Lyα equivalent width distribution of Lyα emitting galaxies at redshift $z \sim 4.5$

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ABSTRACT

Lyα line equivalent widths (EWs) provide important clues to the physical nature of high-redshift Lyman alpha emitters (LAEs). However, measuring the Lyα EW distribution of high-$z$ narrow-band-selected LAEs can be hard because many sources do not have well-measured broad-band photometry. We investigate the possible biases in measuring the intrinsic Lyα EW distribution for a LAE sample at $z \sim 4.5$ in the Extended Chandra Deep Field South (ECDFS). We show that our source selection procedures produce only weak Eddington type bias in both the intrinsic Lyα luminosity function and the Lyα EW distribution. However, the observed EW distribution is severely biased if one only considers LAEs with detections in the continuum. Taking the broad-band non-detections into account requires fitting the distribution of the broad-band-to-narrow-band ratio, which then gives a larger EW distribution scale length. Assuming an exponential form of the intrinsic Lyα EW distribution \(dN/dEW = N \exp^{-EW/W_0}\), we obtain \(W_0 = 167^{+44}_{-19}\) Å (uncorrected for IGM absorption of Lyα), and \(\sigma_g = 160^{+43}_{-12}\) Å for a Gaussian EW distribution). We discuss the likely range of IGM absorption effects in light of recent measurements of Lyα line profiles and velocity offsets. Our data are consistent with Lyα EW being independent of UV luminosity (i.e. we do not see evidence for the ‘Ando’ effect). Our simulations also imply that broad-band images should be 0.5–1 mag deeper than narrow-band images for an effective and reasonably complete LAE survey. Comparing with consistent measurements at other redshifts, we see a strong evolution in Lyα EW distribution with redshift which goes as a power-law form of \(W_0 \propto (1 + z)^{\xi}\), with \(\xi = 1.1 \pm 0.1\) (0.6 ± 0.1) if no IGM corrections are applied to the Lyα line; or \(\xi = 1.7 \pm 0.1\) (1.2 ± 0.1) after applying a maximal IGM–absorption correction to Lyα line for an exponential (a Gaussian) EW distribution from \(z = 0.3\) to 6.5.

Key words: galaxies: active – galaxies: high-redshift – galaxies: starburst.

1 INTRODUCTION

Lyman alpha emission (LAEs) line galaxies are one of two main classes of high-redshift star-forming galaxies selected by rest UV emission (the other class being Lyman Break Galaxies). With the recombination of hydrogen in the ambient interstellar medium (ISM), the ionizing radiation from young stars in galaxies generates prominent Lyα emission. Selected through a significant brightness excess in a narrow-band image (where the Lyα line is located) over a broad-band image (which measures UV continuum), LAEs are typically younger, less massive and less dusty than LBGs (Gawiser et al. 2007; Pirzkal et al. 2007; Finkelstein et al. 2009a; Guaita et al. 2011). The measurement of the Lyα line relative to the UV continuum level is defined as the equivalent width (EW = \(F_{\text{Lyα}}/f_{\text{cont}}\), where \(F_{\text{Lyα}}\) is the Lyα line flux, and \(f_{\text{cont}}\) is the UV continuum flux density). Assuming a typical star formation history and initial mass function, dust-free galaxies with active star formation would have Lyα EWs of 50–200 Å (Charlot & Fall 1993).

However, the observed EWs of LAE galaxies are often larger than expected at $z > 4$. While stellar models predict a maximum intrinsic Lyα EW of 240 Å, Malhotra & Rhoads (2002) reported 60 percent of the Lyα emitters at $z = 4.5$ have intrinsic (‘IGM-corr’) EWs exceeding that value. This is also confirmed by Dawson

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et al. (2004, 2007), Wang et al. (2009) and Zheng et al. (2013, here-after Paper I) for larger LAE samples at $z = 4.5$, and Shimakatu et al. (2006) and Ouchi et al. 2008 for LAE samples at $z = 5.7$. Possible explanations for these large EWs are very low metallicities (as galaxies undergo their first throes of star formation, predicted by Partridge & Peebles 1967), or enhancement of the Ly$\alpha$ EW via a clumpy ISM (Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2009a), or some kind of active galactic nucleus (AGN) contribution. However, recent studies have found evidence for dust in Ly$\alpha$ galaxies (e.g. Lai et al. 2007; Pirzkal et al. 2007; Finkelstein et al. 2008, 2009a), showing that Ly$\alpha$ galaxies are not metal free, and thus large EWs are not generally due to primitive star formation. Dust could produce weird radiative transfer effects and so allow Ly$\alpha$ photons out, at least in some objects. A large fraction of AGNs in the high-redshift LAE samples are also ruled out (Malhotra et al. 2003; Wang et al. 2004; Zheng et al. 2010).

Malhotra et al. (2012) compared the UV size and star formation intensity (i.e. UV luminosity per unit area) of LAEs and LBGs over redshift 2.25 < $z$ < 6. They found that Ly$\alpha$-selected galaxies have a characteristic, constant, small size in rest-frame UV light, unlike LBGs which have been previously shown to decrease in linear size as $H(z)^{-1}$ with increasing redshift, and both LAEs and LBGs have a characteristic star formation intensity. Thus evolution in physical properties of ISM in LAEs over redshifts could yield evolution in Ly$\alpha$ EW distribution.

Measuring the intrinsic Ly$\alpha$ EW distribution can be challenging. One reason is that many LAEs are not detected in broad-band images, thus their Ly$\alpha$ EW cannot be well constrained. Another issue is that LAE selection criteria may have introduced selection biases to the Ly$\alpha$ EW distribution, which have to be carefully explored. In this paper we run Monte Carlo simulations to prove the intrinsic Ly$\alpha$ EW distribution of a LAE sample at $z \sim 4.5$ selected in the Extended Chandra Deep Field South (ECDFS) over a 0.33 deg$^2$ region. The photometric surveys of this sample were presented by Finkelstein et al. (2008, 2009a), and their spectroscopic followup and Ly$\alpha$ luminosity function were presented by Paper I. We briefly introduce our photometric and spectroscopic observations in Section 2, and then present the observed Ly$\alpha$ EW distributions in Section 3. We introduce the Monte Carlo simulations in Section 4, and finally discuss the simulation results and present the evolution of EW distribution over redshift range of 0.3–6.5 in Section 5. Throughout this work, we assume a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$ (Komatsu et al. 2011). At redshift $z = 4.5$, the age of the Universe was 1.38 Gyr, with a scale of 6.8 kpc/arcsec, and a redshift change of $\Delta z = 0.03$ implies a comoving distance change of 19.0 Mpc. Magnitudes are given in the AB system.

2 DATA

2.1 Photometric candidates

We have selected 112 LAE candidates at $z \sim 4.5$ in the GOODS Chandra Deep Field South region (CDF-S; RA 03:31:54.02, Dec. $-27:48:31.5$) in three narrow-bands, including four LAEs in NB656 (Finkelstein et al. 2008), 33 in NB665 and 75 in NB673 (Finkelstein et al. 2009a). All the narrow-band images were obtained with the MOSAIC II camera on CTIO Blanco 4 metre telescope. The NB665 and NB673 candidates were selected from the overlap region between the MOSAIC image and the GOODS CDF-S data), thus only four objects were selected.

The LAE selection criteria were introduced in Rhoads et al. (2000), Rhoads & Malhotra (2001), and Finkelstein et al. (2009a), which require a 5$\sigma$ significance detection in the narrow-band, a 4$\sigma$ significance narrow-band flux density excess over the $R$ band, a factor of 2 ratio of narrow-band flux to broad-band flux density, and no more than 2$\sigma$ detection in the $B$ band. Candidates with GOODS $B$-band coverage were further examined in the GOODS $B$-band image, and those with significant GOODS $B$-band detections were excluded (see Paper I for details). The first three criteria ensure a significant line detection, while the last criterion checks that it is at $z > 4$. The factor of 2 ratio of narrow-band flux to broad-band flux density ensures all candidates have EW$\alpha_{\nu > 1350}$ > 14.6 erg cm$^{-2}$ s$^{-1}$.

2.2 Spectroscopic observations

The spectroscopic followups were presented in Paper I. The spectroscopic observations were taken with IMACS on Magellan Baade telescope. We obtained spectra of 64 out of 112 LAE candidates (three of four in NB656, 17 of 33 in NB665, and 44 of 75 in NB673), and 46 LAEs were spectroscopically confirmed as $z \sim 4.5$ LAEs (three in NB656, 11 in NB665, and 32 in NB673). We did not find any emission line at the wavelength region of the corresponding narrow-band for the remaining 18 candidates, and none of them is an interloper. Due to the large uncertainties in the flux calibration of the spectroscopic data, in this paper we adopt Ly$\alpha$ line flux and EW from photometric data. Note that all targets with photometric line flux $f_{\alpha} > 3.7 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ are confirmed (see Figs 1 and 2 in Paper I), and targets with large EWs are confirmed at a significant higher fraction (see Figs 1 and 2).

3 OBSERVED Ly$\alpha$ EQUIVALENT WIDTH DISTRIBUTION

As pointed out by Shimakatu et al. (2006), the rest-frame EWs of LAEs from photometry are calculated either using narrow-band and a non-overlapping broad-band at redder wavelengths (e.g. Ouchi et al. 2008 for LAEs at $z = 3.1, 3.7$, and 5.7), or narrow-band and an overlapping broad-band (e.g. this work for LAEs at $z = 4.5$, and Ouchi et al. 2010 and Kashikawa et al. 2011 for LAEs at $z = 6.5$). When using an overlapping broad-band, an IGM transmission correction should be applied to the continuum. For our data, $R$ band is $\sim 1$–2 mag deeper than $J$ band, so we choose $R$ band and narrow-band to measure the EWs for our $z \sim 4.5$ LAEs.

Following an approach similar to Malhotra & Rhoads (2002), we calculate the rest-frame Ly$\alpha$ EWs of the LAEs. We use the relations

$$ \frac{N}{W_N} = a_N \times \frac{F_{\alpha_N}}{W_N} + b_N \times \frac{F_{\alpha_N}}{EW_{\alpha}} \times (1+z) \quad (1) $$

$$ \frac{R}{W_R} = a_R \times \frac{F_{\alpha_R}}{W_R} + b_R \times \frac{F_{\alpha_R}}{EW_{\alpha}} \times (1+z). \quad (2) $$

Here $R$ and $N$ are the integrated fluxes in the broad $R$ filter and narrow-band filter. $W_N$ is the narrow-band filter width, defined as
EW distribution at $z \approx 4.5$ 

Malhotra & Rhoads (2002). Solving for EW, we obtain:

$$EW_{\text{rest}} = \frac{b_R \times N \times W_R - b_N \times R \times W_N}{a_N \times R - a_N \times N} \times \frac{1}{1+z}.$$ \hspace{1cm} \text{(3)}$$

For our $z \approx 4.5$ Lyα search, the coefficients become $a_N \approx 1$, $b_N \approx 0.66$, $a_R \sim [0.82, 0.77, 0.74]$ and $b_R \sim [0.63, 0.61, 0.59]$ assuming a composite LAE spectrum (line + continuum $f_\lambda$ (Cont.) $\propto \lambda^{-1}$) for the narrow-band filters [NB656, NB665, NB673], respectively. Unlike Malhotra & Rhoads (2002), here we make no correction to IGM absorption to the Lyα line, which is still poorly understood (see Section 5.2 for further discussion). Throughout this paper, if not specifically stated, we present only Lyα line EW before correction for IGM absorption to the Lyα line.

In the upper panel of Fig. 1 we first plot observed Lyα line flux versus line EW (from equation 3) for our LAE sample. Uncertainties in EWs were obtained through simulations by adding Gaussian noise to broad-band and narrow-band flux densities. A clear trend can be seen that sources with larger EW also have larger uncertainties in EW. This is simply because of the much poorer constraints on continuum fluxes for larger EW sources (most of them have very weak continuum radiation). Specifically, calculations based on equation (1) produce negative continuum fluxes and thus negative EWs for some sources, which could be attributed to the large noise fluctuations in the broad-band photometry. These sources with ‘negative’ line EW indeed have rather large line EW. In Fig. 1 we plot them at the right end by setting $EW = 10^{-5}$ Å (for display only).

In the lower panel of Fig. 1, we plot the EW histogram distribution for all candidates, targeted, and confirmed LAEs. We find that about 44 per cent (39 per cent) of the confirmed (candidate) LAEs show $EW_{\text{rest}} > 154$ Å (intrinsic $EW > 240$ Å, if applying a correction factor of 0.65 for IGM-correction on Lyα line at $z \approx 4.5$ assuming no velocity shift of the line), slightly lower than but consistent with the fraction of 50–60 per cent for the $z = 4.5$ LAEs in LALAv fields (Malhotra & Rhoads 2002; Wang et al. 2009). Dawson et al. (2007) measure the Lyα EW from the spectra according to $EW = (F_\lambda / f_{\lambda, r}) / (1+z)$, where $F_\lambda$ is the flux in the emission line and $f_{\lambda, r}$ is the measured red-side continuum flux density. The fraction of LAEs in Dawson et al. (2007) with $EW > 154$ Å is 31 ± 11 per cent, consistent with our results.

Fig. 2 shows the distributions of $EW_{\text{phot}}$ in the lower EW range (76 of 112 LAEs with $EW < 400$ Å here, and their uncertainties in EWs are reasonably small; see Fig. 1). The EW distribution is often fitted with an exponential law of $dN/dEW = N \exp^{-EW/W_0}$ or a positive Gaussian distribution of $dN/dEW = N \frac{1}{\sqrt{2\pi} \sigma_g} e^{-EW^2/(2\sigma_g^2)}$ (Gronwall et al. 2007; Guaita et al. 2010; Nilsson et al. 2009). Here our photometric sample has a best-fitting exponential scale of $W_0 = 50^{+11}_{-10}$ Å. However, the $W_0$ is not well constrained for our spectroscopically confirmed sample ($W_0$ spec = $217 \pm 179$ Å), likely due to the smaller sample size and/or incompleteness in spectroscopic identifications of LAEs with low EWs. Assuming a Gaussian distribution, we obtain a $\sigma_g = 76^{+13}_{-11}$ Å for the photometric sample, while $\sigma_g$ spec is also poorly constrained at $\sim 189^{+43}_{-34}$ Å.

However, an exponential EW distribution with $W_0 = 50^{+11}_{-10}$ Å (or a Gaussian EW distribution with $\sigma_g = 76^{+13}_{-11}$ Å) implies that only ~8 per cent (3 per cent) of sources with EW greater than 9.0 Å have $EW > 154$ Å, apparently in contradiction to the fact that 39 per cent of our candidate LAEs have $EW_{\text{rest}} > 154$ Å. This is simply because during the fitting to EW distribution, we excluded sources with ‘negative’ line EW, and sources with photometric $EW > 400$ Å for which the uncertainty in EW is very large. Thus the $W_0$ or $\sigma_g$ from photometric sample was significantly underestimated. In
addition, the observed line EW distribution, especially at the low EW range, is likely sensitive to candidate selection criteria, and to the depth of $R$ and narrow-band images, thus could have been biased. For instance, a deeper $R$-band image would allow more LAE candidates with smaller EW pass our selection. To confront these issues, below we do Monte Carlo simulations to obtain the intrinsic EW distribution in our LAE sample.

4 INTRINSIC Ly$\alpha$ EW DISTRIBUTION THROUGH MONTE CARLO SIMULATIONS

In order to obtain the intrinsic Ly$\alpha$ line EW distribution from our LAE sample, we develop a Monte Carlo approach to simulate the LAE selection processes described in Section 2.1. Our method is similar to that done by Shimasaku et al. (2006); however, their aim is to obtain the Ly$\alpha$ luminosity function at $z = 5.7$. Recent observations show that $L^*$ from observed Ly$\alpha$ luminosity functions does not evolve significantly over the redshift range of $3 < z \leq 6.5$ (see fig. 15 of Paper I), so we fix the $L^*$ in our simulation and check the selection process with variable EW distribution. We further use broad-band to narrow-band ratio instead of EW distribution in fitting the intrinsic EW distribution. The band-ratio distribution has much better behaved errors than the EW distribution, and is less sensitive to objects with low-EW values that are boosted above our selection threshold by noise fluctuations.

Starting from an intrinsic Ly$\alpha$ luminosity function, we build large artificial LAE samples by assigning Ly$\alpha$ line luminosity to each source ($L_{\text{Ly}\alpha}$ range: $10^{41.5} \leq L_{\text{Ly}\alpha} \leq 10^{43.45}$). Assuming their Ly$\alpha$ line EW follows the exponential law $dN/dEW = N \exp(-EW/W_0)$ independent of Ly$\alpha$ luminosity, we could further assign line EW to artificial sources (EW range: $EW \geq 1$ Å, considerably below the EW limit of the real sample 9.0 Å) and calculate their expected narrow-band and $R$-band fluxes. By adding Gaussian noise to the narrow-band and $R$-band fluxes (with noise level derived from our real data), and applying the same LAE selection criteria we adopted to select real LAE candidates, we obtain artificial LAE samples for various $W_0$ to compare with our real sample. We start our simulations by adopting a Ly$\alpha$ luminosity function following a Schechter function of

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

with $\log_{10}(L^*) = 42.75$ and $\alpha = -1.5$, which are the best-fitting Ly$\alpha$ luminosity function parameters for our $z = 4.5$ LAE sample in Paper I. Here we assign 3200 000 simulated LAEs with Ly$\alpha$ luminosity in the range of $\log_{10}(L_{\text{Ly}\alpha}) = [41.5, 43.45]$ (binsize = 0.03, and the brightest Ly$\alpha$ luminosity bin has number $> 100$). However, we note that the intrinsic luminosity function could be different from the observed one due to selection effects, and such differences should be measured with our simulations.

In Fig. 3 we compare the input samples of the simulations with the output artificial samples by applying our selection criteria with intrinsic EW distribution in exponential form (the Gaussian form has similar patterns). As introduced in Section 2.1, the selection criteria (see also Finkelstein et al. 2009a) are 5σ detection in narrow-band.
(CR1: NB ≥ 5 σNB), a factor of 2 of narrow-band over broad-band (CR2: fnB ≥ 2 × fnB), a 4σ significance of narrow-band over broad-band (CR3: NB − R ≥ 4 × σNB + σR), and no more than 2σ detection in the R band.

In the upper panel of Fig. 3 the Lyα luminosity distributions of the input samples are plotted as grey lines for various W0, which is simply a Schechter Function. We also plot the ‘observed’ Lyα luminosity distribution by adding Gaussian errors to expected narrow- and broad-band flux densities and re-extract their Lyα luminosities (dark black lines). The ‘observed’ luminosity distributions are slightly different from the intrinsic ones because of noise fluctuations. The dark lines are well consistent with the grey lines at high luminosities, but slightly higher than grey lines at lower luminosities (Lα ≤ 42.6). This is simply the Eddington bias due to photometry uncertainties. The light blue lines plot the distributions of the intrinsic Lyα luminosity of the samples after applying the first selection criterion CR1, and the dark blue line the distributions of the ‘observed’ Lyα luminosity after apply CR1. Clearly CR1 removes most of the faint LAEs below our detection limit (vertical dot–dashed line in the upper panel). CR2 further excludes more faint LAEs (light and dark green lines). After applying CR3, however, there are still small fraction of faint LAEs with intrinsic Lyα luminosity below our detection limit could pass the selection criteria, due to noise fluctuations. However, their ‘observed’ Lyα luminosities are all above the detection limit (dark red lines).

We also plot the ratios of the luminosity distributions to the intrinsic ones, to demonstrate the differences between the input LFs (grey lines, ratio = 1) and the output ones for various exponential scale W0 in Fig. 3. We find that the output LFs are generally consistent with the input ones above the detection limit, except for (1) at high W0, the output ‘observed’ LFs (dark red lines) are consistent with the input ones at high luminosity, slightly higher than input ones (grey lines, ratio = 1) at low to intermediate luminosities due to Eddington bias, and drop only near the detection limit; (2) at low W0 = 50 Å, the output ‘observed’ LFs (dark red lines) are slightly lower than the input ones (grey lines, ratio = 1) by a factor of ~10 per cent, because the selections exclude sources with EW < 9.0 Å, which make more contribution to the whole population (EW > 1 Å in the simulations) at smaller W0. Thus Fig. 3 shows that the detection and selection processes only produce weak bias to the luminosity function.

We further examine this issue through directly fitting the luminosity distributions of the simulated samples, as we did to the real LAE sample in Paper I. To measure the Lα and Φα of the artificial samples, we first scale the input samples (grey lines in Fig. 3) to match the real one, to ensure the number of simulated LAEs with Lyα luminosity in range of log10(L) ~ 42.6–43.3 and EW > 9.0 Å meet our observational data. The same scaling factor was then applied to the simulated output LAE samples. During the fitting we adopt the same luminosity range log10(L) ~ 42.6–43.3 and the same luminosity bins as in Paper I. We also add Poisson noises to the number of sources in each luminosity bin, to simulate the uncertainties of the Luminosity Function. We find that the output L* and Φ* for the ‘observed’ samples at different EW0 are generally consistent with the input values within 1 sigma error bars, which also suggests only weak bias was introduced to LF by the detection and selection processes. At lower W0 < 100 Å slightly higher Φ* was obtained. This is because for EW distribution with lower W0, relatively more simulated LAEs with intrinsic EW < 9.0 Å could be selected due to fluctuations.

Since the observed line EWs suffer from negative values, and very large uncertainties (due to the broad-band weak non-detection), instead of fitting the line EW distribution, we choose to compare the distribution of R to narrow-band flux density ratio of the real LAE sample with artificial samples. Note that the R to narrow-band flux density ratio has a better behaved error distribution (see Malhotra & Rhoads 2002; Wang et al. 2009).

In Fig. 4 we plot the distribution of EIS-R to narrow-band flux density ratio for our real LAEs. Similar to Wang et al. (2009), we find consistent distributions for all our LAE candidates and for the subset of spectroscopically confirmed samples, respectively. The red line presents the best-fitting artificial sample assuming the line EW distribution follows an exponential law dN/dEW = N exp(−EW/W0). The best-fitting EW exponential scale is W0 = 167 ± 11 Å from MUSYC-R data alone. The horizontal lines are corresponding to the one sigma error on R band flux divided by the minimum narrow-band flux.

Figure 4. Histogram of the broad-band (top: EIS-R band and bottom: MUSYC-R band) to narrow-band flux density ratio for our z ~ 4.5 LAE sample. The rest-frame Lyα line EW (GM-corrected Lyα line, marked on the top of the plot) is a monotonic decreasing function of the flux density ratio. The black, blue and green histograms plot distributions for the photometric, targeted, and spectroscopically confirmed samples, respectively. The red line presents the best-fitting artificial sample assuming the line EW distribution follows an exponential law dN/dEW = N exp(−EW/W0). The best-fitting EW exponential scale is W0 = 167 ± 11 Å from MUSYC-R data alone. The horizontal lines are corresponding to the one sigma error on R band flux divided by the minimum narrow-band flux.

Our candidates in CDF-S were selected by Finkelstein et al. (2009a), based on EIS-B, EIS-R and narrow-band images. We later obtained public MUSYC B, V, R, I, and z band data in the same field though covering a smaller area (Gawiser et al. 2006). We note that while MUSYC-B band is slightly shallower than EIS-B, the

1 During the fitting we excluded one object with f(R)/f(NB) − 0.5, because its continuum flux is affected by over-subtraction of a very bright nearby source.
the ‘observed’ EWs are ‘negative’ or very high with large errors, similar to the real LAE sample (see Section 3). In this figure, we plot the intrinsic EW for the output samples to check the selection effects on sources with different intrinsic EWs. We find that the recovery rate remains almost constant at EW > 9.0 Å, except for the trend that the recovery rate slightly increases with decreasing EW from ∼100 to ∼20 Å, and drops only very close the cut-off. We note that a significant fraction of sources with EW below the cut-off could also survive the selection criteria, due to the noise fluctuations in narrow- and broad-band photometry. Therefore, Fig. 3 presents a quasi-Eddington bias pattern that the selection processes yield slightly higher recovery rate for sources with EW < 154 Å than those with EW > 154 Å. This is because that for sources with lower line EWs, the contribution from the continuum emission boosts the narrow-band flux density, yielding more detections in narrow-band, and some low EW objects with EW < 9.0 Å get into the sample.

5.2 The evolution of EW distribution

Does $W_0$ evolve with redshift? Below we present a comparison of the EW distributions at various redshifts. We have shown through simulations that our LAE selection procedures only produce weak bias to EW distributions (Fig. 3), and the major cause of the difference in $W_0$ from direct fitting to the EW distribution ($W_0 = 56$ Å, Fig. 2) and from simulations ($W_0 = 167$ Å) is the LAEs with extremely large or even ‘negative’ EWs. Therefore our $W_0$ derived through simulations can be compared with measurements in other works through fitting the EW distributions directly, as long as the underlying broad-band images are deep enough to give better constraints on EWs, or those LAEs with extremely large or even ‘negative’ EWs have been accounted for correctly. We note that requiring a broad-band detection of LAEs during source selection would also produce severe bias in the LAE EW distribution, since such an approach would naturally exclude sources with large EWs.

For low- and moderate-redshift LAEs, spectroscopic observations are easy and powerful to exclude interlopers and AGN, and the underlying broad-band images are often deep enough to put good constraints on EW measurements. After excluding AGNs found by Finkelstein et al. (2009) in the $z = 0.3$ LAEs (Cowie, Barger & Hu 2010, EGS data only), we get an EW scale of $W_0 = 22 \pm 9$ Å ($\sigma_0 = 41 \pm 10$ Å). This is significantly lower than that of 75 Å from fitting the whole photometric sample. Ciardullo et al. (2012) reported EW scale length of $W_0 = 50^{+44}_{-41}$ Å at $z = 2.1$ and $70^{+35}_{-41}$ Å at $z = 3.1$. Similar or even higher values were also reported by different works, including $W_0 = 48.5 \pm 1.7$ Å at $z = 2.3$ (Nilsson et al. 2009), $\sigma_0 = 130 \pm 10$ Å at $z = 3.1$ and $\sigma_0 = 150^{+110}_{-40}$ Å at $z = 3.7$ (Ouchi et al. 2008). With the spectroscopically confirmed LAEs at $z = 5.7$ and 6.5 from Kashikawa et al. (2011), we get a direct fitting EW scale of $W_0 = 108 \pm 20$ Å and $79 \pm 19$ Å ($\sigma_0 = 156 \pm 17$ and $113 \pm 16$ Å), respectively. By applying our Monte Carlo simulation approach, we also obtained the EW scale for $z = 5.7$ and 6.5 LAEs from Hu et al. (2010), which are $W_0 = 123^{+65}_{-26}$ and $178^{+433}_{-26}$ Å ($\sigma_0 = 125^{+110}_{-40}$ and $134^{+276}_{-4}$ Å), respectively.

Comparing the EW distribution at various redshifts suggests a strong evolution over redshift range of 0.3 to 6.5 (see Fig. 6). Note in the figure the red data points are without corrections to IGM absorption on the Lyα line, which itself clearly evolves with redshift too. Assuming the Lyα line is symmetric and with no velocity offset from the rest frame of the galaxies, we apply IGM absorption corrections (Madau 1995) to $W_0$ (blue data points). Note IGM correction could be different in case of shifted Lyα lines respected to its rest-frame as seen in observations at high redshifts (e.g. Hashimoto et al. 2013).
The EW distribution scale (bottom: exponential distribution scale $W_0$; top: Gaussian distribution scale $\sigma_0$) obtained at different redshifts. The diamonds and squares present direct fitting results by assuming exponential and Gaussian distributions, respectively, and circles present our simulation approach with two kinds of distributions. We also mark results with/without IGM absorption-correction to Lyα line flux in blue/red colours, and we use IGM absorption-correction by Madau (1995) assuming intrinsic symmetric Lyα emission line with zero velocity offset. Data references: Cowie, Barger & Hu (2011) at $z \sim 0.3$, Ciardullo et al. (2012) at $z = 2.1$ and $z = 3.1$; Nilsson et al. (2009) at $z = 2.25$; Ouchi et al. (2008) at $z = 3.1$, and $z = 3.7$, this work at $z = 4.5$, Kashikawa et al. (2011) at $z = 5.7$ and 6.5, and Hu et al. (2010) at $z = 5.7$ and 6.5. The results at $z \sim 0.3$ are from EGS field sample after AGN have been excluded.

In order to quantify the evolution we fit the data points with an analytical function $W_0(z) = A \times (1 + z)^{g}$ and $\xi = 1.1 \pm 0.1$ for exponential scale $W_0$ before corrections for IGM absorption of the Lyα line, and $A = 7.3^{+1.5}_{-1.3}$ and $\xi = 1.7 \pm 0.2$ after. With Gaussian distribution assumption, the scale values of $\sigma_0$ increase, while the redshift evolution slopes flatten ($A = 52^{+10}_{-8}$ and $\xi = 0.6 \pm 0.1$ before IGM-correction, and $A = 30^{+5}_{-5}$ and $\xi = 1.2 \pm 0.1$ after).

Recent infrared spectroscopy shows that there are velocity offsets between rest-frame optical lines compared to Lyα line peak, which may tell the existence of outflows with velocities of hundreds km s$^{-1}$ (Finkelstein et al. 2011; McLinden et al. 2011). If the line is offset to the red of systemic velocity, IGM correction to Lyα flux is not needed. However, Hashimoto et al. (2013) also reported one LAE with $-\sim 1$ velocity offset, and an inverse correlation between velocity offsets and Lyα EWs for LAEs at $z \sim 2$–3 (see their fig. 7, note Shapley et al. 2003 reported similar relation from the composite spectra of 2–3 LBGs). This implies that the escape of Lyα photons could be more complex than a simple outflow enhanced escape. Likely, IGM corrections to Lyα fluxes need to be applied when there is no velocity offset and not applied for LAEs with velocity offsets of hundreds of km s$^{-1}$.

5.3 Is EW$_{\text{Ly}\alpha}$ independent of $L_{\text{Ly}\alpha}$?

Through Monte Carlo simulations we have measured the intrinsic EW distribution of our LAE sample at $z = 4.5$, which is fitted with an exponential law with $W_0 = 167^{+40}_{-10}$ Å. During our simulation we have assumed that the Lyα EW distribution is independent of Lyα luminosity. However, we do not know prior to this work whether this assumption is correct.

In Fig. 7 we plot the Lyα line flux versus $R$ to narrow-band flux density ratio for our LAEs. Since the $R$ to narrow-band flux density ratio is a good indicator of the line EW, such a figure provides an opportunity to examine whether the EW distribution is independent to Lyα line luminosity. In the figure we see no clear correlation between the Lyα line flux and the line EW ($R$ to narrow-band flux density ratio), but larger scatter in $R$ to narrow-band flux density ratio at lower Lyα fluxes. In Fig. 7 we over-plot the contour distributions of our simulated LAE sample (with $W_0 = 167$ Å). The peak and full width at half maximum of band-ratio distributions as a function of Lyα flux in simulation are plotted as the dashed blue line and the dark yellow region. On the right panel the distributions of Lyα flux for observation (green dashed, all candidates) and simulation (black solid) are shown for EIS-R & NB data (bottom) and MUSYC-R & NB data (top), respectively.

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5.4 ‘Ando’ effect

In Fig. 8 we plot the rest-frame Lyα EW versus UV magnitude for our LAEs. Here the UV magnitude refers to the continuum emission in $R$ band excluding the contribution from the Lyα line, and applied a correction factor for IGM absorption (see Section 3). Here, we
do not plot those LAEs whose ‘negative’ line EW are ignored, as their negative continuum flux measurements yield undefined UV magnitudes. In such a plot we see a clear lack of large EW LAEs with large UV luminosities, and the maximum LAE EW in the sample systematically decreases with increasing UV luminosity. This effect is known as the ‘Ando effect’, as first reported in LBGs at $z \sim 5-6$ by Ando et al. (2006), and also detected in LAEs by later works (Shimasaku et al. 2006; Stanway et al. 2007; Deharveng et al. 2008; Ouchi et al. 2008). However, by over-plotting the artificial LAE samples we have simulated, we show that this effect in our sample could be naturally generated through our LAE selection. Actually, the $EW_{\lambda_{\text{Ly}\alpha}} - M_{\text{UV}}$ plane can be expressed as $EW_{\lambda_{\text{Ly}\alpha}} = L_{\lambda_{\text{Ly}\alpha}}/EW_{\lambda_{\text{Ly}\alpha}}$ plane, which is an inverse relation as seen in Fig. 8.

5.5 Implication for NB selection

As we have stated previously, the selection of LAEs relies on both the depth of the narrow-band and the underlying broad-band images. The simulation procedures we have developed provide a powerful approach to test the selection efficiency under various conditions, and such tests could be used to guide future narrow-band imaging surveys.

We adopt one quantity to describe the efficiency of selections for our simulated samples: the number of LAE selected. In Fig. 9 we plot the results of our simulations for various given conditions. We clearly see that deeper narrow-band images yield more LAE candidates, but the role of the broad-band image depth is also important. If the limiting magnitude of the broad-band image is shallower than the narrow-band image, the selection efficiency is poor in the number of LAE selected, and large errors in broad-band image will introduce larger uncertainties in the EW calculation. The selection efficiency steadily rises with deeper broad-band image. However, the rise slows down or even halts if the broad-band images are $> 0.5$–1.0 mag deeper than the narrow-band, indicating that broad-band images much deeper than the narrow-band will not increase the number of LAEs selected if one keeps the selection criteria. Actually, for selections with much deeper broad-band images, the proper approach is to go for line emitter with smaller EW, this could further increase the number of sources selected. Therefore, deeper broad-band images would be always helpful in selections of line emitters, but broad-band images significantly shallower than the narrow-band would be very inefficient. Similar patters could be seen for different $W_0$ (Fig. 9).

6 SUMMARY

In this work we study the intrinsic Ly$\alpha$ EW distribution of our $z \sim 4.5$ LAEs in ECDFS. To derive the intrinsic line EW distribution, we develop essential Monte Carlo simulations to address the selection effects of our LAE selection procedures, and the large uncertainties in line EWs from narrow- and broad-band photometry.

Our approach includes to (1) build artificial LAE samples following given Ly$\alpha$ luminosity function and EW distribution; (2) add observational uncertainties to their expected narrow-band and the underlying broad photometry; (3) run our LAE selection processes to recover the simulated LAEs; and (4) compare the simulated LAE sample with the real LAE sample we obtained in ECDFS, specifically compare their luminosity function and EW distribution. We note that the comparison of EW distribution is performed on the distributions of the narrow- to broad-band flux ratio between simulated and real samples, since the narrow- to broad-band flux ratio is a monotonic decreasing function of line EW and has a much better behaved error distribution.

Our main results are summarized as follows.

(i) With simulations, we find that our LAE selection procedures produce weak (quasi-) Eddington bias to both Ly$\alpha$ luminosity function and EW distribution.

(ii) Direct fitting on EW distribution gives an exponential scale of $W_0 = 50 \pm 11$ Å, while after taking into account the broad-band non-detections, we get $W_0 = 167^{+44}_{-19}$ Å (or Gaussian scale of $\sigma_{\text{EW}} = 160^{+43}_{-12}$ Å) for LAEs at $z \sim 4.5$ through fitting on band-ratio distribution.

(iii) We find our LAE sample is consistent with an assumption that the intrinsic LAE EW distribution is independent to Ly$\alpha$ luminosity, which could naturally produce ‘Ando’ effect in LAE samples.
Our simulations also show that broad-band image ∼0.5–1 mag deeper than the inside narrow-band is most efficient in selecting emission line sources adopting our selection criteria. The simulations are useful to optimize future similar surveys at various redshifts.

We find a strong evolution of the Lyα EW distribution over redshift 0.3 to 6.5, which can be well fitted by a power-law form $W_0 \propto (1+z)^\xi$, with $\xi = 1.1 \pm 0.1$ (or $\xi = 1.7 \pm 0.2$ after applying an IGM-absorption correction to Lyα line) for EW exponential distribution, and $\xi = 0.6 \pm 0.1$ (or $\xi = 1.2 \pm 0.1$ after applying an IGM-absorption correction to Lyα line) for a Gaussian EW distribution.

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