NO X-RAY—BRIGHT TYPE II QUASARS AMONG THE Lyα EMITTERS

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ABSTRACT

The Lyα emitters found at $z = 4.5$ and 5.7 by the Large Area Lyman Alpha (LALA) survey have high equivalent widths in the Lyα line. Such lines can be produced by narrow-lined active galactic nuclei or by stellar populations with a very high proportion of young massive stars. To check for type II (i.e., narrow-lined) quasars, we obtained a deep X-ray image of 49 Lyα sources in a single field of the ACIS instrument on the Chandra X-Ray Observatory. None of these sources was detected with a 3σ limiting X-ray luminosity of $2.9 \times 10^{41}$ ergs s$^{-1}$. For comparison, the two known high-redshift type II quasars have luminosities of $4 \times 10^{43}$ ergs s$^{-1}$ before extinction correction. The sources remain undetected in stacked images of the 49 Lyα sources (with 6.5 Ms effective Chandra on-axis exposure) at 3σ limits of $4.9 \times 10^{42}$. The resulting X-ray–to–Lyα ratio is about 4–24 times lower than the ratio for known type II quasars, while the average Lyα luminosity of the LALA sample is between the two type II's. The cumulative X-ray–to–Lyα ratio limit is also below that of 90% of low-redshift Seyfert galaxies.

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

1. INTRODUCTION

A large population of high-redshift active galactic nuclei (AGNs) would have interesting implications both for the pace of black hole formation and growth in the universe and for cosmic background radiations from the gamma ray to the far-infrared. Of particular interest is the possibility of a large population of type II quasars, i.e., systems whose broad-line regions and soft X-rays are greatly attenuated by large column densities of gas and dust. Population synthesis models of AGNs that are built to explain soft and hard X-ray source counts and backgrounds predict that such objects comprise as much as 90% of the high-redshift quasar population (e.g., Gilli, Salvati, & Hasinger 2001). The first X-ray–selected type II quasars have recently been found (Norman et al. 2002; Stern et al. 2002). These type II quasars show prominent narrow Lyα emission lines, comparable in luminosity [(2–18) $\times 10^{42}$ ergs s$^{-1}$] to the Large Area Lyman Alpha (LALA) sample (>4 $\times 10^{42}$ ergs s$^{-1}$).

The equivalent widths of Lyα emitters selected using narrowband surveys tend to be large (Malhotra & Rhoads 2002, hereafter MR02; Kudritzki et al. 2000). The median equivalent width of the Lyα line is greater than 200 Å in a sample of 160 Lyα emitters at $z = 4.5$ and 18 at $z = 5.7$ (MR02; Rhoads & Malhotra 2001, hereafter RM01). Normal stellar populations can produce Lyα emission with equivalent width 240 Å or less (Charlot & Fall 1993), unless they have a top-heavy initial mass function, zero (or very low) metallicity, and/or extreme youth (age less than 10$^7$ yr). The high equivalent widths could also be explained if AGNs were present in our Lyα emitter sample. However, neither narrowband imaging nor spectroscopy shows evidence of broad emission lines, which rules out classical quasars. Inspired by the recent discovery of type II quasars, we use deep X-ray imaging to search for type II quasars among the Lyα emitters.

2. OBSERVATIONS

2.1. Optical Data and Sample Selection

The LALA survey comprises two fields, located in Boötes (at R.A. = 14$^h$25$^m$37$, \text{decl.} = +35^\circ52$ [J2000.0]) and in Cetus (at R.A. = 02$^h$05$^m$, decl. = $-04^\circ55$ [J2000.0]). Each field is 36$^\prime$ x 36$^\prime$ in size, corresponding to a single field of the 8192 $\times$ 8192 pixel Mosaic CCD cameras at the National Optical Astronomy Observatory’s 4 m telescopes. The X-ray observations described in this Letter are in the Boötes field. In this field, we have LALA survey data in a total of eight narrowband filters. Five are partially overlapping narrowband filters covering 4.37 $< z < 4.57$ for Lyα. There are also two non-overlapping filters of similar width covering 5.67 $< z < 5.80$ ($\lambda$, $\approx$ 8150 and 8230 Å). Imaging data reduction followed the methods described by Rhoads et al. (2000), and Lyα candidates were selected using criteria described by RM01. This resulted in Boötes field samples of $\approx$160 good candidates at $z \approx 4.5$ (see Rhoads et al. 2000; MR02) and 18 at $z \approx 5.7$ (RM01). The Chandra field was placed to maximize the number of large equivalent width sources within the Advanced CCD Imaging Spectrometer (ACIS-I) field of view.

2.2. Chandra Imaging

A total of 178 ks exposure, composed of two individual observations, was obtained using the ACIS on the Chandra X-Ray Observatory in very faint (VFAINT) mode. The first observation, with 120 ks exposure, was taken on 2002 April 16/17 (Chandra observation ID [ObsID] 3130). The second observation, with 58 ks exposure, was taken on 2002 June 9 (ObsID 3482). All four ACIS-I chips and ACIS-S2, ACIS-S3 chips were used, with the telescope aim point centered on the ACIS-I3 chip for each exposure. The aim point of ObsID 3130 is R.A. = 14$^h$25$^m$37.791, decl. = +35$^\circ$36′00″20′′ (J2000.0), and the aim point of ObsID 3482 is R.A. = 14$^h$25$^m$37.564, decl. = +35$^\circ$35′44″32′′, 16′ away from that of ObsID 3130. Because of their large off-axis angle during the observations, the ACIS-S chips have poorer spatial resolution and effective area than the ACIS-I chips. In this Letter, data from any ACIS-S CCD were then ignored.

Data reduction was done with the package CIAO 2.2.1. The level 1 data were reprocessed to clean the ACIS background for VFAINT mode observations and filtered to include only the standard event grades 0, 2, 3, 4, and 6. All bad pixels and columns were also removed. We excluded high background

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time intervals from level 2 files, leaving a net exposure time of 172 ks (120 ks from ObsID 3130 and 52 ks from ObsID 3482). Three images were extracted from the combined event file: a soft image (0.5–2.0 keV), a hard image (2.0–7.0 keV), and a total image (0.5–7.0 keV). The hard and total bands were cut at 7 keV, since the effective area of Chandra decreases above this energy and the instrumental background rises, giving a very inefficient detection of sky and source photons. The average offset between X-ray and optical images was obtained by comparing the X-ray source positions and their optical counterparts (whenever found). Such offset (0.5") has been corrected for all our analyses in this Letter. We ran WAVDETECT (Dobrzycki et al. 1999; Freeman et al. 2002) on the soft, hard, and total band images. A probability threshold of $1 \times 10^{-7}$ (corresponding to 0.5 false sources expected per image) and scales of 1, 2, 4, 8, and 16 pixels were used. The detection is down to a limiting flux of $1.6 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–2.0 keV band and $1.7 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ in the 2.0–10.0 keV band. Given the uncertainty on the value of the total background, we find that more than 65% of the hard X-ray background is resolved to a flux limit of $1.7 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ in the 2.0–10.0 keV band. The detailed results and detected X-ray sources will be published in a future paper (J. X. Wang et al. 2003, in preparation).

2.3. Nondetection of Individual Sources

Forty-nine of the Ly$\alpha$ sources were imaged by the Chandra exposure with different effective exposure times. For every X-ray source and Ly$\alpha$ source, we defined a circular source region centered at the source position and with radius $R_s$ set to the 95% encircled energy radius of Chandra ACIS point-spread function (PSF) at the position. Note that at a larger off-axis angle, we have a larger PSF size. Only one Ly$\alpha$ source overlaps any of the X-ray source regions. The 95% encircled energy radius of Chandra ACIS PSF at the overlapped position is 10".2, and the corresponding X-ray source and Ly$\alpha$ source are 7.5 apart, which is much larger than the 3 $\sigma$ positional error derived from the X-ray image (3.5"). The number of X-ray pixels encircled by all the X-ray–detected source regions is around 80,000, so the probability that one of the 49 Ly$\alpha$ sources fell in an X-ray source region is $\approx (8 \times 10^4) / (5 \times 10^4) \approx 49 \approx 78\%$. Thus, the possible coincidence of one X-ray source with one Ly$\alpha$ source is not statistically significant.

We also performed an X-ray photometry analysis of the 49 Ly$\alpha$ sources. We again used the 95% encircled energy radius $R_s$, (now centered on the Ly$\alpha$ coordinates) as the region to extract source photons and extracted the background from an annulus with $1.2R_s < R < 2.4R_s$, after masking out nearby sources. We also accounted for differences of exposure time between source regions and background regions (mainly due to CCD edge effects and bad columns). In the soft band (0.5–2.0 keV), the counts in the source regions for all 49 sources are less than the 90% significance level upper limits of the expected background, with net counts all less than 2.6. In total band (0.5–7.0 keV), except for one source with net count of 7.8, all other sources have net counts of less than 4 and confidence level less than 90%.

The detection of the only source with 7.8 net counts in total band is right at $2 \sigma$ level. Assuming a power-law spectrum with photon index of 1.4 (from the average spectrum of all sources in the field), this implies an X-ray flux of $6.3 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ in 0.5–10.0 keV. The source is detectable by WAVDETECT with a much lower threshold level ($10^{-4}$), and the distance between the center of the detected X-ray source and the Ly$\alpha$ source is 15.5, while the PSF value there is 9".

However, with a threshold level of $10^{-4}$, we expect 0.15 false X-ray sources (per X-ray image from WAVDETECT) within 15.5 of the 49 Ly$\alpha$ sources, so the statistical significance of the detection remains low. There is no optical continuum counterpart for the possible X-ray source in our broadband optical images. So if real, it should be the counterpart of a Ly$\alpha$ source with a rest-frame equivalent width of greater than 500 A.

We conclude that except one possible detection at the $2 \sigma$ level in total band, none of the Ly$\alpha$ sources are detected by the X-ray observations. Only upper limits of X-ray fluxes of the Ly$\alpha$ sources can be given. For the Ly$\alpha$ source nearest (1.8") to the axis of X-ray observation, there are no photons within $R_s$. The 3 $\sigma$ level upper limits of X-ray counts are 6.61 (Gehrels 1986), and the upper limits for X-ray fluxes (for power-law spectra with a photon index of 1.4) are $1.7 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ for the soft band and $4.7 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ for the total band (0.5–10.0 keV). If we use a photon index of 2, instead, the above two fluxes will change to $1.9 \times 10^{-16}$ and $3.3 \times 10^{-16}$, respectively. Other sources have higher upper limits because of the lower effective areas and larger PSF sizes.

2.4. Cumulative X-Rays from All the LALA Sources

The X-ray imaging data at the positions of all the Ly$\alpha$ sources were stacked, yielding an effective exposure time of 6.5 Ms (75 days). No source was detected in the stacked image in any band (Fig. 1). Since Ly$\alpha$ sources have different off-axis angles to the axis of Chandra observation, they have different PSF sizes at each position, making it hard to define a source region to do photometry. We just sum up the source counts extracted from each source region and the expected background counts derived from each background region. In the soft band, we have 55 counts in total in the source regions, and the expected background is 54.2. In the total band, these two numbers are 164 and 163.1, respectively. It is clear that we did not detect the sources in X-ray even after stacking them. The 3 $\sigma$ upper limits of soft and total band net counts are 26 and 42. Assuming a power-law spectrum with photon index of 1.4, we have 3 $\sigma$ upper limits of $1.8 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–2.0 keV band and $7.9 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–10.0 keV band. For a photon index of 2, these limits translate to $1.9 \times 10^{-17}$ and $5.5 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$.

3. DISCUSSION AND CONCLUSIONS

From the measurements of the X-ray background and from number counts of X-ray sources, one can argue that only a small fraction of Ly$\alpha$ emitters can be X-ray–bright type II quasars. Suppose a fraction $f$ of our sources were type II quasars, i.e., much like the CDF-S202 source and distributed in redshift span $\Delta z$. The known type II’s are at $z = 3.3$ and 3.7. If these sources and the LALA objects at $z = 4.5$ and 5.7 represent the same population, it would imply $\Delta z = 2.4$. The number counts of objects brighter than CDF-S202 and CXO52 in the hard band in one ACIS field is about 160, while there are 49 Ly$\alpha$ sources at $z = 4.47 \pm 0.1$ in the same solid angle. This implies immediately that not more than 27% of the LALA sources should be detectable in our X-ray survey. Even if we deem type II quasars irrelevant to this estimate, given the non-detection of LALA sources, Ly$\alpha$ sources have been found at $z = 3.1$ with number densities comparable to the LALA determinations (Kudritzki et al. 2000), making $\Delta z = 2.6$.

Assuming that we have a type II AGN at $z = 4.5$, with intrinsic photon index of 2 but heavily absorbed, $N_\text{abs} =$
10^{34} \text{ cm}^{-2}, H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = \frac{1}{5}, \text{and } \Omega_{\Lambda} = \frac{3}{5}. The best 3 \sigma upper limits of 0.5–7.0 keV band net count at individual LALA locations correspond to a type II AGN with 2.0–10.0 keV rest-frame intrinsic luminosity of 1.5 \times 10^{44} \text{ ergs s}^{-1}. For stacked images, this number is 2.5 \times 10^{40} \text{ ergs s}^{-1}. The rest-frame intrinsic luminosity of CDFS-202 is 8.0 \times 10^{44} \text{ ergs s}^{-1} (Norman et al. 2002) and 4.2 \times 10^{44} \text{ ergs s}^{-1} for CXO52 (Stern et al. 2001). See Table 1 for corresponding luminosities with no extinction correction applied.

However, if we were to scale the X-ray fluxes with Ly\alpha line flux, which in most cases is the only well-measured property of the LALA sources, we find that about 44 out of 49 sources would have been detected had they been like CDFS-S202. About three sources such as CXO52 would have been detected by these observations. The left panel of Figure 2 shows the comparison, in which the ratio of X-ray 3 \sigma upper limits to Ly\alpha line flux for LALA sources is shown as a histogram and the values of this ratio for the two known type II quasars are marked. The spread in the histogram is due to variation in X-ray flux sensitivity and the variation in Ly\alpha line strength. Also shown is this ratio for cumulative LALA source positions that are 4–24 times lower than either of the known type II quasars. The 3 \sigma upper limit of average X-ray flux from each source is 5.5 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} in the 0.5–10 keV band, compared to a few times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} for the two known type II quasars. Comparison with relatively lower luminosity low-redshift (z < 1) Seyfert galaxies and quasars drawn from the samples of Kriss (1984, 1985) shows that while individually the LALA upper limits are higher than the X-ray/Ly\alpha ratio for about half the low-z sample, the upper limits from the stacked LALA positions are lower than 90% of low-z sources (Fig. 2, right).

Assuming a power-law spectrum with photon index $\Gamma = 2$, the 3 \sigma upper limit of 0.5–2.0 keV flux on the average LALA sources corresponds to an X-ray luminosity of 4.2 \times 10^{42} \text{ ergs s}^{-1} at z = 4.5 (for either 0.5–2.0 keV rest frame or 2.0–8.0 keV rest-frame bandpass, $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = \frac{1}{5}, \Omega_{\Lambda} = \frac{3}{5}$). The Lyman break galaxies (LBGs) at z ≈ 3 have an average luminosity of 6 \times 10^{40} \text{ ergs s}^{-1} (after excluding the four known AGNs), which is consistent with their being starbursts with star formation rates of about 60 $M_\odot$ yr$^{-1}$ (Nandra et al. 2002; Brandt et al. 2001). Clearly, our observations are not sensitive enough to detect starbursts (nor were they designed to be). Taking the difference in star formation rates between Ly\alpha-selected galaxies and LBGs into account and adopting the LBG value for the ratio of star formation to X-ray emission, we should expect an average X-ray luminosity of $\approx 10^{39} \text{ ergs s}^{-1}$.

Could some of the Ly\alpha sources still be AGNs? We have demonstrated that X-ray–bright quasars are at most a minority of the LALA objects. Our composite nondetection implies that even at the 3 \sigma level, only a few percent of LALA sources could resemble CDF-S202, and less than 25% could resemble CXO52. The most plausible way to have luminous AGNs hid-

![Stacked Chandra images of 49 Ly\alpha sources. Left: Soft band (0.5–2.0 keV). Right: Total band (0.5–7.0 keV). The effective exposure time of the stacked images is 6.5 Ms. The images are 40 × 40 pixels in size, and the circles are centered on the stacking position and have a radius of 5 pixels; 1 pixel = 0.5492. The images were smoothed using a program provided by CIAO.](Image)
ing in the LALA sample without violating this constraint is to suppose that they are Compton thick, so that even relatively hard X-rays are obscured. Thermal emission from the obscuring dust would render these objects detectable in the infrared or submillimeter.

Another test relies on optical spectra. The Lyα line is found to be narrow (less than 500 km s⁻¹) in all our spectroscopically confirmed Lyα emitters (e.g., Rhoads et al. 2000, 2003), which is narrower than the typical physical line widths of even type II quasars. For the larger fraction of Lyα sources that are photometrically selected using narrow bands 80 Å wide, we can also rule out velocities greater than 3700 km s⁻¹. Steidel et al. (2002) find at least one case of narrow-lined AGNs in their LBG sample with X-ray luminosity <5 × 10⁴⁷ erg s⁻¹. Their identification of this source as an AGN is based on the detection of narrow lines of N v, C iv, He ii, and C iii in emission. None of the spectra of Lyα emitters shows these lines. In conclusion, we find no evidence for AGNs among the Lyα emitters found in the LALA survey.

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Fig. 2.—Comparison of X-ray–to–Lyα flux ratios. The left panel shows the comparison of this ratio for the 49 Lyα emitters at z = 4.5 from the LALA sample with high-redshift type II quasars. We use 3σ upper limits derived for the total band, since there are no detections. The vertical bars mark the observed ratio for the two known high-redshift type II quasars (see text) and the 3σ upper limit for all the Lyα sources stacked. Since the photon indices of the known type II quasars are different from the assumed photon index for the undetected Lyα emitters, we have adjusted the X-ray fluxes in all sources as if the photon index were γ = 2. The right panel shows comparison with low-redshift (z < 1) Seyfert galaxies and quasars (Kriss 1984, 1985). The solid histogram is as in the left panel, except that we plot the soft band (0.5–2.0 keV, observed; 2.75–11 keV, rest), and the dashed histogram is the comparison sample from Kriss (1984, 1985) adjusted to rest-frame 2.75–11 keV. The 3σ upper limit on the stacked Lyα sources is shown as a vertical bar.