X-RAY CONSTRAINTS ON THE Lyα ESCAPE FRACTION

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ABSTRACT

We have co-added the X-ray flux of all known Lyα emitters (LAEs) in the 4 Ms Chandra Deep Field South (CDF-S) region, achieving the tightest upper limits yet on the X-ray to Lyα ratio. We use the X-ray data to place sensitive upper limits on the average unobscured star formation rate (SFRX) in these galaxies. A very small fraction of Lyα galaxies in the field are individually detected in the X-rays, implying a low fraction of active galactic nucleus activity. After excluding the few X-ray-detected LAEs, we stack the undetected LAEs located in the 4 Ms CDF-S data and 250 ks Extended CDF-S (ECDF-S) data, and compute a 1σ upper limit on SFRX < 1.6, 14, 28, 28, 140, 440, 880 M⊙ yr⁻¹ for LAEs located at z = 0.3 and z = 2.1, 3.1, 3.2, 4.5, 5.7, and 6.5, respectively. The upper limit of SFRX can be then compared to SFRLyα derived from Lyα line and thus can constrain on the Lyα escape fraction (fLyα). The fLyα from X-ray at z = 0.3 is substantially larger than that from UV or Hα. Three X-ray-detected LAE galaxies at z = 0.3 show fLyα ~ 3%−22%, and the average Lyα escape fraction from stacking the X-ray-undetected LAEs show fLyα > 28% at 3σ significance level at the same redshift. We derive a lower limit on fLyα > 14% (84% confidence level, 1σ lower limit) for LAEs at redshift z = 2.1 and z = 3.1−3.2. At z > 4, the current LAE samples are not of sufficient size to constrain SFRX well. By averaging all the LAEs at z ≥ 2, the X-ray non-detection constraints fLyα < 17% (84% confidence level, 1σ lower limit), and rejects fLyα < 5.7% at the 99.87% confidence level from 2.1 < z < 6.5.

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

Online-only material: color figures

1. INTRODUCTION

Lyα emission, the 1216 Å (n = 2 → 1) transition of hydrogen in emission, is a prominent tracer of ionizing photons produced by young stars. This line can carry up to ~6% of the bolometric luminosity of a star-forming galaxy (Partridge & Peebles 1967), therefore it is an easy handle for detection of both star-forming galaxies and active galactic nuclei (AGNs, where Lyα emission is powered by the ionizing photons produced at the accretion disk around the central massive black hole) at redshifts z > 2. The Lyα line-search technique has been used successfully to identify samples of high-redshift galaxies for over a decade, using narrowband images (e.g., Cowie & Hu 1998; Rhoads et al. 2000, 2003; Malhotra & Rhoads 2002; Gawiser et al. 2007; Finkelstein et al. 2008, 2009c; Guaita et al. 2010) and spectroscopic surveys (e.g., Pirzkal et al. 2004; Deharveng et al. 2008; Martin et al. 2008; Rhoads et al. 2009; Blanc et al. 2011). There are thousands of photometrically selected Lyα emitters (hereafter LAEs), with hundreds of spectroscopic confirmations (e.g., Hu et al. 2004; Dawson et al. 2007; Wang et al. 2009) at redshifts ranging from z = 0.3 (Deharveng et al. 2008) to z = 7 (Iye et al. 2006).

Since Lyα line searches have achieved notable success in identifying high-redshift star-forming galaxies, it is very important to understand the radiation transfer of the Lyα emission line. However, interpreting the Lyα line is not trivial, because Lyα photons are resonantly scattered when they interact with the surrounding neutral hydrogen in the interstellar medium (ISM). These radiative transfer effects can be quite complex when considering the presence of dust in a multiphase and moving ISM (Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2009c), and require empirical study of the fraction of Lyα photons which can escape the ISM. Indeed, empirical results on the Lyα escape fraction offer one of the better tools for probing the physics of Lyα escape, which is determined on spatial scales that are usually unresolved in distant or nearby galaxies. On the theoretical side, semianalytical models of LAE populations by Le Delliou et al. (2005) assume a constant escape fraction of fesc = 0.02, and hydrodynamical models of LAEs at z ~ 3 predict fesc = 0.05–0.1 (Nagamine et al. 2010; Shimizu et al. 2011).

On the observational side, to measure the fraction of Lyα photons escaping the ISM (hereafter the Lyα escape fraction), we often require a flux measurement in ultraviolet (UV) continuum or a non-resonant recombination line, such as Hα, and a dust extinction value. The dust-corrected UV luminosity or Hα luminosity, like the intrinsic Lyα luminosity, is mainly contributed by young stars, thus connected to the intrinsic star formation rate (SFR). Recent constraints at z ~ 0.3 (Atek et al. 2009) and at z ~ 2.25 (Hayes et al. 2010) are based on the line ratio between Hα and Lyα. With the optical spectroscopic observation of Galaxy Evolution Explorer (GALEX) selected LAEs, Atek et al. (2009) showed that the Lyα escape fractions span a wide
range (from $f_{\text{esc}} \sim 0.5\%$ to 100\%) and decrease with increasing dust extinction. Hayes et al. (2010) estimated an average Ly$\alpha$ escape fraction of $\sim 5\%$ with a double blind survey targeting Ly$\alpha$ and H$\alpha$ at $z = 2.25$. With the dust-corrected UV emission of 98 LAEs at $z \approx 1.9$–3.8 detected through integral-field spectroscopy survey, Blanc et al. (2011) got a median Ly$\alpha$ escape fraction of 29\%. However, the escape fractions estimated from both of these methods are sensitive to the dust extinction law. For example, under the case B recombination, if we ignore the resonant scattering and velocity field in the gas or ISM geometry, the Ly$\alpha$ escape fraction is presented as $f_{\text{esc}} = 10^{-0.4k_{\text{Ly}}E(B-V)}$ (Atek et al. 2009), and the extinction coefficient at Ly$\alpha$ wavelength goes from $k(1216) \approx 9.9$ to 12.8 for Cardelli et al. (1989) and Calzetti et al. (2000) laws, respectively. This will lead to a factor of two difference in the inferred $f_{\text{esc}}$ when $E(B-V) \gg 0.3$. Meanwhile, the escape fractions estimated here also depend on the selection methods of LAEs. At $z \sim 0.3$, the LAEs are selected from a spectroscopic follow-up of FUV dropouts (Atek et al. 2009), so the escape fractions here refer to a subsample of dropout galaxies at that redshift. At $z \sim 2.25$, the average Ly$\alpha$ escape fraction is estimated from 18 LAEs and 55 H$\alpha$ emitters, and only 6 have both Ly$\alpha$ and H$\alpha$ detection (Hayes et al. 2010). So the escape fraction at $z \sim 2.25$ estimated by Hayes et al. (2010) is a global Ly$\alpha$ escape fraction for all galaxies at that redshift. The narrowband surveys for high-z LAEs can be designed to use the same criteria, e.g., the threshold equivalent width of EW$_{\text{rest}}$(Ly$\alpha$) $\geq 20$ Å and the Ly$\alpha$ line flux limit estimated from narrowband and broadband images, however, we should note that the Ly$\alpha$ escape fraction is dependent on the choice of the threshold equivalent width, and the narrowband exposure depth. Shallower narrowband surveys tend to select bright LAEs, which may have smaller Ly$\alpha$ EWs (e.g., Ando et al. 2006), and a decrease in the value of threshold equivalent width will contain more objects with little-to-no Ly$\alpha$ fluxes as well as interlopers.

X-ray photons, especially hard X-ray photons, can give an extinction-free measurement of star formation in galaxies. First, the X-ray emission of high-redshift star-forming galaxies are mainly from supernovae, hot interstellar gas (i.e., $T > 10^6$–10$^7$ K), and high-mass X-ray binaries (HMXBs), all of which trace star formation ongoing in the last few million years. Nandra et al. (2002), Grimm et al. (2003), Ranalli et al. (2003), and Gilfanov et al. (2004) have shown a linear correlation between $L_X$ and SFR. Calibration with the total SFR from far-infrared (FIR) and ultraviolet (UV) bands for local and high-$z$ ($z \sim 1$ and $z \sim 3$) star-forming galaxies (in the Chandra Deep Field North and South, CDF-N and CDF-S, where the deepest X-ray observations exist) shows relations consistent with Ranalli et al. (2003)\footnote{Ranalli et al. (2003) had calibrated the relations between X-ray luminosities and radio/FIR luminosities, and converted to global SFR (referred to stars with $M > 5 M_\odot$ and Salpeter’s initial mass function (IMF)) following Condon (1992, radio luminosities) and Kennicutt (1998, FIR luminosities).}:

$$SFR_X = 2.2 \times 10^{-40} (L_{\text{0.5–2}}/\text{erg s}^{-1}) M_\odot \text{yr}^{-1}.$$  
$$SFR_X = 2.0 \times 10^{-40} (L_{\text{2–10}}/\text{erg s}^{-1}) M_\odot \text{yr}^{-1}.$$ (1)

Second, X-rays penetrate a typically dusty ISM much more easily than the UV light. For example, a column density of $>10^{22}$ cm$^{-2}$ is required to attenuate 2 keV X-rays by a factor of two. The corresponding reddening would be $E(B-V) = 1.7$ mag, corresponding to $A_V \approx 5$ mag and $A_{UV} \gtrsim 10$ mag, or a factor of $10^4$, based on ratios of dust to gas from either our

Galaxy ($E(B-V) = 1.7 \times 10^{-22}$ mag cm$^2$ atoms$^{-1}$) or from a set of three gravitationally lensed galaxies at high redshift ($E(B-V)/N_H = (1.4 \pm 0.5) \times 10^{-25}$ mag cm$^2$ atoms$^{-1}$; Dai et al. 2006).

In this paper, we present an independent analysis of the Ly$\alpha$ escape fraction at $z \sim 0.3$, $z \sim 1$, and $2 < z < 6.5$, using X-ray emission as a tracer of the intrinsic SFR. We use the new 4Ms Chandra X-ray image in the CDF-S, which includes LAEs at $z \lesssim 0.3$ and 1.0 selected by GALEX, and ground-based narrowband-selected LAEs at $z = 2.1, 3.1, 3.15, 4.5, 5.7, \text{and } 6.5$. By comparing the ratio of derived SFRs from observed Ly$\alpha$ line flux and X-ray, we will perform an independent measurement of the Ly$\alpha$ escape fraction for LAEs. The optical samples and X-ray data are presented in Section 2, and the X-ray detection and stacking results on LAEs are presented in Section 3. The results and discussion on X-ray-constrained Ly$\alpha$ escape fraction are presented in Sections 4 and 5, respectively.

2. OPTICAL AND X-RAY DATA

In the CDF-S region, samples of LAEs have been observed at various redshifts, including LAEs at $z = 0.195$–0.44 and $z = 0.65$–1.25 through GALEX grism spectroscopy (Deharveng et al. 2008; Cowie et al. 2010, 2011), and ground-based narrowband imaging selected LAEs at $z = 2.1$ (Guaita et al. 2010), $z = 3.1$ (Gronwall et al. 2007; R. Ciardullo et al. 2011), $z = 3.15$ (Nilsson et al. 2007), $z = 4.5$ (Finkelstein et al. 2009c), $z = 5.7$ (Wang et al. 2005), and $z = 6.5$ (J. E. Rhoads et al., in preparation). The GALEX LAEs were confirmed by ground-based optical spectroscopy (Cowie et al. 2010, 2011). At higher redshift ($z > 2$), all the narrowband-selected samples typically have a spectroscopic confirmation fraction greater than 70\% (Dawson et al. 2007; Gawiser et al. 2007; Wang et al. 2009). In this paper, we focus on LAEs covered in the CDF-S proper region. The number of LAEs at each redshift and their stacked X-ray properties are presented in Tables 1 and 2.

The 4Ms Chandra Advanced CCD Imaging Spectrometer (ACIS) exposure of the CDF-S is composed of 52 individual ACIS-I observations, 9 of which were obtained in 2000, 12 from 2007 September to November, and 31 from 2010 March to July. The event-2 file and exposure-map files are available at the Chandra Web site (http://cxc.harvard.edu/cdof/cdfs.html). To search for potential X-ray counterparts for our LAEs, we use the 4Ms CDF-S catalog published by Xue et al. (2011) for the following source cross-match and source-masking processes.

3. X-RAY INDIVIDUAL DETECTION AND STACKING PROCEDURE

3.1. Individual Detections in Chandra Images

We search for X-ray counterparts for individual LAEs within a 2$''$ radius. Among LAEs selected in the 4Ms CDF-S region using the GALEX FUV channel (which covers Ly$\alpha$ at $0.195 < z < 0.44$), three of six (found at 0.2 $< z < 0.37$) are detected in X-rays. These three have relatively modest luminosities $L_{2–10keV} < 10^{42}$ erg s$^{-1}$, and have been classified as galaxies from their optical spectra (Cowie et al. 2010, 2011). Their UV and X-ray properties are presented in Table 1. Note that all three detected galaxies show a soft-band X-ray detection, while their hard-band luminosities are upper limits, but remain consistent with their soft-band luminosities under the $\Gamma = 2$ assumption. For Ly$\alpha$ galaxies selected in the GALEX NUV channel (which covers Ly$\alpha$ at 0.65 $< z < 1.2$), the corresponding
number is four X-ray detections out of five objects in the 4 Ms Chandra coverage. These four objects have X-ray luminosities $L_{2-10\ keV} > 6 \times 10^{43}\ erg\ s^{-1}$ and can be classified as AGNs.

X-ray counterparts have previously been detected for a small fraction ($<5\%$) of the LAEs at higher redshifts. Guaita et al. (2010) detected X-rays from 10 of their 216 $z = 2.1$ LAEs in the Extended CDF-S (ECDF-S) region, using the 2 Ms Chandra image for those LAEs in the central CDF-S (Luo et al. 2008) and the 250 ks Chandra image (Lehmer et al. 2005) for those in the wider ECFD-S. Gronwall et al. (2007) and R. Ciardullo et al. (2011, in preparation) selected 278 LAE candidates at $z > 2$ and found no new X-ray detection with the 4 Ms Chandra exposure.

We calculate the X-ray signal-to-noise ratio (S/N) for the X-ray non-detected LAEs, all of which show SFR$_{\alpha} \sim 10^{43}\ erg\ s^{-1}$ (Gehrels 1986), where $S/N$ is the net counts 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 $10^{-17}\ erg\ cm^{-2}\ s^{-1}$. The SFR$_X$ for all LAEs at $z > 2$ are converted with the relationship of Ranalli et al. (2003) from 1$\sigma$ upper limit on $L_{2-10\ keV}$.

Notes.

$^a$ Number of LAEs located in central CDF-S and ECDF-S region for stacking analysis. Reference: LAEs at $z \sim 0.3$ from Deharveng et al. (2008) and Cowie et al. (2011), $z \sim 1$ from Cowie et al. (2011), $z = 2.1$ from Guaita et al. (2010), $z = 3.1$ from Gronwall et al. (2007) and R. Ciardullo et al. (2011, in preparation), $z = 3.15$ from Nilsson et al. (2007), $z = 4.5$ from Finkelstein et al. (2009c), $z = 5.7$ from Wang et al. (2005), and $z = 6.5$ from J. E. Rhoads et al. (in preparation).

$^b$ Notice that the number of counts are extracted from their 50% PSFs and summed up, and not corrected for the apertures.

$^c$ The SFR$_X$ are calculated with $L_{2-10\ keV}$ relation of Ranalli et al. (2003).

$^d$ Due to the rare number of GALEX-selected LAEs, we enlarge the selection area to off-axis angle $\leq 9^\prime$ for $z \sim 0.3$ and 1. Only 2 $z \sim 1$ LAEs were located in ECDF-S region, and did not show any X-ray detection.
count rate to flux, the full and hard bands were extrapolated to the standard upper limit of 10 keV. All X-ray fluxes and luminosities presented in this paper have been corrected for Galactic absorption (Dickey & Lockman 1990). The 4 Ms CDF-S data reach on-axis sensitivity limits of X-ray luminosity $L_{\text{X}}$ at various flux fractions were based on a polynomial (parameterized by the maximum off-axis angle $\theta$ for inclusion in the sample), and the S/N ratios of the stacked signals are also plotted in the lower part. Figure 1, we can see that the mean luminosity can be better constrained by excluding LAEs with larger off-axis angles. This is mainly because the Chandra ACIS has much larger PSF and much lower collection area at larger off-axis angles, so that including those LAEs with large off-axis angles would bring strong fluctuations to the signal without necessarily increasing the S/N. In the following study, we exclude those LAEs with ACIS off-axis angle above $6^{\circ}$, and the number of LAEs used for stacking and their stacked results at relative redshifts are presented in Table 2.

4. RESULTS AND DISCUSSION

4.1. SFR–Luminosity Correlation

We adopted the relations established at $z = 0$ to convert luminosities to SFRs for our LAE samples: Kennicutt (1998) for conversion of the $L_{\text{Ly} \alpha}$ luminosity (assuming case B conditions and Salpeter's initial mass function (IMF) with mass limits 0.1 and 100 $M_\odot$), and Ranalli et al. (2003) for the X-ray luminosities:

$$SFR_{\text{Ly} \alpha} = 9.1 \times 10^{-43} L_{\text{Ly} \alpha} M_\odot \text{yr}^{-1},$$

$$SFR_{\text{X}} = 2.0 \times 10^{-40} L_{2-10} M_\odot \text{yr}^{-1}. \quad (2)$$

Note that these relations might give uncertainties as well as the factor of ~2 dispersion (e.g., dust extinction, burst age, and IMF) when applied to individual sources. However, previous X-ray stacking works (e.g., Nandra et al. 2002; Seibert et al. 2002; Lehmer et al. 2005; Reddy & Steidel 2004) have proved reasonable $L_X$–$SFR_X$ connection on local starburst galaxies and $1 \lesssim z \lesssim 3$ Lyman break galaxies (LBGs).

Table 1 shows the SFR estimates based on the $L_{\text{Ly} \alpha}$ (“$SFR_{\text{Ly} \alpha}$”) luminosity and 2–10 keV (“$SFR_X$”) luminosity for three $z \sim 0.3$ $GALEX$-selected LAEs. Table 2 shows the $SFR_X$ estimates from the stacking signal of the X-ray-undetected LAEs at $z \sim 0.3$, 1, 2, 3, 4, 5, 5.7, and 6.5. It can be seen that $z \gtrsim 4.5$, the $SFR_X$ limits are weaker due to a larger luminosity distance and comparatively smaller Ly$\alpha$ sample size.

Note that low-mass X-ray binaries (LMXBs) can also contribute to X-ray emission from galaxies, but they have longer evolutionary timescales (on the order of the Hubble time), and therefore track the integrated star formation history of galaxies (i.e., the total stellar mass). Where LMXBs are important, e.g., for nearby normal galaxies (Colbert et al. 2004) and luminous infrared galaxies (Lehmer et al. 2010), the X-ray luminosity can be fitted as a function of both galaxy stellar mass and SFR:

$$L_{2-10 \text{keV}} = \alpha \times M_\star + \beta \times SFR_X. \quad (3)$$

Here, $L_X$, $M_\star$, and $SFR_X$ have units of erg s$^{-1}$, $M_\odot$, and $M_\odot$ yr$^{-1}$, respectively, and constants $\alpha/(10^{39} \text{erg s}^{-1} M_\odot^{-1}) = 1.51$ and 0.91, and $\beta/(10^{39} \text{erg s}^{-1} M_\odot^{-1} \text{yr}^{-1}) = 0.81$ and 1.62 for Colbert et al. (2004) and Lehmer et al. (2010), respectively. The differences in the parameters might be introduced by the high obscuration in luminous infrared galaxies. We can see from these relations, the contribution of X-ray emission from LMXBs can be ignored in actively star-forming galaxies, which often have low dust extinction ($0 \lesssim E(B-V) \lesssim 3$), lower stellar mass ($M_\star \lesssim 10^9 M_\odot$), and more active star formation ($SFR_X \gtrsim 1 M_\odot \text{yr}^{-1}$) than local galaxies (e.g., Guaita et al. 2011). In terms of the specific star formation rate (SSFR), which is defined as the ratio of SFR to stellar mass, we can neglect the LMXB term whenever $\beta \times SFR_X \gg \alpha \times M_\star$, so that SSFR $\gg \alpha/\beta \sim 10^{-9}$ yr$^{-1}$, i.e., whenever the typical stellar ages are much below 1 Gyr.

The $SFR_X$ of high-redshift star-forming galaxies was measured by Nandra et al. (2002), who detected a stacked X-ray signal of $z \sim 3$ LBGs in the Hubble Deep Field North. The average X-ray luminosity of $z \sim 3$ LBGs is $L_{2-10} = 3.4 \times 10^{41}$ erg s$^{-1}$ (6$\sigma$ significance), implying an $SFR_X = 64 \pm 13 M_\odot$ yr$^{-1}$, in excellent agreement with the extinction-corrected UV

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10 PSF radii at various flux fractions were based on a polynomial approximation of the off-axis ACIS-I PSF, as discussed in http://cxc.harvard.edu/chandra-users/0192.html.
The LAEs Samples Used in This Work and Their Average SFRs and Average Ly$\alpha$ Escape Fractions in the 4 Ms CDF-S Region

| Redshift | $\mathrm{Ig} L(\text{Ly}\alpha)\text{[unl]}^b$ | EW(Ly$\alpha$)[rest,lim]$^b$ (Å) | SFR$^a_X$ | SFR$^{1250}_{\text{Ly}\alpha}$ (M$_\odot$ yr$^{-1}$) | SFR$^{1250}_{\text{UV}}$ | $A^{1250}_{0}$ (mag) | $f_{\text{esc}}^{1250}/(\text{Ly}\alpha)^a$ | $f_{\text{esc}}^{1250}/(\text{Ly}\alpha)^a$ |
|----------|---------------------------------|---------------------------------|------------|-----------------|-----------------|-----------------|---------------------|---------------------|
| 0.217$^a$ | ...                             | ...                             | 1.0        | 0.22            | 2.9             | 1.25 ± 0.35     | 3.3$^{+1.2}_{-1.0}$ | 22.0                |
| 0.220$^a$ | ...                             | ...                             | 10.9       | 0.3             | ...             | ...             | ...                 | 2.8                 |
| 0.374$^a$ | ...                             | ...                             | 21.7       | 2               | 6.2             | 2.00 ± 0.00     | ...                 | 5.1                 |
| >0.3      | 41.2                            | 20                              | <1.6       | 0.9             | ...             | ...             | ...                 | >56.3               |
| >1.0      | 42.6                            | 20                              | <84        | 5.7             | ...             | ...             | ...                 | >6.8                |
| 2.1       | 41.8                            | 20                              | <14        | 1.9             | 2.4             | 1.2$^{+0.5}_{-1.2}$ | 26$^{+13}_{-9}$ | >14                 |
| 3.1       | 42.1                            | 20                              | <28        | 2.6             | 5.3             | <0.6             | 28$^{+21}_{-19}$ | >9.4                |
| 3.2       | 42.9                            | 22                              | <28        | 2.3             | 4.2             | 0.8$^{+0.3}_{-0.5}$ | 26$^{+16}_{-6}$ | >8.3                |
| 4.5       | 42.6                            | 16                              | <439       | 6.0             | 24              | 1.5$^{+3.1}_{-1.1}$ | 6$^{+3}_{-5}$ | >4.3                |
| 5.7       | 42.8                            | 11                              | <439       | 5.5             | ...             | ...             | ...                 | >1.3                |
| 6.5       | ...                             | ...                             | <876       | 5               | ...             | ...             | ...                 | >0.57               |

Notes.

$^a$ The three LAEs at $z \sim 0.3$ are individually detected, and the other results of LAEs are stacked or averaged.

$^b$ The selection limits on L(Ly$\alpha$) and EW(Ly$\alpha$) for our sample. Note that the LAEs at $z \sim 0.3$ and 1 are selected through broadband dropout first, then applied spectroscopic observation. Their EW(Ly$\alpha$) are estimated from their optical spectra, and select EW$\text{rest} > 20$ Å for comparison with LAEs at higher redshifts. Other surveys for LAEs at $z > 2$ are selected through narrowband selection, with nearly same selection criteria on EW(Ly$\alpha$). Although LAEs at $z = 4.5$ show threshold of Ly$\alpha$ EW $> 16$ Å, only <6% of them have EW $> 20$ Å.

$^c$ The SFR$^a_X$ for all LAEs at $z > 2$ are converted with the relationship of Ranalli et al. (2003) from 1σ upper limit on $L_{2–10keV}$. The SFR$^{1250}_{\text{Ly}\alpha}$ and SFR$^{1250}_{\text{UV}}$ are converted with Kennicutt (1998).

$^d$ The $\lambda_{1250}$ were converted from the dust properties of different SED fitting papers under Calzetti et al. (2000) dust law: Finkelstein et al. (2011) for $z \sim 0.3$ LAEs, Guaita et al. (2011) for $z \sim 2$ LAEs, Gawiser et al. (2007) for $z \sim 3.1$ LAEs, Nilsson et al. (2007) for $z \sim 3.5$ LAEs, and Finkelstein et al. (2008) for $z \sim 4.5$ LAEs.

$^e$ See the text (Sections 4.2 and 4.4) for the definitions of the Ly$\alpha$ escape fraction estimated from extinction-corrected UV flux and X-ray luminosity.

estimates. In the same field, Laird et al. (2006) found the average SFR$^a_X$ of 42.4 ± 7.8 $M_\odot$ yr$^{-1}$ for $z \sim 3$ LGBs. Additionally, Lehmer et al. (2005) reported the average SFR$^a_X$ of ~30 $M_\odot$ yr$^{-1}$ for $z \sim 3$ LGBs in CDF-S (old 1 Ms Chandra exposure). Lehmer et al. also stacked LGBs in CDF-S at $z \sim 4$, 5, and 6, and did not obtain significant detections (<3σ), deriving rest-frame 2.0–8.0 keV luminosity upper limits (3σ) of 0.9, 2.8, and 7.1 × 10$^{-41}$ erg s$^{-1}$, corresponding to SFR$^a_X$ upper limits of 18, 56, and 142 $M_\odot$ yr$^{-1}$, respectively. Note also that a ~3σ stacking signal of the optically bright subset (brightest 25%) of LGBs at $z \sim 4$ was detected, corresponding to an average SFR$^a_X$ of ~28 $M_\odot$ yr$^{-1}$. Reddy & Steidel (2004) examined the stacked radio and X-ray emission from UV-selected spectroscopically confirmed galaxies in the redshift range 1.5 $\lesssim z \lesssim 3.0$. Their sample showed SFR$^a_X$ ~ 50 $M_\odot$ yr$^{-1}$, and found a consistent SFR$^a_X$/SFR$_{\text{UV} \text{[unconv]}}$ ~ 4.5–5.0 for galaxies over the redshift range 1.5 $\lesssim z \lesssim 3.0$. These studies demonstrate the value of stacking the deepest X-ray observations to measure star formation activity, with little sensitivity to dust.

The LAEs’ X-ray emission should be directly connected to the intrinsic SFR, since LAEs are thought to be less massive and much younger than LGBs at high redshift (e.g., Venemans et al. 2005; Pirzkal et al. 2007; Finkelstein et al. 2008, 2009c), and the AGN fraction in LAEs is also very small (<5%, e.g., Zheng et al. 2010). An X-ray detection could give us a more accurate unbiased SFR estimate, or more properly an upper limit, since faint AGNs may contribute to the X-ray flux. 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 ($L_{2–8\text{keV}} < 2.8 \times 10^{42}$ 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 much deeper 2 Ms CDFS-S field and a larger 250 ks ECFDS-S field, Guaita et al. (2010), Gronwall et al. (2007), and Zheng et al. (2010) found a smaller 3σ upper limit on the luminosity of ~1.9 × 10$^{41}$ erg s$^{-1}$, 3.1 × 10$^{41}$ erg s$^{-1}$, and 2.4 × 10$^{42}$ erg s$^{-1}$ at $z = 2.1$, $z = 3.1$, and $z = 4.5$, respectively. These imply upper limits of unobscured average SFR$^a_X < 43$, 70, and 290 $M_\odot$ yr$^{-1}$, respectively. The above results are not surprising, since we would expect that LAEs have lower SFR rates than LGBs.

4.2. $f_{\text{esc}}^{1\text{Ly}\alpha}$ from X-Rays

The average $f_{\text{esc}}^{1\text{Ly}\alpha}$ calculated using SFR$^{1250}_{\text{Ly}\alpha}$ and SFR$^a_X$ for LAEs at different redshifts are presented in Table 3. The sample selection limits are also presented in Table 3. We should note that the LAEs at $z \sim 0.3$ and 1 are selected among the GALEX FUV and NUV band dropout galaxies with EW(Ly$\alpha$) $> 20$ Å from their follow-up GALEX spectra. So the LAE samples at $z \lesssim 1$ are quite different compared to the LAE samples at $z > 2$, which are selected from narrowband excess over broad band with nearly same criteria on the equivalent width $EW(Ly\alpha)$ (estimated from the broadband to narrowband ratio). In the following discussion, we treat them separately.

We only take the soft-band upper limits for $z > 2$ LAEs, because soft-band flux are more sensitive than the total band and hard band, and at $z > 2$, the observed soft-band X-ray photons are closer to rest-frame hard photons, and therefore more robust to a change in photon index $\Gamma$ (see Figure 2 of Wang et al. 2007) assumed when converting X-ray count rate to flux.

At $z \sim 0.3$, we only have $L_{0.5–2\text{keV}}$ for the three Ly$\alpha$ selected galaxies. Although they are not detected in the hard X-ray band, their 3σ upper limit on $L_{2–10\text{keV}}$ shows good consistency with their $L_{0.5–2\text{keV}}$ (See Table 1). Here we use the SFR$^a_X$-$L_{0.5–2\text{keV}}$ relation from Ranalli et al. (2003), since our detections are in the
to a larger luminosity distance, and comparatively smaller Lyα sample sizes.

If the LAEs do not evolve from \(z = 3.2\) to \(z = 2.1\), then we can combine the samples in this redshift range to obtain a more robust limit on the escape fraction. A 1\(\sigma\) upper limit on the soft-band flux is derived as \(f_{\text{Ly}α-2\text{keV}} < 8.5 \times 10^{-19} \text{ erg cm}^{-2} \text{s}^{-1}\). This implies an SFR_{Lyα}/SFR_X > 14%–28% (due to the different SFR_{Lyα} average value) during the redshift range 2.1 \(< z \leq 3.2\).

This value is consistent with the median value of \(f_{\text{Ly}α/\text{UV}}\) \(\sim 29\%\) from blank fields spectroscopically selected LAEs at \(1.9 < z < 3.8\) (Blanc et al., 2011), but larger than the value of \(f_{\text{Ly}α} > 2\%\), 5%–10% in some theoretical models of LAEs (e.g., Le Delliou et al. 2005; Shimizu et al. 2011).

4.3. \(f_{\text{Ly}α}\) with 4 Ms CDF-S Data

There is no X-ray detection for LAEs co-added at any individual redshift bin (\(z > 2\)). By co-adding the 53 LAEs at 2.1 \(\leq z \leq 3.2\), we reach an X-ray flux limit of 8.5 \(\times 10^{-19} \text{ erg cm}^{-2} \text{s}^{-1}\) (1\(\sigma\)), but still do not detect X-ray photons from these galaxies. This means that the SFR is truly low, as indicated by the Lyα line strength. To increase our sensitivity to detect the SFR of LAEs, which is relatively low when compared to continuum-selected star-forming galaxies at comparable redshifts, we co-add all the undetected LAEs between redshifts 2 and 6.5. The average X-ray emission is still undetected at a 1\(\sigma\) flux level of 7.6 \(\times 10^{-19} \text{ erg cm}^{-2} \text{s}^{-1}\). To convert the flux into luminosity and hence SFR, we need to model the redshift distribution of the sources.

Let us, instead, predict the expected X-ray counts on this average image of Lyα galaxies. Assuming the Lyα escape fraction for LAEs is \(f_{\text{Ly}α}\), then SFR_X = \(\text{SFR}_{\text{Ly}α}/(f_{\text{Ly}α}) = (L_X/5 \times 10^{39} \text{ erg s}^{-1}) M_\odot \text{yr}^{-1}\), we get

\[
L_{2-10\text{keV, rest}} = 5 \times 10^{39} \text{ erg s}^{-1} \frac{\text{SFR}_{\text{Ly}α}/M_\odot \text{yr}^{-1}}{2.0 \times f_{\text{Ly}α}} \times 10^{40} \text{ erg s}^{-1}.
\]  

If we assume that all LAEs have an effective X-ray photon index of \(\Gamma = 2\), then with the X-ray count rate to flux conversion of 6.64 \(\times 10^{-12} \text{ erg cm}^{-2}\) at soft band and SFR_{Lyα} from Table 3, we estimate that the expected number of X-ray photons at \(\sim 4\) Ms CDF-S for LAEs should be \(\text{SFR}_{\text{Ly}α}/(f_{\text{Ly}α} \times 1000) \times [8.0, 3.0, 3.0, 1.3, 0.7, 0.5])\) for LAEs at \(z = [2.1, 3.1, 3.2, 4.5, 5.7, 6.5]\). This means that we should observe \(\sim 3\) soft X-ray photons per \(z = 2.1\) LAE galaxy in the 4 Ms CDF-S field when \(f_{\text{Ly}α} \approx 5\%\), and the observed expected soft X-ray photons decreases to \(\sim 1\) when \(f_{\text{Ly}α}\) increases to 15%. Since the background X-ray photons per point source on the ACIS-I CCDs varies from position to position, we take the background value extracted from each LAE candidate, and add the estimated X-ray photons from their corresponding SFR_{Lyα} to analyze the probability on \(f_{\text{Ly}α}\). By co-adding all LAEs between redshift \(z = 2\) and 6.5, the estimated counts are plotted in Figure 3 as a function of \(f_{\text{Ly}α}\). The signal should be S/N \(> 3\) when \(f_{\text{Ly}α} < 5\%\), and S/N \(> 1\) when \(f_{\text{Ly}α} < 17\%\). So we can reject the value of 5% at 99.87% confidence level, and report that the real value of \(f_{\text{Ly}α} > 17\%\) in 84% confidence level.

4.4. \(f_{\text{Ly}α}(\text{X-Ray})\) versus \(f_{\text{Ly}α}(\text{UV/Optical})\)

The escape fraction of LAEs has also been discussed using other tracers of the total SFR. Atek et al. (2009) studied \(z = 0.3\) LAEs from Attek et al. 2009; light blue crosses and dotted lines: \(f_{\text{Ly}α}\) from blank field spectroscopic survey of 98 LAEs at 1.9 < \(z < 3.8\). Note that \(\sim 2\) star formation dominated LAEs in the central CDF-S region (excluding the four AGNs with individual X-ray detections), so at \(z > 1\) the escape fraction is poorly constrained (with \(f_{\text{Ly}α} > 1\sigma\)) > 7%.

At \(z > 2\), we do not obtain an X-ray detection after stacking the 69 star formation dominated LAEs in the central CDF-S field, or after stacking the 351 LAEs in the ECDF-S field (see Table 2). We get the 1\(\sigma\) upper limits (same as below) on the intrinsic (dust-free) SFRs as SFR_X < [14, 28, 28, 139, 440, 876] \(M_\odot \text{yr}^{-1}\) for LAEs at \(z = [2.1, 3.1, 3.2, 4.5, 5.7, 6.5]\). The observed SFRs from the Lyα line are around 1.9, 2.6, and 2.3 \(M_\odot \text{yr}^{-1}\) for \(z = 2.1, 3.1\), and 3.2 LAEs on average, and \(\sim 5\) \(M_\odot \text{yr}^{-1}\) for \(z > 4\) LAEs. The ratio SFR_{Lyα}/SFR_X measures the Lyα escape fraction: \(f_{\text{Ly}α} = SFR_{\text{Ly}α}/SFR_X\) (see Table 3).

This is plotted in Figure 2, showing the constraints on \(f_{\text{Ly}α}\) as a function of redshift. At \(z = 2.1\), the Lyα escape fraction of LAEs is above 14\%. At \(z = 3.1\) and 3.2, the \(f_{\text{Ly}α}\) is greater than 8% and 9%, respectively. Combining the two samples at \(z < 3\), we increase the upper limit to \(f_{\text{Ly}α} > 14\%\), the same as the upper limit at \(z = 2.1\). At higher redshifts, the limits are weaker due...
0.3 LAEs by using the extinction-corrected Hα to Lyα ratio, which has a range of \( f_{\text{esc}}^{\text{Lyα}} / f_{\text{Hα}} \sim 0.5\% - 100\% \) and a median value of \( \sim 20\% \). Blanc et al. (2011) studied \( 1.9 < z < 3.8 \) LAEs through extinction-corrected UV to Lyα ratio and found an average \( f_{\text{esc}}^{\text{Lyα}} \sim 29\% \). The \( f_{\text{Lyα}} \) for LAEs estimated from the ratio of SFR_{Lyα} and dust-corrected SFR_{UV}, \( f_{\text{esc}}^{\text{Lyα}} \sim \text{SFR}_{\text{Lyα}} / (\text{SFR}_{\text{UV}}/10^{-A_{\text{1200}}/2.5}) \), also exist for our sample. Gauza et al. (2011), Gawiser et al. (2007), and Nilsson et al. (2007) did the stacked SED fitting on the samples at \( z = 2.1 - 3.2 \). At \( z \sim 0.3 \) and 4.5, Finkelstein et al. (2008, 2011) did individual SED fitting for LAEs with existing Hubble and Spitzer observations. The dust properties of the SED fitting results at different redshifts are converted to \( A_{1200} \) (see in Table 3) using Calzetti et al. (2000). The \( f_{\text{esc}}^{\text{Lyα}} / f_{\text{Hα}} \) from dust-corrected UV to Lyα ratio for our sample show no evolution from \( z \sim 2 \) to \( z \sim 3.2 \), as \( f_{\text{esc}}^{\text{Lyα}} / f_{\text{Hα}} \sim 26\% \), and is consistent with \( \sim 29\% \) of Blanc et al. 2011. At \( z \sim 4.5 \), the SED fitting results might be affected by the poor spatial resolution of Spitzer. As an independent estimate on \( f_{\text{esc}}^{\text{Lyα}} \) from X-ray, our \( f_{\text{esc}}^{\text{Lyα}} \) at \( z = 0.3 \) are located at the low end of Atek et al. (2009), while consistent at \( 1.9 < z < 3.8 \) with Blanc et al. 2011 (see Figure 2), and the \( f_{\text{esc}}^{\text{Lyα}} / f_{\text{Hα}} \) from the SED fitting results at \( z = 2.1, 3.1, 3.2, \) and 4.5. The LAEs at \( z \sim 0.3 \) seem different compared to high-redshift LAEs, as they are more AGN contaminated (AGN fraction of \( \sim 15\% - 40\% \), e.g., Scarlata et al. 2009; Cowie et al. 2010; Finkelstein et al. 2009b) and more massive (Finkelstein et al. 2009a). At high redshift, the AGN fraction in LAEs is very low (AGN fraction \( \lesssim 5\% \); Zheng et al. 2010, and references therein), and AGNs are relatively easy to detect in this deepest Chandra field, so the lower limit of \( f_{\text{esc}}^{\text{Lyα}} \) should be very robust. Our X-ray constraints on the \( f_{\text{esc}}^{\text{Lyα}} \), as well as the \( f_{\text{esc}}^{\text{Lyα}} / f_{\text{Hα}} \) estimated from SED fitting, show that the Lyα escape fraction need not evolve during the redshift \( 2.1 \lesssim z \lesssim 3.2 \).

Hayes et al. (2011) and Blanc et al. (2011) also reported the global evolution of \( f_{\text{esc}}^{\text{Lyα}} \), which is defined as the ratio of integrated Lyα luminosity functions from LAEs and the global extinction-corrected SFR density at different redshift.

The global extinction-corrected SFR densities were integrated from Hα or UV luminosity. However, we should point out that at \( z = 1, 3, 4, \) and 5, the SFR_{X} / SFR_{UV,corr} \sim 4.5 - 5 for LBGs, consistent with the dust extinction values from other methods (Nandra et al. 2002; Lehmer et al. 2005; Reddy & Steidel 2004). Note that the Lyα luminosity functions of LAEs do not evolve during \( 3 \lesssim z \lesssim 6 \) (e.g., see Ouchi et al. 2008), while the relative numbers of LAEs to LBGs increased with redshift from \( z \sim 3 \) to 6.5 (e.g., Clement et al. 2011), the evolution trend of global \( f_{\text{esc}}^{\text{Lyα}} \) could be explained as the evolution of relative numbers of LAEs to LBGs at different redshift, with little implication on the Lyα escape mechanism for LAEs only. X-ray constraints on the \( f_{\text{esc}}^{\text{Lyα}} \) of LAEs are independent of dust-extinction law, and we have found the same lower limits of \( f_{\text{esc}}^{\text{Lyα}} \) for LAEs at \( z \sim 0.3, 1, \) and 1, and LAEs at \( z = 2.1 \) and 3.2 with different average SFR_{Lyα} values. However, a larger sample of LAEs with deep X-ray observation is needed to give a constraint on the evolution of \( f_{\text{esc}}^{\text{Lyα}} \) in LAE only.

4.5. Implications from Simulated SFR_{X}–L_{X} Relationship

We should note that the X-ray radiation from galaxies is predicted to be relatively low for the youngest stellar populations. Mas-Hesse et al. (2008) predict the soft X-ray to far-infrared luminosities ratio in star-forming galaxies from synthesis models. They find that the ratio is dependent on the age of the star formation episode for ages \( < 500 \) Myr. After 30 Myr, the correlation becomes stable and is consistent with SFR_{X} - L_{soft} relation of Ranalli et al. 2003. In the hard X-ray band, Mas-Hesse & Cervino (1999) predicted that a few HMXB should be active in starbursts that are older than \( 5-6 \) Myr, contributing a few times \( 10^{38} \) erg s\(^{-1}\) to the total X-ray luminosity. Recent Chandra studies in the interacting galaxy pair NGC 4038/4039 (the Antennae; Rangelov et al. 2011) found that 22 of 82 X-ray binaries are coincident or nearly coincident with star clusters. The ages of these clusters were estimated by comparing their multi-band colors with predictions from stellar evolutionary models. They found 14 of the 22 coincident sources are hosted by star clusters with ages of \( \sim 6 \) Myr or less. So the HMXBs in star-forming galaxies might form earlier than suggested in the Mas-Hesse & Cervino (1999) model. The estimates of LAE ages are based on SED fitting and are quite uncertain. Such results have been reported at \( z = 2.1 \) (Guaita et al. 2011), 2.25 (Nilsson et al. 2009), 3.1 (Gawiser et al. 2007), 4.5 (Finkelstein et al. 2008), and \( z = 4.0-5.5 \) (Pirzkal et al. 2007). All the results show that the best-fit age parameter is 20–40 Myr, but extends to \( \sim 0.1-1 \) Gyr at the 68% confidence level. Given this range of best-fit ages, we expect that a minority of the LAEs in our sample will be younger than 15 Myr. This would imply a modest upward correction to the SFR inferred from X-rays, and a corresponding correction downward in the \( f_{\text{esc}}^{\text{Lyα}} \); both corrections might reasonably be factors of \( \sim 1.2-1.5 \).

5. CONCLUSIONS

From the 4 Ms X-ray Chandra image of CDF-S, we find that the \( f_{\text{esc}}^{\text{Lyα}} \) from X-rays for LAEs at \( z \sim 0.3 \) are about \( \sim 2-7 \) times larger than that from dust-corrected UV or Hα. We co-added 69 Lyα emitting galaxies between redshifts \( 2 < z < 6.5 \). None of these galaxies were individually detected. The absence of signal in the co-added image implies an average flux of less than \( 7.6 \times 10^{-19} \) erg cm\(^{-2}\) s\(^{-1}\) (1σ). This implies that the SFRs in these galaxies are quite modest, as indicated by the Lyα line...
emission, and the ratio of the average Lyα line intensity to the upper limits of X-ray flux constrains the Lyα escape fraction $f_{\text{Esc}}^{\text{Ly}{\alpha}} > 17\%$ at 84% confidence level.

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REFERENCES

Ando, M., Ohta, K., Iwata, I., et al. 2006, ApJ, 645, L9
Atek, H., Kunth, D., Schaerer, D., et al. 2009, A&A, 506, L1
Blanc, G. A., Adams, J., Gebhardt, K., et al. 2011, ApJ, 736, 31
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Clement, B., Cuby, J.-G., Courbin, F., et al. 2011, arXiv:astro-ph/1105.4235
Ciardullo, R., Gronwall, C., Wolf, C., et al. 2011, arXiv:astro-ph/1109.4685
Colbert, E. J. M., Heckman, T. M., Ptak, A. F., et al. 2004, ApJ, 602, 231
Condon, J. J. 1992, ARA&A, 30, 575
Cowie, L. L., & Hu, E. M. 1998, AJ, 115, 1319
Dai, X., Kochanek, C. S., Chartas, G., & Mathur, S. 2006, ApJ, 637, 53
Dawson, S., Rhoads, J. E., Malhotra, S., et al. 2007, ApJ, 671, 1227
Deharveng, J. M., Small, T., Barlow, T. A., et al. 2008, ApJ, 680, 1072
Dickey, J., & Lockman, F. 1990, ARA&A, 28, 215
Finkelstein, S. L., Cohen, S. H., Malhotra, S., & Rhoads, J. E. 2009a, ApJ, 700, 276
Finkelstein, S. L., Cohen, S. H., Malhotra, S., et al. 2009b, ApJ, 703, 162
Finkelstein, S. L., Cohen, S. H., Moustakas, J., et al. 2011, ApJ, 733, 117
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
Gehrels, N. 1986, ApJ, 303, 336
Gillfanov, M., Grimm, H. J., & Sunyaev, R. 2004, Nucl. Phys. B, 132, 369
Grimm, H. J., Gillfanov, M., & Sunyaev, R. 2003, MNRAS, 339, 793
Gronwall, C., Ciardullo, R., Hickey, T., et al. 2007, ApJ, 667, 79

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Guaita, L., Gawiser, E., Padilla, N., et al. 2010, ApJ, 714, 255
Guaita, L., Acquaviva, V., Padilla, N., et al. 2011, ApJ, 733, 114
Hansen, M., & Oh, S. P. 2006, MNRAS, 367, 979
Hayes, M., Østlin, G., Schaerer, D., et al. 2010, Nature, 464, 562
Hayes, M., Schaerer, D., Østlin, G., et al. 2011, ApJ, 730, 8
Hu, E. M., Cowie, L. L., Capak, P., et al. 2004, AJ, 127, 563
Iye, M., Ota, K., Kashikawa, N., et al. 2006, Nature, 443, 14
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Laird, E. S., Nandra, K., Hobbs, A., & Steidel, C. C. 2006, MNRAS, 373, 217
Lei Delliou, M., Lacey, C., Baugh, C. M., et al. 2005, MNRAS, 357, 11
Lehner, B. D., Alexander, D. M., Bauer, F. E., et al. 2010, ApJ, 724, 559
Lehner, B. D., Brandt, W. N., Alexander, D. M., et al. 2005, ApJS, 161, 21
Lehner, B. D., Brandt, W. N., Alexander, D. M., et al. 2008, ApJ, 681, 1163
Luo, B., Bauer, F. E., Brandt, W. N., et al. 2008, ApJS, 179, 19
Malhotra, S., & Rhoads, J. E. 2002, ApJ, 565, L71
Malhotra, S., Wang, J., Rhoads, J. E., et al. 2003, ApJ, 585, L25
Martin, C. L., Sawicki, M., Dressler, A., & McCarthy, P. 2008, ApJ, 679, 942
Mas-Hesse, J. M., & Cervino, M. 1999, in IAU Symp. 193, Wolf–Rayet Phenomena in Massive Stars and Starburst Galaxies, ed. K. A. van der Hucht, G. Koenigsberger, & P. R. J. Elenens (San Francisco, CA: ASP), 550
Mas-Hesse, J. M., Ott–Floranes, H., & Cervino, M. 2008, A&A, 483, 71
Nagamine, K., Ouchi, M., Springel, V., & Hernquist, L. 2010, PASJ, 62, 1455
Nandra, K., Mushotzky, R. F., Arnaud, K., et al. 2002, ApJ, 576, 625
Neufeld, D. A. 1991, ApJ, 370, L85
Nilsson, K. K., Moller, P., Moller, O., et al. 2007, A&A, 471, 71
Nilsson, K. K., Tapken, C., Moller, P., et al. 2009, A&A, 498, 13
Ouchi, M., Shimakatu, K., Akiyama, M., et al. 2008, ApJS, 176, 301
Partridge, R. B., & Peebles, P. J. E. 1967, ApJ, 148, 377
Pizka, N., Malhotra, S., Rhoads, J. E., & Xu, C. 2007, ApJ, 667, 49
Pizka, N., Xu, C., Malhotra, S., et al. 2004, ApJ, 154, 501
Ranalp, P. Comastri, A., & Setti, G. 2003, A&A, 399, 39
Rangelove, B., Prestwich, A. H., & Chandar, R. 2011, ApJ, 741, 86
Reddy, N. A., & Steidel, C. C. 2004, ApJ, 603, 13
Rhoads, J. E., Malhotra, S., Pirzkal, N., et al. 2009, ApJ, 697, 942
Rhoads, J. E., Dey, A., Malhotra, S., et al. 2003, AJ, 125, 1006
Rhoads, J. E., Malhotra, S., Dey, A., et al. 2000, ApJ, 545, L85
Scarabata, C., Colbert, J., Teplitz, H. I., et al. 2009, ApJ, 704, L98
Seibert, M., Heckman, T. M., & Meurer, G. R. 2002, AJ, 124, 46
Shimizu, I., Yoshida, N., & Okamoto, T. 2011, MNRAS, 418, 2273
Venemans, B. P., Rottgering, H. J. A., Miley, G. K., et al. 2005, A&A, 431, 793
Wang, J. X., Malhotra, S., & Rhoads, J. E. 2005, ApJ, 622, 77
Wang, J. X., Malhotra, S., Rhoads, J. E., et al. 2009, ApJ, 706, 762
Wang, J. X., Rhoads, J. E., Malhotra, S., et al. 2004, ApJ, 608, L21
Wang, J. X., Zheng, Z. Y., Malhotra, S., et al. 2007, ApJ, 699, 765
Xue, Y. Q., Luo, B., Brandt, W. N., et al. 2011, ApJS, 195, 10
Zheng, Z. Y., Wang, J. X., Finkelstein, S. L., et al. 2010, ApJ, 718, 52