ACCELERATED EVOLUTION OF THE Lyα LUMINOSITY FUNCTION AT $z \gtrsim 7$ REVEALED BY THE SUBARU ULTRA-DEEP SURVEY FOR Lyα EMITTERS AT $z = 7.3$

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ABSTRACT

We present the ultra-deep Subaru narrowband imaging survey for Lyα emitters (LAEs) at $z = 7.3$ in the Subaru/XMM-Newton Deep Survey (SXDS) and Cosmic Evolution Survey (COSMOS) fields ($\sim$0.5 deg$^2$) with a total integration time of 106 hr. Exploiting our new sharp bandwidth filter, NB101, installed on the Suprime-Cam, we have reached $L$(Lyα) = 2.4 × 10$^{42}$ erg s$^{-1}$ (5σ) for $z = 7.3$ LAEs, about four times deeper than previous Subaru $z \gtrsim 7$ studies, which allows us to reliably investigate the evolution of the Lyα luminosity function (LF) for the first time down to the luminosity limit same as those of Subaru $z = 3.1–6.6$ LAE samples. Surprisingly, we only find three and four LAEs in the SXDS and COSMOS fields, respectively, while one expects a total of $\sim$65 LAEs by our survey in the case of no Lyα LF evolution from $z = 6.6$ to 7.3. We identify a decrease of the Lyα LF from $z = 6.6$ to 7.3 at the >90% confidence level from our $z = 7.3$ Lyα LF with the best-fit Schechter parameters of $L^*$ = 2.7$^{+0.9}_{-1.2} \times 10^{42}$ erg s$^{-1}$ and $\phi^* = 3.7^{+17.6}_{-3.3} \times 10^{-4}$ Mpc$^{-3}$ for a fixed $\alpha = -1.5$. Moreover, the evolution of the Lyα LF is clearly accelerated at $z > 6.6$ beyond the measurement uncertainties including cosmic variance. Because no such accelerated evolution of the UV-continuum LF or the cosmic star formation rate (SFR) is found at $z < 7$, but suggested only at $z > 8$, this accelerated Lyα LF evolution is explained by physical mechanisms different from a pure SFR decrease but related to the Lyα production and escape in the process of cosmic reionization. Because a simple accelerating increase of intergalactic medium neutral hydrogen absorbing Lyα cannot be reconciled with Thomson scattering of optical depth measurements from WMAP and Planck, our findings may support new physical pictures suggested by recent theoretical studies, such as the existence of Ht clumpy clouds within cosmic ionized bubbles that are selectively absorbing Lyα and the large ionizing photon escape fraction of galaxies causing weak Lyα emission.

Key words: cosmology: observations – dark ages, reionization, first stars – galaxies: formation – galaxies: high-redshift – galaxies: luminosity function, mass function

Online-only material: color figures

1. INTRODUCTION

Lyα emitters (LAEs) are young star-forming galaxies and are essential for exploring a very high redshift universe. A large number of systematic narrowband imaging surveys has been carried out for LAEs at $z \sim 7$ (Iye et al. 2006; Ota et al. 2008, 2010; Shibuya et al. 2012) and beyond $z \sim 8$ (Willis & Courbin 2005; Cuby et al. 2007; Willis et al. 2008; Sobral et al. 2009; Hibon et al. 2010; Tilvi et al. 2010; Clément et al. 2012; Krug et al. 2012; Mattei et al. 2014). In these studies, whether or not the Lyα luminosity function (LF) of LAEs evolves from $z = 6.6$ is debated, while no evolution of the Lyα LF in $z = 3.1–5.7$ (Ouchi et al. 2008) and a decrease from $z = 5.7$ to 6.6 (Kashikawa et al. 2006, 2011; Ouchi et al. 2010; Hu et al. 2010) have been identified. Hibon et al. (2010), Tilvi et al. (2010), and Krug et al. (2012) conclude that there is no evolution of the Lyα LF from $z = 6.6$ to 7.7. On the other hand, Clément et al. (2012) place an upper limit on the Lyα LF based on their result of no detection of $z = 7.7$ LAE, and rule out no evolution of the Lyα LF in $z = 6.6–7.7$. Moreover, observations for $z = 7.0$ and 7.3, LAEs have been conducted by Ota et al. (2010) and Shibuya et al. (2012), and these authors have found that the number density and the Lyα luminosity density decrease from $z = 5.7$ to 7.0–7.3. However, they cannot clearly find whether the Lyα LF evolves from $z = 6.6$ to 7.0–7.3 due to the large uncertainties in their LF measurements. Their large uncertainties originate from the relatively shallow imaging that just reaches the bright Lyα luminosity limit of $L$(Lyα) $\sim 10^{43}$ erg s$^{-1}$. The contradictory results for the Lyα LF evolution may be caused by small statistics and systematic uncertainties such as contamination and cosmic variance. To reliably investigate the evolution of the Lyα LF at $z \gtrsim 7$, one needs an ultra-deep narrowband imaging survey in large areas down to the Lyα luminosity limit comparable to those of $z \lesssim 6.6$ LAE samples.

Studies of the Lyα LF evolution are important for understanding galaxy evolution and cosmic reionization. The Lyα damping wing of neutral hydrogen in the intergalactic medium (IGM) around galaxies attenuates Lyα photons significantly. Thus, a volume-averaged neutral hydrogen fraction, xH$\alpha$, of IGM would be constrained by the evolution of the Lyα LF at an epoch of $x_{H\alpha} \sim 0.1$–1.0 (Malhotra & Rhoads 2004; Hu et al. 2005; Iye et al. 2006; Kashikawa et al. 2006, 2011; Ota et al. 2008, 2010; Ouchi et al. 2010; Shibuya et al. 2012). The evolution of the Lyα luminosity density between $z = 5.7$ and 6.6 suggests $x_{H\alpha} = 0.2 \pm 0.2$ at $z = 6.6$, which is corrected for the intrinsic
UV luminosity evolution effect with the cosmic star formation rate (SFR) density change (Ouchi et al. 2010). An Lyα emitting fraction of UV-continuum-selected galaxies is similarly used as a probe of cosmic reionization. Previous studies have reported that the Lyα emitting fraction of Lyman break galaxies (LBGs) decreases from $z \sim 6$ to 7 in contrast to the increase of the Lyα emitting fraction from $z \sim 3$ to 6, and some authors have claimed that the neutral hydrogen fraction increases from $z \sim 6$ to 7. (Pentericci et al. 2011; Schenker et al. 2012; Ono et al. 2012; Treu et al. 2012; Caruana et al. 2012, 2014; Pentericci et al. 2014; Schenker et al. 2014). By comparison with theoretical models, these studies suggest $x_{\text{HI}} \gtrsim 0.5$ at $z \sim 7$.

Other observational studies have also focused on investigations of when and how cosmic reionization took place. Observations of the (Gunn & Peterson 1965, hereafter GP) trough in quasar (QSO) spectra indicate $x_{\text{HI}} \sim 10^{-4}$ at $z \sim 6$ (Fan et al. 2006), suggesting that cosmic reionization has been completed at this redshift. Measurements of the polarization of the cosmic microwave background (CMB) by WMAP constrain the optical depth of Thomson scattering, $\tau_{\text{e}} = 0.081 \pm 0.012$, and indicate that the universe was reionized at $z_{\text{e}} = 10.1 \pm 1.0$ for the case of instantaneous reionization (Hinshaw et al. 2013; Bennett et al. 2013). Recent observational studies with Planck show that the electron scattering optical depth is $\tau_{\text{e}} = 0.089^{+0.012}_{-0.014}$, and that the instantaneous reionization redshift is $z_{\text{e}} = 11.1 \pm 1.1$ (Planck Collaboration et al. 2013). Totani et al. (2006) estimate $x_{\text{HI}}$ with the shape of Lyα damping wing absorption found in the optical afterglow spectrum of GRB 050904 at $z \sim 6.3$, and obtain $x_{\text{HI}} < 0.17$ (68% confidence level) at this redshift. In a recent study of gamma-ray bursts (GRBs), the unprecedentedly bright optical afterglow spectrum of GRB 130606A at $z \sim 5.9$ suggests $x_{\text{HI}} = 0.1-0.5$ (Totani et al. 2014). Mortlock et al. (2011) report observations of a QSO at $z = 7.085$, ULAS J1120+0641, and claim $x_{\text{HI}} > 0.1$ at this redshift from the near-zone transmission profile. Bolton et al. (2011) use radiative transfer simulations with model absorptions of an inhomogeneous IGM around ULAS J11201+0641, and obtain $x_{\text{HI}} > 0.1$.

Although the CMB observations rule out instantaneous reionization at a late epoch, it is difficult to understand how reionization proceeds in the cosmic history. As illustrated in Figure 23 of Ouchi et al. (2010), there are large uncertainties in the $x_{\text{HI}}$ estimates from previous observational studies, and one cannot distinguish between various models of reionization history. A redshift of $\sim 7$ is the observational limit of optical instruments that enable us to conduct a deep and wide-field imaging survey. The differences in reionization history in models are relatively large at $z \gtrsim 7$ (see Figure 23 of Ouchi et al. 2010). A measurement of the Lyα LF at $z \sim 7$ with a good statistical accuracy is useful to constrain $x_{\text{HI}}$ near the observational limit and to address this issue of cosmic reionization history.

In this paper, we present the results of our ultra-deep narrowband imaging survey for $z = 7.3$ LAEs. Using this sample, we derive the Lyα LF with accuracies significantly better than those of previous $z \gtrsim 7$ studies. We investigate the Lyα LF evolution at $z \gtrsim 7$ with this Lyα LF and discuss the cosmic reionization history. We describe the details of our $z = 7.3$ LAE survey and selection of our LAE candidates in Section 2. We derive the $z = 7.3$ Lyα LF and compare it with previous studies of $z \sim 7.3$ in Section 3. We examine the evolution of the Lyα LF at $z = 5.7-7.3$, and discuss cosmic reionization with the constraints of the electron scattering optical depth measurements of the CMB in Section 4. 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 WMAP and Planck results (Hinshaw et al. 2013; Planck Collaboration et al. 2013).

2. IMAGING OBSERVATIONS AND DATA REDUCTION

2.1. NB101 Observations

We have carried out an ultra-deep large-area narrowband imaging survey with Subaru/Suprime-Cam (Miyazaki et al. 2002) to study LAEs at $z = 7.3$ down to the faint Lyα luminosity limit. For these observations, we have developed a new custom narrowband filter, NB101. The filter transmission of NB101 is centered at $\lambda_c = 10095$ Å and NB101 is designed to have a narrow and sharp FWHM of $\Delta \lambda = 90$ Å. The NB101 filter identifies LAEs in the redshift range of $z = 7.302 \pm 0.037$. We show the filter response curve of our NB101 in Figure 1. Note that there is a Suprime-Cam narrowband filter, NB1006, at a similar wavelength (Shibuya et al. 2012). The NB1006 filter has a central wavelength of $\lambda_c = 10052$ Å slightly bluer than that of our NB101, and an FWHM of $\Delta \lambda = 214$ Å about two to three times broader than that of our NB101. Similarly, there is another Suprime-Cam narrowband filter of NB973 targeting $z = 7.0$ LAEs with a central wavelength of $\lambda_c = 9755$ Å and an FWHM of $\Delta \lambda = 200$ Å (Iye et al. 2006; Ota et al. 2008, 2010) that is also much broader than the FWHM of our NB101 filter. Since our NB101 filter has a significantly narrower/sharper FWHM than the NB1006 and NB973 filters, our NB101 filter is more sensitive to an emission line than the NB1006 and NB973 filters. Although the survey volume is smaller for NB1006 than for NB1006 and NB973, the line sensitivity is more important for the observational studies of $z \gtrsim 7$ sources whose LF’s exponential edge is near the observational limit. At $z = 7.3$, our NB101 filter allows us to reach a Lyα flux limit $\sim 160\%$ faster than Shibuya et al.’s NB1006 surveys. Thus, we can reach the Lyα luminosity

![Figure 1. Filter response curve of NB101 is shown with the red line. The blue and black lines represent the response curves of NB1006 and $\zeta$ bands, respectively. These response curves are based on actual lab measurements and include the quantum efficiency of Hamamatsu CCDs (Kamata et al. 2008), airmass, transmission + reflection of the instrument, and telescope optics. For clarity, peaks of these curves are normalized to 1.0. The upper abscissa axis indicates a redshift of Lyα that corresponds to the wavelength. Note that NB1006 widely covers a redshift range of $z = 7.2-7.3$, and that NB101 targets a narrow redshift range centered at $z = 7.3$.](image-url)
limit of LAEs much fainter than the previous Subaru studies for \( z \sim 7 \) LAEs.

With our new \( NB101 \) filter, we observed two independent fields, the Subaru/XMM-Newton Deep Survey (SXDS) and the Cosmic Evolution Survey (COSMOS) fields. The SXDS field is located at 02\(^h\)18\(^m\)00\(^s\), −05\(^\circ\)00\('\)00\("\) (J2000) (Furusawa et al. 2008; Ouchi et al. 2008, 2010). It consists of five subfields of \( \sim 0.2 \) deg\(^2\), SXDS-C, N, S, E, and W. We choose a field of \( \sim 0.2 \) deg\(^2\) to cover the southern half of SXDS-C and the northern half of SXDS-S, where bright stars do not exist and \( Hubble \) Space Telescope (\( HST \)) CANDELS (Grogin et al. 2011; Koekemoer et al. 2011), \( UKIRT \) UKIDSS (Lawrence et al. 2007), \( Spitzer \) SpUDS (PI: J. Dunlop) and SEDS (PI: G. Fazio) data are also available (see Figure 2 in Ota et al. 2010). The target field of COSMOS is an area of \( \sim 0.2 \) deg\(^2\) centered at 10\(^h\)00\(^m\)28\(^s\), +02\(^d\)12\('\)21\("\) (J2000) (Scoville et al. 2007). In the COSMOS field, CANDELS and UltraVISTA (PI: J. Dunlop) imaging data exist. Each SXDS and COSMOS field is covered by one pointing of the Suprime-Cam whose field of view is 918 arcmin\(^2\). Our observations were conducted in 2010–2013. The total on-source integration time is 106 hr where 36.3 and 69.5 hr correspond to 36.3 and 69.5 hr in the SXDS and COSMOS fields, respectively.

The SXDS and COSMOS \( z' \) data include the images taken by the Subaru intensive program conducted in 2009–2011 (PI: H. Furusawa).

### Table 1

| Field | Band | Exposure Time (s) | PSF Size\(^a\) (arcsec) | Area (arcmin\(^2\)) | \( m_{\text{lim}} \)\(^b\) (5\(\sigma\) AB mag) | Date of Observations |
|-------|------|------------------|--------------------------|----------------------|--------------------------|----------------------|
| SXDS  | \( NB101 \) | 57600            | 0.78                     | 2.9 \times 10\(^2\) | 24.6                     | 2010 Dec 29–2011 Jan 1 |
|       | \( NB101 \) | 73200            | 0.86                     | 24.3                 | 2012 Dec 11–14           |
|       | \( NB101 \) (final) | 130800\(^c\)  | 0.80                     | 7.9 \times 10\(^2\) | 24.9                     | ... |
| COSMOS | \( NB101 \) | 83510.6          | 0.72                     | 24.8                 | 2010 Dec 29–2011 Jan 2   |
|       | \( NB101 \) | 61200            | 0.99                     | 23.7                 | 2012 Dec 11–14           |
|       | \( NB101 \) | 105600           | 0.90                     | 24.4                 | 2013 Feb 9–12            |
|       | \( NB101 \) (final) | 250310.6\(^d\)  | 0.77                     | 8.4 \times 10\(^2\) | 25.1                     | ... |

Archival broadband data\(^d\)

| SXDS  | Band | Exposure Time (s) | PSF Size\(^a\) (arcsec) | Area (arcmin\(^2\)) | \( m_{\text{lim}} \)\(^b\) (5\(\sigma\) AB mag) |
|-------|------|------------------|--------------------------|----------------------|--------------------------|
|       | \( B \) | 0.84             | 7.9 \times 10\(^2\)     | 28.1                 |
|       | \( V \) | 0.84             | 27.7                     |
|       | \( R \) | 0.84             | 27.6                     |
|       | \( i' \) | 0.84             | 27.3                     |
|       | \( z' \) | 0.80             | 26.9                     |
| COSMOS | \( B \) | 0.95             | 8.4 \times 10\(^2\)     | 27.7                 |
|       | \( V \) | 1.32             | 26.4                     |
|       | \( R \) | 1.05             | 26.9                     |
|       | \( i' \) | 0.95             | 26.6                     |
|       | \( z' \) | 0.84             | 26.8                     |

### Notes.

\(^a\) The FWHM value of PSF.

\(^b\) The 5\(\sigma\) limiting magnitude in a circular aperture with a diameter of 2 times PSF FWHM.

\(^c\) The total on-source integration times correspond to 36.3 and 69.5 hr in the SXDS and COSMOS fields, respectively.

\(^d\) The Broadband images are archival data presented in Furusawa et al. (2008) for SXDS and Capak et al. (2007) for COSMOS. The SXDS and COSMOS \( z' \) data are also listed in Table 1.
survey areas correspond to the comoving survey volumes of $1.2 \times 10^5$ and $1.3 \times 10^5$ Mpc$^3$ for the SXDS and COSMOS fields, respectively.

2.2. Photometry

The source detection and photometry are performed with SExtractor version 2.5.0 (Bertin & Arnouts 1996). Sources are identified with the criterion: contiguous $>5$ pixels with a flux greater than the 2σ level of sky fluctuation. We conduct the source detection in our NB101 images, and obtain the broadband photometry at the positions of the sources. We detect a total of 69,387 objects in the SXDS and COSMOS fields down to the 5σ limits of aperture magnitudes that are $NB101 = 24.9$ (SXDS) and 25.1 (COSMOS). Here, we define the aperture magnitude of $MAG_{\text{APER}}$ of SExtractor with an aperture size of 2 times the point-spread function (PSF) FWHM, and use the aperture magnitude for measuring colors of objects. For total magnitude estimates, we apply an aperture correction value of 0.3 to the aperture magnitudes. Because $MAG_{\text{AUTO}}$ of SExtractor gives biased magnitude measurements for faint objects around the detection limits, we use this aperture correction technique. Ono et al. (2012) study $z$-dropout galaxies at $z \sim 7$ using Subaru Suprime-Cam data, and derive the aperture correction value of $\sim 0.3$ mag. We apply the same aperture correction value as Ono et al. (2012) because the PSF FWHM of Ono et al.’s data ($\sim 0.8''-0.9''$) is similar to that of our NB101 data. The reliability of this technique is investigated in Section 2.3.

2.3. Photometric Sample of $z = 7.3$ LAEs

We isolate $z = 7.3$ LAE candidates from all of the objects detected in Section 2.2 based on a narrowband excess of Ly$\alpha$ emission and no detection of blue continuum flux. Figures 2 and 3 show the color–magnitude diagrams of the $NB101$ magnitude and the narrowband excess color, $\z' - NB101$, for the objects detected in the SXDS and COSMOS fields. The detected objects have a color of $\z' - NB101 \approx +0.2$ on average in the magnitude range of $22 < NB101 < 24$. To determine the $\z' - NB101$ color criterion for our LAE candidate selection, we assume a model spectrum of $z = 7.3$ LAE that has an Ly$\alpha$ line and a flat ultraviolet (UV) continuum (i.e., $f_\nu = \text{const}$.) with an IGM absorption (Madau 1995). Based on the model spectrum, we adopt the criterion that $\z' - NB101 \geq 3.0$, which corresponds to LAEs with a rest-frame equivalent width, EW$_0$, of EW$_0 \gtrsim 0$ Å, which is similar to the criterion adopted by Shibuya et al. (2012). Note that, due to photometric errors, this small limit of the EW$_0$ criterion gives us a chance to select high-$z$ dropout galaxies and foreground red objects, which are the potential contamination sources. Because this EW$_0$ limit gives a more complete sample, we apply this EW$_0$ limit. We discuss the effect of this small EW$_0$ limit in Section 4.2.

Adding another criterion of no detectable continuum flux bluer than Ly$\alpha$, we define the selection criteria of $z = 7.3$ LAEs:

\begin{equation}
NB101 < NB101_{5\sigma} \quad \text{and} \quad B > B_{3\sigma} \\
\quad \text{and} \quad V > V_{3\sigma} \quad \text{and} \quad R > R_{3\sigma} \quad \text{and} \quad i' > i'_{3\sigma} \quad (1)
\end{equation}

where the indices of $5\sigma$ and $3\sigma$ denote the $5\sigma$ and $3\sigma$ detection limits of the images, respectively.

We apply these photometric criteria to all of our detected objects, and identify three and four $z = 7.3$ LAE candidates in the SXDS and COSMOS fields, respectively. We show the snapshot images of these LAE candidates in Figure 4. In our NB101 ultra-deep survey, we have reached a $\sigma$ limiting flux of $\geq 6.5 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ corresponding to a limiting
luminosity of $L_{\text{Ly}\alpha} \simeq 4.1 \times 10^{42} \text{erg s}^{-1}$ in the SXDS field, and $\approx 3.8 \times 10^{42} \text{erg s}^{-1} \text{cm}^{-2}$ equivalent to $L_{\text{Ly}\alpha} \simeq 2.4 \times 10^{42} \text{erg s}^{-1}$ in the COSMOS field. These limiting luminosities are derived from the $5\sigma$ limiting magnitudes of $NB101$ and the $1\sigma$ limiting magnitudes of $z'$. These are conservative estimates because the limiting luminosity values are larger than those calculated with the $>1\sigma$ limiting magnitudes of $z'$. In the calculations for the Ly$\alpha$ luminosities, we assume that Ly$\alpha$ emission is placed at the central wavelength of the narrow band. Ouchi et al. (2008) derive the Ly$\alpha$ luminosities in the same manner as ours, and compare these Ly$\alpha$ luminosities with spectroscopic luminosities. They find that both measurements agree well within the error bars and that the difference in these values is small (see Section 3.3 for the effects of the Ly$\alpha$ luminosity uncertainties in an Ly$\alpha$ LF derivation). The $NB101$ image of the COSMOS field is the deepest image in our $NB101$ data. The $5\sigma$ limiting luminosity in the COSMOS field is about four times deeper than previous Subaru studies for LAEs at $z \sim 7$ (Ota et al. 2008, 2010; Shibuya et al. 2012). Moreover, the $5\sigma$ limiting luminosity is comparable to those of previous Subaru $z = 3.1$--$6.6$ LAE surveys (Shimasaku et al. 2006; Kashikawa et al. 2006, 2011; Ouchi et al. 2008, 2010).

We present the photometric properties of our $z = 7.3$ LAE candidates in Table 2. The total magnitudes listed in Table 2 are obtained by the aperture-correction technique explained in Section 2.2. We compare the total magnitude and MAG\_AUTO of SExtractor for the most luminous LAE candidate which probably includes a negligible bias in the MAG\_AUTO estimate, and find that these two magnitudes are consistent within the errors. Thus, it is reasonable to use the total magnitudes given by the aperture-correction technique that requires the assumption that $z = 7.3$ LAEs are point sources (Ono et al. 2010, 2012).

### Table 2

| ID               | $B$  | $V$  | $R$  | $i'$ | $z'$ | $NB101^a$ | $NB101$(Total)$^a$ | $J$  | $H$  | $L$(Ly$\alpha$) $(10^{42} \text{erg s}^{-1})$ |
|------------------|------|------|------|------|------|-----------|-------------------|------|------|-----------------------------------------------|
| NB101-SXDS-2904  | $>28.6$ | $>28.3$ | $>28.1$ | $>27.8$ | $>27.4$ | $24.50^{+0.16}_{-0.14}$ | $24.20^{+0.12}_{-0.11}$ | ... | ... | 9.68                                          |
| NB101-SXDS-46782 | $>28.6$ | $>28.3$ | $>28.1$ | $>27.8$ | $>27.4$ | $24.84^{+0.23}_{-0.19}$ | $24.54^{+0.17}_{-0.15}$ | ... | ... | 5.72                                          |
| NB101-SXDS-59407 | $>28.6$ | $>28.3$ | $>28.1$ | $>27.8$ | $>27.4$ | $24.80^{+0.22}_{-0.18}$ | $24.50^{+0.16}_{-0.14}$ | ... | ... | 6.13                                          |
| NB101-COSMOS-5156 | $>28.3$ | $>27.0$ | $>27.4$ | $>27.2$ | $>27.3$ | $24.98^{+0.23}_{-0.18}$ | $24.68^{+0.16}_{-0.14}$ | ... | ... | 3.82                                          |
| NB101-COSMOS-37050 | $>28.3$ | $>27.0$ | $>27.4$ | $>27.2$ | $>27.3$ | $24.84^{+0.19}_{-0.16}$ | $24.54^{+0.14}_{-0.12}$ | $25.42^{+0.06}_{-0.05}$ | $25.39^{+0.06}_{-0.05}$ | 5.11                                          |
| NB101-COSMOS-37548 | $>28.3$ | $>27.0$ | $>27.4$ | $>27.2$ | $>27.3$ | $25.03^{+0.23}_{-0.19}$ | $24.73^{+0.17}_{-0.14}$ | ... | ... | 3.39                                          |
| NB101-COSMOS-103966 | $>28.3$ | $>27.0$ | $>27.4$ | $>27.2$ | $>27.3$ | $25.07^{+0.23}_{-0.19}$ | $24.77^{+0.17}_{-0.15}$ | ... | ... | 3.01                                          |

Notes.

$a$ The magnitudes with the $1\sigma$ error measured with an aperture whose diameter is $2\times$ PSF FWHM.

$b$ The total magnitudes which are obtained by the aperture-correction technique explained in Section 2.2.
We investigate our \( z = 7.3 \) LAE candidates in the \( J \) and \( H \) images of the \textit{HST CANDELS} fields which are subfields of our COSMOS and SXDS survey areas. Two out of seven LAE candidates, NB101-COSMOS-37050 and NB101-COSMOS-37548, fall in the CANDELS field of COSMOS. We detect NB101-COSMOS-37050 both in the \( J \) and \( H \) images (Figure 4), but NB101-COSMOS-37548 is not detected in either the \( J \) or \( H \) data. We obtain the \( J \) and \( H \) magnitudes of NB101-COSMOS-37050 and present the magnitudes in Table 3. There are no counterparts of LAE candidates found in the CANDELS field of SXDS.

We examine whether \( z = 7.2–7.3 \) LAEs found by Shibuya et al. (2012) are identified in our \textit{NB101} data. Shibuya et al. (2012) have observed the SXDS subfield same as our survey area with their \textit{NB1006} filter (Section 2.1), and obtained two photometric LAE candidates, SXDS-NB1006-1 and SXDS-NB1006-2. However, neither of the two LAEs of Shibuya et al. (2012) are detected in our \textit{NB101} images. Because Shibuya et al. (2012) report that their spectroscopy indicates that one of them, SXDS-NB1006-2, resides at \( z = 7.215 \), the redshift of SXDS-NB1006-2 is out of our survey redshift range of \( z = 7.302 \pm 0.037 \) where \textit{NB101} has a sensitivity for a \( \text{Ly} \alpha \) emission line. Thus, the reason for no detection of SXDS-NB1006-2 is clear, while the reason for another object, SXDS-NB1006-1, is unknown. Since SXDS-NB1006-1 is not confirmed by their spectroscopic follow-up observations, it is possible that the \( \text{Ly} \alpha \) emission of SXDS-NB1006-1 also falls in the wavelength that is not covered by \textit{NB101}. Note that the FWHM of \textit{NB1006} is 214 Å, while \textit{NB101} is only 90 Å (Section 2.1).

### 3. LUMINOSITY FUNCTION

#### 3.1. Contamination of Our Sample

We investigate the contamination of our \( z = 7.3 \) LAE sample. The sources of possible contamination are spurious objects, transients, and foreground interlopers. First, our \textit{NB101} images of the SXDS and COSMOS fields were taken in 2010–2011 and 2010–2013, respectively (see Table 1). We stack the \textit{NB101} data of the SXDS field observed in 2010–2011 and 2010–2013 and obtain \textit{NB101} images for the two epochs. Similarly, we make three \textit{NB101} stacked images of the COSMOS field at three epochs, 2010–2011, 2012, and 2013. The 5\( \sigma \) limiting magnitudes of these epoch images are summarized in Table 1. The results of independent photometry at the different epochs of our observations are shown in Table 3. All of the magnitudes of our LAE candidates in the multi-epochs are consistent within the \( \simeq 95\% \) significance levels of the photometric errors. We find no variable signatures of transients in our LAEs. Because our LAEs are selected from narrowband images taken over three to four years, the fraction of transient contamination in our LAE sample is very small. Similarly, all of our LAEs, except NB101-SXDS-46782 and NB101-COSMOS-37050, are detected at the \( >3\sigma \) levels in the \( \gtrsim 2 \) epoch images. Thus, our LAEs, except NB101-SXDS-46782 and NB101-COSMOS-37050, are not spurious sources. NB101-SXDS-46782 and NB101-COSMOS-37050 are found only at the \( \simeq 2\sigma \) levels in the 2012 and 2012–2013 epoch images, respectively. However, we have identified the sources of NB101-SXDS-46782 and NB101-COSMOS-37050 in these epoch images by visual inspection. It is likely that NB101-SXDS-46782 and NB101-COSMOS-37050 are also not spurious sources. Second, spectroscopic follow-up observations for one of our candidates, NB101-SXDS-2904, were conducted with Keck/NIRSPEC, LRIS, and MOSFIRE, and a single emission line that is probably \( \text{Ly} \alpha \) is clearly detected from this object by all of these Keck spectroscopic observations (M. Ouchi et al., in preparation). Although only one LAE in our sample is observed by spectroscopy, no foreground interlopers are, so far, found by spectroscopic observations.

#### 3.2. Detection Completeness and Surface Number Density

We estimate detection completeness as a function of the \textit{NB101} magnitude using Monte-Carlo simulations. We distribute a number of pseudo-LAEs with various magnitudes in our \textit{NB101} images, and detect the pseudo-LAEs in the same manner as our source extraction for real sources (Section 2.2). Here, we assume that \( z = 7.3 \) LAEs are point sources whose profiles are obtained by the stack of bright point sources in our \textit{NB101} images. We define the detection completeness as the fraction of the numbers of the extracted pseudo-LAEs to all of the input pseudo-LAEs, and obtain the detection completeness presented in Figure 5. We find that the detection completeness is typically \( \gtrsim 90\% \) for luminous sources with \( \textit{NB101} \lesssim 24.5 \) and nearly 50\% at around the \( 5\sigma \) limiting magnitude of \( \textit{NB101} \simeq 25 \).

Figure 6 shows the surface number densities of \( z = 7.3 \) LAEs. The surface number densities are calculated by dividing the number counts of LAEs by our effective survey areas shown in Section 2.1. We correct these surface number densities for the detection completeness. The uncertainties of the surface densities of \( z = 7.3 \) LAEs are defined with the Poisson errors for small number statistics (Gehrels 1986). The values of columns

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**Table 3** Magnitudes of our \( z = 7.3 \) LAE Candidates in the Different Epoch

| ID              | \( \text{NB101}^a \) (2010\(^b\)) | \( \text{NB101}^a \) (2012\(^b\)) | \( \text{NB101}^a \) (2013\(^b\)) |
|-----------------|----------------------------------|----------------------------------|----------------------------------|
| NB101-SXDS-2904 | \( 24.51^{+0.22}_{-0.18} \)    | \( 24.39^{+0.26}_{-0.21} \)    | \( \ldots \)                     |
| NB101-SXDS-46782| \( 24.74^{+0.32}_{-0.22} \)    | \( 25.03^{+0.34}_{-0.36} \)    | \( \ldots \)                     |
| NB101-SXDS-59407| \( 24.70^{+0.30}_{-0.23} \)    | \( 24.76^{+0.40}_{-0.29} \)    | \( \ldots \)                     |
| NB101-COSMOS-5156| \( 25.03^{+0.31}_{-0.24} \)    | \( 24.65^{+0.71}_{-0.43} \)    | \( 24.86^{+0.40}_{-0.29} \)    |
| NB101-COSMOS-37050| \( 24.66^{+0.21}_{-0.17} \)    | \( 24.69^{+0.75}_{-0.44} \)    | \( 24.96^{+0.84}_{-0.47} \)    |
| NB101-COSMOS-37548| \( 25.19^{+0.37}_{-0.27} \)    | \( 24.07^{+0.36}_{-0.27} \)    | \( 24.95^{+0.36}_{-0.30} \)    |
| NB101-COSMOS-103966| \( 25.11^{+0.34}_{-0.26} \)    | \( 24.97^{+1.04}_{-0.52} \)    | \( 24.76^{+0.55}_{-0.27} \)    |

**Notes.**

\( ^a \) The magnitudes with the 1\( \sigma \) error measured with an aperture whose diameter is 2 times PSF FWHM.

\( ^b \) The values in parenthesis present the epochs of data used for the stacked images. 2010, 2012, and 2013 indicate the epochs of 2010–2011, 2012, and 2013 observing periods, respectively.

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**Figure 5.** Detection completeness of our \textit{NB101} images. The filled squares and open circles represent the completeness in the SXDS and COSMOS fields, respectively.
“0.8413” in Tables 1 and 2 of Gehrels (1986) are used for the upper and lower limits of the Poisson errors, respectively.

3.3. $z = 7.3$ Ly$\alpha$ Luminosity Function

We calculate the Ly$\alpha$ $EW_\alpha$ of LAEs from the NB101 and $z'$ magnitudes, and estimate the Ly$\alpha$ luminosities of LAEs with these $EW_\alpha$ and the NB101 total magnitudes. For the errors on the Ly$\alpha$ luminosities, we carry out Monte Carlo simulations under the assumption that the spectrum of LAEs has an Ly$\alpha$ line and a flat UV continuum (i.e., $f_{\nu} = \text{const.}$) with the IGM absorption, following the methods applied in Shimasaku et al. (2006); Ouchi et al. (2008, 2010). Again, in the calculations for the Ly$\alpha$ luminosities, we assume that Ly$\alpha$ emission is placed at the central wavelength of the narrow band. Similarly, we derive the Ly$\alpha$ LF of $z = 7.3$ LAEs in the same manner as Ouchi et al. (2008, 2010). We calculate the volume number densities of LAEs in each Ly$\alpha$ luminosity bin, dividing the observed surface number densities of LAEs by our survey volumes based on a top-hat filter transmission curve assumption. This procedure of Ly$\alpha$ LF derivation is known as the classical method. Note that there are two uncertainties for the Ly$\alpha$ LFs derived by the classical method. (1) An Ly$\alpha$ flux of an LAE at the fixed narrowband magnitude varies by the LAE’s redshift. (2) A redshift distribution of LAEs depends on an Ly$\alpha$ EW. In order to evaluate such uncertainties, Shimasaku et al. (2006) and Ouchi et al. (2008) perform Monte Carlo simulations. In these simulations, they generate a mock catalogue of LAEs with a set of Schechter parameters ($\phi^\ast$, $L^\ast$, $\alpha$) and a Gaussian sigma for a probability distribution of Ly$\alpha$ $EW_\alpha$, and uniformly distribute the LAEs of the mock catalogue in a comoving volume over the redshift range that a narrowband covers. They “observe” these LAEs with narrow- and broadband to be the same as the real band response. They select LAEs using the same criteria as were used for selecting the actual LAEs and derive the number densities and color distributions from the mock catalogue. By comparing the results of these simulations with the observational results, they find the best-fit Schechter parameters of Ly$\alpha$ LFs (see Shimasaku et al. 2006; Ouchi et al. 2008, for more details of the simulations). They confirm that the LFs estimated from the simulations are consistent with those derived by the classical method.

Figure 7 presents the Ly$\alpha$ LF of our $z = 7.3$ LAEs in all fields that include both the SXDS and COSMOS fields. The error bars of this LF include uncertainties from Poisson statistics and cosmic variance. Here, we estimate the cosmic variance uncertainty, $\sigma_{\text{c}}$, with

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

where $b_{\text{g}}$ and $\sigma_{\text{DM}}(z, R)$ are the bias parameter and the density fluctuation of dark matter at a redshift of $z$ in a radius of $R$, respectively. We calculate $\sigma_{\text{DM}}(z, R)$ with the growth factor, following Carroll et al. (1992) with the transfer function given by Bardeen et al. (1986) (see also Mo & White 2002). Note that the radius of $\sigma_{\text{DM}}(z, R)$ corresponds to that of a sphere which has a survey volume the same as ours, i.e., $2.5 \times 10^5$ Mpc$^3$. The value of $\sigma_{\text{DM}}(z, R)$ at $z = 7.3$ is estimated to be 0.041. Because the bias parameter of $b_{\text{g}} = 3.6 \pm 0.7$ is obtained for $z = 6.6$ (Ouchi et al. 2010), we adopt $b_{\text{g}} \simeq 4$ for $z = 7.3$ LAEs under the assumption that $b_{\text{g}}$ does not significantly evolve at $z = 6.6$–7.3. With this procedure, we estimate the cosmic variance uncertainty to be $\sigma_{\text{c}} \simeq 0.16$. In Figure 7, we plot the LFs from two independent fields of SXDS and COSMOS. Because these LFs are consistent within the statistical+cosmic variance uncertainties of the entire-field LF in two luminosity bins, log $L_{\text{Ly}\alpha} = 42.7$ and 42.9 erg s$^{-1}$, we confirm that our errors on the entire-field LF explain the cosmic variance effects based on the real observational data of SXDS and COSMOS on the independent sky.

We fit a Schechter function (Schechter 1976) to our $z = 7.3$ Ly$\alpha$ LF by minimum $\chi^2$ fitting. The Schechter function is defined by

$$\phi(L) dL = \phi^\ast (L/L^\ast)^\alpha \exp(-L/L^\ast) d(L/L^\ast),$$

where $\phi^\ast$ and $L^\ast$ represent the characteristic number density and luminosity, respectively, and $\alpha$ is a power-law slope of the faint-end LF. Because the luminosity range of our LF is not wide, the parameter of $\alpha$ in the Schechter function cannot be determined. We fix a power-law slope of $\alpha = -1.5$, which is a fiducial value used for low-$z$ Ly$\alpha$ LFs (e.g., Malhotra & Rhoads 2004; Kashikawa et al. 2006, 2011; Ouchi et al. 2008, 2010). In the calculations for the $\chi^2$ values, we adopt an upper error as 1$\sigma$ in the case that models are beyond the data point.

Figure 6. Surface number density of our $z = 7.3$ LAEs as a function of the NB101 magnitude. The circles and squares represent the surface number densities in the SXDS and COSMOS fields. The filled and open symbols indicate the ones with and without the detection completeness correction, respectively.

Figure 7. Ly$\alpha$ LF of our $z = 7.3$ LAEs. Red filled circles represent the Ly$\alpha$ LF derived with the data from all entire fields, i.e., both the SXDS and COSMOS fields. The red open circles and squares denote our Ly$\alpha$ LFs estimated with the data of the SXDS and COSMOS fields, respectively. In the brightest luminosity bin, we also plot the upper error of the Ly$\alpha$ LF in COSMOS field. The best-fit Schechter function for the Ly$\alpha$ LF of the entire fields is shown with the red curve. (A color version of this figure is available in the online journal.)
of our LF. Similarly, a lower error is adopted in the case where models are below the data point of our LF. We obtain the best-fit Schechter parameters of $\phi^* = 3.7^{+17.6}_{-3.3} \times 10^{-4} \text{ Mpc}^{-3}$ and $L_{\text{Ly} \alpha}^* = 2.7^{+8.0}_{-6.4} \times 10^{42} \text{ erg s}^{-1}$ with the fixed $\alpha = -1.5$, and present these best-fit values in Table 4. The best-fit Schechter function is shown in Figure 7 with a red solid line.

3.4. Comparison with $z \simeq 7.3$ Lyα LFs of Previous Studies

We compare our $z = 7.3$ Lyα LF with those obtained by previous studies for LAEs at $z = 7.0-7.7$, assuming that the Lyα LF does not significantly evolve at $z = 7.3 \pm 0.4$. In Figure 8, we plot the previous Subaru measurements of the Lyα LF at $z = 7.0$ (Iye et al. 2006; Ota et al. 2008, 2010) and 7.3 (Shibuya et al. 2012) which include spectroscopy results. These previous Subaru results are consistent with the bright end of our Lyα LF within the uncertainties, while these previous Subaru studies typically reach $L(\text{Ly} \alpha) \sim 10^{43} \text{ erg s}^{-1}$ which is significantly shallower than our ultra-deep survey. Similarly, the black solid line of Figure 8 presents the upper limits of the Lyα LF given by the Very Large Telescope (VLT) observations that identify no LAEs at $z = 7.7$ (Clément et al. 2012). These upper limits of the Lyα LF are consistent with our results.

In Figure 8, the number densities of the Lyα LF of the 4 m telescope results are about a factor of several or an order of magnitude larger than those of the Subaru+VLT results beyond the uncertainties. We discuss these discrepancies of $z \simeq 7.3$ Lyα LF measurements between the Subaru+VLT and 4 m telescope results in Section 4.1.

4. DISCUSSION

4.1. Discrepancies in the $z \simeq 7.3$ Lyα LF Estimates

In Section 3.4, we find discrepancies in $z \simeq 7.3$ Lyα LFs between the Subaru+VLT results (including ours) and the 4 m telescope results (Hibon et al. 2010; Tilvi et al. 2010; Krug et al. 2012). It is possible that the discrepancies could be explained by cosmic variance effects. However, all of these 4 m telescope LF measurements fall above the Subaru+VLT LF estimates. It is difficult to reconcile all of the 4 m telescope measurements as chance fluctuations of cosmic variance. Another possible explanation for the discrepancies is contamination. Clément et al. (2012) mention the results of VLT/X-Shooter spectroscopic follow-up observations for the brightest five out of seven photometric LAE candidates of Hibon et al. (2010), and report that no Lyα emission lines from these Hibon et al. candidates are identified (see J. G. Cuby et al., in preparation). More recently, Faisst et al. (2014) conducted spectroscopic follow-up observations for the brightest two out of four photometric candidates of Krug et al. (2012), and they detected no Lyα emission line from the Krug et al. candidates (see also Jiang et al. 2013). There is a similar spectroscopic study that reports no detection of Lyα from $z > 7$ LAEs whose sample is composed of 4 m telescope data (Matthee et al. 2014). Thus, the photometric samples of Hibon et al. (2010) and Krug et al. (2012) include a significant number of contamination sources that are probably more than a half of their LAE candidates, which are indicated by spectroscopic follow-up studies. Spectroscopic observations for the LAE candidates of Tilvi et al. (2010) have not been carried out so far. However, it is possible that the Tilvi et al. sample includes a large amount of contamination because of sample selection from the 4 m telescope data similar to those of Hibon et al. (2010) and Krug et al. (2012). We conclude that our Lyα
LF is consistent with those from the Subaru and VLT studies whose results are supported by spectroscopic observations (Iye et al. 2006; Ota et al. 2008, 2010; Shibuya et al. 2012; Clément et al. 2012), and that our Lyα LF agrees with the results of the recent deep spectroscopic follow-up observations for the LAE candidates from the 4 m telescope data (Clément et al. 2012; Faisst et al. 2014; Jiang et al. 2013).

4.2. Decrease in Lyα LF from z = 6.6 to 7.3

In this section, we examine whether the Lyα LF evolves from z = 6.6 to 7.3. As described in Section 2.3, we reach an Lyα limiting luminosity of $2.4 \times 10^{42}$ erg s$^{-1}$ which is comparable to those of previous Subaru z = 3.1–6.6 studies (Shimasaku et al. 2006; Kashikawa et al. 2006, 2011; Ouchi et al. 2008, 2010; Hu et al. 2010). Moreover, the size of the survey area, $\approx 0.5$ deg$^2$, is comparable to those in these Subaru studies. Our ultra-deep observations in the large areas allow us to perform a fair comparison of the Lyα LF at different redshifts. We compare our Lyα LF at $z = 7.3$ with those at $z = 5.7$ and 6.6 in Figure 9, and summarize the best-fit Schechter parameters at $z = 5.7, 6.6,$ and 7.3 in Table 4. For the $z = 5.7$ and 6.6 data, we use the Lyα LF measurements of Ouchi et al. (2010) derived from the largest LAE samples, to date, at these redshifts, and the Lyα LF measurements include all of the major Subaru survey data (Shimasaku et al. 2006; Kashikawa et al. 2006, 2011) and the cosmic variance uncertainties in their errors. Nevertheless, the difference in the best-estimate Lyα LFs is negligibly small between these studies. In Figure 9, we find a significant decrease of the Lyα LFs from $z = 6.6$ to 7.3 largely beyond the error bars. In our survey, we expect to find 65 $z = 7.3$ LAEs in the case of no Lyα LF evolution from $z = 6.6$ to 7.3, but identify only 7 $z = 7.3$ LAEs from our observations that are about an order of magnitude smaller than the expected LAEs.

To quantify this evolution, we evaluate the error distribution of Schechter parameters. Because we fix the Schechter parameter of $\alpha$ to $-1.5$, we examine the error distribution of $L_{\text{Lyα}}$ and $\phi^*$ with the fixed value of $\alpha = -1.5$. Figure 10 shows error contours of the Schechter parameters of $z = 7.3$ Lyα LF, together with those of $z = 6.6$ LF (Ouchi et al. 2010). Our measurements indicate that the Schechter parameters of $z = 7.3$ LF are different from those of $z = 6.6$ Lyα LF, and that the Lyα LF decreases from $z = 6.6$ to 7.3 at the >90% confidence level. Because our $z = 7.3$ Lyα LF is derived with the same procedures as the $z = 6.6$ Lyα LF (Ouchi et al. 2010), one expects no systematic errors raised by the analysis technique for the comparison of the $z = 6.6$ and 7.3 results. From this aspect, it is reliable that the Lyα LF declines from $z = 6.6$ to 7.3 significantly. Here, we also discuss the possibilities of the LF decrease mimicked by our sample biases. In Section 3.1, we assume that there is no contamination in our $z = 7.3$ LAE sample. If some contamination sources exist, the $z = 7.3$ Lyα LF corrected for contamination should fall below the present estimate of the $z = 7.3$ Lyα LF. In this case, our conclusion regarding the significant LF decrease is further strengthened. In Section 2.3, we define the selection criterion of the rest-frame Lyα EW of $\text{EW}_0 \gtrsim 14 \text{ Å}$ for our $z = 7.3$ LAEs. This criterion of the EW$_0$ limit is slightly different from that of the LAEs for the $z = 6.6$ Lyα LF estimates. However, the EW$_0$ limit for the $z = 6.6$ LAEs is $\text{EW}_0 \gtrsim 14 \text{ Å}$ (Ouchi et al. 2010) which is larger than our EW$_0$ limit of $z = 7.3$ LAEs. Because our EW$_0$ limit gives more $z = 7.3$ LAEs to our sample than that of $z = 6.6$ LAEs, the conclusion of the Lyα LF decrease from $z = 6.6$ to 7.3 is unchanged by the EW$_0$ limit.

4.3. Accelerated Evolution of Lyα LF at $z \gtrsim 7$

Figure 9 implies that the decrease in the Lyα LF from $z = 6.6$ to 7.3 is larger than that from $z = 5.7$ to 6.6, i.e., there is an accelerated evolution of the Lyα LF at $z = 6.6$–7.3. To evaluate this evolution quantitatively, we calculate the Lyα luminosity densities, $\rho_{\text{Lyα}}$, down to the common luminosity limit of $\log L_{\text{Lyα}} = 42.4 \text{ erg s}^{-1}$ reached by the observations for LAEs at $z = 5.7, 6.6,$ and 7.3. Similarly, we estimate the total Lyα luminosity densities, $\rho_{\text{Lyα tot}}$, which are integrated down to $L_{\text{Lyα}} = 0$ with the best-fit Schechter functions. Figure 11
quickly at significantly different, we conclude that the Lyα luminosity density starts evolving faster at $z \gtrsim 7$, while the UV luminosity density rapidly decreases at $z \sim 8$ and beyond. The $\rho_{\text{Ly}^\alpha}$ and $\rho_{\text{UV}}$ knees are indicated with the arrows.

(A color version of this figure is available in the online journal.)

Figure 11. Evolution of Lyα and UV luminosity densities. The red circles are the Lyα luminosity densities obtained by this study, Ouchi et al. (2010), and Ouchi et al. (2008) for $z = 7.3, 6.6$, and $5.7$, respectively. The blue circles are the UV luminosity densities given by Bouwens et al. (2014) for $z = 5.9, 6.8, 7.9$, and $10.4$, and Ellis et al. (2013) for $z = 9.0$. The left ordinate axis refers to the Lyα luminosity densities, and the right ordinate axis is for the UV luminosity densities. The Lyα luminosity density starts evolving faster at $z \sim 7$, while the UV luminosity density rapidly decreases at $z \sim 8$ and beyond. The $\rho_{\text{Ly}^\alpha}$ and $\rho_{\text{UV}}$ knees are indicated with the arrows.

Table 5 summarizes the values of these Lyα luminosity densities at each redshift. Here, we use $\log(1+z)$ for the abscissa in Figure 11, because we compare the evolution of $\rho_{\text{Ly}^\alpha}$ with that of UV luminosity densities, $\rho_{\text{UV}}$, derived by Oesch et al. (2013) who use $\log(1+z)$ (see Section 4.4). In this figure, we find a rapid decrease of the Lyα luminosity density at $z = 6.6–7.3$. To quantify this evolution, we calculate ratios of $\rho_{\text{Ly}^\alpha}/\rho_{\text{UV}}$, which are shown in Table 5, where $z_1$ and $z_2$ are redshifts. We fit the evolution of $\rho_{\text{Ly}^\alpha}$ to the power-law function,

$$
\rho_{\text{Ly}^\alpha} \propto (1+z)^{n(\rho)},
$$

and obtain $n(\rho) = -5.0_{-0.5}^{+4.2}$ at $z = 5.7–6.6$ and $n(\rho) = -20.8_{-9.4}^{+5.1}$ at $z = 6.6–7.3$. Because these values of $n(\rho)$ are significantly different, we conclude that the Lyα LF evolves quickly at $z \gtrsim 7$.

We also investigate pure-luminosity and number density evolution cases to test whether this rapid Lyα LF evolution is dominated by an $L^*$ or $\phi^*$ decrease. These evolution cases are examined by the minimum $\chi^2$ fitting. For example, to evaluate the pure-luminosity evolution from $z = 6.6$ to $7.3$, we take a set of three parameters of $L^*_{z=6.6}$, $L^*_{z=7.3}/L^*_{z=6.6}$, and $\phi^*$, where $L^*_{z=6.6}$ and $L^*_{z=7.3}/L^*_{z=6.6}$ are Schechter parameters of $L^*$ at $z = 6.6$ and a ratio of $z = 7.3 L^*$ to $z = 6.6 L^*$, respectively. Here, $\phi^*$ is a common value in $z = 6.6$ and 7.3, and the Schechter parameter of $\alpha$ is fixed to $-1.5$. We prepare Schechter functions at $z = 6.6$ and 7.3 with the sets of three parameters, and search

| Redshift Range | $\rho_{\text{Ly}^\alpha}$ Evolution$^a$ | $n(\rho)$$^b$ |
|----------------|--------------------------------------|----------------|
| $z = z_1$ to $z_2$ | $\rho_{\text{Ly}^\alpha}/\rho_{\text{UV}}$ | $n(\rho)$ |
| $z = 5.7$ to $6.6$ | $0.53 \pm 0.37$ | $-5.0_{-0.5}^{+4.2}$ |
| $z = 6.6$ to $7.3$ | $0.16 \pm 0.09$ | $-20.8_{-9.4}^{+5.1}$ |
| $z = 7.3$ to $8.0$ | $0.09 \pm 0.07$ | $-11.2_{-7.0}^{+5.7}$ |

Notes.

$^a$ Best-fit values of luminosity density ratio, $\rho_{\text{Ly}^\alpha}/\rho_{\text{UV}}$, and $\phi^*$, where the indices of $z_1$ and $z_2$ denote redshifts.

$^b$ Power-law slope $n(\rho)$ defined with Equation (4).
for the best-fit parameters that minimize $\chi^2$ by the simultaneous fit of Schechter functions to $z = 6.6$ and 7.3 Lyα LFs. In this way, we obtain the best-fit parameter of $L_{*}^{z=7.3}/L_{*}^{z=6.6}$, which corresponds to a fraction of $L^*$ for the pure-luminosity evolution between $z = 6.6$ and 7.3. Similarly, we estimate $L_{*}^{z=7.3}/L_{*}^{z=5.7}$ and $L_{*}^{z=6.6}/L_{*}^{z=5.7}$ at the redshift ranges. We also evaluate the pure-number density evolution with the ratios of $\phi^*$ in the same manner. We summarize the best-fit parameters for these pure-luminosity and number density evolutions in Table 6. Figure 12 shows evolutions of the $L^*$ and $\phi^*$ ratios from $z = 5.7$ to a redshift of $z$. In Figure 12, the shaded area denotes the $L^*$ (and $\phi^*$) evolution at $z = 5.7$–6.6 with the measurement uncertainties, and indicates the extrapolation of this evolutionary trend to $z = 7.3$. We find that the ratios of $L^*$ and $\phi^*$ drop from $z = 6.6$ to 7.3 below the shaded area. Similar to Equation (4), we approximate the pure $L^*$ and $\phi^*$ evolutions by power laws whose indices are $n(L^*)$ and $n(\phi^*)$:

$$L^* \propto (1 + z)^{n(L^*)}$$
$$\phi^* \propto (1 + z)^{n(\phi^*)}.$$ (5)

We summarize the best-fit $n(L^*)$ and $n(\phi^*)$ values in Table 6. In either case of the pure-luminosity or number density evolution, the indices of $n$ at $z = 6.6$–7.3 is significantly smaller than those at $z = 5.7$–6.6. These results are consistent with our conclusion of an accelerated evolution of the Lyα LF at $z \gtrsim 7$. The $\chi^2$ values are comparable for the pure-luminosity and number density evolution cases (see Table 6), although the $\chi^2$ values of the pure-luminosity evolution are slightly smaller than those of the pure-number density evolution. The available Lyα LF data do not have accuracies with which we can discuss the dominant component of the evolution at $z = 5.7$–7.3. Nevertheless, if we assume the Lyα LF evolution is dominated by a pure $L^*$ evolution whose $\chi^2$ values are smaller than those of a pure $\phi^*$ evolution, we find that, in the pure $L^*$ evolution, the decreases in the Lyα LF are 30% ([$1 - L_{*}^{z=6.6}/L_{*}^{z=5.7}$] × 100) and 70% ([$1 - L_{*}^{z=7.3}/L_{*}^{z=5.7}$] × 100) at $z = 5.7$–6.6 and 5.7–7.3, respectively. In other words, the typical LAE has gotten brighter by 1.4 times from $z = 6.6$ to 5.7 and 3.3 times from $z = 7.3$ to 5.7.

4.4. Implications from the Accelerated Evolution of Lyα LF

In Section 4.3, we find that the Lyα LF shows the accelerated evolution at a redshift beyond $z \sim 7$. We refer to the redshift starting a rapid decrease in the Lyα luminosity density as “$\rho$ Lyα knee” which is indicated in Figure 11. In contrast with this evolution of the Lyα LF, there is no such a rapid decrease in the UV LF at $z \sim 7$, but only at $z > 8$, if any (Oesch et al.

Table 6: Best-fit Parameters for Pure-Luminosity and Number Density Evolution Cases

| Redshift Range | $L_{*}^{z=6.6}$ Evolution $^a$ | $L_{*}^{z=6.7}$ Evolution $^a$ | $\chi^2(L^*)^b$ | $n(L^*)^f$ | $\phi^*$ Evolution $^d$ | $\phi^*/\phi_{2.5}^*$ | $\chi^2(\phi^*)^c$ | $n(\phi^*)^f$ |
|----------------|-------------------|-------------------|-----------------|-------------|-------------------|-------------------|-----------------|-------------|
| $z = 5.7$–6.6  | $0.70^{+0.09}_{-0.06}$ | 4.2 | $-2.8^{+1.0}_{-0.7}$ | $0.54^{+0.10}_{-0.09}$ | 4.7 | $-4.9^{+1.7}_{-1.4}$ |
| $z = 6.6$–7.3  | $0.4^{+0.09}_{-0.07}$ | 1.6 | $-9.8^{+2.2}_{-2.0}$ | $0.18^{+0.09}_{-0.07}$ | 1.8 | $-19.5^{+4.6}_{-3.6}$ |

Notes:

$^a$ Best-fit value of $L_{*}^{z=6.6}$, where the indices of $z_1$ and $z_2$ indicate redshifts.

$^b$ $\chi^2$ for the best-fit $L_{*}^{z=6.6}$.

$^c$ Power-law slope $n(L^*)$ of Equation (5) for pure-luminosity evolution case.

$^d$ Best-fit value of $\phi_{2.5}^*/\phi_{2.5}^*$.

$^e$ Power-law slope $n(\phi^*)$ of Equation (5) for pure-number density evolution case.

![Figure 12](image-url)
2013; Bouwens et al. 2014). Figure 11 compares the evolution of \(\rho^{\text{Ly}\alpha}\) (red symbols) and \(\rho^{\text{UV}}\) (blue symbols). Although the rapid decrease of the UV LF at \(z > 8\) is still an open question (see, e.g., Ellis et al. 2013; Robertson et al. 2013), we refer to the redshift starting this possible rapid decrease of the UV LF as the “\(\rho^{\text{UV}}\) knee.” Again, there is a significant redshift difference between \(\rho^{\text{Ly}\alpha}\) and \(\rho^{\text{UV}}\) knees (Figure 11). Because the evolution of \(\rho^{\text{UV}}\) correlates with the cosmic SFR history, the accelerated evolution of the Ly\(\alpha\) LF found at \(z \sim 7\) does not originate from a rapid decrease of the SFR density. To explain this accelerated evolution of the Ly\(\alpha\) LF, physical mechanisms related to the Ly\(\alpha\) production and escape processes must exist. The simple interpretation of the Ly\(\alpha\) LF decrease is that the Ly\(\alpha\) damping wing of the IGM given by cosmic reionization absorbs Ly\(\alpha\) of galaxies strongly toward high redshifts. Here, we first investigate this simple scenario of cosmic reionization in Sections 4.4.1 and 4.4.2 and then discuss the physical origin of the accelerated evolution of the Ly\(\alpha\) LF with various possible scenarios in Section 4.4.3.

### 4.4.1. Constraints on \(x_{\Hi}\) at \(z = 7.3\)

In Sections 4.4.1 and 4.4.2, we discuss the simple scenario of cosmic reionization that contributes to the accelerated evolution of the Ly\(\alpha\) LF. We define \(T_{\text{Ly}\alpha}^{\text{IGM}}\) as an Ly\(\alpha\) transmission through the IGM at a redshift of \(z\) and calculate \(T_{\text{Ly}\alpha,z=7.3}/T_{\text{Ly}\alpha,z=5.7}\) to estimate \(x_{\Hi}\) at \(z = 7.3\). Because cosmic reionization has been completed at \(z = 5.7\) (Fan et al. 2006), the Ly\(\alpha\) damping wing absorption of the IGM is negligible at \(z = 5.7\).

Section 4.3 presents the estimates of the Ly\(\alpha\) luminosity densities from the Ly\(\alpha\) LF for various redshifts (Fan et al. 2006) and this study at \(z = 5.7\) and 7.3, respectively (Table 4). There are two estimates of the Ly\(\alpha\) luminosity densities, the observed Ly\(\alpha\) luminosity density, \(\rho^{\text{Ly}\alpha}\), and the total one, \(\rho^{\text{Ly}\alpha,\text{tot}}\). Ouchi et al. (2010) calculate these two Ly\(\alpha\) luminosity densities with their data and confirm that the ratio of these different estimates agrees within the error bars (see Figure 19 of Ouchi et al. 2010). Thus, we adopt these Ly\(\alpha\) luminosity density for our fiducial results for cosmic reionization which include no systematic bias from observations. With the values shown in Table 4, we obtain

\[
\rho_{z=7.3}^{\text{Ly}\alpha,\text{tot}} / \rho_{z=5.7}^{\text{Ly}\alpha,\text{tot}} = 0.20.
\]

Because the Ly\(\alpha\) LF evolution is made not only by cosmic reionization but also by the SFR change in galaxy evolution, we subtract the effect of the SFR density evolution from the Ly\(\alpha\) luminosity density evolution. An SFR of a galaxy is correlated with the UV luminosity. The UV luminosity of \(z = 7.3\) LAE in principle can be estimated by the subtraction of the Ly\(\alpha\) line flux from the \(z\)-band flux. However, we cannot derive the reliable UV luminosities from our data. This is because large uncertainties exist in the \(z\)-band magnitude and the contamination of an unknown amount of IGM absorption which makes a significant bias in the estimate of the UV continuum as demonstrated in the simulations of Shimakaki et al. (2006). To derive a reliable UV LF of \(z \geq 6\) LAEs, one needs deep near-infrared data, such as \(J\) and \(H\) images, which cover the continuum emission longward of the Ly\(\alpha\) line for most LAEs, but no such data are available for LAE studies to date. Since we cannot derive a reliable UV LF of \(z = 7.3\) LAE from our data, we quantify \(\rho^{\text{UV}}\) at \(z = 5.7–7.3\) given by the other observations. We use \(\rho^{\text{UV}}\) measured with the samples of dropout galaxies (Bouwens et al. 2009, 2011), and estimate \(\rho^{\text{UV}}\) at \(z = 5.7\) and 7.3 by the interpolation of this evolution. We, thus, obtain

\[
\rho_{z=7.3}/\rho_{z=5.7}^{\text{UV}} = 0.70.
\]

Following the procedure of Ouchi et al. (2010), we estimate

\[
\rho^{\text{Ly}\alpha} = \kappa T_{\text{Ly}\alpha}^{\text{IGM}} \int_{\text{esc}}^{\text{esc}} / \rho^{\text{UV}},
\]

where \(\kappa\) is a factor converting from UV to Ly\(\alpha\) luminosities, which depends on stellar population. \(f^{\text{esc}}\) is a fraction of Ly\(\alpha\) emission escape from a galaxy through the interstellar medium (ISM) absorption including galactic neutral hydrogen and dust attenuation. With Equation (6),

\[
T_{\text{Ly}\alpha,z=7.3}^{\text{IGM}} / T_{\text{Ly}\alpha,z=5.7}^{\text{IGM}} = \kappa_{z=7.3} T_{\text{Ly}\alpha,z=5.7}^{\text{esc}} / \rho_{z=5.7}^{\text{Ly}\alpha}/\rho_{z=5.7}^{\text{UV}}.
\]

Assuming that the stellar population of LAEs is the same at \(z = 5.7\) and 7.3 (i.e., \(\kappa_{z=5.7} = 1\)), we can derive the total LAE LF for various redshifts from the systemic velocity by 0 and 360 km s\(^{-1}\), respectively. The value of \(T_{\text{Ly}\alpha,z=7.3}^{\text{esc}} / T_{\text{Ly}\alpha,z=5.7}^{\text{esc}} = 0.29\) corresponds to \(x_{\Hi} = 0.0\) and \(~0.8\) in the former and the latter case, respectively. Because recent studies have reported that the Ly\(\alpha\) line emission of LAE at \(z = 2.2\) is redshifted by \(~200\) km s\(^{-1}\) (Hashimoto et al. 2013; Shibuya et al. 2014), we take \(x_{\Hi} = 0.5\) which is the \(x_{\Hi}\) value interpolated by the Ly\(\alpha\) velocity shift in Figure 25 of Santos (2004). McQuinn et al. (2007) predict Ly\(\alpha\) LF for various \(x_{\Hi}\) values with radiative transfer simulations. By the comparison of our Ly\(\alpha\) LF with these simulation results in Figure 4 of McQuinn et al. (2007), we obtain \(x_{\Hi} = 0.7\). In the models of Dijkstra et al. (2007a, 2007b), the Ly\(\alpha\) transmission fraction of the IGM is related to the size of typical ionized bubbles, and Furlanetto et al. (2006) predict \(x_{\Hi}\) from the size of the ionized bubble with the analytic model. Based on Figure 6 of Dijkstra et al. (2007b), our estimates of the Ly\(\alpha\) transmission fraction of IGM at \(z = 5.7–7.3\) suggest that the typical size of the ionized bubble is very small, \(~2\) comoving Mpc, and the estimated neutral hydrogen fraction is \(~0.6\) from the top panel of Figure 1 of Furlanetto et al. (2006). Based on these results of \(x_{\Hi}\), we conclude the neutral hydrogen fraction is relatively high, \(x_{\Hi} = 0.3–0.8\) at \(z = 7.3\) which includes the uncertainties of the various model predictions and the Ly\(\alpha\) transmission fraction estimated from the observations.

In Figure 13, we plot our estimate of \(x_{\Hi}\) at \(z = 7.3\), and compare it with those from previous studies. The measurements of the Ly\(\alpha\) LF imply \(x_{\Hi} < 0.63\) at \(z = 7.0\) (Ota et al. 2010), and this result is consistent with our estimate of \(x_{\Hi} = 0.3–0.8\) at \(z = 7.3\). The studies of Ly\(\alpha\) emitting fraction by Penetucci et al. (2011), Schenker et al. (2012), Ono et al. (2012), Treu et al. (2012), Caruana et al. (2012, 2014), Penetucci et al. (2014), and Schenker et al. (2014) indicate \(x_{\Hi} = 0.5\) at \(z \sim 7\), and these estimates are also comparable to ours within
Figure 13. Evolution of the neutral hydrogen fraction of the IGM. Top and bottom panels are the same plots but with the ordinate axes of linear and logarithmic scales, respectively. The red filled circle is the $x_{\text{HI}}$ estimate from our Ly$\alpha$ LF at $z = 7.3$. The blue filled triangle, square, diamond, and pentagon denote the $x_{\text{HI}}$ values from the Ly$\alpha$ LF evolution presented in Malhotra & Rhoads (2004), Kashikawa et al. (2011), Ouchi et al. (2010), and Ota et al. (2010), respectively. The blue open diamond and circle indicate the $x_{\text{HI}}$ constraints given by the clustering of LAEs (Ouchi et al. 2010) and the Ly$\alpha$ emitting galaxy fraction (Pentericci et al. 2011; Schenker et al. 2012, 2014; Ono et al. 2012; Treu et al. 2012; Caruana et al. 2012, 2014; Pentericci et al. 2014). The magenta filled triangles show the $x_{\text{HI}}$ measurements from the optical afterglows of GRBs (Totani et al. 2006, 2014). The green filled squares and open triangle are the $x_{\text{HI}}$ constraints provided from the GP test of QSOs (Fan et al. 2006) and the size of QSO near zone (Mortlock et al. 2011; Bolton et al. 2011), respectively. The hatched and gray regions represent the 1σ ranges for the instantaneous reionization redshifts obtained by nine-year WMAP (Hinshaw et al. 2013; Bennett et al. 2013) and WMAP+Planck (Planck Collaboration et al. 2013), respectively. The dotted, dashed, and solid lines show models A, B, and C, respectively (Choudhury et al. 2008).

(A color version of this figure is available in the online journal.)

Figure 14. Evolution of Thomson scattering optical depth, $\tau_{el}$. The hatched and gray regions indicate the 1σ ranges of the $\tau_{el}$ measurements of $\tau_{el} = 0.081 \pm 0.012$ and $\tau_{el} = 0.089^{+0.026}_{-0.024}$ obtained by nine-year WMAP (Hinshaw et al. 2013; Bennett et al. 2013) and WMAP+Planck (Planck Collaboration et al. 2013), respectively. The dotted, dashed, and solid curves represent the models A, B, and C, respectively (Choudhury et al. 2008).

estimates, but also from the errors of the UV LF measurements and the variance of the theoretical model results.

It is implied that the amount of IGM neutral hydrogen may increase quickly at $z \sim 7$. However, the results of the $x_{\text{HI}}$ evolution are based on various assumptions that should be examined carefully. In Section 4.4.1, we assume $\int^{z=5.7}_{z=7.3} f_{\text{esc}}^{\text{Ly}_{\alpha}}/f_{\text{esc}}^{\text{Ly}_{\alpha}} < 1$. Observational studies show that the Ly$\alpha$ escape fraction of LAEs increases from $z \sim 3$ to $z \sim 6$, i.e., $f_{\text{esc}}^{\text{Ly}_{\alpha},z=6}/f_{\text{esc}}^{\text{Ly}_{\alpha},z=6} < 1$ (Ouchi et al. 2008; Hayes et al. 2011; see also Ono et al. 2010). If this trend continues to $z = 7.3$, the intrinsic Ly$\alpha$ escape fraction with no IGM absorption would be $f_{\text{esc}}^{\text{Ly}_{\alpha},z=7.3}/f_{\text{esc}}^{\text{Ly}_{\alpha},z=6} < 1$. In this case, we obtain the value of $T_{\text{esc}}^{\text{IGM},z=7.3}/T_{\text{esc}}^{\text{IGM},z=5.7}$ where is smaller than our estimate above (see Equation (7)) and an $x_{\text{HI}}$ estimate higher than our result of $x_{\text{HI}} = 0.3-0.8$ at $z = 7.3$.

4.4.2. Comparison with Optical Depth of Thomson Scattering

In this section, we investigate whether the relatively high value of our $x_{\text{HI}}$ estimate can explain the Thomson scattering optical depth, $\tau_{el}$, measurements given by WMAP and Planck. Because one needs to know $x_{\text{HI}}$ evolution at $z = 0-1100$ to derive $\tau_{el}$, we use three models of the $x_{\text{HI}}$ evolution (Choudhury et al. 2008) that cover typical scenarios of the early and relatively late cosmic reionization history. We refer to these three $x_{\text{HI}}$ evolution models as models A, B, and C corresponding to the minimum halo masses for reionization sources that are $\sim 10^9$, $\sim 10^{10}$, and $\sim 5 \times 10^5$ $M_\odot$, respectively, at $z = 6$ in the semi-analytic models of Choudhury et al. (2008). We present the $x_{\text{HI}}$ evolution of models A, B, and C in Figure 13, and $\tau_{el}$ as a function of redshift for these models in Figure 14. In Figure 14, the hatched and gray regions represent the 1σ range of $\tau_{el}$ measured by WMAP and WMAP+Planck, respectively. While models A and B are consistent with our $x_{\text{HI}}$ estimate at $z = 7.3$ in Figure 13, the models A and B fall far below the $\tau_{el}$ measurements of WMAP and WMAP+Planck in Figure 14. These results require reionization that proceeds at an epoch earlier than models A and B. Model C is a very early reionization model that agrees with the lower end of the error of our $x_{\text{HI}}$ estimate at $z = 7.3$ in Figure 13. However, model C is barely consistent with the WMAP result within the 1σ error.
in Figure 14. Moreover, in Figure 14, the τ_{el} value from WMAP+Planck is higher than the one of model C beyond the uncertainty. Thus, there is a possible tension between our estimate of high x_{HI} and the CMB measurements of high τ_{el}. A similar tension between τ_{el} and galaxy observation results is also claimed by Robertson et al. (2010) who discuss UV luminosities of reionization sources that are based on observational quantities independent from the Lyα LF of our study.

4.4.3. Physical Origin of the Accelerated Evolution of Lyα LF

The physical origin of the accelerated Lyα LF evolution could be something other than the rapid increase of neutral hydrogen at z ≥ 7, because the τ_{el} measurements have a tension with the high x_{HI} value that is estimated with our Lyα LF under the assumption that the Lyα LF evolution is given by the combination of cosmic reionization and cosmic SFR density evolution. Similarly, large values of x_{HI} estimates at z ∼ 6–7 are obtained from the Lyα damping wing absorption techniques with LAEs (Kashikawa et al. 2006, 2011; Ota et al. 2008, 2010; Ouchi et al. 2010; Shibuya et al. 2012), LBGs (Pentericci et al. 2011; Schenker et al. 2012; Ono et al. 2012; Treu et al. 2012; Caruana et al. 2012, 2014; Pentericci et al. 2014; Schenker et al. 2014), QSOs (Bolton et al. 2011), and GRBs (Totani et al. 2014). Recent theoretical studies suggest a few physical pictures that explain the τ_{el} measurements and the large x_{HI} estimates given by the Lyα damping wing absorption measurements. The first picture is the presence of clumpy neutral hydrogen clouds in ionized bubbles at the end of reionization epoch. Lyα line and UV continuum from objects would be attenuated by a number of optically thick absorption systems that have large H I column densities such as Lyman limit systems (Bolton & Haehnelt 2013; Xu et al. 2014). The absorption systems of the clumpy H I clouds do not contribute to the volume-limited value of x_{HI}; significantly, but to the attenuation of the Lyα-line and UV continuum emitted from objects. Interestingly, recent ALMA observations report a possible H I cloud emitting [C II]158 μm near a star-forming galaxy at z = 6.6 (Ono et al. 2014), supporting this physical picture. If this picture is correct, our finding of an accelerated Lyα LF evolution indicates that the number of such clumpy H I clouds rapidly increases at z > 7. The second picture is the increase of ionizing photon escape fraction toward high-z (Dijkstra et al. 2014). Lyα photons are produced by recombination following photoionization in the ionized gas of a galaxy. The more the ionizing photons escape from the galaxy, the smaller the amount of recombination is. Under significant escape of the ionizing photons, Lyα emission is not efficiently produced by ionized clouds in a galaxy. This picture reconciles with the increase of the ionizing photon escape fraction suggested by Nakajima & Ouchi (2014) from the ionization parameter evolution. If this picture is correct, the accelerated Lyα LF evolution would suggest either a sudden decrease of the gas covering fraction of galaxies or a boosting of the ionization parameter which would create density-bounded clouds in galaxies. However, in this picture, the high x_{HI} values given by the UV-continuum studies of QSOs and GRBs are not explained. Additional physical mechanisms would be required for these x_{HI} results of the UV-continuum studies.

Another possibility is that the tension between the x_{HI} estimates and τ_{el} would not exist because the uncertainty of the x_{HI} estimates is very large (Figure 13). In fact, tension is found at the significance level only beyond ~σ. It is not clear whether the tension is a hint for the discrepancy between the x_{HI} and τ_{el} estimates. One of the dominant factors of the x_{HI} uncertainty is the error in the Lyα LFs, which is largely caused by statistical errors due to the small LAE samples. To obtain a large sample of LAEs, it is necessary to carry out narrowband imaging observations in survey fields significantly wider than this study. One promising project is the Subaru/Hyper Suprime-Cam (HSC) survey which will complete 30 deg^2 and 3.5 deg^2 narrowband observations for LAEs at z = 5.7–6.6 and 5.7–7.3, respectively, with a depth comparable to those accomplished by the present Subaru surveys. With the strong constraint of x_{HI} given by the HSC survey, we will address the problem of whether the tension is a discrepancy between x_{HI} and τ_{el} estimates and a new physical picture is really needed.

5. SUMMARY

We have conducted an ultra-deep Subaru/Suprime-Cam imaging survey for z = 7.3 LAEs with our custom narrowband filter, NB101, which has a sharp bandpass for a high sensitivity of the faint line detection. We have observed a total of ~0.5 deg^2 sky of SXDS and COSMOS fields with integration times of 36.3 and 69.5 hr, respectively. We have reached a 1σ limiting luminosity of L(Lyα) ~ 2.4 × 10^{42} erg s^{-1}, which is about four times deeper than those achieved by the previous Subaru studies for z > 7 LAEs and comparable to the luminosity limits of previous Subaru z = 3.1–6.6 LAE surveys. Our observations allow us to derive the Lyα LF at z = 7.3 with unprecedented accuracy and to examine the Lyα LF evolution from z = 6.6 to 7.3 reliably. The major results of our study are listed below.

1. We identify three and four LAEs in the SXDS and COSMOS fields, respectively. These numbers are surprisingly small because we expect to find a total of ~65 LAEs in our survey in the case of no evolution of the Lyα LF from z = 6.6 to 7.3. We derive the Lyα LF at z = 7.3 with our data, carefully evaluating uncertainties of Poisson statistics and cosmic variance. We fit Schechter functions to our Lyα LF, and obtain the best-fit Schechter parameters, L_{Lyα}^{*} = 2.7^{+8.9}_{-1.0} × 10^{42} erg s^{-1} and φ^* = 3.7^{+17}_{-3.3} × 10^{-4} Mpc^{-3} with a fixed α = -1.5.

2. We compare our Lyα LF with the previous measurements of the Lyα LF at z ∼ 7.3. Our Lyα LF measurements are consistent with those of the previous Subaru and VLT studies, but significantly smaller than those of the 4 m telescope observations. The significant differences in the Lyα LF between the 4 m telescope programs and Subaru+VLT studies including ours could not be explained by cosmic variance. It is possible that 4 m telescope results are derived with highly contaminated LAE samples, as suggested by the recent spectroscopic follow-up observations that found no emission lines in the LAEs of the 4 m telescope samples.

3. We identify a decrease in the Lyα LF from z = 6.6 to 7.3 significantly at the >90% confidence level in the Schechter function parameter space (Figure 10), compared with the Lyα LFs at z = 6.6 obtained from the largest LAE sample of the Subaru survey with estimates of the cosmic variance uncertainties. Using our Lyα LFs at z = 7.3 and the Subaru results at z = 5.7–6.6, we find a rapid decrease of the Lyα LF indicated by the evolution of the Lyα luminosity density ratios (Figure 11). Approximating the evolution of the Lyα luminosity density with the power-law function, (1 + z)^{α_{Lyα}}, we obtain n(ρ) = −5.0^{+14}_{−15} at z = 5.7–6.6 and n(ρ) = −20.8^{+5.1}_{−9.7} at z = 6.6–7.3. Because these values of n(ρ) are significantly different beyond the uncertainties, we
conclude that there is an accelerated evolution of the Lyα LF at $z \gtrsim 7$.

4. Because no accelerated evolution of the UV-continuum LF or the cosmic SFR is found at $z \sim 7$, but suggested only at $z \gtrsim 8$, if at all (Oesch et al. 2013; Bouwens et al., 2012), this accelerated Lyα LF evolution is explained by physical mechanisms different from pure SFR decreases for galaxies but related to the Lyα production and escape in the process of cosmic reionization. We discuss a simple scenario of cosmic reionization that contributes to the accelerated evolution of the Lyα LF. Subtracting the effect of the galaxies’ SFR evolution from the decrease in the Lyα luminosity density, we estimate the ratio of Lyα transmission of the IGM to be $T_{\text{Lyα}}^{\text{IGM},z=7.3}/T_{\text{Lyα}}^{\text{IGM},z=5.7} = 0.29$.

By the comparison of theoretical models, we obtain $x_{\text{HI}} = 0.3$–0.8 whose large uncertainty includes the variance of the theoretical model predictions. Although this result is consistent with previous $z \sim 7$ studies that use the Lyα damping wing absorption, tension would exist between the $x_{\text{HI}}$ estimate and the Thomson scattering optical depth, $\tau_{\text{el}}$, measurements from WMAP and Planck at the significance level only beyond $\sim 1\sigma$. If this tension is a hint for the discrepancies between the $x_{\text{HI}}$ and $\tau_{\text{el}}$ estimates, these results support new physical pictures such as the clumpy neutral gas cloud absorption and the increase of the ionizing photon escape fraction suggested by recent theoretical studies.

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Facility: Subaru (Suprime-Cam)

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