandra Deep Field South (CDF-S), we found one quasar from 112 LAE candidates at $z \sim 4.5$ (Zheng et al. 2010). Excluding that LAE-
AGN, the remaining did not show any detection even with stacking methods. At redshift 4 \(\leq z \leq 2\), more AGNs are found through deep X-ray surveys, but the AGN fraction is still <5% (Gawiser et al. 2007, Guaita et al. 2010, Ouchi et al. 2008). This is quite different compared with the \(z \sim 0.3\) LAEs detected through GALEX, where the AGN fraction is as high as 15%-40% (Finkelstein et al. 2009a, Scarlata et al. 2009, Cowie et al. 2010).

Here we report spectroscopic observations of \(z \sim 4.5\) Ly\(\alpha\) emitters in the 0.34 deg\(^2\) ECDFS region. This region has an extraordinary amount of complementary data, including high-resolution optical images as the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) from the *Hubble Space Telescope*, deep ground-based *UBVRIzJHK* photometry from MUSYC and EIS, mid- and far- IR observations from *Spitzer*, GOODS, EIS and MUSYC, deep radio data from VLA array (Miller et al. 2008, 2011), and deep X-ray data from *Chandra* (Giacconi et al. 2002; Alexander et al. 2003; Lehmer et al. 2005; Luo et al. 2008; Xue et al. 2011). Our candidates and spectroscopic targets are mainly from two narrowband images designed for \(z \sim 4.5\) LAE hunting by Finkelstein et al. (2009c). We present our photometric and spectroscopic observations in \(\S 2\), spectroscopic results in \(\S 3\), and discuss the AGN contamination fraction, the constraints on Population III stars, and the properties of luminosity functions in \(\S 4\). This paper (paper I) contains the main results of the spectroscopic surveys. Throughout this work, we assume a cosmology with \(H_0 = 71\) km s\(^{-1}\) Mpc\(^{-1}\) (Wright et al. 2006), \(\Omega_m = 0.27\) and \(\Omega_{\Lambda} = 0.73\). At redshift \(z = 4.5\), the age of the universe was 1.36 Gyr, with a scale of 6.7 kpc/" and redshift bin of \(\delta z = 0.03\) implies a comoving distance of 18.75 Mpc. Magnitudes are given in the AB system.

2. OBSERVATION

2.1. Candidate Selection through Narrowband Imaging

The LAE candidates were selected using narrowband imaging of the GOODS *Chandra Deep Field* South (CDF-S; RA 03:31:54.02, Dec -27:48:31.5, J2000) obtained at the Blanco 4m telescope at Cerro Tololo InterAmerican Observatory (CTIO) with the MOSAIC II camera. Three 80 Å wide narrowband filters were utilized to obtain deep narrowband images (2.75 hr of observation in NB656, Finkelstein et al. 2008; 5 hr in NB665 and 5.5 hr in NB673, Finkelstein et al. 2009c). The LAE candidates are selected in Finkelstein et al. (2009c), based on a 5 \(\sigma\) significance detection in the narrowband, a 4 \(\sigma\) significance narrowband flux excess over the R band, a factor of 2 ratio of narrowband flux to broadband flux density, and no more than 2 \(\sigma\) significant flux in the B-band. The first three criteria ensure a significant line detection, while the last criterion checks that it is at \(z > 4\). With these criteria, we have selected 4 candidates in NB656 (Finkelstein et al. 2008), 42 in NB665 and 85 in NB673 (11
candidates were selected in both NB665 and NB673, Finkelstein et al. 2009c. Candidates with GOODS B-band coverage were further examined in GOODS B-band image, and 3 candidates in NB665 and 5 candidates in NB673 with significant GOODS B-band detections were excluded (see the table). So finally we select 112 LAE candidates at $z \sim 4.5$.

2.2. Spectroscopic Observations

Our spectroscopic data were obtained using the IMACS (Dressler et al. 2006) short camera ($f/2$, with a 27.2 diameter field of view) on the 6.5 m Magellan I Baade Telescope in 2009 September 10-11 (through Steward Observatory time, PI Rhoads) with the 200 line/mm grism and 2009 November 11-12 (NOAO PID 2009B-0371, PI Finkelstein) with the 300 line/mm grism. The 200 line/mm grism has a $\lambda_{\text{blaze}} = 6600 \, \text{Å}$ and a resolution of 2.037 Å pixel$^{-1}$ with a range of 4000-10500 Å, and the 300 line/mm grism has a same $\lambda_{\text{blaze}} = 6700 \, \text{Å}$, and a resolution of 1.341 Å pixel$^{-1}$ with a range of 4000-9200 Å. Five multislit masks (see Table 2) were observed for 2.8-4.5 hr in 0.5 hr increments. The masks have slit widths of 0.8 arcsec. Each slit mask included approximately 20 candidate Ly$\alpha$ emitters (mixed in with roughly $\sim$150 (with 200 line/mm grism) or $\sim$50 (with 300 line/mm grism) other spectroscopic targets). Of these, 16 candidates were covered by more than one mask. In total we had targeted 64 LAE candidates.

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. The wavelength residuals in the calibration is about $\sim$2 pixels.

After 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.

To control for possible spatial shifts along the slits between individual exposures of a

---

1The NB656 candidates were selected only in the overlap area between the MOSAIC image and the GOODS CDF-S data, which is why only four objects were selected. The other two catalogs consist of all selected candidates over the overlap region between the MOSAIC image and the ESO Imaging Survey, which consists of a much larger area.

2http://obs.carnegiescience.edu/Code/cosmos/Cookbook.html
Table 1. Number of Candidate, Targeted and Confirmed Ly$\alpha$ Emitters at $z \sim 4.5$ in Each Narrow Band Filter in the CDF-S field.

| Filter       | Seeing | $\text{mag}_{\text{limit}}^a$ | Candidates$^b$ | Targeted$^c$ | Confirmed$^c$ |
|--------------|--------|-------------------------------|----------------|--------------|--------------|
| NB665 (Ha0)  | 0''.90 | 24.9                          | 4              | 3            | 3            |
| NB665 (Ha8)  | 0''.92 | 25.0                          | 33             | 17           | 11           |
| NB673 (Ha16) | 0''.91 | 25.2                          | 75             | 44           | 32           |

$^a$5-$\sigma$ limiting magnitude at corresponding narrowband.

$^b$11 LAE candidates were covered by both Ha8 and Ha16 filter, and we had divided them into corresponding narrowband (5 into NB665 candidates and 6 into NB673 candidates) due to their narrowband flux.

$^c$6 of 11 LAE candidates covered by both Ha8 and Ha16 filter were targeted, 3 were confirmed as NB665 LAEs and 3 were confirmed as NB673 LAEs, and the confirmation is consistent with the narrowband division.

Table 2. Number of Targeted and Confirmed Ly$\alpha$ Emitters at $z \sim 4.5$ in Each Mask in the CDF-S field.

| Mask | Grism (line/mm) | Exp. Time (ks) | Targeted | Confirmed |
|------|-----------------|----------------|-----------|-----------|
| 1    | 200             | 10.2           | 20        | 11        |
| 2    | 200             | 12.2           | 26        | 20        |
| 3    | 300             | 16.2           | 22        | 15        |
| 4    | 300             | 14.4           | 16        | 15        |
| 5    | 300             | 14.4           | 10        | 7         |
mask, we measured the trace locations of the 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.

3. SPECTROSCOPIC RESULTS

3.1. Line Identification

We identified 46 single emission lines as Lyα-emitting galaxies at $z \sim 4.5$, among our 64 LAE candidates. In the remaining 18 candidates, 1 is possible (NB673-27) due to its strange spectra, 3 lost by CCD gap (NB665-15) or contaminated by sky lines (NB665-32 and NB665-38) from nearby slits, 9 are undetected, and 5 show continuum breaks with little-to-no Lyα line. In this work, the fraction of spectroscopic confirmation is about 70%-80%, and the contamination fraction is about 14%-19%. We present a catalog of the 46 confirmed Lyα-emitting galaxies at $z \sim 4.5$ in CDF-S region in Table 3 and their redshift distribution is plotted in figure 3. There were 11 candidates detected in both NB665 and NB673 images, and 6 of 11 were targeted, and we had divided them into corresponding narrowband due to their narrowband flux. 3 were confirmed as NB665 LAEs and 3 were confirmed as NB673 LAEs, and the confirmation is consistent with the division (see figure 3). In Figure 1, we present narrowband stamps of all the candidates, targets and confirmed LAEs. Their Lyα flux distributions are plotted in Figure 2. It is well seen that all the targets with $f_{\text{Ly} \alpha} > 3.7 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ are confirmed as LAEs.

Beyond the multiple emission lines in the low-redshift interlopers, we may identify Lyα emission by its characteristically asymmetric morphology. Following Rhoads et al. (2003, 2004), we perform two measurements of the line asymmetry: the wavelength-based asymmetry defined as $a_{\lambda} = (\lambda_{10,r} - \lambda_p)/(\lambda_p - \lambda_{10,b})$, and the flux-based asymmetry defined as $a_f = (\int_{\lambda_{10,b}}^{\lambda_{10,r}} f_\lambda d\lambda)/(\int_{\lambda_p}^{\lambda_{10,b}} f_\lambda d\lambda)$, where the $\lambda_p$ is the wavelength of the emission-line peak, and the $\lambda_{10,b}$ and $\lambda_{10,r}$ are the wavelengths where the flux density equals 10% of the peak on the blue side and red side, respectively. In figure 4, we plot $a_{\lambda}$ versus $a_f$ for the 46 confirmed LAEs. The error bars on $a_{\lambda}$ and $a_f$ are estimated based on a large number of Monte-Carlo simulations, in which we added random noise to each data bin. There are 34 LAEs show both $a_{\lambda}$ and $a_f$ greater than 1, and only 2 LAEs show both $a_{\lambda} < 1$ and $a_f < 1$ even with their 1-$\sigma$ error. These two LAEs (NB665-14 and NB673-72) have extended 2-d spectra, so the asymmetry of their Lyα lines are hard to measure. We also notice that the asymmetry measured with the 300 line/mm grism show less dispersion than that measured with 200 line/mm grism, this is mainly due to the more exposure time observed with 300
Fig. 1.— Narrowband stamps (size: 10′′ x 10′′, 0.27″ per pixel) of all LAE candidates, including confirmed LAEs with red circles, un-confirmed candidates with blue circles, and un-targeted candidates without any marks. There are 7 objects marked as blue circles without red-dashed diagonal lines, except 673-27 which shows strange profile and is hard to judge, the other 6 objects show continuum with little-to-no Lyα emission line. All stamps are divided into 13 lines (line 2 is empty, and line 11, 12 have 27, 26 candidates, respectively), with a decrease bin of $\Delta \log_{10}(f_{Ly\alpha})$ of 0.07 dex for nearby two lines. It is well seen that the candidates with larger $f_{Ly\alpha}$ are more likely LAEs at $z \sim 4.5$. 

$Lg(f_{Ly\alpha})$

-15.89
-15.96
-16.03
-16.10
-16.17
-16.24
-16.31
-16.38
-16.45
-16.52
-16.59
-16.66
-16.73
-16.80
Fig. 2.— Lyα flux distributions of all candidates (empty histogram), IMACS targets (grey filled histogram) and confirmed Lyα emitters (blacked filled histogram). Candidates selected in different narrowbands (NB665 and NB673) are plotted in the middle and top panels. The 11 LAE candidates covered in both NB665 and NB673 are divided into corresponding narrowband based on their Lyα fluxes.
Fig. 3.— Narrowband filter transmission curves (low-right axis) and redshift distributions of confirmed LAEs (top-left axis). Redshift distributions confirmed with filters NB656, NB665, and NB673 (from left to right) show same colors as the filters’ transmission curves, Orange and light green filed histograms are confirmed candidates observed in both NB673 and NB665 filters. The NB656 candidates are selected with a much smaller area and shallower narrowband image compared with NB665 and NB673,
line/mm grism than with 200 line/mm grism, also due to the better spectral resolution for 300 line/mm grism than that for 200 line/mm grism.

3.2. Spectroscopic Calibration

We use one standard star UID1147 (Pirzkal et al. 2005) to calibrate the spectra. The comparison of Ly\(\alpha\) line fluxes integrated from spectroscopy and estimated from photometry is plotted in the figure. A large dispersion is seen in the flux-flux plot, and line flux from optical spectra with 10.2 ks exposure of grism-200 are systematic larger than that from photometric data, which might be due to the slit-loss of the standard star observation. In the following process we only take the line flux from photometric data.

There are 22 targets observed more than once. Four of them show no line but continuum and are excluded as LAEs. Two LAEs observed twice were confirmed with single frame’s spectra, since their another spectra were affected by CCD gap or bright star contamination. The redshift values estimated from the line peak of the 16 multi-frame confirmed LAEs show consistence within 1 pixel.

The four candidates show no line but continuum are all visible in the 2-d spectra of grism-300, while only two can be resolved in the grism-200 spectra. From table 2 we can see the first day observation with grism-200 show a relative low successful-fraction. This is mainly due to a lack of at least 2 ks exposure time compared with other frames.

3.3. The stacked Spectrum

We follow Wang et al. (2009) to stack the spectra of the confirmed Ly\(\alpha\) emitters in order to understand the nature of the line emitters. Excluding the spectra with very large background noise at the estimated line wavelengths, we stack 28 confirmed Ly\(\alpha\) emitters at \(z \sim 4.5\) with grism 300 line/mm observation (see Figure). We co-add the spectra in a variance-weighted method, and using a 2\(\sigma\) clipping algorithm (one iteration) to remove artificial features(e.g., sky line residuals, ccd edges, etc) in the co-addition of each spectrum.

The only visible line feature in the composite spectrum is the asymmetric Ly\(\alpha\) line (highlighted in the cutout of Figure). We obtained wavelength-based asymmetry of \(a_\lambda = 1.49^{+0.26}_{-0.13}\) and flux-based asymmetry of \(a_f = 1.45^{+0.06}_{-0.07}\), consistent with those expected from the asymmetric profile of high-redshift Ly\(\alpha\) emission line. The error bars on \(a_\lambda\) and \(a_f\) are estimated based on a large number of Monte-Carlo simulations, in which we added random noise to each data bin.
Fig. 4.— Plot of two measurements of the line asymmetry for 46 Lyα emitters (see text for definitions of $a_\lambda$ and $a_f$.) The orange triangles and red stars are LAEs confirmed with 10.2 ks exposure and 12.2 ks exposure with 200 line/mm grism observation, and the green diamonds and cyan squares are LAEs confirmed with 16.2 ks exposure and 14.4 ks exposure with 300 line/mm grism, respectively.
Fig. 5.— The Ly$\alpha$ photometry line flux compared with their spectroscopic Ly$\alpha$ line flux. The orange and red stars are LAEs confirmed with 10.2 ks exposure and 12.2 ks exposure with 200 line/mm grism observation, and the cyan and green diamonds are LAEs confirmed with 16.2 ks exposure and 14.4 ks exposure with 300 line/mm grism, respectively.
Fig. 6.— The co-add spectrum of selected 28 LAEs with grism 300 line/mm spectra. The Lyα line is highlighted in the cutout, and the co-add spectrum at estimated position of CIV, HeII and Lyman series are also plotted. The errors of the co-add spectrum is plotted in red dotted line.
There is no possible He II $\lambda$ 1640 Å or CIV $\lambda$1549 Å emission line near the expected wavelength (assuming the line width same to the Ly$\alpha$ line width). At the expected wavelengths of NV $\lambda$ 1240 Å , the significance is about $\sim$1 $\sigma$. So neither line was detected, with upper limits $< 2\sigma$ in all the cases. We determined the 2$\sigma$ upper limits under the assumption that the undetected line has a physical width equal to the observed Ly$\alpha$ width. The resulting limits on the line ratios are $f$(NV$\lambda$1240)$/f$(Ly-$\alpha$) $< 7.2\%$, $f$(CIV$\lambda$1549)$/f$(Ly-$\alpha$) $< 9.2\%$ and $f$(HeII$\lambda$1640)$/f$(Ly-$\alpha$) $< 6.5\%$. Our constrain on CIV is weaker than the previous work by Dawson et al. (<8\%; Dawson et al. 2004) based on 11 LAEs spectra with Keck and Wang et al. (<3.7\%; Wang et al. 2009) based on 110 LAEs spectra with IMACS, while the constrain on HeII is stronger than Dawson et al. (<13\%) and comparable to Wang et al. (<7.4\%).

4. DISCUSSION

4.1. AGN fraction and Unobscured Star Formation Rate

The X-ray analysis on this sample has been done by Zheng et al. (2010) with the old 2Ms CDFS data. We found one detection in ECDFS region, which has been spectroscopically confirmed by Treister et al. (2009) as a type 1 quasar at $z = 4.48$. X-ray stacking of the remaining sources shows a marginal detection (2.4$\sigma$), while spectroscopic data show that about half of the signal was from one LBG and one possible LAE (NB673-27). Excluding the two, we estimated a constraint (3$\sigma$) on the average X-ray luminosity of $L_{2-8\text{keV,rest}} < 2.4 \times 10^{42}$ erg s$^{-1}$ (Zheng et al. 2010). With the 4 Ms CDF-S data, we can decrease the average X-ray luminosity to $L_{2-8\text{keV,rest}} < 1.6 \times 10^{42}$ erg s$^{-1}$. With the ratio of Ly$\alpha$ to X-ray fluxes for typical AGNs, we can estimate that fewer than 2.1\% (4.2\%) of our LAEs could be high redshift type 1 (type 2) AGNs, and those hidden AGNs likely show low rest frame equivalent widths.

We also check the AGN properties (e.g, the broad emission lines or high ionized emission line such as CIV) in the spectra of our confirmed LAEs. No AGN lines have been identified in this work (Note that we did not target the 5 brightest LAEs including the quasar). We follow Dawson et al. (2007) and Wang et al. (2009) to use the line ratio of CIV and Ly$\alpha$ from the composite optical spectra to constrain the upper limit of AGN contamination fraction. Wang et al. (2009) showed that the CIV line flux is invisible even with stacking 110 Ly$\alpha$ emitters at $z \sim 4.5$. They can only give a upper limit of the CIV to Ly$\alpha$ line ratio of $< 3.7\%$ (2$\sigma$). Compared with the typical ratio of CIV to Ly$\alpha$ line in type II AGNs of 22\% (Ferland & Osterbrock 1986), the AGN contribution to LAEs is $\leq 3.7/22 = 17\%$. In this work, we have presented the composite spectra of 28 Ly$\alpha$ emitters at $z \sim 4.5$ in Section 3.4.
The upper limit of our CIV to Ly$\alpha$ line ratio is $<12.7\%\ (2\sigma)$, much weaker compared with the constraint of Wang et al. (2009).

Deep radio data is also an independent method to check the existence of AGNs. In ECDFS field, there exists deep radio data taken with the VLA array and covered the entire ECDFS field to a typical sensitivity of 7.2 $\mu$Jy per 2.8'' × 1.6'' beam (Miller et al. 2008, 2011). The radio catalogue from Miller et al. was searched with a match radius of 3'' with our LAE candidates and two objects were found. One object (J033127.2-274247, with a separation of $<1''$) is the X-ray detected and spectroscopically confirmed $z=4.48$ quasar. The other one (NB673.21) with separations of 2.4'' to radio detections, is contaminated by other nearby sources within 3'' in their optical B-band image. So the X-ray detected $z = 4.48$ quasar also shows significant radio emission. The radio stacking of the remaining 111 LAE candidates reveal no-detection, and we get down to 0.67 uJy rms ($\sim 7.5$/sqrt(110)). Since AGNs can be divided into radio-load and radio-quiet AGNs, and we don’t know the relative number of radio-loud AGN and their characteristic radio luminosity, it is impossible to constrain the AGN fraction from the radio stacking results.

Compared to AGNs, the star-formation activity in star-forming galaxies also contribute X-ray and radio emissions, and the X-ray and radio emission in star-forming galaxies are unobscured by dust (Zheng et al. 2011). Although the X-ray and radio radiation from galaxies are much fainter than that from AGNs, the number density of galaxies is significantly larger than that of AGNs. Xue et al. (2011) pointed out that in the 4Ms CDFS region, the X-ray radiation from galaxies begin to dominate the faint flux end in the log($N$) − log($S$) plot. If the X-ray radiation is all due to star formation (Ranalli et al. 2003), our X-ray average flux would correspond to a 3$\sigma$ upper limit of unobscured star-formation rate (SFR) $<320\ M_\odot\ yr^{-1}$. If the radio fluxes are converted into star formation rate using the conversion rate of Yun et al. (2001), the rms sensitivity of the radio map corresponds to upper limit of SFR $\sim1700\ M_\odot/yr$ at $z\sim4.5$. The radio stacking of the remaining 111 LAE candidates can be translates to a 3-$\sigma$ upper limit of SFR $\sim150M_\odot/yr$ at $z\sim4.5$. The average SFR from the Ly$\alpha$ emission line (with the relation from Kennicutt 1998) is about $5\ M_\odot\ yr^{-1}$. If we assume that the SFR from X-ray or radio is consistent with the intrinsic SFR, the ratio of SFRs from observed Ly$\alpha$ and from upper limits of X-ray or radio can be used to constrain the Ly$\alpha$ escape fraction, which is $f_{esc}(Ly\alpha) > 1.6-3.3\%$ for $z \sim 4.5$ LAEs at 99% confidence level.
4.2. Population III stars

Population III stars (or Pop III stars) are thought to have very strong HeII emission (HeII $\lambda$ 1640 line, the Balmer $\alpha$ transition of singly ionized helium). In this work, we get the upper limit of HeII-to-Ly$\alpha$ ratio of $< 6.5\%$, comparable with $< 7.4\%$ of Wang et al. 2009. Our upper limit can be converted to $\log(Q_{He^+}/Q_H) < 1.46$, where $Q_{He^+}$ and $Q_H$ are ionizing fluxes for He+ and H, respectively (Schaerer 2003). Wang et al. had pointed out that it is not easy to rule out the existence of Pop III stars in LAEs at $z \approx 4.5$, since the constraints only reach the maximum predicted values for metal-free populations with IMFs including very massive stars (Schaerer 2003), and the fraction of Pop III galaxies among LAE samples at $z \sim 4.5$ could be very small (e.g., Scannapieco et al. 2003). Recently, McLinden et al. (2010) reported the discovery of outflows in two LAEs at $z \sim 3.1$, in which the Ly$\alpha$ emission had a slightly higher redshift (outflow velocity $\sim 300$ km/s) than the rest-frame optical [OIII] emission. In the co-add process above, we fix the Ly$\alpha$ peak as the systemic redshift for each LAEs. If there exists outflows, there should be about $\lesssim 1.5$ Å blue-shift for the HeII line in the rest frame. So the existence of outflows will increase the uncertainty of HeII emission in our stacked spectrum. If we assume the line width as 5 Å in the rest frame, there is still no detection, and the upper limit of HeII-to-Ly$\alpha$ ratio increases to $< 8.4\%$.

4.3. Ly$\alpha$ Luminosity Function

We now present the Ly$\alpha$ luminosity function (LF) based on our spectroscopically confirmed LAE samples at $z \sim 4.5$ in ECDFS. We choose a modified version of the $V/V_{max}$ method in Dawson et al. (2007). Dawson et al. (2007) had considered two types of incompleteness in Ly$\alpha$ LF measurement: the target incompleteness (i.e., not all candidates were targeted) and the spectroscopic sensitivity depth. The target incompleteness is the ratio of all candidates’ number to targets’ number at relative Ly$\alpha$ flux bins (see figure 7). We ignore the spectroscopic sensitivity incompleteness, as our spectroscopic depth are much more deeper than the photometry depth. We also take into account the narrowband incompleteness in our Ly$\alpha$ LF calculation. The narrowband incompleteness was estimated following Hibon et al. (2010): we added 200 artificial star-like objects (LAEs are point sources in these NB images) per bin of 0.1 mag on the NB673 image, then ran SExtractor on this image for object detection, and got a direct measure of the narrowband incompleteness by counting the number of artificial stars detected in each magnitude bin.

The comoving volume $V_{max}$ for each confirmed LAE was calculated, here $V_{max}$ was the volume where the source could be selected by our survey. The survey area is 34’$\times$ 33’ from $z = 4.44$ to $z = 4.56$ (NB665 and NB673 filters) and 160 square arcmins from $z = 4.36$ to $z = $
Fig. 7.— Distribution of the Lyα fluxes for all candidate LAEs (empty histogram), and those targeted (light grey histogram) and spectroscopically confirmed (dark grey histogram) LAEs. The dash-dotted line shows the spectroscopic successful fraction (i.e., the ratio of the confirmed number to the targeted number per flux bin).
Fig. 8.— Differential Lyα Luminosity Function for our $z = 4.5$ sample, computed using the $V/V_{\text{max}}$ method. The error bars are the $1\sigma$ statistical uncertainties given by the root variance of the $1/V_{\text{max}}$. The black solid histogram gives the number of individual sources contributing to each luminosity bin. The dotted curve shows the best-fitting model for Wang et al. 2009 with a fixed faint-end slope $\alpha = -1.5$. The yellow, green and blue points are presented for narrowband NB656, NB665 and NB673 data, respectively. The vertical color lines show the detection limits at corresponding narrowband.
Fig. 9.— Contour plot of the fitting parameters $L^*$ and $\Phi^*$ on the differential Ly$\alpha$ Luminosity Function for our sample. Here red, blue and green contours are fitting results on our all, NB673 only, and NB665 only samples, with confidence level of 68% and 90% ($\Delta \chi^2 = 2.3$ and 4.6). We compare $L^*$ and $\Phi^*$ from various surveys at different redshifts. W09: Wang et al. (2009); D07: Dawson et al. (2007); O08: Ouchi et al. (2008); S06: Shimasaku et al. (2006); K11: Kashikawa et al. (2011); H11: Hu et al. 2011; O10: Ouchi et al. 2010. Best-fitting parameters obtained by fixing $\alpha = -1.5$ are taken for all surveys except for D07 ($\alpha = -1.6$).
4.43. The target incompleteness and narrowband incompleteness were taken into account.

The derived Ly$\alpha$ luminosity function of LAEs at $z \sim 4.5$ in ECDFS is plotted in Figure 8. Following Malhotra & Rhoads (2004), we fit the luminosity function with a Schechter function

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

In fitting, we choose to fix the faint-end slope $\alpha = -1.5$ since our data are not deep enough to constrain the Ly$\alpha$ LF at the faint end. The best-fit parameters are $\log(L^*) = 42.86 \pm 0.10$ and $\log(\Phi^*) = -3.40 \pm 0.14$ ($\chi^2/dof = 13.2/7$). When applying the same method of the Ly$\alpha$ LF measurements on the two narrowband images, NB665 and NB673, respectively, the best-fit parameters are $\log(L^*) = 42.80 \pm 0.21$ and $\log(\Phi^*) = -3.42 \pm 0.33$ ($\chi^2/dof = 0.6/3$) for NB665 data, and $\log(L^*) = 42.87 \pm 0.11$ and $\log(\Phi^*) = -3.21 \pm 0.15$ ($\chi^2/dof = 30.3/7$) for NB673 data. We plot the contour of the fitted $L^*$ and $\Phi^*$ in Figure 9, which show some kind of coherence. The contour plot of fitting parameters on NB665 and NB673 differ at a confidence level $P > 90\%$, implying a $\sim 2\sigma$ variance on $L^*$ and $\Phi^*$. Compared to previous work, the best-fitted $L^*$ and $\Phi^*$ are consistent with the range of values found in various surveys at $3 \leq z \leq 6.5$ (see Figure 9).

Ouchi et al. (2010) had found a $\sim 2\sigma$ decrease on $L^*$ and $\Phi^*$ from Ly$\alpha$ LF at $z = 5.7$ to $z = 6.6$ in the 1 deg$^2$ Subaru Deep Field (SDF). They thought that their field is large enough to ignore the cosmic variance, so the $\sim 2\sigma$ difference is probable due to the neutral hydrogen during the universe reionization. We found that their $L^*$ and $\Phi^*$ from Ly$\alpha$ LF at $z= 5.7$ and $z = 6.5$ are located in the 1-$\sigma$ contour area of our $L^*$ and $\Phi^*$ from NB673 and NB665, respectively. And their comoving volume of $8 \times 10^5$ Mpc$^{-3}$ and $1 \times 10^6$ Mpc$^{-3}$ at $z = 5.7$ and $z = 6.5$ in the SDF, respectively, are about 3$\sim$4 times larger than our volume of $2.3 \times 10^5$ Mpc$^{-3}$ per narrowband image at $z = 4.5$. So the $2\sigma$ difference of Ly$\alpha$ LF at $z = 5.7$ and $z = 6.5$ may be also due to the cosmic variance.

5. CONCLUSION

We present a spectroscopically confirmed LAEs at $z \sim 4.5$ in the ECDFS region. This sample is from two contiguous narrowband images (NB665 and NB673), and a much smaller region of a shallower narrowband image (NB656). The main scientific results are summarized as below:

- We identify 46 $z \sim 4.5$ LAEs, 5 LBGs and 1 [OIII] emitters from our targeted 68 LAE candidates. The Ly$\alpha$ confirmation fraction is about 70$\%$$-$80$\%$, and the contamina-
tion fraction is about 14%-19%. All targets with $f_{\text{Ly} \alpha} > 3.7 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ are confirmed.

- We do not find any CIV or HeII lines over 2-$\sigma$ significance in the spectra of the confirmed LAEs, even with stacking methods. 3

- There is one quasar previously confirmed as type 1 AGN at $z = 4.48$ in our sample, which is also detected with the deep X-ray and radio observations. The remaining LAEs are not detected in X-ray or radio even with stacking methods, and the stacked upper limits in radio and X-ray can be converted to average SFR as $\text{SFR}_{\text{Radio}} < 150$ M$_{\odot}$ and $\text{SFR}_{X} < 200$ M$_{\odot}$, respectively.

- The upper limit of HeII to Ly$\alpha$ line ratio in our coadded spectrum can be converted to $Q_{\text{He}^+}/Q_{H^+} < -1.46$. However, we cannot exclude the existence of Pop III stars, and the existence of outflows will increase the uncertainty in determining the real position of HeII line.

- The Ly$\alpha$ luminosity functions in our sample are consistent with the previous surveys at $3 \leq z \leq 6.5$, as $\log(L^*) = 42.86 \pm 0.10$ and $\log(\Phi^*) = -3.40 \pm 0.14$ with $\chi^2/\text{dof} = 13.2/7$. However, the Ly$\alpha$ LF differs at > 90% confidence level in the individual narrowband images, implying the existence of cosmic variance. This difference is comparable to the Ly$\alpha$ LF evolution at $z = 5.7$ and 6.5.

We would like to thank the support of NSF grant AST-0808165 and NOAO TSIP program. The work of JXW is supported by National Basic Research Program of China (973 program, Grant No. 2007CB815404), and Chinese National Science Foundation (Grant No. 10825312, 10773010).
Table 3. Spectroscopically Confirmed Lyα Emitters at z~ 4.5 in the CDF-S field

| Obj     | Ra     | Dec    | Redshift | Mask | $F_{Ly\alpha}^a$ | EW$_{rest}^b$ (Å) | Spec.$^c$ grade | FWHM$_d$ (Å) | $a_\lambda$ | $a_{flux}$ |
|---------|--------|--------|----------|------|-----------------|----------------|----------------|-------------|-------------|------------|
| CH8-1–665-24 | 53.20420 | -27.81722 | 4.431 | 4 | 2.66±0.54 | 149.1$^{+3.64}_{-3.61}$ | 1 | 11.0±0.7 | 0.9±0.0 | 0.7±0.0 |
| CH8-2–665-26 | 53.22515 | -27.83356 | 4.431 | 3 | 1.98±0.65 | 56.3$^{+11.0}_{-11.0}$ | 1 | 12.3±2.8 | 1.3±0.5 | 1.4±0.2 |
| CHa-2–656-2 | 53.16571 | -27.85415 | 4.411 | 3 | 3.93±0.40 | >10000 | 1 | 11.1±0.4 | 2.2±0.5 | 0.9±0.1 |
| CHa-3–656-3 | 53.24325 | -27.89433 | 4.391 | 4 | 4.15±0.42 | >10000 | 1 | 10.1±0.9 | 1.5±0.4 | 1.3±0.2 |
| CHa-4–656-4 | 53.20102 | -27.86025 | 4.364 | 3 | 3.11±0.34 | 124.6$^{+29.5}_{-27.5}$ | 2 | 8.3±1.3 | 3.0±3.0 | 3.3±1.0 |
| CS2-1–673-35 | 53.03973 | -27.77323 | 4.512 | 3 | 2.42±0.63 | >10000 | 1 | 5.4±1.8 | 1.1±1.5 | 0.9±1.2 |
| CS2-2-673-36 | 53.06737 | -27.81233 | 4.542 | 3 | 3.46±0.62 | 189.7$^{+46.8}_{-46.8}$ | 1 | 10.0±0.4 | 1.0±0.4 | 0.7±0.1 |
| CS2-3–673-39 | 53.10224 | -27.79322 | 4.500 | 3 | 2.47±0.47 | 166.6$^{+42.9}_{-42.9}$ | 1 | 9.4±0.9 | 1.5±0.4 | 1.5±0.1 |
| CS2-4–673-42 | 53.11923 | -27.93295 | 4.527 | 3 | 2.27±0.37 | 111.4$^{+11.3}_{-11.7}$ | 1 | 7.4±1.2 | 2.7±0.4 | 1.3±0.3 |
| CS2-5–673-44 | 53.13542 | -27.72973 | 4.500 | 3 | 2.57±0.37 | 42.4$^{+5.3}_{-5.5}$ | 1 | 6.4±1.1 | 0.9±0.7 | 1.0±1.6 |
| CS2-8–673-52 | 53.16770 | -27.88614 | 4.500 | 4 | 2.05±0.36 | 703.0$^{+497.0}_{-262.0}$ | 2 | 11.2±1.5 | 1.2±1.3 | 1.3±1.2 |
| 673-5–665-11 | 52.90865 | -27.86655 | 4.505 | 5 | 5.80±0.58 | >10000 | 1 | 9.3±0.7 | 1.1±1.0 | 1.3±1.0 |
| 673-16–665-13 | 52.94718 | -27.89357 | 4.507 | 4 | 5.87±0.59 | 37.6$^{+9.0}_{-9.0}$ | 1 | 10.1±3.1 | 1.6±0.5 | 0.9±1.3 |
| 665-31 | 53.29958 | -27.91411 | 4.458 | 5 | 2.86±0.86 | >10000 | 1 | 15.9±1.7 | 2.5±0.8 | 3.0±1.0 |
| 665-34 | 53.32557 | -27.79347 | 4.480 | 3 | 3.28±0.71 | 48.1$^{+13.7}_{-13.7}$ | 1 | 10.3±0.7 | 0.8±1.1 | 1.3±0.2 |
| 665-39 | 53.35505 | -27.81548 | 4.456 | 3 | 5.33±0.72 | >10000 | 1 | 10.0±0.5 | 1.2±0.0 | 1.3±0.3 |
| 673-3–665-8 | 52.89650 | -27.86801 | 4.505 | 5 | 4.73±0.58 | 85.2$^{+10.3}_{-10.3}$ | 1 | 10.3±0.4 | 1.0±0.3 | 0.7±0.0 |
| 673-10 | 52.92503 | -27.81979 | 4.515 | 2 | 2.28±0.33 | >10000 | 2 | 9.0±1.1 | 2.5±0.0 | 1.5±0.2 |
| 673-11 | 52.92717 | -27.76996 | 4.520 | 3 | 3.11±0.62 | 36.4$^{+8.9}_{-9.1}$ | 1 | 12.4±1.1 | 2.0±0.0 | 1.0±0.1 |
| 673-13 | 52.93424 | -27.78658 | 4.520 | 5 | 4.17±0.38 | 21.8$^{+5.5}_{-5.5}$ | 1 | 12.2±2.9 | 1.7±0.0 | 0.9±0.1 |
| 673-24 | 52.97977 | -27.71705 | 4.532 | 3 | 2.02±0.41 | 206.0$^{+19.2}_{-18.9}$ | 2 | 7.3±2.7 | 1.3±0.5 | 1.0±0.3 |
| 673-28 | 53.00088 | -27.82576 | 4.512 | 4 | 1.98±0.34 | 65.8$^{+18.8}_{-18.3}$ | 1 | 8.8±0.5 | 0.9±0.4 | 1.1±0.3 |
| 673-37 | 53.08812 | -27.99047 | 4.525 | 3 | 1.97±0.62 | >10000 | 1 | 9.6±1.1 | 1.1±0.4 | 1.4±0.2 |
| 673-60 | 53.22586 | -27.98279 | 4.500 | 4 | 2.98±0.64 | 728.4$^{+317.8}_{-210.7}$ | 1 | 14.4±1.3 | 1.0±0.0 | 1.1±0.2 |
| 673-61 | 53.23241 | -27.96140 | 4.517 | 5 | 3.71±0.64 | >10000 | 1 | 8.3±1.0 | 3.2±1.2 | 1.6±0.4 |
| 673-66 | 53.33446 | -27.94221 | 4.515 | 4 | 2.54±0.65 | 35.0$^{+4.5}_{-4.7}$ | 1 | 9.9±1.1 | 2.1±0.7 | 1.6±0.3 |
Table 3—Continued

| RA     | DEC    | z        | Te (K)  | N   |EW (Å)  | EWRA (Å)  | Nspec | jk  | L (erg s⁻¹ cm⁻²) |
|--------|--------|----------|---------|-----|--------|------------|-------|-----|-----------------|
| 673-69 | 53.34030 | -27.94488 | 4.515   | 3   | 2.95±0.63 | 33.5±7.8    | 1     | 10.3±3.7 | 0.9±0.3     | 1.1±0.3  |
| 673-74 | 53.35577 | -27.79243 | 4.525   | 4   | 3.56±0.36 | 27.0±1.2    | 1     | 8.5±0.9  | 0.9±1.0     | 1.0±0.4  |
| 673-7  | 52.91647 | -27.87911 | 4.500   | 4   | 2.75±0.33 | 3130.6±2173.5| 1    | 11.5±1.9 | 1.2±0.0     | 0.9±0.2  |
| CS2-7-673-51 | 53.16261 | -27.80360 | 4.528   | 2   | 2.56±0.40 | 237.3±112.1| 1     | 12.4±0.7  | 1.4±0.0     | 1.2±0.1  |

673-10  52.90203 -27.71201 4.475  2  2.87±0.42 >10000  2  7.5±0.4  1.4±0.7  1.0±0.2
673-14  52.99119 -28.00636 4.484  2  3.09±0.58 >10000  1  9.0±0.3  0.6±0.0  1.2±0.1
673-9   52.90171 -27.75258 4.454  2  5.42±0.68 20.4±5.2   | 1  10.9±0.1 | 1.3±0.4 | 1.2±0.0 |
673-12  52.93412 -27.99292 4.500  2  2.50±0.50 >10000  2  10.3±0.2  0.8±0.0  1.1±0.1
673-14  52.93851 -27.69510 4.505  2  2.22±0.61 >10000  3  8.6±0.2  0.9±0.0  1.1±0.2
673-17  52.94978 -27.81017 4.516  2  6.48±0.61 69.3±15.8  | 1  10.6±2.0 | 1.6±0.0 | 1.0±0.0 |
673-21  52.96696 -27.72211 4.518  2  7.17±0.61 85.2±9.8   | 1  10.0±1.3 | 1.5±0.0 | 1.1±0.1 |
673-22  52.97540 -27.69971 4.493  2  2.07±0.35 109.2±34.2  | 1  8.4±0.3  | 0.9±0.3 | 0.8±0.0  |
673-4   52.89806 -27.67007 4.521  2  2.09±0.63 86.7±22.9   | 3  5.4±0.3  | 0.7±0.4 | 1.0±0.2  |
| CS2-6-673-46 | 53.13893 | -27.69562 | 4.528 | 2 | 1.93±0.61 | 134.1±23.1| 1    | 8.6±1.2  | 1.7±0.6     | 0.9±0.1  |
673-8   52.91662 -27.75173 4.508  2  4.05±0.63 >10000  1  10.3±1.9 | 0.7±0.2     | 1.1±0.0  |
665-9   53.23400 -27.56236 4.452  1  3.34±0.45 >10000  3  7.2±0.4  | 1.2±0.5     | 0.8±0.1  |
665-30  53.28141 -27.56315 4.480  1  6.09±0.71 157.0±55.8  | 2  12.2±0.2 | 0.6±0.9 | 1.0±0.7  |
665-40  53.36504 -27.75002 4.482  1  4.20±0.66 132.7±17.7   | 1  10.5±0.3 | 1.0±1.0 | 1.3±0.2  |
673-54  53.17277 -27.64484 4.549  1  3.90±0.64 >10000  1  10.1±0.9  | 1.5±0.0     | 1.3±0.1  |
673-72  53.34993 -27.83262 4.516  1  4.48±0.59 286.2±148.3  | 1  12.2±0.4 | 0.7±0.1 | 0.7±0.1  |

a The Lyα line flux is calculated from the narrowband and broadband photometry in the unit of 10⁻¹⁷ erg s⁻¹ cm⁻².

b LAEs with non-detection in the R-band are marked with EW > 10000Å.

c LAEs confirmed from their spectra are assigned grades, here 1 means very good quality, 2 means not
very significant, and 3 means low s/n.

\( ^d \) The Ly\( \alpha \) line widths are directly measured from their spectra and not corrected for the instrument profiles.
REFERENCES

Alexander, D. et al. 2003, AJ, 126, 539
Cowie, L. L. & Hu, E., 1998, AJ, 115, 1319
Cowie, L. L. Barger, A. J. & Hu, E. 2010, ApJ, 711, 928
Dawson, S., Rhoads, J.E., Malhotra, S., et al. 2004, ApJ, 617, 707
Dawson, S., Rhoads, J.E., Malhotra, S., et al. 2007, ApJ, 671, 1227
Finkelstein, S. L., Cohen, S. H., Malhotra, S., Rhoads, J. E., et al. 2009a, ApJ, 703, 162
Finkelstein, S. L., Cohen, S. H., Malhotra, S., & Rhoads, J. E. 2009b, ApJ, 700, 276
Finkelstein, S. L., Rhoads, J. E., Malhotra, S., & Grogin, N. 2009c, ApJ, 691, 465
Finkelstein, S. L., Rhoads, J. E., Malhotra, S., Grogin, N., & Wang, J. X. 2008, ApJ, 678, 655
Gawiser, E., Francke, H., Lai, K., et al., 2007, ApJ, 671, 278
Giacconi, R. et al. 2002, ApJS, 139, 369
Giavalisco, M. et al. 2004, ApJL, 600, 93
Gronwall, C. et al. 2007, ApJ, 667, 79
Guaita, L. et al. 2010, ApJ, 714, 255
Hibon, P., Cuby, J. -G., et al. 2010, A&A, 515, 97
Iye, M., Ota, K, Kashikawa, N., et al. 2006, Nature, 443, 14
Kashikawa, N., Shimasaku, K. et al. 2011, astro-ph/1104.2330
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Lehmer, B.D., Brandt, W. N., et al. 2005, ApJS, 161, 21
Luo, B., Bauer, F. E., Brandt,W. N., et al. 2008, ApJS, 179, 19
Malhotra, S., Wang, J, Rhoads, J. E., et al. 2003, ApJ, 585, L25
Malhotra, S., Rhoads, J. 2002, ApJL, 565, 71
Malhotra, S., Rhoads, J. 2004, ApJL, 617, 5
McInerney, E., Finkelstein, S. L., Rhoads, J. E., Malhotra, S., et al. 2011, ApJ, 730, 136
Miller, N., et al. 2008, ApJS, 179, 114
Miller, N., et al. 2011, in prep.
Nilsson, K. K., Tapken, C., et al. 2009, A&A, 498, 13
Ono, Y., et al. 2010, ApJ, 724, 1524
Ouchi, M., Shimasaku, K., et al. 2008, ApJS, 176, 301
Ouchi, M. Shimasaku, K. et al. 2010, ApJ, 723, 869
Partridge, R. B. & Peebles, P. J. E. 1967, ApJ, 148, 377
Pirzkal, N., Sahu, K. C., et al. 2005, ApJ, 622, 319
Ranalli, P., Comastri, A., & Setti, G. 2003, A&A, 399, 39
Rhoads, J. et al. 2000, ApJL, 545, 85
Rhoads, J. et al. 2003, ApJ, 125, 1006
Rhoads, J. et al. 2009, ApJ, 697, 942
Scannapiecco, E., Schneider, R., & Ferrara, A. 2003, ApJ, 589, 35
Scarlata, C. et al. 2009, ApJL, 704, 98
Schaerer, D. 2003, A&A, 397, 527
Steidel, C. C., et al. 1996, ApJL, 462, 17
Treister, E., Virani, S., Gawiser, E., et al. 2009, ApJ, 693, 1713
Wang, J. X., Rhoads, J. E., Malhotra, S., et al. 2004, ApJL, 608, 21
Wang, J. X., Malhotra, S., & Rhoads, J. E., 2005, ApJL, 622, 77
Wang, J. X., Zheng, Z. Y., Malhotra, S., et al. 2007, ApJ, 669, 765
Xue, Y. Q. et al. 2011, ApJS, 195, 10
Zheng, Z. Y., Wang, J. X., Finkelstein, S. L., et al. 2010, ApJ, 718, 52
Zheng, Z. Y., Malhotra, S., Wang, J. X., Rhoads, J., Finkelstein, S. L. et al. 2011, astroph/1106.2811