BRIGHT AND FAINT ENDS OF Lyα LUMINOSITY FUNCTIONS AT z = 2 DETERMINED BY THE SUBARU SURVEY: IMPLICATIONS FOR AGNs, MAGNIFICATION BIAS, AND ISM H I EVOLUTION

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ABSTRACT

We present the Lyα luminosity functions (LFs) derived by our deep Subaru narrowband survey that identifies a total of 3137 Lyα emitters (LAEs) at z = 2.2 in five independent blank fields. This sample of LAEs is the largest to date and covers a very wide Lyα luminosity range of log L_{Lyα} = 41.7 - 44.4 erg s^{-1}. We determine the Lyα LF at z = 2.2 with unprecedented accuracy and obtain the best-fit Schechter parameters of L^{*}_{Lyα} = 5.29^{+1.07}_{-1.13} \times 10^{42} erg s^{-1}, \phi^{*}_{Lyα} = 6.32^{+3.08}_{-2.31} \times 10^{-4} Mpc^{-3}, and \alpha = -1.75^{+0.10}_{-0.09}, showing a steep faint-end slope. We identify a significant hump at the LF bright end (log L_{Lyα} > 43.4 erg s^{-1}). Because all of the LAEs in the bright-end hump have a bright counterpart(s) in either the X-ray, UV, or radio data, this bright-end hump is not made by gravitational lensing magnification bias but by active galactic nuclei (AGNs). These AGNs allow us to derive the AGN UV LF at z \sim 2 down to the faint magnitude limit of M_{UV} \simeq -22.5 and to constrain the faint-end slope of the AGN UV LF, \alpha_{AGN} = -1.2 \pm 0.1, which is flatter than those at z > 4. Based on the Lyα and UV LFs from our and previous studies, we find an increase of Lyα escape fraction f^{Lyα}_{esc} from z = 0 to 6 by two orders of magnitude. This large f^{Lyα}_{esc} increase can be explained neither by the evolution of stellar population nor by outflow alone, but by the evolution of neutral hydrogen H I density in the interstellar medium that enhances dust attenuation for Lyα by resonance scattering. Our uniform expanding shell models suggest that the typical H I column density decreases from N_{HI} \sim 7 \times 10^{19} \text{ cm}^{-2} (z \sim 0) to \sim 1 \times 10^{18} \text{ cm}^{-2} (z \sim 6) to explain the large f^{Lyα}_{esc} increase.

Key words: galaxies: evolution -- galaxies: formation -- galaxies: high-redshift -- galaxies: luminosity function, mass function

1. INTRODUCTION

Deep narrowband and spectroscopic observations identify Lyα emitters (LAEs), most of which are continuum-faint star-forming galaxies with a prominent Lyα emission line (e.g., Cowie & Hu 1998; Hu et al. 1998; Rhoads et al. 2000; Steidel et al. 2000; Malhotra & Rhoads 2002; Hayashino et al. 2004; Matsuda et al. 2004; Taniguchi et al. 2005; Iye et al. 2006; Kashikawa et al. 2006, 2012; Shimasaku et al. 2006; Dawson et al. 2007; Gronwall et al. 2007; Murayama et al. 2007; Ouchi et al. 2008; Finkelstein et al. 2009; Guaita et al. 2010; Adams et al. 2011; Shibuya et al. 2012; Yamada et al. 2012; Konno et al. 2014; Cassata et al. 2015; Sobral et al. 2015). LAEs are found at a wide redshift range of z \sim 0–8, and Lyα luminosity functions (LFs) of LAEs are used for probes of galaxy evolution and cosmic reionization (e.g., Ouchi et al. 2008, 2010; Kashikawa et al. 2011; Shibuya et al. 2012; Konno et al. 2014). In Lyα LFs, there are important characteristics at the faint end. Galaxies at the faint end dominate in abundance, and faint-end slopes of Lyα LFs are determined by mass, star formation activities, physical conditions of the interstellar medium (ISM), and feedback effects that are key for understanding galaxy evolution (e.g., Santos et al. 2004; Rauch et al. 2008). Although Lyα LFs at various redshifts have been derived by previous observations, faint-end slopes of the Lyα LFs are poorly constrained, in contrast with those of UV LFs (e.g., Reddy & Steidel 2009; Hathi et al. 2010; Oesch et al. 2010; Sawicki 2012; Alavi et al. 2014; Bouwens et al. 2015; Parsa et al. 2015). The faint-end LF slopes are quantified with \alpha, one of the three Schechter function parameters (Schechter 1976), depending on the other two parameters, characteristic Lyα luminosity L^{*}_{Lyα} and density \phi^{*}_{Lyα}. Previous observational studies report \alpha values for z = 2–3 Lyα LFs (e.g., Cassata et al. 2011), assuming a fixed parameter of L^{*}_{Lyα} or \phi^{*}_{Lyα}. There are some studies that constrain \alpha values with no assumptions (e.g., Gronwall et al. 2007; Hayes et al. 2010), but the uncertainties of the Schechter parameters are very large owing to the small number of LAEs. Although \alpha is a parameter depending on L^{*}_{Lyα} and \phi^{*}_{Lyα}, so far none of the observational studies have determined \alpha simultaneously with L^{*}_{Lyα} and \phi^{*}_{Lyα} owing to the small statistics of LAEs whose Lyα luminosity range is limited. In theoretical studies, Gronke et al. (2015) predict the three Schechter function parameters of Lyα LFs at z = 3–6, based on the measurements of UV LFs and Lyα equivalent width (EW) probability distribution functions (PDFs), and argue that the faint-end slopes of the Lyα LFs are steeper than those of the UV LFs.

Another important characteristic of Lyα LFs is found at the bright end. The bright-end LFs are key for understanding massive-galaxy formation, as well as faint active galactic nuclei (AGNs; e.g., Gawiser et al. 2006; Ouchi et al. 2008; Zheng et al. 2013). Here we define faint AGNs as AGNs whose LFs overlap with non-AGN galaxy LFs in the luminosity ranges. The faint AGNs may play an important role in contributing to the UV radiation background (e.g., Giallongo et al. 2015).
Faint AGNs are useful probes for quasar fueling lifetime, feedback, and duty cycle (e.g., Hopkins et al. 2006; Fiore et al. 2012). Faint AGNs are spectroscopically identified for most LAEs at \( z \sim 3-4 \) in the bright-end \( \text{Ly}\alpha \) LF at \( \log L_{\text{Ly}\alpha} \gtrsim 43.5 \; \text{erg s}^{-1} \) (Gawiser et al. 2006; Ouchi et al. 2008). The bright-end LF includes an interesting physical effect, magnification bias. The magnification bias effect boosts luminosities of high-\( z \) galaxies by the gravitational lensing magnification given by foreground massive galaxies and flattens the bright-end LFs (e.g., Mason et al. 2015; see Figure 3 of Wyithe et al. 2011). In the observational studies, humps of the bright-end Ly\( \alpha \) LF are found at \( z = 3-7 \) (Gawiser et al. 2006; Ouchi et al. 2008; Matthee et al. 2015). In order to estimate the contributions of faint AGNs to the bright-end LFs, it is important to investigate the properties of the bright-end galaxies with deep multiwavelength data such as X-ray, UV, and radio images.

The intermediate redshift range of \( z \sim 2-3 \) is the best for investigating faint- and bright-end Ly\( \alpha \) LFs. This is because \( z \sim 2-3 \) is the lowest redshift range where Ly\( \alpha \) emission falls in the optical observing window, which allows us to identify very faint LAEs and a large number of bright LAEs by fast optical surveys. Moreover, because the number densities of AGNs peak at \( z \sim 2-3 \), the effect of faint AGNs would clearly appear at the Ly\( \alpha \) LF bright end. For these reasons, in the past few years various surveys have been conducted to study LAEs at \( z \sim 2-3 \). Although the Ly\( \alpha \) LFs at \( z \sim 3 \) are well determined (e.g., Gronwall et al. 2007; Ouchi et al. 2008), those at \( z \sim 2 \) are derived with uncertainties larger than those at \( z \sim 3 \) owing to difficulties of \( \lambda \)-band observations at \( <3000-4000 \; \text{Å} \), to which Ly\( \alpha \) emission lines of \( z \sim 2 \) objects are redshifted. Thus, the evolution of Ly\( \alpha \) LFs from \( z \sim 2 \) to 3 is under debate. Nilsson et al. (2009) first claim that there is a possible evolution of LAE number densities between \( z = 2.25 \) and \( \sim 3 \), albeit with the large uncertainties originating from the small sample. Subsequent studies have identified \( z \sim 2 \) LAEs by narrowband imaging and spectroscopic observations and discussed the evolution of Ly\( \alpha \) LFs and the integrations of Ly\( \alpha \) LFs, luminosity densities (LDs), at \( z = 2-3 \). Cassata et al. (2011) and Blanc et al. (2011) have carried out blank-field spectroscopy for LAEs at \( 2 < z < 6.6 \) and \( 1.9 < z < 3.8 \), respectively, and concluded no evolution of the Ly\( \alpha \) LDs from \( z = 2 \) to 3. On the other hand, Ciardullo et al. (2012) show that the Ly\( \alpha \) LF evolves from \( z = 2.1 \) to 3.1 significantly by the narrowband imaging surveys in ECDP-S (see also Guaita et al. 2010). Because the \( z \sim 2 \) LAE samples of these studies are limited in the LAE numbers (which are equal to or less than several hundred) and the Ly\( \alpha \) luminosity dynamic range (which is a factor of \( \sim 10 \)), these discrepancies may be raised by the sample variances and the differences of Ly\( \alpha \) luminosity coverages.

Evolution of Ly\( \alpha \) LFs at \( z \lesssim 2-3 \) is also discussed extensively. Deharveng et al. (2008) claim that there is a substantial drop in the Ly\( \alpha \) LFs from \( z \sim 3 \) to \( \sim 0.3 \) (see also Cowie et al. 2010, 2011; Berger et al. 2012; Wold et al. 2014). A similar evolutionary trend can be found in the Ly\( \alpha \) escape fraction at \( z \sim 0-6 \) (e.g., Blanc et al. 2011; Hayes et al. 2011; Zheng et al. 2013) that is defined by the ratio of the observed to the intrinsic Ly\( \alpha \) fluxes. The physical origin of the rapid evolution may be dust attenuation within galaxies. From the observations of UV-continuum slope of Lyman break galaxies (LBGs), dust extinction, \( E(B-V) \), decreases toward higher redshift (e.g., Bouwens et al. 2015). Because the Ly\( \alpha \) escape fraction clearly depends on \( E(B-V) \) (e.g., Kornei et al. 2010; Atek et al. 2014), dust extinction would explain the rapid evolution of the Ly\( \alpha \) LF and Ly\( \alpha \) escape fraction. To understand the major physical mechanisms related to the Ly\( \alpha \) escape processes at high \( z \) and their dependence on redshift, determining Ly\( \alpha \) LFs at \( z \sim 2 \) is important.

In this paper, we present our analyses and results of the Ly\( \alpha \) LFs at \( z = 2.2 \) based on our large LAE sample given by Subaru narrowband observations (Nakajima et al. 2012, 2013; see also Kusakabe et al. 2015). This sample contains 317 LAEs at \( z = 2.2 \) with a wide Ly\( \alpha \) luminosity range of \( 41.7 \lesssim \log L_{\text{Ly}\alpha} \lesssim 44.4 \; \text{erg s}^{-1} \), enabling us to examine the faint-bright ends and the evolution of Ly\( \alpha \) LFs. We describe the details of our observations and our \( z = 2.2 \) LAE candidate selection in Section 2. We derive the Ly\( \alpha \) LFs at \( z = 2.2 \) and compare the LFs with those of previous studies in Section 3. We investigate the Ly\( \alpha \) LF and LD evolution from \( z \sim 2 \) to 3 and extend the discussion to the wider redshift range of \( z \sim 0-8 \) in Section 4. Finally, we discuss the physical origins of the bright end of our \( z = 2.2 \) Ly\( \alpha \) LFs and the Ly\( \alpha \) LD evolution at \( z \sim 0-8 \) in Section 5. Throughout this paper, we adopt AB magnitudes (Oke 1974) and concordance cosmology with a parameter set of \( (h, \Omega_m, \Omega_{\Lambda}, \sigma_8) = (0.7, 0.3, 0.7, 0.8) \) consistent with the 9 yr WMAP and Planck 2015 results (Hinshaw et al. 2013; Planck Collaboration et al. 2015).

2. OBSERVATIONS AND SAMPLE SELECTION

2.1. NB387 Observations

We have conducted a deep and large-area narrowband imaging survey for \( z = 2.2 \) LAEs with Subaru/Suprime-Cam (Miyazaki et al. 2002). For these observations, we developed a new narrowband filter, NB387, with a central wavelength, \( \lambda_c \), of 3870 Å and an FWHM of 94 Å to identify LAEs in the redshift range of \( z = 2.14-2.22 \). With our NB387 filter, we have observed five independent blank fields, the Subaru/XMM-Newton Deep Survey (SXDS) field (Furusawa et al. 2008), the Cosmic Evolution Survey (COSMOS) field (Scoville et al. 2007), the Chandra Deep Field South (CDFS; Giacconi et al. 2001), the Hubble Deep Field North (HDFN; Capak et al. 2004), and the SSA22 field (e.g., Steidel et al. 2000), in 2009 July 20 and December 14–16 and 19–20. The SXDS field consists of five subfields of \( \sim 0.2 \; \text{deg}^2 \), SXDS-C, SXDS-N, SXDS-S, SXDS-E, and SXDS-W (Furusawa et al. 2008). We cover these five SXDS subfields, COSMOS, CDFS, HDFN, and SSA22 by one pointing of Suprime-Cam, whose field of view is \( \sim 0.2 \; \text{deg}^2 \). We thus have NB387 imaging data in a total of nine pointing positions of Suprime-Cam. We summarize the details of our observations, as well as image qualities, in Table 1. In this study, we do not use the data of the SXDS-E subfield owing to the poor seeing size of \( \sim 2'' \) in FWHM of the point-spread function (PSF; see Table 1). During our observations, we have taken spectro-photometric standard stars Feige 34, LDS 749B, and G93-48 (Oke 1990) for photometric calibration. Each standard star has been observed more than twice under the photometric condition with air masses of 1.1–1.3.

2.2. Data Reduction

Our NB387 data are reduced with the Suprime-Cam Deep Field REDuction (SDFRED) package (Yagi et al. 2002; Ouchi et al. 2004). The data reduction process includes the subtraction
of bias estimated with overscan regions, flat fielding, distortion +atmospheric-dispersion correction, cosmic-ray rejection, sky subtraction, image shifting, and stacking. In the cosmic-ray rejection process, we use LA.Cosmic (van Dokkum 2001). Before the image shifting, we mask out bad pixels and satellite trails.

After the stacking process, we calculate photometric zero points of the NB387 images from the standard-star data (see Section 2.1). We estimate the errors in the photometric zero points based on colors of stellar objects in the two-color diagram of NB387 and two adjacent broadband profiles in the blue and red sides of NB387 (e.g., $u^* - \text{NB387}$ and $B - \text{NB387}$ in SDSS). We compare the colors of stellar objects and the template 175 Galactic stars (Gunn & Stryker 1983), and we regard the offsets as the uncertainties. The inferred uncertainties are $\lesssim 0.05$ mag, which are negligibly small for our study.

All of the NB387 images, except the SXDS-E data, have a PSF FWHM of $0''7 - 1''2$ and reach the $5\sigma$ limiting magnitudes of $24.9 - 26.5$ in a $2''0$-diameter circular aperture. We summarize the qualities of these reduced NB387 images in Table 1. We mask out the imaging regions that are contaminated with halos of bright stars, CCD blooming, and the low signal-to-noise ratio pixels near the edge of the images. After the masking, the total survey area is 5138 arcmin$^2$, i.e., $\approx 1.43$ deg$^2$. If we assume a simple top-hat selection function for LAEs whose redshift distribution is defined by the FWHM of NB387, this total survey area corresponds to a comoving volume of $\approx 1.32 \times 10^{12}$ Mpc$^3$.

In our analysis and LAE selection, we use archival $U$- and $B$-band data, as well as our NB387 images. In the SDSS field, the $u^*$- and $B$-band data are taken with CFHT/MegaCam (S. Foucaud et al. 2016, in preparation) and Subaru/Suprime-Cam.

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### Table 1

Summary of NB387 Observations and Data

| Band | Field | Exposure Time (hr) | PSF FWHM$^a$ (arcsec) | Area$^b$ (arcmin$^2$) | $m_{lim}^c$ (mag) | Date of Observations | Reference$^d$ |
|------|-------|-------------------|----------------------|----------------------|------------------|---------------------|-------------|
| NB387 | SXDS-C | 3.2 | 0.88 | 587 | 25.7 | 2009 Dec 14–16 | 1, 2 |
|      | SXDS-N | 2.5 | 0.70 | 409 | 25.6 | 2009 Dec 16 | 1, 2 |
|      | SXDS-S | 2.5 | 0.85 | 775 | 25.7 | 2009 Dec 16 | 1, 2 |
|      | SXDS-E | 3.3 | 1.95 | ... | ... | 2009 Dec 19, 20 | 1, 2 |
|      | SXDS-W | 1.8 | 1.23 | 232 | 25.1$^i$ | 2009 Dec 16, 19 | 1, 2 |
|      | COSMOS | 4.5 | 0.97 | 845 | 26.1 | 2009 Dec 14–16 | 2 |
|      | CDFS | 8.0 | 0.85 | 577 | 26.4 | 2009 Dec 14–15 | 2, 3 |
|      | HDFN | 9.3 | 0.90 | 913 | 26.5 | 2009 Dec 14–16 | 2 |
|      | SSA22 | 1.0 | 0.91 | 800 | 24.9 | 2009 Jul 20 | 2 |
|      | Total | 36.1 | ... | 5138 | ... | ... | ... |

|      | Archival Broadband Data | |
|------|------------------------|------|
| $U$  | SXDS-C | 0.85 | 26.9 | 4 |
|      | SXDS-N | 0.85 | 26.9 | 4 |
|      | SXDS-S | 0.85 | 26.9 | 4 |
|      | SXDS-E | 0.85 | 26.9 | 4 |
|      | SXDS-W | 0.85 | 26.9 | 4 |
|      | COSMOS | 0.90 | 27.2 | 5 |
|      | CDFS | 0.80 | 28.0 | 6 |
|      | HDFN | 1.29 | 26.4$^j$ | 7 |
|      | SSA22 | 1.00 | 26.3 | 8 |
| $B$  | SXDS-C | 0.80 | 27.5 | 9 |
|      | SXDS-N | 0.84 | 27.8 | 9 |
|      | SXDS-S | 0.82 | 27.8 | 9 |
|      | SXDS-E | 0.82 | 27.5 | 9 |
|      | SXDS-W | 0.78 | 27.7 | 9 |
|      | COSMOS | 0.95 | 27.5 | 10 |
|      | CDFS | 0.97 | 26.9 | 11 |
|      | HDFN | 0.77 | 26.3$^k$ | 7 |
|      | SSA22 | 1.02 | 26.7 | 8 |

Notes.

$^a$ We homogenize the PSF sizes of broadband and narrowband images in each field (see Section 2.2).

$^b$ The effective area for the $z = 2.2$ LAE selection. The effective areas of SXDS-C, SXDS-N, SXDS-S, SXDS-E, and SXDS-W are limited by the $u^*$ image, which covers 77% of SXDS (see Nakajima et al. 2012 for details). The area of CDFS is constrained by the deep $U$-band image taken with VLT/VIMOS (Nonino et al. 2009).

$^c$ The $5\sigma$ limiting magnitude in a circular aperture with a diameter of 2''0.

$^d$ References: (1) Nakajima et al. 2012; (2) Nakajima et al. 2013; (3) Kusakabe et al. 2015; (4) S. Foucaud et al. 2016, in preparation (see also Nakajima et al. 2012); (5) McCracken et al. 2010; (6) Nonino et al. 2009; (7) Capak et al. 2004; (8) Hayashino et al. 2004; (9) Furusawa et al. 2008; (10) Capak et al. 2007; (11) Hildebrandt et al. 2006.

$^e$ We do not use the NB387 image of SXDS-E since the PSF FWHM is relatively large.

$^f$ We use 2''5 and 3''0 diameter apertures for NB387 of SXDS-W and $UB$ of HDFN, respectively, owing to bad seeings.
(Furusawa et al. 2008), respectively. The $u^*$- and B-band images in the COSMOS field are obtained with CFHT/MegaCam (McCracken et al. 2010) and Subaru/Suprime-Cam (Capak et al. 2007), respectively. We use VLT/VIMOS U-band (Nonino et al. 2009) and MPG 2.2 m Telescope/WFI B-band (Hildebrandt et al. 2006) images in CDFS (see Kusakabe et al. 2015 for more details) and KPNO 4 m Telescope/MOSAIC prime focus camera U-band and Subaru/Suprime-Cam B-band images in HDFN (Capak et al. 2004). In the SSA22 field, we use the $u^*$-band data of CFHT/MegaCam and B-band data of Subaru/Suprime-Cam (Hayashino et al. 2004). The properties of these optical broadband data are also summarized in Table 1. Note that in CDFS, Nakajima et al. (2013) do not use the VLT/VIMOS U-band image, but only the MPG 2.2 m Telescope/WFI U-band image (Gawiser et al. 2006; Cardamone et al. 2010), which is significantly shallower than the VLT/VIMOS U-band data. The deep VLT/VIMOS U-band image allows us to remove foreground contamination efficiently, although the area coverage of VLT/VIMOS U-band data is smaller than that of MPG 2.2 m Telescope/WFI U-band data. We thus use the deep VLT/VIMOS U-band image.

To measure colors of objects precisely, we align our NB387 images with the broadband data using bright stellar objects commonly detected in the NB387 and the broadband images. After the image alignment process, we match the PSF sizes of broadband and narrowband images in each field, referring to these stellar objects.

2.3. Photometric Sample of $z = 2.2$ LAEs

Our source detection and photometry are performed with SExtractor (Bertin & Arnouts 1996). We use the PSF-homogenized images (Section 2.2) to measure colors of objects. We identify sources that are made of contiguous $>5$ pixels whose counts are above the $>2\sigma$ brightness of the background fluctuations in our NB387 images. We obtain a circular aperture magnitude of SExtractor’s MAG_APER with an aperture diameter of 2.5 in the SXDS-W field, 3 in the HDFN field, and 2 in the other fields, and we define a $5\sigma$ detection limit magnitude with the aperture size in each field. The different aperture diameters are applied, because the PSF sizes of the homogenized images in the SXDS-W and HDFN are large, 1.23 and 1.29, respectively. We use the aperture magnitudes to calculate colors of the sources and adopt MAG_AUTO of SExtractor for our total magnitudes. All magnitudes of the sources are corrected for Galactic extinction of $E(B-V) = 0.020, 0.018, 0.008, 0.012,$ and 0.08 in the SXDS, COSMOS, CDFS, HDFN, and SSA22 fields, respectively (Schlegel et al. 1998). We thus obtain source catalogs that contain 42,995 (SXDS), 31,401 (COSMOS), 24,451 (CDFS), 36,236 (HDFN), and 8942 (SSA22) objects with aperture magnitudes brighter than the $5\sigma$ detection limit magnitudes.

We select $z = 2.2$ LAE candidates based on narrowband excess colors of $U-N_{387}$ and $B-N_{387}$, in the same manner as Nakajima et al. (2012), who present the first results of the NB387 observations in the SXDS field. Here $U$ indicates $u^*$ or $U$. Figure 1 presents two-color diagrams of $B-N_{387}$ versus $U-N_{387}$. In this figure, we plot colors of model galaxies and Galactic stars to define the selection criteria for $z = 2.2$ LAE candidates. Based on Figure 1, we apply the color criteria (Nakajima et al. 2012, 2013; Kusakabe et al. 2015)

$$U - N_{387} > 0.5 \text{ and } B - N_{387} > 0.2$$

(1)

to obtain $z = 2.2$ LAE candidates whose rest-frame Ly$\alpha$ EWs, $EW_0$, are $EW_0 \gtrsim 20-30$ Å. After the visual inspection to remove spurious sources, such as ghosts, bad pixels, and surviving cosmic rays (see Nakajima et al. 2012 for more details), we identify 3137 LAE candidates in our survey fields. The sample of these LAE candidates is referred to as the full sample. This is so far the largest LAE sample in the large-area field surveys (cf. 187 and 250 LAEs at $z \approx 2.2$ with $EW_0 > 20$ Å observed by Nilsson et al. 2009 and Guaita et al. 2010, respectively). We summarize the details of the full sample in Table 2.

We make a subsample with the uniform criterion of Ly$\alpha$ $EW_0 > 60$ Å to compare the Ly$\alpha$ LF at $z = 3.1$ of Ouchi et al. (2008) (see Section 4.1), and we refer to the subsample as the EWgt60 sample. We apply the color criteria of

$$U^* - N_{387} > 0.9 \text{ and } B - N_{387} > 0.2$$

in SXDS, COSMOS, and SSA22,

(2)

$$U - N_{387} > 0.8 \text{ and } B - N_{387} > 0.2$$

in CDFS,

(3)

$$U - N_{387} > 1.0 \text{ and } B - N_{387} > 0.2$$

in HDFN

(4)

for the EWgt60 sample. After the visual inspection, we obtain 985 LAE candidates for the EWgt60 sample, which is summarized in Table 2.

3. LUMINOSITY FUNCTION

3.1. Contamination

We investigate the contamination sources of our LAE samples that are low-emitters whose emission lines are redshifted to the bandpass of NB387. The major strong emission that enters into the NB387 bandpass is [O II] $\lambda EW_{\lambda 3727}$. However, our survey area of 5138 arcmin$^2$ (Section 2.2) corresponds to the comoving volume of $1.22 \times 10^5$ Mpc$^3$ for [O II] emitters at $z = 0.04$, which is three orders of magnitude smaller than the survey volume of our $z = 2.2$ LAEs (1.32 x 10$^5$ Mpc$^3$). Moreover, the color criterion defined by Equation (1) corresponds to a relatively large rest-frame EW limit of $\gtrsim 70$ Å for $z = 0.04$ [O II] emitters. Ciardullo et al. (2013) examine [O II] LF and EW distributions at $z \sim 0.1$ and find that the [O II] EW distribution has an exponential scale of 8.0 Å, which is significantly smaller than our selection criterion for [O II] emitters (i.e., $EW_0 \sim 70$ Å). Based on our survey parameters (see Sections 2.2–2.3) and Ciardullo et al.’s [O II] LF and EW distribution, the expected number of [O II] emitters at $z = 0.04$ in our full sample is $\sim 3 \times 10^{-2}$. Therefore, the probability of the [O II] emitter contamination would be very small. We further discuss the possibility that our bright sources would include C iv $\lambda 1548$ and C iii $\lambda 1909$ emitters at $z \sim 1.5$. These C iv and C iii emitters should be mostly AGNs, because these emitters have to have a C iv or C iii LF greater than 30 Å to pass our selection criterion. This EW value is significantly larger than that of the star-forming galaxies. Because, in Section 5.2, we find that our AGN UV LF is consistent with the previous Sloan Digital Sky Survey (SDSS) measurements, only
a negligibly small fraction of the \(z \sim 1.5\) AGNs are included in our sample. Nevertheless, spectroscopic follow-up observations for our LAEs have been conducted with Magellan/IMACS, MagE, and Keck/LRIS by Nakajima et al. (2012), Hashimoto et al. (2013), Shibuya et al. (2014), and M. Rauch et al. (2016, in preparation). A total of 43 LAEs are spectroscopically confirmed. These spectroscopic observations find no foreground interlopers such as \([\text{O}\ ii]\) emitters at \(z = 0.04\) that show \([\text{O}\ ii]\) \(\lambda 5007\) emission at 5200 Å (see, e.g., Nakajima et al. 2012). We note that these spectroscopic redshift confirmations are limited to the bright LAEs with NB387 \(\lesssim 24.5\), and that the number of the faint LAEs confirmed by spectroscopy is small. However, the contamination rate at the faint end is probably not high. This is because the EW criterion of our selection corresponds to \(\sim 70\) Å for the major foreground faint emitters of \(z = 0.04\) \([\text{O}\ ii]\) emitters. Most of these potential contamination sources do not pass this large EW limit, as discussed above. Thus, the effects of contamination sources are negligibly small in our LAE samples.

### 3.2. Detection Completeness

We evaluate detection completeness in each field by Monte Carlo simulations, following the procedures of Konno et al. (2014). We randomly distribute a total of \(\sim 5000\) artificial sources mimicking LAEs in each NB387 image, and we detect
the artificial sources in the same manner as the real source identifications (Section 2.3). Here we assume that LAEs at $z = 2.2$ are point sources, and we use profiles obtained by the stack of 500 bright point sources in each NB387 image. We define the detection completeness as a fraction of the number of the detected artificial sources to all of the input artificial sources. We obtain the detection completeness as a function of NB387 magnitude, repeating this process with various magnitudes of the input artificial sources. Figure 2 shows the results of these Monte Carlo simulations. We find that the detection completeness is typically $\gtrsim 90\%$ for relatively bright sources ($NB387 < 24.5$) in all fields and $\sim 50\%$ at around the $5\sigma$ limiting magnitude of NB387 in each field (see Table 1).

| Field     | All LAE Sample | X-ray Detection | UV Detection | Radio Detection | Culled Sample |
|-----------|----------------|-----------------|--------------|----------------|---------------|
| SXDS-C    | 277            | 3 [3]           | 3 [3]        | 0 [0]          | 274           |
| SXDS-N    | 239            | 4 [4]           | 5 [4]        | 0 [0]          | 234           |
| SXDS-S    | 374            | 5 [3]           | 5 [4]        | 1 [1]          | 367           |
| SXDS-W    | 44             | 0 [0]           | 0 [0]        | 0 [0]          | 44            |
| COSMOS    | 642            | 20 [10]         | 10 [10]      | 7 [5]          | 619           |
| CDFS      | 423            | 6 [4]           | …            | 6 [4]          | 415           |
| HDFN      | 967            | 7 [1]           | 11 [1]       | …              | 950           |
| SSA22     | 171            | …               | 3 […]        | …              | 168           |
| Total     | 3137           | 45              | 37           | 14             | 3071          |

Notes.

- The number of $z = 2.2$ LAE candidates after the color selection and rejection of spurious objects.
- The number of $z = 2.2$ LAE candidates detected in the X-ray data. The values in square brackets represent the number of objects that are also detected in the UV and/or radio data.
- The number of $z = 2.2$ LAE candidates detected in the UV data taken by GALEX. The values in square brackets show the number of objects that are also detected in the X-ray and/or radio data.
- The number of $z = 2.2$ LAE candidates detected in the radio data. The values in square brackets show the number of objects that are also detected in the X-ray and/or UV data.
- The number of $z = 2.2$ LAE candidates with no counterpart detection(s) in multiwavelength data of X-ray, UV, and radio.
- The number of LAEs in SXDS-W is small. This is because the limiting magnitude in SXDS-W is brighter than those in the other fields by $\sim 0.5$ mag, and the effective area of SXDS-W is smaller than those of the other fields by a factor of $\sim 3$ (Table 1). The combination of the bright limiting magnitude and the small area reduces the number of LAEs in SXDS-W.
- The total number of $z = 2.2$ LAE candidates. The values in parentheses indicate the total number of LAEs found in the SXDS and COSMOS fields.

Figure 2. Detection completeness, $f_{\text{det}}$, of our NB387 images. The symbols represent the completeness in a magnitude bin of $\Delta m = 0.5$ mag for the SXDS-C (squares), SXDS-N (diamonds), SXDS-S (hexagons), SXDS-W (pentagons), COSMOS (circles), CDFS (inverted triangles), HDFN (triangles), and SSA22 (cross marks) fields. For presentation purposes, we slightly shift all of the points along the abscissa.

3.3. Cosmic Variance

To include field-to-field variation in the error bar of our Ly$\alpha$ LFs, we calculate the cosmic variance uncertainty, $\sigma_{\text{c}}$, with

$$\sigma_{\text{c}} = b_{\gamma} \sigma_{\text{DM}}(z, R),$$

where $b_{\gamma}$ and $\sigma_{\text{DM}}(z, R)$ are the bias parameter of galaxies and the density fluctuation of dark matter in a sphere with a radius $R$ at a redshift $z$, respectively. We estimate $\sigma_{\text{DM}}(z, R)$ with the growth factor, following Carroll et al. (1992), with the transfer function given by Bardeen et al. (1986) (see also Mo & White 2002). The value of $\sigma_{\text{DM}}(z, R)$ at $z = 2.2$ is estimated to be 0.055. Since Guaita et al. (2010) find the bias parameter of $b_{\gamma} = 1.8 \pm 0.3$ from the clustering analysis of $z = 2.1$ LAEs in the EDCF-S field, we adopt this value for $b_{\gamma}$ in Equation (5). We thus obtain the cosmic variance uncertainty of $\sigma_{\text{c}} \approx 0.099$.

3.4. Ly$\alpha$ Luminosity Functions

We derive the Ly$\alpha$ LFs at $z = 2.2$ from the full and EWgt60 samples, adopting the classical method of the Ly$\alpha$ LF derivation (Ouchi et al. 2010; Konno et al. 2014), whose accuracy is confirmed by Monte Carlo simulations (Shimasaku et al. 2006; Ouchi et al. 2008).

We calculate Ly$\alpha$ EWs of our LAEs from the aperture magnitudes of NB387 and B and obtain Ly$\alpha$ luminosities of our LAEs from these EWs and the total magnitudes of NB387. We estimate photometric errors of Ly$\alpha$ luminosities, performing Monte Carlo simulations under the assumption that the SEDs of LAEs have Ly$\alpha$ line located at $\lambda_{\text{cen}}$ of NB387 and a flat UV continuum (i.e., $f_{\nu} = \text{const.}$) with the intergalactic medium (IGM) absorption of Madau (1995). We calculate volume number densities of LAEs in an Ly$\alpha$ luminosity bin, dividing the number counts of LAEs by our comoving survey volume ($\sim 1.32 \times 10^6$ Mpc$^3$; see Section 2.2) under the assumption of the top-hat filter transmission curve. We correct these number densities for the detection completeness estimated in Section 3.2. Note that Ouchi et al. (2008) investigate the incompleteness of the narrowband color selection based on the Monte Carlo simulations and find that the incompleteness by the color is not significant.
The Astrophysical Journal, 823:20 (17pp), 2016 May 20

![Figure 3](image)

**Figure 3.** Top: Lyα LF of our $z = 2.2$ LAEs with a luminosity bin of $\Delta \log L_{\text{Ly\alpha}} = 0.1$. The red filled circles represent the Lyα LF derived from the full sample, and the red solid curve denotes the best-fit Schechter function. The black open symbols show the Lyα LFs in the SXDS-C (squares), SXDS-N (diamonds), SXDS-S (hexagons), SXDS-W (pentagons), COSMOS circles, CDFS (inverted triangles), HDFN (triangles), and SSA22 (crosses) fields. For clarity, we slightly shift all the points along the abscissa. The magenta filled circles and orange filled squares are the results from Cassata et al. (2011) and Blanc et al. (2011), respectively. Bottom: Lyα LF at $z = 2.2$ derived from the SXDS and COSMOS fields. The blue and black filled circles represent the Lyα LFs from the SXDS+COSMOS/All and SXDS+COSMOS/Culled subsamples, respectively. The blue and black solid curves show the best-fit Schechter functions of our best-estimate Lyα LFs using the SXDS+COSMOS/All and SXDS+COSMOS/Culled subsamples, respectively. The magenta filled circles and orange filled squares are the same as the top panel of this figure.

The top panel of Figure 3 presents the best estimate of our Lyα LF at $z = 2.2$ from the full sample. We also plot the Lyα LF measurements derived from each field’s data. The error bars of the Lyα LF include uncertainties from Poisson statistics and cosmic variance obtained in Section 3.3. For the Poisson errors, we use the values in columns “0.8413” in Tables 1 and 2 of Gehrels (1986) for the upper and lower limits of the Poisson errors, respectively. The best estimate Lyα LF covers an Lyα luminosity range of $\log L_{\text{Ly\alpha}} = 41.7$–44.4 erg s$^{-1}$. Our Lyα luminosity limit of $\log L_{\text{Ly\alpha}} = 41.7$ erg s$^{-1} (5.0 \times 10^{41}$ erg s$^{-1}$) is one order of magnitude fainter than the $L_{\text{Ly\alpha}}^*$ values at $z = 3–6$ (log $L_{\text{Ly\alpha}}^* = 42.8$ erg s$^{-1}$; Shimasaku et al. 2006; Gronwall et al. 2007; Ouchi et al. 2008).

We fit a Schechter function (Schechter 1976) to our $z = 2.2$ Lyα LF by minimum $\chi^2$ fitting. The Schechter function is defined by

$$
\phi_{\text{Ly\alpha}}(L_{\text{Ly\alpha}})dL_{\text{Ly\alpha}} = \phi_{\text{Ly\alpha}}^* \left( \frac{L_{\text{Ly\alpha}}}{L_{\text{Ly\alpha}}^*} \right) ^{\alpha} \exp \left( -\frac{L_{\text{Ly\alpha}}}{L_{\text{Ly\alpha}}^*} \right) d\left( \frac{L_{\text{Ly\alpha}}}{L_{\text{Ly\alpha}}^*} \right)
$$

(see Section 1 for the definitions of the parameters). For our fitting with the Schechter function, we use Lyα LF measurements from the studies of ours, Blanc et al. (2011), and Cassata et al. (2011). We do not include the results from the other studies, because there exist unknown systematics, which is discussed in Section 3.5. We determine three parameters of the Schechter function simultaneously and obtain the best-fit Schechter parameters of $\alpha = -1.75 \pm 0.10$, $L_{\text{Ly\alpha}}^* = 5.29 \pm 1.67 \times 10^{42}$ erg s$^{-1}$, and $\phi_{\text{Ly\alpha}}^* = 6.32 \pm 3.08 \times 10^{-4}$ Mpc$^{-3}$. This is the first time that three Schechter function parameters with no fixed parameter(s) have been determined, and the faint-end slope of $\alpha$ is reasonably well constrained. Table 3 presents these best-fit Schechter parameters. We show the best-fit Schechter function in the top panel of Figure 3 and error contours of the Schechter parameters in Figure 4.

The top panel of Figure 3 shows an excess of the number densities beyond the best-fit Schechter function at the bright end of $\log L_{\text{Ly\alpha}} > 43.4$ erg s$^{-1}$. We refer to this excess as the bright-end hump. In our Schechter function fit, we include the data of the bright-end hump. Because the errors of the Lyα LF at the faint end are significantly smaller than those at the bright end, the best-fit parameters are not significantly changed by the inclusion of the bright-end hump data (see footnote of Table 3).

Ouchi et al. (2008) find that there is a possible excess of the Lyα LFs at $z = 3.1$ and 3.7 similar to the bright-end hump, and they claim that 100% of LAEs host AGNs at the bright ends of $\log L_{\text{Ly\alpha}} > 43.6$ and 43.4 erg s$^{-1}$, respectively, based on the large-area LAE survey with the multiwavelength data set. Thus, the bright-end hump of our $z = 2.2$ Lyα LF may be produced by AGNs. To examine whether our LAEs at the bright end include AGNs, we use the XMM-Newton source catalog in the SXDS field (Ueda et al. 2008), the Chandra1.8 Ms catalog in the COSMOS field (Elvis et al. 2009), the Chandra 4 Ms source catalog in the CDFS field (Xue et al. 2011), and the Chandra 2 Ms catalog in the HDFN field (Alexander et al. 2003). The typical sensitivity limits of these X-ray data are $\sim 10^{-16}$ to $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ for the SXDS and COSMOS fields and $\sim 10^{-17}$ to $10^{-16}$ erg cm$^{-2}$ s$^{-1}$ for the CDFS and HDFN fields. We use GALEX far-UV (FUV) and near-UV (NUV) images for the UV data and obtain these images from the Multimission Archive at STScI (see also

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**Table 3**

| Sample | $\alpha$ | $L_{\text{Ly\alpha}}^*$ | $\phi_{\text{Ly\alpha}}^*$ |
|--------|----------|-------------------------|---------------------------|
| Full$^a$ | $-1.75 \pm 0.10$ | $5.29 \pm 1.67$ | $6.32 \pm 3.08 \times 10^{-4}$ |
| SXDS+COSMOS/All$^b$ | $-1.87 \pm 0.08$ | $7.83 \pm 3.22$ | $2.99 \pm 1.27 \times 10^{-4}$ |
| SXDS+COSMOS/Culled$^c$ | $-1.72 \pm 0.11$ | $4.28 \pm 0.99$ | $7.33 \pm 2.83 \times 10^{-4}$ |

**Notes.**

- $^a$ The full sample, which is constructed from the SXDS, COSMOS, CDFS, HDFN, and SSA22 fields.
- $^b$ In the case in which we do not include the data at $\log L_{\text{Ly\alpha}} > 43.4$ erg s$^{-1}$ with the bright-end hump for our fitting, the best-fit Schechter parameters are $\alpha = -1.72 \pm 0.09$, $L_{\text{Ly\alpha}}^* = 4.80 \pm 2.84 \times 10^{42}$ erg s$^{-1}$, and $\phi_{\text{Ly\alpha}}^* = 7.40 \pm 2.31 \times 10^{-4}$ Mpc$^{-3}$.
- $^c$ The sample of LAEs found in the SXDS and COSMOS fields.
- $^d$ The sample of LAEs with no multiwavelength counterpart detection(s) in the SXDS and COSMOS fields.

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Zamojski et al. 2007 for the COSMOS field). The GALEX images reach the 3σ detection limit of ∼25–26 mag. The Very Large Array 1.4 GHz source catalogs of Simpson et al. (2006) (SXDS), Schinnerer et al. (2007) (COSMOS), and Miller et al. (2013) (CDFS) are used for the radio data. These radio data reach an rms noise level of ∼10 μJy beam−1. We find that a majority of our bright LAEs are detected in the multiwavelength data, and we summarize the numbers of these LAEs in Table 2. Under the column of “culled sample” in Table 2, we show the numbers of LAEs with no counterpart detection(s) in the X-ray, UV, and radio data. As shown in Table 2, the SXDS and COSMOS fields have the data that cover all of the X-ray, UV, and radio wavelengths. Moreover, the X-ray, UV, and radio data spatially cover the entire fields of SXDS and COSMOS with the similar sensitivities. We make a subsample that is composed of all 1576 LAEs found in the SXDS and COSMOS fields, and we refer to this subsample as SXDS+COSMOS/All. We then make another subsample consisting of 1538 LAEs with no multiwavelength counterpart detection(s) in the SXDS and COSMOS fields, which is dubbed SXDS+COSMOS/Culled.

In the bottom panel of Figure 3, we plot the Lyα LFs derived from the subsamples of SXDS+COSMOS/All and SXDS+COSMOS/Culled. We fit the Schechter function to these Lyα LFs and the complementary Lyα LF data of Blanc et al. (2011) and Cassata et al. (2011), and we present the best-fit Schechter parameter sets and the error contours in Table 3 and Figure 4, respectively. Comparing the Lyα LF of the SXDS+COSMOS/All subsample with that of the full sample, in Figures 3 and 4, we find that the Lyα LF of the SXDS+COSMOS/All subsample is consistent with that of the full sample within the uncertainties. Figure 4 indicates that the Schechter fitting results of the full sample and the SXDS+COSMOS/All subsample are very similar to the one of the SXDS+COSMOS/Culled subsample, which are determined in the wide luminosity range of log L_{Lyα} = 41.7–44.4 erg s−1. However, there are no objects in the SXDS+COSMOS/Culled subsample that have log L_{Lyα} > 43.4 erg s−1. The Lyα LF of the SXDS+COSMOS/Culled subsample does not have a bright-end hump such as found in those of the full sample and the SXDS+COSMOS/All subsamples. These comparisons suggest that the bright-end hump of the z = 2.2 Lyα LF originates from AGNs that are bright in the X-ray, UV, and/or radio wavelength(s). We discuss more details of the bright-end hump in Sections 5.1 and 5.2.

3.5. Comparison with Previous Studies

We compare our best-estimate Lyα LF with those from previous studies at z ∼ 2. In Figure 5, we plot the Lyα LFs obtained by narrowband imaging surveys (Hayes et al. 2010; Ciardullo et al. 2012; see also Guaita et al. 2010) and blankfield spectroscopic surveys (Blanc et al. 2011; Cassata et al. 2011; Ciardullo et al. 2014). Hayes et al. (2010) carry out deep imaging with two narrowband filters covering Lyα and Hα lines and report the Lyα LF and the Lyα escape fraction of z = 2.2 LAEs. Ciardullo et al. (2012) derive the Lyα LF of z = 2.1 LAEs based on the narrowband data of Guaita et al. (2010). In both studies, the Lyα EW criterion of narrowband excess colors is EW0 = 20 Å, comparable to our studies. Blanc et al. (2011) and Ciardullo et al. (2014) obtain the Lyα LFs by the spectroscopic observations of the Hobby Eberly Telescope Dark Energy Experiment (HETDEX) Pilot Survey for LAEs at 1.9 < z < 3.8 and 1.90 < z < 2.35, respectively. Cassata et al. (2011) make a spectroscopic sample of LAEs at 2 < z < 6.6 with the VIMOS VLT Deep Survey. In these spectroscopic surveys, most of the LAEs have an Lyα EW greater than 20 Å. Table 4 summarizes the best-fit Schechter parameters (and Lyα luminosity ranges of the observations) given by our and the previous studies.

In Figure 5 and Table 4, we find that our z = 2.2 Lyα LF is generally consistent with those of the previous studies in the measurement ranges of the Lyα luminosity overlaps. However, there exist some noticeable differences. The Lyα LF of Ciardullo et al. (2012) is not similar to ours and Blanc et al. (2011) at the bright end, but similar to ours and Cassata et al. (2011) at the faint end. In contrast, the Lyα LF of Ciardullo et al. (2014) is not consistent with ours and Cassata et al. (2011) at the faint end, but consistent with ours and Blanc et al. (2011) at the bright end. Because Ciardullo et al. (2012, 2014) cover the reasonably wide Lyα luminosity ranges of 42.1 < log L_{Lyα} < 42.7 erg s−1 and 41.9 < log L_{Lyα} < 43.7 erg s−1, respectively, the origins of these differences at the bright and faint ends are not clear. As clarified in Table 4, most of the previous studies fit the Schechter function to their Lyα LFs, assuming a fixed parameter. Hayes et al. (2010) constrain three Schechter function parameters.
Figure 5. Comparison of our $z = 2.2$ Ly$\alpha$ LF with the previous measurements of Ly$\alpha$ LF at $z \sim 2$. The red filled circles denote our Ly$\alpha$ LF, and the red solid curve is the best-fit Schechter function, which are the same as in the top panel of Figure 3. The magenta filled circles represent the Ly$\alpha$ LF given by Cassata et al. (2011) at $2 < z < 3$. The orange stars and squares show the LFs by Blanc et al. (2011) based on the spectroscopic surveys of LAEs at $1.9 < z < 2.8$ and $1.9 < z < 3.8$, respectively. The black solid, dashed, and dotted lines are the best-fit Schechter functions obtained by Hayes et al. (2010) and Ciardullo et al. (2012, 2014), respectively. Since the previous Ly$\alpha$ LF estimates are limited in the ranges of $\log L_{\text{Ly}\alpha} = 41.3 - 42.9$ erg s$^{-1}$ (Hayes et al. 2010), 42.1 - 42.7 erg s$^{-1}$ (Ciardullo et al. 2012), and 41.9 - 43.7 erg s$^{-1}$ (Ciardullo et al. 2014), we show the black lines within these ranges.

Table 4

| Study            | $\alpha$   | $L_{\text{Ly}\alpha}^\#$ (10$^{42}$ erg s$^{-1}$) | $\phi_{\text{Ly}\alpha}^\#$ (10$^{-4}$ Mpc$^{-3}$) | $\log L_{\text{Ly}\alpha}$ Range |
|------------------|------------|--------------------------------------------------|--------------------------------------------------|----------------------------------|
| This work        | $-1.75 \pm 0.10$ | $5.29^{+1.67}_{-1.13}$                           | $6.32^{+1.00}_{-2.31}$                           | 41.7 - 44.4                      |
| Hayes et al. (2010) | $-1.49 \pm 0.27$ | $14.5^{+2.7}_{-3.8}$                            | $2.34^{+3.1}_{-1.0}$                            | 41.3 - 42.9                      |
| Blanc et al. (2011) | $-1.7$ (fixed) | $16.3^{+9.4}_{-10.8}$                           | $1.0^{+5.4}_{-0.9}$                            | 42.6 - 43.6                      |
| Cassata et al. (2011) | $-1.6 \pm 0.12$ | $5.0$ (fixed)                                    | $7.1^{+7.4}_{-4}$                              | 41.2 - 43.1                      |
| Ciardullo et al. (2012) | $-1.65$ (fixed) | $2.14^{+0.68}_{-0.52}$                           | $13.8^{+1.7}_{-1.5}$                           | 42.1 - 42.7                      |
| Ciardullo et al. (2014) | $-1.6$ (fixed) | $39.8^{+9.82}_{-16.4}$                           | $0.36^{+4}$                                    | 41.9 - 43.7                      |

Note. $^\#$ Ciardullo et al. (2014) do not show the errors of $\phi_{\text{Ly}\alpha}^\#$, although they present the uncertainties of the total number densities of LAEs integrated down to $\log L_{\text{Ly}\alpha} = 41.5$ erg s$^{-1}$, $\phi_{\text{int}} = 9.77^{+3.1}_{-2.8}$ × 10$^{-4}$ Mpc$^{-3}$.

parameters simultaneously, but the uncertainties of these parameters are large owing to small statistics (see also Gronwall et al. 2007 for $z \sim 3$). Our study constrains three Schechter parameters simultaneously, using the large LAE sample of 3137 LAEs covering the wide Ly$\alpha$ luminosity range ($\log L_{\text{Ly}\alpha} = 41.7 - 44.4$ erg s$^{-1}$).

4. Ly$\alpha$ LF AND DENSITY EVOLUTION

4.1. Evolution of Ly$\alpha$ LFs

In this section, we first examine the evolution of Ly$\alpha$ LFs at $z \sim 2$–3 and then investigate the evolution from $z \sim 0$ to 6 with the compilation of the Ly$\alpha$ LF data taken from the literature.

For the $z \sim 3$ data, we use the Ly$\alpha$ LF of Ouchi et al. (2008). The $z = 3.1$ Ly$\alpha$ LF of Ouchi et al. (2008) is derived in the same manner as ours (see Sections 3.2–3.4). Because the EW criterion of Ouchi et al. (2008) is EW $\geq 60$ Å, we compare the Ly$\alpha$ LF obtained from our EWgt60 sample (Section 2.3). The Ly$\alpha$ LF and the best-fit Schechter function (parameters) for the EWgt60 sample are presented in the left panel of Figure 6 (Table 5). The left panel of Figure 6 indicates that the Ly$\alpha$ LFs increase from $z \sim 2$ to 3.

To quantify this evolutionary trend, we show the error contours of the Schechter parameters of our $z = 2.2$ Ly$\alpha$ LF (red contours) and the $z = 3.1$ Ly$\alpha$ LF (blue contours) in the right panel of Figure 6. Here we apply our best-fit $z = 2.2$ Ly$\alpha$ LF slope of $\alpha = -1.8$ (Section 3.4) to the $z = 3.1$ LF result, because $\alpha$ is not determined in the $z = 3.1$ Ly$\alpha$ LF. Comparing the $z = 2.2$ and 3.1 error contours in the right panel of Figure 6, we find that the Ly$\alpha$ LF increases from $z = 2.2$ to 3.1 at the $>90\%$ confidence level. However, this increase is not large, only within a factor of $\sim 2$ (see Table 5). Note that there exist no systematic errors raised by the analysis technique in the comparison of our $z = 2.2$ and Ouchi et al.’s $z = 3.1$ Ly$\alpha$ LFs, because our $z = 2.2$ Ly$\alpha$ LF is derived in the same manner as Ouchi et al. (2008) based on the similar Subaru narrowband data (Sections 3.2–3.4).

We extend our investigation of Ly$\alpha$ LF evolution from $z = 2$–3 to $z = 0$–6. The left panel of Figure 6 compares our best-estimate Ly$\alpha$ LF at $z = 2.2$ with the Ly$\alpha$ LFs at $z = 0.3$, 0.9, 3.1, 3.7, and 5.7 taken from the literature. The right panel of Figure 6 shows the error contours of our Schechter function fitting, where we fix the $\alpha$ value to our best-fit slope $\alpha = -1.8$ of our $z = 2.2$ Ly$\alpha$ LF. The Ly$\alpha$ LFs at $z = 0.3$ and 0.9 are
Figure 6. Left: evolution of Lyα LF from \( z = 0 \) to 6. The red filled circles are our \( z = 2.2 \) Lyα LF of the EWgt60 sample, and the blue filled circles denote the LF at \( z = 3.1 \) derived by Ouchi et al. (2008). The orange, magenta, red, blue, cyan, and green curves show the best-fit Schechter functions of the Lyα LFs at \( z = 0.3 \) (Cowie et al. 2010), 0.9 (Barger et al. 2012), 2.2 (this work), 3.1, 3.7, and 5.7 (Ouchi et al. 2008), respectively. These Schechter functions are derived with a fixed slope value of \( \alpha = -1.8 \), which is the best-fit value of our \( z = 2.2 \) Lyα LF. Right: error contours of Schechter parameters, \( L_{\text{Lyα}}^* \) and \( \phi_{\text{Lyα}}^* \). The orange, magenta, red, blue, cyan, and green contours represent the error contours of the Schechter parameters at \( z = 0.3, 0.9, 2.2, 3.1, 3.7, \) and 5.7, respectively. The inner and outer contours indicate the 68% and 90% confidence levels, respectively.

Table 5

Best-fit Schechter Parameters and Lyα Luminosity Densities

| Redshift | \( L_{\text{Lyα}}^* \) (10^{42} \text{ erg s}^{-1}) | \( \phi_{\text{Lyα}}^* \) (10^{-4} \text{ Mpc}^{-3}) | \( \rho_{\text{Lyα obs}}^* \) (10^{49} \text{ erg s}^{-1} \text{ Mpc}^{-3}) | Reference |
|----------|---------------------------------|-----------------|-----------------|----------------|
| 0.3      | 0.71±0.52                       | 1.12±0.24       | 0.055±0.019     | Cowie et al. (2010) |
| 0.9      | 9.22±1.56                       | 0.12±0.04       | 0.165±0.050     | Barger et al. (2012) |
| 2.2      | 5.29±1.17                       | 6.32±3.98       | 5.93±0.22       | This work (best estimate) |
| 2.2      | 4.87±0.83                       | 3.37±0.80       | 2.17±0.13       | This work (EW60 sample) |
| 3.1      | 8.49±1.85                       | 3.90±1.27       | 4.74±0.96       | Ouchi et al. (2008) |
| 3.7      | 9.16±2.03                       | 3.31±1.42       | 4.36±0.73       | Ouchi et al. (2008) |
| 5.7      | 9.09±3.67                       | 4.44±4.69       | 5.81±1.87       | Ouchi et al. (2008) |
| 6.6      | 6.69±1.42                       | 4.17±2.79       | 3.86±0.96       | Ouchi et al. (2010) |
| 7.3      | 3.23±2.51                       | 2.82±1.76       | 1.12±2.30       | Konno et al. (2014) |

Notes. For \( z = 2.2 \) (best estimate), the best-fit Schechter parameters are determined with the full sample (Section 3.4), while for the other cases, \( L_{\text{Lyα}}^* \) and \( \phi_{\text{Lyα}}^* \) are derived with a fixed value of \( \alpha = -1.8 \), which is consistent with the best-fit value for our Lyα LF at \( z = 2.2 \). Note that EW0 limits for the selection of LAEs at \( z = 0.3, 0.9, 2.2 \) (best estimate), 2.2 (EW60 sample), 3.1, 3.7, 5.7, 6.6, and 7.3 are EW0 = 15, 20, \~{}30–30 Å for all of the samples listed in Table 5 except for those of Ouchi et al.'s \( z = 3.1 \) and 3.7 samples and our EW60 sample. In the right panel of Figure 6, there is a significant increase of Lyα LFs in \( L_{\text{Lyα}}^* \) and/or \( \phi_{\text{Lyα}}^* \) from \( z = 3 \) to 3, albeit with the uncertain decrease of \( \phi_{\text{Lyα}}^* \) from \( z = 0.3 \) to 0.9, which is first claimed by Deharveng et al. (2008). The right panel of Figure 6 also suggests no significant evolution of the Lyα LFs at \( z = 3–6 \), which is concluded by Ouchi et al. (2008).  

4.2. Lyα LD Evolution

We calculate the Lyα LDs,

\[
\rho_{\text{Lyα obs}}^* = \int_{L_{\text{Lyα lim}}}^{\infty} L_{\text{Lyα}} \phi_{\text{Lyα}}^* (L_{\text{Lyα}}) dL_{\text{Lyα}},
\]  

at \( z = 0–8 \) with the Lyα LFs shown in Section 4.1, where \( L_{\text{Lyα lim}}^* \) is the Lyα luminosity limit for the Lyα LD estimates. We choose the common Lyα luminosity limit of \( L_{\text{Lyα lim}}^* = 41.41 \text{ erg s}^{-1} \), which corresponds to 0.03L_{Lyα,z=3}.  

There are two systematic uncertainties for estimates of the Lyα LFs. One uncertainty is the choice of Lyα luminosity limits. The Lyα luminosity limit can be lower than \( L_{\text{Lyα lim}}^* = 41.41 \text{ erg s}^{-1} \) to estimate representative Lyα LFs. However, we confirm that the estimated Lyα LFs are not largely different even if we integrate the Lyα LFs down to a fainter luminosity of \( L_{\text{Lyα lim}}^* = 40.0 \text{ erg s}^{-1} \). The largest Lyα LD difference of \~{}0.4 dex is found at \( z = 0.3 \), because the \( L_{\text{Lyα}}^* \) value at \( z = 0.3 \) is significantly smaller than those at the other redshifts. Another uncertainty is Lyα EW limits for selection of LAEs. Lyα LFs are based on LAE samples selected with an Lyα EW limit (i.e., \( EW_{\alpha} \gtrsim 10–30 \text{ Å} \)). Ouchi et al. (2008) estimate Lyα LFs for all (EW > 0 Å) LAEs and find that the Lyα LFs are slightly larger than those for their EW-limited LAE samples (EW0 > 10–30 Å) by \~{}0.1 dex at most. These levels of differences do not change the results of the Lyα LD.
evolution in this section, which is at the level of an order of magnitude. For these Lyα LFs, we do not correct the Lyα flux attenuation by neutral hydrogen (H I) in the IGM. The Lyα LFs represent the amount of Lyα photons escaping not only from the ISM of galaxies but also from the HI IGM.

For comparison, we also use UV LFs taken from the literature (Bouwens et al. 2015). The UV LD is defined by

\[ \rho_{\text{obs}}^{\text{UV}} = \int_{L_{\text{lim}}^{\text{UV}}}^{\infty} L_{\text{UV}} \phi_{\text{UV}}(L_{\text{UV}}) dL_{\text{UV}}, \]

where \( L_{\text{lim}}^{\text{UV}} \) is the UV luminosity limit for the UV LD estimates and \( \phi_{\text{UV}}(L_{\text{UV}}) \) is the best-fit Schechter function for the UV LF measurements. Here the value of \( L_{\text{lim}}^{\text{UV}} \) is 0.03 \( L_{\text{lim}}^{\text{UV},z=3} \) (\( M_{\text{UV}} = -17.0 \) mag). The top panel of Figure 7 presents the evolution of the Lyα LDs as a function of redshift, whose data are summarized in Table 5. In the top panel of Figure 7, we also plot the UV LDs of dust-uncorrected and dust-corrected UV LDs obtained by Bouwens et al. (2015). Similar to the evolutionary trends of Lyα LFs described in Section 4.1, we find a significant increase of Lyα LDs from \( z \sim 2 \) to 3 beyond the measurement errors. Moreover, there is a rapid increase of Lyα LDs by nearly two order of magnitudes from \( z \sim 0 \) to 3 and a plateau of Lyα LDs between \( z \sim 3 \) and 6. The decrease of Lyα LDs at \( z \gtrsim 6 \) is also found. For more details, see Section 4.1 and the literature (e.g., Deharveng et al. 2008; Ouchi et al. 2008; Cowie et al. 2010, 2011; Barger et al. 2012; Ciardullo et al. 2012; Konno et al. 2014; Wold et al. 2014).

The Lyα LD evolution is different from the UV LD evolution in the top panel of Figure 7. There is an increase of UV LDs from \( z \sim 0 \) to 3, but the increase is only about an order of magnitude, which is not as large as the one of Lyα LDs. At \( z \sim 3 \sim 6 \), the UV LDs show a moderate decrease and no evolutionary plateau like the one found in the Lyα LD evolution. At \( z \gtrsim 6 \), the decrease of Lyα LDs is faster than the
one of UV LDs toward high $z$. We discuss the physical origins of these differences in Section 5.3.

5. DISCUSSION

5.1. Bright-end Hump of the Ly$\alpha$ LF

In the top panel of Figure 3, we find the bright-end hump of our $z = 2.2$ Ly$\alpha$ LF at log $L_{Ly\alpha}$ $\gtrsim$ 43.4 erg s$^{-1}$. The objects in the bright-end hump have UV continuum magnitudes of $M_{UV} \gtrsim -25$. There are two possibilities to explain this hump. One possibility is the existence of AGNs that have a strong Ly$\alpha$ emission line (e.g., Ouchi et al. 2008). Another possibility is the magnification bias (e.g., Wyithe et al. 2011; Mason et al. 2015). The gravitational lensing of foreground massive galaxies increases luminosities of LAEs at $z = 2.2$ that make the hump at the bright-end LF. The bottom panel of Figure 3 shows that all galaxies brighter than log $L_{Ly\alpha}$ = 43.4 erg s$^{-1}$ have a bright counterpart(s) in X-ray, UV, and/or radio data, suggesting that these galaxies have AGNs. If we remove these galaxies from our sample, the shape of the Ly$\alpha$ LF is explained by the simple Schechter function with no hump (see the black solid line and black filled circles in the bottom panel of Figure 3). These results indicate that the bright-end hump is almost fully explained by AGNs that have magnitudes of $M_{UV} \gtrsim -25$. These AGNs are significantly fainter than QSOs and regarded as faint AGNs. The magnification bias would exist, but it is very weak. The major physical mechanism of the bright-end hump is not the magnification bias.

5.2. Faint AGN UV LF

In Section 5.1, we discuss that the bright-end hump is made of faint AGNs (log $L_{Ly\alpha}$ $>$ 43.4 erg s$^{-1}$), all of which have the counterpart(s) in the X-ray, UV, and radio data. Using the abundance and the UV continuum magnitudes ($M_{UV} \gtrsim -25$) of these faint AGNs, we derive faint AGN UV LFs. These faint AGN UV LFs complement the bright AGN UV LFs obtained by cosmological large-scale surveys such as SDSS. To estimate the faint AGN UV LFs, we measure $i$-band magnitudes at the positions of the faint AGNs. Here we choose the $i$-band magnitudes for UV continuum magnitude estimates, because we compare our results with the SDSS AGN study of Ross et al. (2013), who use $i$-band magnitudes to derive their AGN UV LF. All of our faint AGNs are detected at $>5\sigma$ levels in our $i$-band images. Note that the $5\sigma$ limiting magnitudes of our $i$-band images correspond to $M_{UV} = -17.9$, $-18.6$, $-20.2$, $-19.7$, and $-18.5$ mag for the faint AGNs at $z = 2.2$ in the SXDS, COSMOS, CDFS, HDFN, and SSA22 fields, respectively. We calculate the volume number densities of the faint AGNs in a UV-continuum magnitude bin, dividing the number counts of faint AGNs by the comoving survey volume ($\sim 1.32 \times 10^8$ Mpc$^3$). Figure 8 presents these UV LFs of our faint AGNs with black open circles, which we call raw UV LFs. The errors of the raw UV LFs are the Poisson errors for small number statistics (Gehrels 1986).

Because AGNs do not always have Ly$\alpha$ emission that can be identified by our narrowband observations, the raw UV LFs are incomplete. The raw UV LFs are regarded as the lower limits of the AGN UV LFs. To evaluate the incompleteness, we use the relation of Ly$\alpha$ EWs and UV-continuum magnitudes (the Baldwin effect) given by Dietrich et al. (2002). Dietrich et al. (2002) obtain the median values of Ly$\alpha$ EWs at a given UV-continuum magnitude bin based on 744 AGNs at $z \sim 0$–5, where a negligibly small fraction ($\sim 10\%$) of damped Ly$\alpha$ systems and low-quality data are removed from their AGN sample. Note that we do not take into account UV continuum indices of AGNs, because our sample is too small to make statistically useful subsamples with the additional parameter of the UV continuum indices. In Figure 9, we plot the median values with the black filled diamonds. Because no PDFs of Ly$\alpha$ EWs are presented in Dietrich et al. (2002), the errors of the black filled diamonds represent the measurement uncertainties of Ly$\alpha$ EWs. Figure 9 shows a correlation, indicating that UV-continuum-faint AGNs have large Ly$\alpha$ EWs. The red and blue lines in Figure 9 represent our selection limits of log $L_{Ly\alpha}$ $> 43.4$ erg s$^{-1}$ (for the objects in the bright-end hump) and the EEW $\geq 20$–30 Å (for our LAE sample), respectively. In Figure 9, we find that these selection limits (red and blue lines) are far below the median values (black diamonds) at $M_{UV} \lesssim -22.5$. Thus, the faint AGN UV LFs at $M_{UV} \lesssim -22.5$ can be determined with reasonable completeness corrections. Because the Ly$\alpha$ EW PDFs are not given in Dietrich et al. (2002), one cannot simply estimate the incompleteness. However, all of the median values at $M_{UV} \lesssim -22.5$ are placed above the selection limits. The maximum correction factor is $\sim 2$ in the most extreme case that the Ly$\alpha$ EW PDF has a bottom-heavy distribution. This is because about half of the AGNs at maximum could fall below our selection limits, which can keep the median values as high as those obtained by Dietrich et al. (2002). For our faint AGNs at $M_{UV} \lesssim -22.5$, we correct the raw UV LFs for the incompleteness with the maximum correction factor, and we plot the maximally corrected UV LFs with the open squares in Figure 8. Because the real UV LFs should be placed between the raw UV LFs and the maximally corrected UV LFs, we define the best-estimate UV LFs by the average of the raw and maximally corrected UV LFs with the conservative error bars that completely cover the $1\sigma$ uncertainties of these two UV LFs. The red circles in Figure 8 represent the best-estimate UV LFs. In Figure 8, we also present the AGN UV LFs at $z \sim 2.2$ derived with the SDSS DR9 data (the blue circles; Ross et al. 2013) and the 2dF-SDSS LRG and QSO survey data (the green circles; Croom et al. 2009). There is a magnitude-range overlap of our, Ross et al.’s, and Croom et al.’s AGN UV LF estimates at $M_{UV} \simeq -24.8$. The number densities from our, Ross et al.’s, and Croom et al.’s studies agree very well within the uncertainties at the overlap magnitude, indicating that our AGN UV LF estimates are reliable. We also confirm that the AGN UV LF in our study is also consistent with that in Jiang et al. (2006).

We fit a double-power-law function to the AGN UV LFs of ours, Ross et al. (2013), and Croom et al. (2009). The double-power-law function for the AGN number density, $\phi_{AGN}(M_{UV})$, is defined by

$$
\phi_{AGN}(M_{UV}) = \frac{\phi_{AGN}^*}{10^{0.4(\alpha_{AGN}+1)(M_{UV}-M_{AGN}^*)} + 10^{0.4(\beta_{AGN}+1)(M_{UV}-M_{AGN}^*)}},
$$

where $\phi_{AGN}^*$ and $M_{AGN}^*$ are the characteristic number density and magnitude of AGNs, respectively. The parameters of $\alpha_{AGN}$ and $\beta_{AGN}$ determine the faint- and bright-end slopes of the AGN UV LFs, respectively. We obtain the best-fit parameters of $\alpha_{AGN} = 1.8 \pm 0.2 \times 10^{-6}$ Mpc$^{-3}$, $M_{AGN}^* = -26.2 \pm 0.1$, $\alpha_{AGN} = -1.2 \pm 0.1$, and $\beta_{AGN} = -3.3 \pm 0.1$ and present the
estimate the incompleteness at this range (see the text for details).

The blue dashed line denotes the EW0 function obtained by Dietrich et al. (2015), and the black open circles and squares represent the raw and maximally corrected AGN UV LFs, respectively (see the text for details). At $M_{UV} \gtrsim -22.5$, we plot only the raw UV LF as lower limits with black arrows, because one cannot estimate the incompleteness at this range (see the text for details). For display purposes, we slightly shift the black symbols along the abscissa. The blue and green circles are the AGN UV LFs at $z \sim 2.2$ derived from the SDSS DR9 data set (Ross et al. 2013) and the 2dF-SDSS LRG and QSO survey data set (Croom et al. 2009), respectively. The red curve shows the best-fit function for the AGN UV LFs of ours, Ross et al. (2013), and Croom et al. (2009). The black dotted and dashed curves represent the best-fit functions under the assumptions of the PLE and LEDE models introduced by Ross et al. (2013), respectively. We also display the UV LF of z = 2 LBGs obtained by Reddy & Steidel (2009) with the cyan circles. The cyan solid curve represents the best-fit Schechter function of the LBG UV LF within a range of the observed UV-continuum magnitude (i.e., $M_{UV} > -22.8$), while the cyan dashed curve denotes the function extrapolated to $M_{UV} < -22.8$.

Figure 8. UV LF of faint AGNs. The red filled circles denote the best-estimate AGN UV LFs, and the black open circles and squares represent the raw and maximally corrected AGN UV LFs, respectively (see the text for details). At $M_{UV} \gtrsim -22.5$, we plot only the raw UV LF as lower limits with black arrows, because one cannot estimate the incompleteness at this range (see the text for details). For display purposes, we slightly shift the black symbols along the abscissa. The blue and green circles are the AGN UV LFs at $z \sim 2.2$ derived from the SDSS DR9 data set (Ross et al. 2013) and the 2dF-SDSS LRG and QSO survey data set (Croom et al. 2009), respectively. The red curve shows the best-fit function for the AGN UV LFs of ours, Ross et al. (2013), and Croom et al. (2009). The black dotted and dashed curves represent the best-fit functions under the assumptions of the PLE and LEDE models introduced by Ross et al. (2013), respectively. We also display the UV LF of z = 2 LBGs obtained by Reddy & Steidel (2009) with the cyan circles. The cyan solid curve represents the best-fit Schechter function of the LBG UV LF within a range of the observed UV-continuum magnitude (i.e., $M_{UV} > -22.8$), while the cyan dashed curve denotes the function extrapolated to $M_{UV} < -22.8$.

Figure 9. Ly$\alpha$ EW$_0$ as a function of UV-continuum magnitude of AGNs. The black diamonds represent the median values of the observed Ly$\alpha$ EW$_0$ at a given UV-continuum magnitude, and the black dashed line is a best-fit linear function obtained by Dietrich et al. (2002). The error bars of the black diamonds indicate the measurement uncertainties of the Ly$\alpha$ EWs. The red solid line shows a locus of the luminosity for log$L_{Ly\alpha} = 43.4$ erg s$^{-1}$, which is a selection criterion for our faint AGNs. The blue dashed line denotes the EW$_0$ threshold for selection of our $z = 2.2$ LAEs (i.e., $\sim 20$–30 Å).

best-fit function with the red line in Figure 8. Our results suggest that the faint-end slope $\alpha_{AGN}$ is moderately flat at $M_{UV} \sim -23$–25.

Ross et al. (2013) and Croom et al. (2009) show that the faint-end slopes at $z \sim 2.2$ are $\alpha_{AGN} = -1.3^{+0.7}_{-0.1}$ and $-1.4 \pm 0.2$, respectively, which are consistent with our result. Because relatively steep faint-end slopes ($\alpha_{AGN} \sim -1.5$–1.8) are obtained for $z = 4$–6.5 AGNs (Ikeda et al. 2011; Giallongo et al. 2015), our moderately flat faint-end slope at $z \sim 2.2$ would suggest that the faint-end slope steepens toward high $z$.

Figure 8 displays the two models of a pure luminosity evolution (PLE) model and a luminosity evolution and density evolution (LEDE) model that are introduced by Ross et al. (2013). Comparing these two models, we find that the LEDE model explains our AGN UV LFs better than the PLE model. This comparison suggests that the AGN UV LF evolution involves both luminosities and densities.

5.3. Ly$\alpha$ Escape Fraction Evolution and the Physical Origins

In Section 4.2, we compare the evolution of the Ly$\alpha$ and UV LFs and conclude that the evolutions of Ly$\alpha$ and UV LDs are different. To understand the physical origins of the differences between Ly$\alpha$ and UV LD evolutions, we investigate the evolution of Ly$\alpha$ escape fractions, $f_{Ly\alpha}^{esc}$. The Ly$\alpha$ escape fraction evolution is investigated by previous studies (e.g., Bian et al. 2011; Hayes et al. 2011). In this study, we revisit the Ly$\alpha$ escape fraction evolution, because there are significant progresses on the estimates of Ly$\alpha$ LFs from recent Subaru, VLT, and HETDEX pilot surveys (e.g., Cassata et al. 2011; Ciardullo et al. 2014; Konno et al. 2014) and UV LFs from HST UDF12, CANDELS, and HFF programs (e.g., Bourbons et al. 2015).

The Ly$\alpha$ escape fraction is defined by

$$f_{Ly\alpha}^{esc} = \frac{\rho_{SFRD, Ly\alpha}}{\rho_{SFRD, int, UV}},$$

where $\rho_{SFRD, Ly\alpha}$ are the star formation rate densities (SFRDs) estimated from the observed Ly$\alpha$ LFs. The variable of $\rho_{SFRD, int, UV}$ represents SFRDs calculated from the intrinsic UV LFs, which are UV LDs corrected for dust extinction. Note that the contribution from AGN luminosities to Ly$\alpha$ LFs and UV LDs is negligibly small owing to the low AGN abundance, and that we regard these Ly$\alpha$ and UV photons as produced by star formation.
We use the Lyα LDs shown in Figure 7 (Section 4.2) and derive $\rho_{\text{obs, Ly}\alpha}$. In the estimation of star formation rates (SFRs) from the Lyα luminosities, we apply

$$SFR (M_\odot \text{yr}^{-1}) = L_{\text{Ly}\alpha} \left(\text{erg s}^{-1}\right)/(1.1 \times 10^{42}),$$

(11)

which is the combination of the Hα luminosity–SFR relation (Kennicutt 1998) and the case B approximation (Brocklehurst 1971). For $\rho_{\text{int,UV}}$, we use the dust-extinction-corrected SFRDs derived by Bouwens et al. (2015). The SFRDs are estimated from the UV LDs that are integrated values of UV LFs down to $0.03L_{\text{UV}}$ (Section 4.2). The SFRs are estimated from UV luminosities with the equation (Madau et al. 1998)

$$SFR (M_\odot \text{yr}^{-1}) = L_{\text{UV}} \left(\text{erg s}^{-1} \text{Hz}^{-1}\right)/(8 \times 10^{27}),$$

(12)

where $L_{\text{UV}}$ is the UV luminosity measured at 1500 Å. The dust extinction values are evaluated from the UV-continuum slope measurements with the relation of Meurer et al. (1999). The UV LDs corresponding to these SFRDs are presented in Figure 7. Note that the Salpeter IMF is assumed in Equations (11) and (12).

From these SFRDs, we estimate Lyα escape fractions with Equation (10). The bottom panel of Figure 7 presents the Lyα escape fractions at $z \sim 0$–8. We fit a power-law function of $\alpha(1 + z)^n$ to these Lyα escape fraction estimates at $z \sim 0$–6, where $n$ is the power-law index. We obtain the best-fit function of $f_{\text{esc}}^{\alpha} = 5.0 \times 10^{-4} \times (1 + z)^{2.5}$. The best-fit function is shown in the bottom panel of Figure 7. The best-fit function indicates a large increase of Lyα escape fractions from $z \sim 0$ to 6 by two orders of magnitude, although the data points of $z > 6$ depart from the best-fit function. This trend is similar to the one claimed by Hayes et al. (2011). We compare the results of Hayes et al. (2011) with this study in the bottom panel of Figure 7. Although the general evolutionary trend is the same in Hayes et al.’s and our results, there is an offset between these two results. This offset is explained by the differences of the Lyα and UV luminosity limits for deriving the Lyα and UV LDs from Lyα and UV LFs, respectively. In fact, we obtain Lyα escape fractions consistent with those of Hayes et al. (2011), if we calculate the Lyα escape fractions with the same Lyα and UV luminosity limits as those of Hayes et al. (2011). In other words, the choice of Lyα and UV luminosity limits moderately changes the Lyα escape fraction estimates, but the two-order-of-magnitude evolution of Lyα escape fractions is significantly larger than these changes. It should be noted that, if we calculate $f_{\text{esc}}^{\alpha}$ with our Lyα LF and Sobral et al.’s Hα LFs, we obtain $f_{\text{esc}}^{\alpha} = 0.013$, which is consistent with our original estimate with the UV LFs ($f_{\text{esc}}^{\alpha} = 0.011$). Thus, there are no significant systematics in $f_{\text{esc}}^{\alpha}$ estimates for the choices of UV and Hα LFs. Recently, Matthee et al. (2016) obtained the $f_{\text{esc}}^{\alpha}$ value at $z = 2.2$ from the Lyα/Hα flux measurements of their 17 Hα emitters. They obtained a median value of $f_{\text{esc}}^{\alpha} = 0.016 \pm 0.005$, which is also consistent with ours. At $z > 6$, there exist the departures of the Lyα escape fraction estimates from the best-fit function (the bottom panel of Figure 7). Moreover, the departure becomes larger toward high $z$. There is a decrease of Lyα escape fractions from $z \sim 6$ to 8 by a factor of $\sim 2$. Because the redshift range of $z \sim 6$ corresponds to the epoch of reionization (EoR), this decrease of Lyα escape fractions at $z > 6$ is explained by the increase of Lyα scattering of H i in the IGM at the EoR. In other words, it is likely that the physical origin of the $f_{\text{esc}}^{\alpha}$ decrease at $z \geq 6$ is cosmic reionization. This result is in a different form from the previous results that claim the signature of cosmic reionization based on the Lyα LF decrease at $z > 6$ (e.g., Kashikawa et al. 2006, 2011; Ouchi et al. 2010; Shibuya et al. 2012; Jiang et al. 2013; Konno et al. 2014) and the Lyα-emitting galaxy fraction decrease at $z > 6$ (e.g., Pentericci et al. 2011; Ono et al. 2012; Treu et al. 2013; Schenker et al. 2014). Here we discuss the physical mechanism of the large, two-order-of-magnitude increase of $f_{\text{esc}}^{\alpha}$ from $z \sim 0$ to 6. Note that $f_{\text{esc}}^{\alpha}$ is defined as the ratio of the Lyα LD to the UV LD of star-forming galaxies. Since these LDs are mainly contributed by continuum-faint galaxies with $M_{UV} > -19$, the majority of which show Lyα in emission (Stark et al. 2010), we regard LAEs as a dominant population of high-$z$ star-forming galaxies in the following discussion.

There are four possible physical mechanisms for the large $f_{\text{esc}}^{\alpha}$ increase from $z \sim 0$ to 6: evolutions of stellar population, outflow, dust extinction, and Lyα scattering of H i in the galaxy’s ISM. It should be noted that the IGM absorption of Lyα becomes strong from $z \sim 0$ to 6, and that the evolution of IGM absorption suppresses $f_{\text{esc}}^{\alpha}$ (see below for the quantitative arguments), which cannot be a physical mechanism for the $f_{\text{esc}}^{\alpha}$ increase toward high $z$. For the possibility of stellar population evolution, the estimates of $f_{\text{esc}}^{\alpha}$ would increase if more ionizing photons for a given SFR were produced in galaxies that have very massive stars found in the early stage of star formation. However, the average/median stellar ages of LAEs for a constant star formation history are 10–300 Myr at $z = 2–6$ (e.g., Gawiser et al. 2006; Pirzkal et al. 2007; Lai et al. 2008; Ono et al. 2010a, 2010b; Gudaite et al. 2011), which are comparable with those at $z \sim 0$ (e.g., Cowie et al. 2011; Hayes et al. 2014). Because there are no systematic differences in stellar ages by redshift, the difference of stellar population does not explain the large increase of $f_{\text{esc}}^{\alpha}$. For the possibility of outflow, it is likely that gas outflow of galaxies helps Lyα photons escape from the ISM, because the Lyα resonance wavelength of the ISM is redshifted by the bulk gas motion of outflow. If there is a systematic difference in outflow velocities, the $f_{\text{esc}}^{\alpha}$ values change. Because the typical outflow velocities of LAEs are 50–200 km s$^{-1}$ and show no systematic change over the redshift range of $z \sim 0$–6 (Hashimoto et al. 2013; Wofford et al. 2013; Erb et al. 2014; Shibuya et al. 2014; Rivera-Thorsen et al. 2015; Stark et al. 2015), the galaxy outflow would not be a major reason for the large $f_{\text{esc}}^{\alpha}$ increase. For the possibility of dust extinction evolution, it is thought that the amount of dust in galaxies decreases from $z \sim 0$ to 6, and that galaxies with small dust extinction have large $f_{\text{esc}}^{\alpha}$ values. Because the dust attenuation of Lyα is enhanced by the resonance scattering of H i in the galaxy’s ISM, which depends on the H i density, we first obtain crude estimates of dust extinction effects with no resonance scattering. We estimate the luminosity-averaged stellar extinction, $E(B-V)_*$, from the dust-corrected and dust-uncorrected UV LDs by the equation

$$\rho_{\text{int, UV}} = (10^{0.4 \times E(B-V)_*} \times k_{UV} \times \rho_{\text{uncorr, UV}})^{1/2},$$

(13)

These outflow velocity measurements are obtained for UV-continuum-bright galaxies, except for a few lensed galaxies. Because the outflow velocities of LAEs are similar to those of LBGs (150–200 km s$^{-1}$; e.g., Hashimoto et al. 2013; Erb et al. 2014; Shibuya et al. 2014), UV-continuum-faint galaxies would have an outflow velocity comparable to that of UV-bright galaxies.
where $\rho^{\text{uncorr,UV}}_{\text{SFRD}}$ are the dust-uncorrected UV SFRDs (Section 4.2) calculated with Equation (12). The value of $k_{\text{UV}}$ is the extinction coefficient at 1500 Å, which is derived with Calzetti’s extinction law (Calzetti et al. 2000), $k_{\text{UV}} = 10.3$. We thus obtain $E(B - V)$ values over $z \sim 0 - 6$. From these $E(B - V)$ values, we estimate $f_{\text{esc, dust}}$ with

$$f_{\text{esc, dust}} = 10^{-0.4 \times k_{1216} \times E(B - V)_{\text{gas}}}$$

(14)

where $k_{1216}$ is the extinction coefficient at 1216 Å, $k_{1216} = 12.0$, estimated with Calzetti et al.’s law. Here we adopt $E(B - V)_{\text{gas}} = E(B - V)_0/0.44$ (Calzetti et al. 2000).

The MCLya code has four physical parameters to describe the velocity measurements for the low-$z$ and high-$z$ LAEs and LBGs so far obtained (Jones et al. 2012; Hashimoto et al. 2013; Shibuya et al. 2014; Rivera-Thorsen et al. 2015; Stark et al. 2015).

The MCLya code computes the Ly$\alpha$ radiative transfer in an expanding homogeneous shell of ISM H$\text{i}$ and dust that surrounds a central Ly$\alpha$ source. The dust extinction effects are self-consistently calculated for the resonance line of Ly$\alpha$. The MCLya code has four physical parameters to describe the physical properties of the shell: $N_{\text{H}1}$, the nebular dust extinction $E(B - V)_{\text{gas}}$, the radial expansion velocity $v_{\text{exp}}$, and the Doppler parameter $b$, which includes both thermal and turbulent gas motions within the shell. Each redshift shown in Figure 7, we derive the best-estimate $N_{\text{H}1}$ value, using the $E(B - V)_{\text{gas}}$ values obtained above. We set $b = 12.8$ km s$^{-1}$, which is a fiducial value, although the $b$ parameter negligibly changes our results. For $v_{\text{exp}}$, we adopt the average outflow velocity of galaxies at $z \sim 0 - 6$, $v_{\text{exp}} = 150$ km s$^{-1}$ (Jones et al. 2012; Hashimoto et al. 2013; Shibuya et al. 2014; Rivera-Thorsen et al. 2015; Stark et al. 2015). Because the outflow velocity measurements available to date have large uncertainties, we allow a moderately large range of outflow velocities, $v_{\text{exp}} = 50 - 200$ km s$^{-1}$, which includes most of the outflow velocity measurements for the low-$z$ and high-$z$ LAEs and LBGs so far obtained (Jones et al. 2012; Hashimoto et al. 2013; Shibuya et al. 2014; Rivera-Thorsen et al. 2015; Stark et al. 2015).

Here we estimate the H$\text{i}$ column density, $N_{\text{H}1}$, of the ISM needed to explain the large $f_{\text{esc}}$ increase from $z \sim 0$ to 6 with the nonresonant extinction values obtained by the observational data. We use the 3D Ly$\alpha$ Monte Carlo radiative transfer code MCLya of Verhamme et al. (2006) and Schaerer et al. (2011). The MCLya code computes the Ly$\alpha$ radiative transfer in an expanding homogeneous shell of ISM H$\text{i}$ and dust that surrounds a central Ly$\alpha$ source. The dust extinction effects are self-consistently calculated for the resonance line of Ly$\alpha$. The MCLya code has four physical parameters to describe the physical properties of the shell: $N_{\text{H}1}$, the nebular dust extinction $E(B - V)_{\text{gas}}$, the radial expansion velocity $v_{\text{exp}}$, and the Doppler parameter $b$, which includes both thermal and turbulent gas motions within the shell. Each redshift shown in Figure 7, we derive the best-estimate $N_{\text{H}1}$ value, using the $E(B - V)_{\text{gas}}$ values obtained above. We set $b = 12.8$ km s$^{-1}$, which is a fiducial value, although the $b$ parameter negligibly changes our results. For $v_{\text{exp}}$, we adopt the average outflow velocity of galaxies at $z \sim 0 - 6$, $v_{\text{exp}} = 150$ km s$^{-1}$ (Jones et al. 2012; Hashimoto et al. 2013; Shibuya et al. 2014; Rivera-Thorsen et al. 2015; Stark et al. 2015). Because the outflow velocity measurements available to date have large uncertainties, we allow a moderately large range of outflow velocities, $v_{\text{exp}} = 50 - 200$ km s$^{-1}$, which includes most of the outflow velocity measurements for the low-$z$ and high-$z$ LAEs and LBGs so far obtained (Jones et al. 2012; Hashimoto et al. 2013; Shibuya et al. 2014; Rivera-Thorsen et al. 2015; Stark et al. 2015).
The picture of the $N_{\text{H}}$ decrease is consistent with the increase of the ionization parameter toward high $z$ suggested by Nakajima & Ouchi (2014). Because high-$z$ galaxies with a high ionization parameter may have density-bounded nebulae (see Figure 12 of Nakajima & Ouchi 2014), a large fraction of neutral hydrogen in the ISM is ionized, which shows a small $N_{\text{H}}$. The $N_{\text{H}}$ decrease is also consistent with the picture that the ionizing photon escape fraction increases toward high $z$ (e.g., Inoue et al. 2006; Ouchi et al. 2009; Dijkstra et al. 2014; Nakajima & Ouchi 2014). Our results suggest that the large $f^{\text{Ly}\alpha}_{\text{esc}}$ increase is self-consistently explained by the decreasing $N_{\text{H}}$, which weakens the ISM dust attenuation through the Ly$\alpha$ resonance scattering. If we assume the expanding shell models, the typical $N_{\text{H}}$ decreases from $\sim 7 \times 10^{15}$ ($z \sim 0$) to $\sim 1 \times 10^{18}$ cm$^{-2}$ ($z \sim 6$).

6. SUMMARY

We conducted the deep and large-area Subaru/Suprime-Cam imaging survey with the narrowband filter NB387. We observed five independent blank fields of SXDS, COSMOS, CDFs, HDFN, and SSA22, whose total survey area is $\sim 1.43$ deg$^2$. We made a sample consisting of 3137 LAEs at $z = 2.2$, which is the largest LAE sample to date and is about an order of magnitude larger than the typical LAE samples in previous studies. The sample covers a very wide Ly$\alpha$ luminosity range of $\log L_{\text{Ly} \alpha} = 41.7 - 44.4$ erg s$^{-1}$ that allowed us to determine bright and faint ends of the Ly$\alpha$ LFs. The major findings of our study are summarized below.

1. Using our large LAE sample, we derive the Ly$\alpha$ LFs at $z = 2.2$ with small uncertainties including Poisson statistics and cosmic variance errors (Figure 5). We fit a Schechter function to our best-estimate Ly$\alpha$ LF at $z = 2.2$ and obtain the best-fit Schechter parameters of $L^*_{\text{Ly} \alpha} = 5.29^{+1.67}_{-1.13} \times 10^{42}$ erg s$^{-1}$, $\alpha_{\text{Ly} \alpha} = 6.33^{+3.08}_{-2.31} \times 10^{-4}$ Mpc$^{-3}$, and $\alpha = 1.75^{+0.10}_{-0.09}$ with no a priori assumptions in the parameters. We find that the faint-end slope of the Ly$\alpha$ LF at $z = 2$ is steep. The faint-end slope is comparable to that of UV-continuum LFs at $z \sim 2$ reported by Reddy & Steidel (2009) and Alavi et al. (2014).

2. In our best-estimate Ly$\alpha$ LF at $z = 2.2$, we find a bright-end hump at $\log L_{\text{Ly} \alpha} \gtrsim 43.4$ erg s$^{-1}$, where the Ly$\alpha$ LF significantly exceeds the best-fit Schechter function (Figure 5). We investigate our LAEs making the bright-end hump with multil wavelength data of X-ray, UV, and radio that are available in the SXDS and COSMOS fields. We find that all of the LAEs at $\log L_{\text{Ly} \alpha} > 43.4$ erg s$^{-1}$ are detected in the X-ray, UV, or radio band. This result indicates that this bright-end hump does not originate from the gravitational lensing magnification bias but from AGNs.

3. We identify a moderate but significant increase of the Ly$\alpha$ LF by a factor of $\lesssim 2$ from $z \sim 2$ to 3. We extend our investigation from $z = 2$ to 3 to $z = 0$--8 and present the overall evolutionary trends of Ly$\alpha$ LFs: the large increase of the Ly$\alpha$ LFs from $z \sim 0$ to 3, no evolution of the Ly$\alpha$ LFs at $z \sim 3$--6, and the decrease of the Ly$\alpha$ LFs at $z \sim 6$ and beyond. Calculating the Ly$\alpha$ LFs by the integrations of these Ly$\alpha$ LFs, we show that Ly$\alpha$ LFs increase nearly by two orders of magnitude from $z \sim 0$ to 3, and that Ly$\alpha$ LFs decrease by a factor of 2 from $z \sim 6$ to 8 (see also Deharveng et al. 2008; Ouchi et al. 2008; Konno et al. 2014). This increase at $z \sim 0$--3 is significantly faster than the one of UV LDs, and the decrease at $z \gtrsim 6$ is more rapid than the one of UV LDs.

4. Based on the LAEs with the detection(s) in the X-ray, UV, or radio band, we derive the AGN UV-continuum LF at $z \sim 2$ down to the faint magnitude limit of $M_{\text{UV} \alpha} \sim -22.5$. We find that our AGN UV LF covers a magnitude range fainter than the previous studies, with an overlap at $M_{\text{UV} \alpha} \sim -24.8$ with the SDSS DR9 measurements (Ross et al. 2013) and the 2dF-SDSS results (Croom et al. 2009), and we confirm that our AGN UV LF agrees well with the SDSS results at the overlap magnitude. Fitting the double-power-law function to the AGN UV LF data obtained by our and previous studies, we constrain the faint-end slope of the AGN UV LF at $z \sim 2$, $\alpha_{\text{AGN}} = -1.2 \pm 0.1$, which is flatter than those at $z = 4 - 6.5$, $\alpha_{\text{AGN}} = -1.5$--1.8, given by Ikeda et al. (2011) and Giallongo et al. (2015).

5. We estimate $f^{\text{Ly}\alpha}_{\text{esc}}$ values from the Ly$\alpha$ and UV LDs at $z \sim 0$--8 given by our and previous studies. There is a significant $f^{\text{Ly}\alpha}_{\text{esc}}$ decrease at $z \gtrsim 6$ that can be explained by the Ly$\alpha$ scattering of the IGM H I at the EoR. We find a large $f^{\text{Ly}\alpha}_{\text{esc}}$ increase from $z \sim 0$ to 6 by two orders of magnitude. This large $f^{\text{Ly}\alpha}_{\text{esc}}$ increase can be explained neither by stellar population nor by outflow because there exist no significant evolutions in stellar population and outflow in LAEs at $z \sim 0$--6. The dust extinction in no Ly$\alpha$ resonance scattering can partly explain the $f^{\text{Ly}\alpha}_{\text{esc}}$ increase at $z \sim 0$--6, but there remains a significantly large discrepancy at $z < 4$. Thus, the Ly$\alpha$ resonance scattering in H I ISM is an important effect to explain the large $f^{\text{Ly}\alpha}_{\text{esc}}$ increase. Based on the average $E(B-V)_{\text{gas}}$ values for nonresonance nebular lines estimated with the observational data, our simple expanding shell models of MCLya suggest that the typical H I column density of ISM should decrease from $\sim 7 \times 10^{19}$ ($z \sim 0$) to $\sim 1 \times 10^{18}$ cm$^{-2}$ ($z \sim 6$) to explain the large $f^{\text{Ly}\alpha}_{\text{esc}}$ increase.

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