X-RAY PROPERTIES OF THE z ~ 4.5 Lyα EMITTERS IN THE CHANDRA DEEP FIELD SOUTH REGION

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ABSTRACT

We report the first X-ray detection of Lyα emitters (LAEs) at redshift z ~ 4.5. One source (J033127.2-274247) is detected in the Extended Chandra Deep Field-South (ECDF-S) X-ray data and has been spectroscopically confirmed as a z = 4.48 quasar with L_X = 4.2 × 10^{44} erg s^{-1}. The single detection gives an Lyα quasar density of ~ 2.7 × 10^{-6} Mpc^{-3}, consistent with the X-ray luminosity function of quasars. Another 22 LAEs in the central Chandra Deep Field-South region are not detected individually, but their co-added counts yield an S/N = 2.4 (p = 99.83%) detection at soft band, with an effective exposure time of ~36 Ms. Further analysis of the equivalent width (EW) distribution shows that all the signals come from 12 LAE candidates with EW_{rest} < 400 Å and 2 of them contribute about half of the signal. From follow-up spectroscopic observations, we find that one of the two is a low-redshift emission-line galaxy, and the other is a Lyman break galaxy at z = 4.4 with little or no Lyα emission. Excluding these two and combined with ECDF-S data, we derive a 3σ upper limit on the average X-ray flux of F_{0.5–2keV} < 1.6 × 10^{-18} erg cm^{-2} s^{-1}, which corresponds to an average luminosity of ⟨L_{0.5–2keV}⟩ < 2.4 × 10^{42} erg s^{-1} for z ~ 4.5 LAEs. If the average X-ray emission is due to star formation, it corresponds to a star formation rate (SFR) of <180–530 M⊙ yr^{-1}. We use this SFR_X as an upper limit of the unobscured SFR to constrain the escape fraction of Lyα photons and find a lower limit of f_{esc, Lyα} > 3%–10%. However, our upper limit on the SFR_X is ~7 times larger than the upper limit on SFR_X on the average X-ray-to-Lyα line ratio, we estimate that fewer than 3.2% (6.3%) of our LAEs could be high-redshift type 1 (type 2) active galactic nuclei (AGNs) and those hidden AGNs likely show low rest-frame EWs.

Key words: galaxies: active – galaxies: high-redshift – galaxies: starburst – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Narrowband surveys have discovered thousands of candidate Lyα emitters from z = 2.25–6.96 (e.g., Nilsson et al. 2009; Gawiser et al. 2007; Rhoads et al. 2000, 2003; Dawson et al. 2007; Ouchi et al. 2008; Wang et al. 2005; Iye et al. 2006). Hundreds have been spectroscopically confirmed (e.g., Hu et al. 2004; Dawson et al. 2004; Venemans et al. 2005; Dawson et al. 2004, 2007; Ouchi et al. 2008; Wang et al. 2009). Recent studies have found evidence for dust in Lyα galaxies (e.g., Finkelstein et al. 2008, 2009b; Lai et al. 2007; Pirzkal et al. 2007), showing that Lyα galaxies are not all primitive. This dust may help to explain the “problem” of the observed equivalent widths (EWs) of high-z LAEs. These EWs are often larger than expected even from normal star formation (Malhota & Rhoads 2002). Possible scenarios for causes of these large EWs include very low metallicities or enhancement of the Lyα EW via a clumpy interstellar medium (ISM; Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2009b).

Active galactic nuclei (AGNs) can also account for high Lyα EWs of Lyα emitters (LAEs hereafter). X-ray studies of LAEs can help us to detect AGNs. However, unlike the LAEs in the local universe, where the AGN fraction is as high as 15%–40% (e.g., Scarlata et al. 2009; Cowie et al. 2010; Finkelstein et al. 2009a, 2009c), the observed AGN fraction at high redshift is small, from 3%–7% at z = 2.1 (Guita et al. 2010), 5%–13% at z ~ 2.25 (Nilsson et al. 2009), 1%–5% at z ~ 3.1–3.7 (Gronwall et al. 2007; Ouchi et al. 2008; Lehmer et al. 2009), to <5% at z ~ 4.5 (Malhotra et al. 2003; Wang et al. 2004), and <1% at z ~ 5.7 (Ouchi et al. 2008). This trend is in line with the observed decrease in the number density of quasars at z > 2 (e.g., Figure 14 of Yencho et al. 2009).

In addition to measuring AGN contributions, X-ray emission is also a useful measure of the unobscured star formation activity, mainly from supernovae (SNe), hot interstellar gas (i.e., T > 10^{6}–10^{7} K), high-mass X-ray binaries (HMXBs), and low-mass X-ray binaries (LMXBs). The first three object classes evolve rapidly and therefore track the current star formation rate (SFR). The LMXBs have longer evolutionary time scales (on the order of the Hubble time) and therefore track the integrated star formation history of galaxies (i.e., the total stellar mass). Colbert et al. (2004) give a relationship of L_{2–8keV} = \alpha \times M_\odot + \beta \times SFR from X-ray observations of nearby galaxies, where L_X, M_\odot, and SFR have units of erg s^{-1}, M_\odot, and M_\odot yr^{-1}, respectively, and constants \alpha = 1.3 \times 10^{39} erg s^{-1} M_\odot^{-1} and \beta = 0.7 \times 10^{39} erg s^{-1} (M_\odot yr^{-1})^{-1}. When SFR > 5 M_\odot yr^{-1}, many authors (Grimm et al. 2003; Ranalli et al. 2003; Persic et al. 2004) show that the galaxies’ non-nuclear X-ray emission can be used as a linear SFR indicator for high-redshift star-forming galaxies, which might be dominated by HMXBs. Laird et al. (2005) stacked the X-ray flux from UV-selected star-forming galaxies at z ~ 1 in the Hubble Deep Field North and found a mean 2–10 keV rest-frame luminosity of (2.97 ± 0.26) \times 10^{40} erg s^{-1}, corresponding to an X-ray-derived SFR (hereafter...
The first X-ray observations of high-redshift LAEs were presented in Malhotra et al. (2003) and Wang et al. (2004) at z ∼ 4.5 with two 170 ks Chandra exposures. No individual LAEs were detected, and a 3σ upper limit on the X-ray luminosity (L_{2-8 keV} < 2.8 \times 10^{42} \text{ erg s}^{-1}) was derived by an X-ray stacking method (Wang et al. 2004). From a stacking analysis of the non-detected LAEs in the 2 Ms CDF-S field, Gronwall et al. (2007) and Guita et al. (2010) found a smaller 3σ upper limit on the luminosity of 3.1 \times 10^{41} \text{ erg s}^{-1} at z = 3.1 and z = 2.1. These imply upper limits of unobscured SFRX < 70 M_\odot yr^{-1} and < 43 M_\odot yr^{-1}, respectively (using the L_X-SFR calibration of Ranalli et al. 2003). Until now, there has been no detection of LAEs at z > 4 in the X-rays, even with stacking analyses (Malhotra et al. 2003; Wang et al. 2004; Ouchi et al. 2008). In this paper, we match 113 z ∼ 4.5 LAE candidates with the deepest 2 Ms Chandra exposure of the CDF-S and a shallower (∼240 ks) but wider-area exposure of the Extended Chandra Deep Field-South (ECDF-S).

2. OPTICAL AND X-RAY DATA

The LAE candidates were selected with narrowband imaging of the GOODS CDF-S (R.A. 03:31:54.02, decl. -27:48:31.5, J2000) at the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO) with the MOSAIC II camera. Three 80 Å wide narrowband filters (NB656, NB665, and NB673) were utilized to obtain deep narrowband images (Finkelstein et al. 2008, 2009b). The LAE candidates are selected based on a 3σ detection in the narrow band, a 4σ significant narrowband flux excess over the broadband continuum image (here, an R-band image from the ESO Imaging Survey (EIS); Arnouts et al. 2001), a factor of 2 ratio of narrowband flux to broadband flux density, and no more than 2σ significant flux in the EIS-B band. Candidates with GOODS B-band coverage were further examined in the GOODS B-band image, and those with significant B-band detections were excluded. These conditions are satisfied by 113 LAE candidates with the Chandra CDF-S and ECDF-S coverage, including 4 in the NB656 filter (Finkelstein et al. 2008), 39 in NB665, and 81 in NB673 (including 11 that were detected in both NB665 and NB673). The EWs of our LAEs were calculated from our narrowband and EIS-R broadband data. Finkelstein et al. (2008, 2009b) have previously studied the 14 objects from this sample that lie within the GOODS Hubble Space Telescope field. For these sources, we choose the deeper GOODS V band to calculate the EWs.

The 2 Ms Chandra X-Ray Observatory Advanced CCD Imaging Spectrometer (ACIS) exposure of the CDF-S is composed of 23 individual ACIS-I observations. We downloaded the raw data from the Chandra public archive and reduced the data using the Chandra Interactive Analysis of Observations software version 4.0 (CIAO4.0). Each observation was filtered to include only standard ASCA event grades 0, 2, 3, 4, and 6. Cosmic-ray afterglows, ACIS hot pixels, and bad pixels were removed, along with all data taken during high background time intervals. All exposures were then added to produce a combined event file with a net exposure of 1.9 Ms. The Chandra exposure of the ECDF-S is composed of nine individual ACIS-I observations obtained in 2004, covering ∼0.3 deg^2 with four pointings. We reprocessed the X-ray raw data of the four pointings separately. The averaged net exposure per pointing at ECDF-S was 238 ks. The aspect offset of both CDF-S and ECDF-S data was examined and no offset above 0.1′ was found in either field. We used the published X-ray source catalogs of the 2 Ms CDF-S (Luo et al. 2008) and the 240 ks ECDF-S (Lehmer et al. 2005) in the following source-match and source-mask processes.

3. X-RAY IMAGING RESULTS

3.1. X-ray Individual Detection

In this paper, we focus on the X-ray data with an off-axis angle <8′, because the spatial resolution of ACIS-I data degrades rapidly for off-axis angles >8′. This excludes 22 LAEs from our sample, leaving a total of 91 LAEs at z ∼ 4.5 covered by Chandra images with off-axis angle θ < 8′. Of these, 22 are covered by the 2 Ms CDF-S exposure and 86 by the shallower ECDF-S exposures, with 17 sources covered by both (see Figure 1). We choose a radius of 3″ to match X-ray counterparts to our LAE sample, as our narrowband data have a seeing of 0.9′′, and the radius of 50% point-spread function (PSF) regions of Chandra ACIS-I reaches 2′′8 at the edge of our selection area. Only one LAE (J033127.2-274247) has an individually detected X-ray counterpart (ECDF-S-J033127.2-274247), with a spatial offset <0.4 between the NB673 and X-ray coordinates. This object has previously been spectroscopically identified as an unobscured z = 4.48 quasar (Treister et al. 2009), with full-band luminosity of L_{0.5–10 keV} = 4.2 \times 10^{43} \text{ erg s}^{-1} (assuming Γ = 1.4; Lehmer et al. 2005). We measured the f_{1.4 keV}/f_{0.5–10 keV} ≈ 0.065, consistent with expectations from a quasar template (f_{1.4 keV}/f_{0.5–10 keV} ∼ 0.05; Sazonov et al. 2004).

There are two LAEs (J033204.9-280414 and J033154.1-274159) located in 95% PSF circles of two ECDF-S sources with offsets between X-ray and optical of 4′5 and 4′1, respectively.

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5. The NB656 data were much shallower than the other two bands, thus the galaxies were selected in a different way (see Finkelstein et al. 2008)—we search for the NB656 candidates from the positions of the galaxies that were detected in GOODS V band but not in GOODS B band. Thus, we were only able to select galaxies over the GOODS region, 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 EIS, which consists of a much larger area.

6. http://cxc.harvard.edu/cal/ASPECT/fix_offset/fix_offset.cgi
Figure 1. Chandra image of CDF-S plus ECDF-S. X-ray-detected sources are marked with red (CDF-S) and magenta (ECDF-S) circles, while optically selected LAEs are marked with blue “X”s. Those LAEs selected for our stacking analysis are marked by green boxes. The large yellow circles presented the selection area (off-axis angle $\theta < 8'$) in each ACIS-I image where we considered LAEs for inclusion in our analysis.

These offsets are too large to reliably associate the Ly$\alpha$ and X-ray sources, thus we do not classify them as X-ray detections, and we exclude these sources from our X-ray stack (Section 3.2).

We plot the X-ray signal-to-noise ratio ($S/N$) distribution of the remaining X-ray flux measurements in Figure 2. This comprises 106 exposures on 88 distinct LAEs (22 are covered by the 2 Ms CDF-S exposure and 84 by the shallower ECDF-S exposures, with 17 sources covered by both and one source covered by two ECDF-S pointings, see Figure 1). The $S/N$s were calculated as $S/N = S/(\sqrt{T + 0.75} + 1)$ (Gehrels 1986), where $S$ and $T$ are the net counts and total counts extracted from their 50% PSF circles\(^7\) at 0.5–2, 2–7, and 0.5–7 keV bands, respectively. When converting from PSF-corrected count rate to flux, the full and hard bands were extrapolated to the standard upper limit of 10 keV. All X-ray fluxes have been corrected for Galactic absorption (Dickey & Lockman 1990). To convert from X-ray counts to fluxes, we have assumed power-law spectra with photon index of $\Gamma = 2$ (except where explicitly stated otherwise), which generally represents the X-ray spectra of both starburst galaxies and type 1 AGNs. For the LAEs without individual X-ray detections, we derived 3$\sigma$ upper limits to their X-ray fluxes (see Figure 4).

3.2. Stacking Analysis

To determine the mean X-ray properties of the high-redshift LAEs that are too weak to be directly detected, we employed a stacking technique similar to that described in Wang et al. (2004) and Laird et al. (2006). The only difference was in the count extraction, we chose the 50% PSF regions here for the non-detections rather than 80% PSFs (as in Wang et al.) or fixed radius of 1$''$5 (as in Laird et al.). Small apertures give better upper limits on non-detections, and constant size is difficult for flux estimation here. After masking out the detected X-ray sources, the net and background counts were measured in the CDF-S and ECDF-S separately (see Figure 1 and Table 1). We computed two stacks: (1) the CDF-S data alone and (2) all available data (CDF-S and ECDF-S). For objects in the overlap between the CDF-S and ECDF-S coverage, only their CDF-S data were included in stack (1), while data from both images were included in stack (2).

A marginal signal was found from the stacking of the CDF-S data in the soft band, while no signals were found in the other band of CDF-S or from the ECDF-S stacking. When cumulat- ing the 22 LAEs in the central CDF-S in the soft X-ray band,

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\(^7\) The background counts ($B = T - S$) were first extracted from an annulus with 1.2 $R_{50\% PSF} < R < 2.4 R_{50\% PSF}$ (after masking out nearby X-ray sources) and then scaled to their 50% PSF regions by dividing the ratio of cumulated exposure in background region and source region.
The net counts and exposure time can be converted to an average flux of \( F_{\text{soft}} \) = 26.6 and 74.4, which yields an \( S/N \) of 2.2. In principle, the increase in effective exposure of a factor of 1.44 (52 Ms/36 Ms) should imply an expected value of \( S/N = 2.4 \times \sqrt{1.44} = 2.9 \). However, given the small numbers of X-ray photons involved, the count rates in the CDF-S and ECDF-S are in fact consistent at \(<2\sigma\). The effective 52 Ms exposure decreases our soft band signal to \( \langle f_{0.5-2.0\text{keV}} \rangle = (6.4 \pm 2.9) \times 10^{-18} \text{ erg cm}^{-2}\text{s}^{-1} \), corresponding to an average luminosity of \( <L_{0.5-2\text{keV}} > = 1.3 \times 10^{42} \text{ erg s}^{-1} \) for LAEs at \( z \sim 4.5 \). We also stacked the images of our LAEs together. Since the stacked samples in ECDF-S were within their background fluctuations, we only stacked the 22 LAEs located in CDF-S. The resulting stacked image shows a signal consistent with the analysis above, which becomes apparent to visual inspection when smoothed with a Gaussian matched to the ACIS PSF size (see Figure 3).

Table 1

Stacking Results of Undetected LAEs Located in the ECDF-S and CDF-S Field with Off-axis Angle <8'

| X-ray Field | Number\(^a\) | \( \text{Net}_5 \) | \( \text{Total}_5 \) | \( \text{Net}_{05-7} \) | \( \text{Total}_{05-7} \) | \( F_X (>3\sigma) \)\(^c\) | Time (Ms) | Notes |
|-------------|-------------|----------------|-----------------|----------------|----------------|-----------------|--------|-------|
| ECDF-S      | 83          | 0.2           | 26              | −3.2           | −3.1           | 90              | 1.44   | 7.49 | 3.98 | 16.2 |
| ECDF-S+QSO  | 84          | 11.9          | 38              | −1.5           | 66             | 10.3            | 2.58   | 7.53 | 5.51 | 16.4 |
| CDF-S       | 22          | 26.6          | 101             | 0.6            | 157            | 27.2            | 1.99   | 157  | 5.17 | 38.5 |
| CDF-S\(^b\) | 20          | 14            | 75              | 1.4            | 127            | 15.4            | 202    | 1.57 | 32.7 |
| CDF-S (EW(Lyα)\text{rest} \geq 400 Å) \( \)\(^d\) | 10          | 1.8           | 36              | 1.3            | 73             | 4.8             | 109    | 1.6  | 9.8  | 15.8 |
| CDF-S (EW(Lyα)\text{rest} < 400 Å) \( \)\(^d\) | 12          | 24.8          | 65              | −2.4           | 84             | 22.4            | 149    | 3.1  | 6.9  | 20.0 |
| CDF-S (EW(Lyα)\text{rest} < 400 Å) \( \)\(^d\) | 10          | 12.2          | 39              | −1.6           | 54             | 10.6            | 93     | 2.4  | 6.3  | 16.9 |

Notes:

\(^a\) Number of LAEs selected for stacking analysis. 17 LAEs were covered by both CDF-S and ECDF-S and 1 LAE in ECDF-S was covered by two ECDF-S pointings.

\(^b\) The \( 3\sigma \) flux limits are obtained by first calculating the \( 3\sigma \) upper limit on counts as \( \text{Net} + 3\times(\text{Total} + 0.75 + 1)/(\text{PSF-fraction}) \). Here, "Net" and "Total" are the net and total counts in the 50% PSF region, respectively, while "PSF-fraction" here is 50%. The counts are then divided by effective integration time and multiplied by the count rate to flux conversion factor. The tabulated flux limits are in units of \( 10^{-17} \text{ erg cm}^{-2}\text{s}^{-1} \).

\(^d\) The 22 LAEs in central CDF-S are divided into two subsamples from their rest-frame EW. We found that when choosing EW(Lyα)\text{rest} < 400 Å, the subsample gets its maximum \( S/N \) at soft band as \( S/N = 2.73 \).

\(^e\) Two LAEs which show \( S/N > 1 \) and contribute about half of the marginal signal were excluded in the analysis.
Figure 3. Stacked X-ray image of LAEs in central CDF-S. Top: 22 LAEs with the interloper; bottom: 20 LAEs excluding the interloper and the LBG at $z = 4.4$; left: 0.5–2.0 keV band; right: 2.0–7.0 keV band. The effective exposure time of the stacked images is $\sim 36$ Ms for stacking 22 LAEs. The images are $\sim 20'' \times 20''$ in size, and the circles are centered on the stacking position and have a radius of 2''. The images were smoothed using a Gaussian kernel having FWHM = 1''2, which approximates a matched filter for point-sources detection given the $\sim 1''$ ACIS-I spatial resolution in these data. A marginal detection ($S/N = 2.4$) is seen at the top left panel, while excluding the two candidate LAEs which contribute about half of the marginal signal, the signal is no longer convincingly above the brightest noise peaks in the image (bottom left).

We performed Monte Carlo simulations to check the significance of the stacked signal. By randomly choosing 22 positions on the source-masked CDF-S image, then cumulating source and background counts, we obtained distributions of both the net counts and the soft band $S/N$ distribution (Figure 2). The net counts in the simulations agreed very well with a Poisson distribution having a mean of 74 (the expected total background counts in 22 apertures). Both the Monte Carlo simulation and the Poisson distribution gave a probability of $P(S/N < 2.4) = 99.83\%$ for obtaining a signal as strong as the observed one by chance. We also use a jackknife test on our stacking result (see the insets in Figure 2). This test is to validate the sample by using subsets of the data from which one or two sources have been excluded. The jackknife test shows that there are two sources that contribute about half of the stacked signal. We regard these as suspected X-ray sources.

We have recently obtained optical spectroscopy of $\sim 75\%$ of our LAE sample (Z. Y. Zheng et al. 2010, in preparation), using the IMACS spectrograph on the Magellan 6.5 m telescope, including the two LAE candidates (NB673-27 and NB673-62) which have $S/N_{\text{soft}} > 1$ in CDF-S and contributed about half of the X-ray signal. One (NB673-27) is confirmed as a low-redshift emission-line galaxy based on strong continuum flux blueward of the emission line. The other object (NB673-62) was confirmed as an LBG at $z = 4.4$ with little-to-no Ly$\alpha$ flux present. As our aim is to analyze the X-ray properties of the LAEs at $z = 4.5$, we excluded these two objects in the following stacking analysis. The remaining 20 LAEs in the central CDF-S had net and background counts of 14 and 61, which yields an $S/N = 1.4$, with an effective exposure time of 32.7 Ms. Our Monte Carlo simulations give a probability of $P(S/N < 1.4) = 96.03\%$ for obtaining a signal as the observed one by chance. The stacked X-ray image of the 20 LAEs is also plotted in Figure 3, which is less distinguishable as being above the noise. We thus give a $3\sigma$ upper limit on the average flux as $\langle f_{0.5-2} \rangle < 1.6 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ for the 20 LAEs in CDF-S. Including the ECDF-S data, the effective exposure increases to 48.9 Ms, implying a decreased $3\sigma$ ($1\sigma$) upper limit of average flux as $\langle f_{0.5-2} \rangle \lesssim 1.2 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ ($6.3 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$), corresponding to a luminosity of $\langle L_{0.5-2\text{keV}} \rangle \lesssim 2.4 \times 10^{42}$ erg s$^{-1}$ ($1.2 \times 10^{42}$ erg s$^{-1}$).

4. DISCUSSION

4.1. Quasar Contribution to LAEs

One LAE (J033127.2-274247) was detected in X-ray in ECDF-S, which was spectroscopically identified as a $z = 4.48$ unobscured AGN with Ly$\alpha$ luminosity of $L_{\text{Ly}$\alpha$} = 2.4 \times 10^{43}$ erg s$^{-1}$. This yields a direct high-$z$ Ly$\alpha$ quasar density of $2.7^{+4.5}_{-2.2} \times 10^{-6}$ Mpc$^{-3}$ (1$\sigma$ Poisson error; Gehrels 1986), which is consistent with X-ray luminosity function of AGNs at high redshift (the comoving space density for all spectral
type AGNs with $43 < \log L_\alpha < 45$ at redshift $4 < z < 5$ is $2.3 \times 10^{-6}$ Mpc$^{-3}$; Yencho et al. 2009). Since Chandra ACIS does not have uniform sensitivity across the field of view, it is hard to directly get the fraction of galaxies hosting a quasar with X-ray luminosity above some value of $L_X$ (e.g., see Figure 4, there are three LAEs with X-ray upper limit fluxes higher than the detected one in ECDF-S). If we only consider the LAEs in CDF-S, then the type 1 quasar fraction should be $\lesssim 5\%$ with $L_{0.5-2\text{keV}} > 2 \times 10^{43}$ erg s$^{-1}$.

Following Wang et al. (2004) and Malhotra et al. (2003), we compare the X-ray to Ly$\alpha$ flux ratios of LAEs with three known high-redshift type 2 quasars (see Figure 4), CDF-S 202 ($z = 3.7$; Norman et al. 2002), CXO 52 ($z = 3.288$; Stern et al. 2002), and HDFX 28 ($z = 2.011$; Dawson et al. 2003), and with a type 1 quasar template derived from Sazonov et al. (2004). The Ly$\alpha$-selected AGNs at $z = 4.5$ (a type 1 AGN, this work), at $z = 3.7$ (Ouchi et al. 2008), at $z = 3.1$ (a type 1 AGN from Gronwall et al. 2007 and one from Ouchi et al. 2008), and at $z = 2.25$ (nine AGNs; Nilsson et al. 2009) are also plotted in Figure 4. Since there are many values from different redshifts, Figure 4 is plotted in luminosity, and the soft X-ray luminosities are converted by assuming a photon index of $\Gamma = 2$. We only consider the soft band observations because they are more sensitive than the total band 0.5–10 keV. Also, high-redshift AGNs have effective power-law indexes are often different, as $\Gamma = 1.8$ (type 1 AGNs) or $\Gamma < 1$ (type 2 AGNs).

This introduces at least 50% difference in X-ray photometric flux normalization in the 0.5–10 keV band, but less than 10% in the 0.5–2 keV band (see Figure 2 of Wang et al. 2007). So in Wang et al. 2004, who choose $\Gamma = 2$ to get the $1\sigma$ upper limit of 0.5–10 keV band flux to Ly$\alpha$ ratio of the $z = 4.5$ LAEs at Large Area Lyman Alpha field, their type 2 AGN fraction of $< 4.8\%$ should be two times larger, as $< 9.6\%$ compared with type 2 AGN like CXO 52.

After scaling the X-ray luminosities with Ly$\alpha$ line luminosities, most of the Ly$\alpha$-selected AGNs are located within the region where type 1 and type 2 quasars are located. All the 20 LAEs in CDF-S are fainter in X-rays than HDFX 28, our type 1 quasar and Sazonov’s template, greater than 50% and 70% of them are fainter than CDF-S 202 and CXO 52. This indicates that about half of our LAEs at $z = 4.5$ can be type 2 quasars like CDF-S 202. By comparing with LAEs in ECDF-S region, we can find that only CDF-S allows us to resolve almost all of the type 1 AGN as well as some kind of type 2 AGN in our LAE sample. However, the average X-ray ($1\sigma$ upper limit) to Ly$\alpha$ ratio is 16 and 20 times below those of type 2 quasars such as CDF-S 202 and CXO 52, and 31, 40, and 78 times below our LAE-QSO, the type 1 quasar template and LAE-QSO at $z = 3.1$. This implies that $< 6.3\%$ of our LAEs can be type 2 AGNs like CXO 52 and CDF-S 202 and $< 3.2\%$ of our LAEs can be type 1 quasar like our LAE-QSO.

4.2. SFR from X-ray and Escaping Fraction of Ly$\alpha$ Photons

The average flux ($3\sigma$ upper limit) of our stacking analysis in the soft band corresponds to an average X-ray luminosity of $\langle L_{0.5-2\text{keV}} \rangle = 2.4 \times 10^{42}$ erg s$^{-1}$. If we assume that this is due to HMXBs, using the empirical relation between the 0.5–2 keV luminosity and SFR of the nearby star-forming galaxies (Ranalli et al. 2003), we derive the upper limit of SFR as
The lower limit of $f_{\text{esc},\alpha}$ could rise by an additional factor of 2–3 based on the recent SFR$_{\alpha}$ calibrations from Rosa-Gonzalez et al. (2009) and Mas-Hesse et al. (2008), which show that more X-ray photons are produced through star-forming activities.

### 4.3. Existence of Weak AGN in High-$z$ Star-forming Galaxies?

Any weak AGNs at high redshift should be captured in the narrowband surveys, provided their Ly$\alpha$ emission is strong enough. However, the AGN fractions among LAE samples reported in the literature refer to quasar fractions ($L_{\alpha} > 4 \times 10^{43} \text{ erg s}^{-1}$) for all samples at redshifts $z > 3$. This is mainly due to the inadequate depths of X-ray exposures, apart from the two CDFs. At $z \sim 2.1$, Guaita et al. did not report the X-ray luminosities, which can be as low as $10^{42} \text{ erg s}^{-1}$ in CDF-S. In the local universe, a large fraction of weak AGNs were reported based on multiple methods including X-rays (Finkelman et al. 2009). Although the LAEs of Gronwall et al. are located in the CDF-S where the X-ray luminosity is complete above $10^{42} \text{ erg s}^{-1}$, they only found one X-ray-detected LAE in ECFD-S, with $L_X = 2.8 \times 10^{41} \text{ erg s}^{-1}$. They used a stacking analysis to derive a $3\sigma$ upper limit of $3.8 \times 10^{41} \text{ erg s}^{-1}$ on the mean 0.5–2 keV luminosity of their LAEs. Their stacking is based on the old 1 Ms CDF-S, but when we repeated this stack using the 2 Ms CDF-S data, we also found no signal ($S/N < 1$). The new data decreased the $3\sigma$ upper limit luminosity to $3.1 \times 10^{41} \text{ erg s}^{-1}$ at $z \sim 3.1$. In contrast, our $z \approx 4.5$ stacking analysis gives a $3\sigma$ upper limit luminosity to $2.4 \times 10^{42} \text{ erg s}^{-1}$, where weak AGNs with luminosity of $\sim 10^{42} \text{ erg s}^{-1}$ might be hidden.

As mentioned in Section 1, AGNs could be the cause of high EWs of LAEs. The rest-frame EWs of two Ly$\alpha$-selected AGNs in CDF-S (see Figure 5) are $\sim 30 \text{ Å}$ (our work) and $\sim 100 \text{ Å}$ (Gronwall et al. 2007). In Subaru/XMM Deep Field survey, the two Ly$\alpha$-selected AGNs at $z = 3.7$ and 3.1 show rest-frame EWs of 60–70 Å. At $z = 2.25$, all the nine Ly$\alpha$-selected AGNs in the COSMOS field show a rest-
frame EW range of $25 \, \text{Å} < \text{EW}_{\text{rest}} < 160 \, \text{Å}$ (Nilsson et al. 2009). Although the intrinsic Lyα EW for AGN is uncertain, the rest-frame Lyα EWs of bright AGNs are typically in the range 50–150 Å (Charlot & Fall 1993, and references therein). Charlot & Fall (1993) show that AGNs which are completely surrounded by neutral hydrogen gas have rest-frame Lyα EWs of $827 \alpha^{-1}/(3.4)^{\alpha} \, \text{Å}$ (ignoring absorption by dust), where $\alpha$ is the spectral index blueward of the Lyα line. According to the template of Sazonov et al. (2004), $\alpha = 1.7$, which yields $\text{EW}_{\text{rest}} \approx 300 \, \text{Å}$. Considering the scattering in the IGM, Dijkstra & Wyithe (2006) show that the intrinsic distribution of EW should be centered on $\text{EW}_{\text{rest}} = 100 \, \text{Å}$ with $\sigma_{\text{EW}} = 30 \, \text{Å}$. We also check the three type 2 quasars in Figure 5. Only type 2 quasars like CXC 52 would be selected as an LAE candidate with a large EW; the other two are either too faint or have an insufficient narrowband-to-broadband contrast to be selected as LAEs. Prior to examination of the optical spectra of our LAEs, only from the view of X-ray and optical images, we found that LAEs in CDF-S with $\text{EW}_{\text{rest}}(\text{Ly} \alpha) < 400 \, \text{Å}$ dominate the signal as shown in Figure 3—indeed, this subsample has a soft band $S/N$ as high as 2.7 (see Table 1). This is mainly due to the two LAEs which show $S/N_{\text{soft}} > 1$ (Figure 2) and contribute about half of the net counts. As mentioned in Section 3.2, spectroscopic results show that the two LAE candidates are not Lyα galaxies at $z \approx 4.5$. Excluding these two objects from the stack, the subsample with $\text{EW}_{\text{rest}}(\text{Ly} \alpha) < 400 \, \text{Å}$ decreased to an $S/N$ of 1.7. This level of signal could be simply a Poisson fluctuation in the photon statistics. Alternatively, it may be due to some low-luminosity AGN in the sample (as seen in the low-redshift Lyα-selected AGNs at $z \approx 0.3$) or to star formation in the modest number of foreground and LBGs that enter the sample. Low-luminosity AGN entering our sample could be either type 1 or type 2. The type 1 AGNs are most likely confined to the $\text{EW}_{\text{rest}}(\text{Ly} \alpha) < 400 \, \text{Å}$ subsample, while the type 2 AGNs show a larger dispersion in both $\text{EW}_{\text{rest}}$ (Figure 5) and other properties (Figure 4). This can be explained by the distinct mechanisms for the extinction of Lyα photons and the X-ray absorption for type 2 AGN, e.g., extinction of Lyα photons by narrow line region and absorption of X-ray photons by dust torus. Then, most Lyα-selected AGNs are likely to be hidden in the low $\text{EW}_{\text{rest}}$ region.

5. CONCLUSION

Our work shows that X-ray observation is an effective method to identify AGN as well as foreground objects in LAE samples. One X-ray-detected LAE is spectroscopically confirmed as a type 1 quasar at $z = 4.5$. A stack of 22 other LAEs in the CDF-S field yields a marginal detection. However, 2 of these 22 sources contribute about half of the stacked X-ray signal, and these 2 were found to be a foreground interloper and an LBG at $z = 4.4$ without strong Lyα emission. The mean flux of the remaining 20 sources, while positive, is not significantly different from zero. Including the ECDF-S data, we obtain a $3\sigma$ upper limit on the average X-ray luminosity of $2.4 \times 10^{42} \, \text{erg} \, \text{s}^{-1}$. Compared to their average Lyα luminosity, we estimate that fewer than 3.2% (6.3%) of our LAEs could be high-redshift type 1 (type 2) AGNs, and those hidden AGNs might show low $\text{EW}_{\text{rest}}$. Using the relationship of X-ray emission and star-forming activity from low-redshift star-forming galaxies, we obtained an upper limit on the unobscured SFR of SFR $< 180–530 \, M_\odot \, \text{yr}^{-1}$. Compared to the SFR estimated from their average Lyα luminosity, we find a lower limit on the escape fraction of Lyα photons, $f_{\text{esc,Ly} \alpha} > 3\%–10\%$. Doubling the depth of the CDF-S X-ray observations is planned in 2010 and 2011 (see Chandra Electronic Bulletin 89). This will strengthen the power of X-ray diagnostics of LAEs, especially for revealing their unobscured SFR, for the new discovery of Lyα-selected quasars and weak AGN, and for excluding the low-redshift contamination.

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