Subaru FOCAS Survey of $z = 7$–7.1 Ly$\alpha$ Emitters: A Test for $z \gtrsim 7$ Ly$\alpha$ Photometric Luminosity Functions

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ABSTRACT

Recent observations of $z \gtrsim 7$ Ly$\alpha$ emitters (LAEs) have derived a variety of Ly$\alpha$ luminosity functions (LFs) with contradictory results, evolution or non-evolution from $z \lesssim 6$, the epoch after reionization. This could be because most of $z \gtrsim 7$ LFs comprise photometric candidates and might include some contaminations. We conducted the Subaru Telescope Faint Object Camera And Spectrograph narrowband NB980 ($\lambda_c \sim 9800$A, FWHM $\sim 100$A) imaging and spectroscopy survey of $z = 7$–7.1 LAEs to compare its "contamination-free" result with $z \gtrsim 7$ photometric Ly$\alpha$ LFs previously derived. We imaged the Subaru Deep Field and the sky around a cluster MS 1520.1+3002 and found one LAE candidate, but spectroscopy did not reveal Ly$\alpha$ though deep enough to detect it. We calculated the expected number of LAEs in our survey, using five $z = 7$ and three $z = 7.7$ Ly$\alpha$ LFs from recent surveys. Seven of them are consistent with null detection ($0.1^{+1.8}_{-0.1}$–$1.1^{+3.2}_{-1.0}$ LAEs) within errors including Poisson statistics and cosmic variance, but average values ($0.7$–$1.1$ LAEs) predicted from one $z = 7$ and two $z = 7.7$ LFs among the seven indicate nearly a single detection. The remaining one $z = 7$ LF predicts $3.0^{+5.2}_{-2.0}$ LAEs. As to $z = 7$, the discrepancy likely comes from different LAE selection criteria. For $z = 7.7$, there are two possibilities; (1) If $z = 7.7$ LAEs are somehow brighter in Ly$\alpha$ luminosity than lower redshift LAEs, $z = 7.7$ LF is observed to be similar to or higher than lower redshift LFs even if attenuated by neutral hydrogen. (2) All/most of the $z = 7.7$ candidates are not LAEs. This supports the decline of LF from $z \sim 6$ to 7.7 and reionization at $z \sim 6$–7.7.

Key words: cosmology: observations – galaxies: evolution – galaxies: high-redshift.

1 INTRODUCTION

Ly$\alpha$ emitters (LAEs) can be a probe of cosmic reionization, since their Ly$\alpha$ emission is absorbed or scattered by neutral hydrogen if the universe is not completely ionized, causing Ly$\alpha$ luminosity function (LF) to decline as the fraction of neutral hydrogen in intergalactic medium (IGM) increases (Rhoads & Malhotra 2001). From $z = 3$ to 5.7, the Ly$\alpha$ LF was observed not to evolve (e.g., Ouchi et al. 2008). Also, many authors constructed statistically large and uniform samples of $z = 5.7$ and 6.6 LAEs with some candidates spectroscopically confirmed (Shimasaku et al. 2006; Kashikawa et al. 2006; Ouchi et al. 2008, 2010; Nakamura et al. 2011). They found that the Ly$\alpha$ LF significantly declines from $z = 5.7$ to 6.6, suggesting that the universe could be partly neutral at $z = 6.6$. The decline of the LF was further supported with large spectroscopic samples newly obtained by independent observations of Hu et al. (2010) and Kashikawa et al. (2011). Meanwhile, Ota et al. (2008, 2010) found that Ly$\alpha$ LF also declines from $z = 5.7$–6.6 to 7. These studies all imply that neutral fraction might increase with redshift at $z > 6$.

Moreover, Hu et al. (2010) noticed that average Ly$\alpha$ equivalent width (EW) is slightly smaller at $z = 6.6$ than 5.7. Kashikawa et al. (2011) also found that Ly$\alpha$ EW distributions of $z \sim 3$–5.7 LAEs are similar, but EWs of $z = 6.6$ LAEs are smaller. On the other hand, some Lyman break galaxies (LBGs) are known to show strong Ly$\alpha$ emission, while some do not. Fraction of Ly$\alpha$ emitting LBGs increases from $z \sim 3$ to 6 (Stark et al. 2011), but suddenly drops from $z \sim 6$ to 7 (Ono et al. 2012; Pentericci et al. 2011; Schenker et al. 2012). The lower EW and Ly$\alpha$ LBG fraction at $z > 6$ could be due to the rapid evolution of neutral fraction from $z \sim 6$ to 7. This is consistent with the idea of the partly neutral Universe suggested by the decline of the Ly$\alpha$ LF.
However, some authors found a fair number of $z = 7$ and 7.7 LAE candidates and claim that the Lyα LF does not evolve from $z = 5.7$–6.6 to 7–7.7 (Ihara et al. 2011, 2012; Tilvi et al. 2010; Krug et al. 2012). Their results contradict late reionization at $z < 7.7$. Conversely, Clément et al. (2011) also surveyed $z = 7.7$ LAEs but did not detect any LAEs and support reionization at $z < 7.7$. Interestingly, all the LFs implying no evolution at $z \gtrsim 6$ are based on photometric samples. If they suffer some contaminations, the conclusion would be different. The best way to reveal this is to identify all the candidates by spectroscopy. However, this requires very expensive campaigns that observe many candidates spread over different sky locations with sufficiently long integration to ensure detections or non-detections of Lyα. Alternatively, simpler but indirect method is to conduct one imaging and spectroscopy survey and compare its contamination free result with the photometric LFs.

Here, we use our imaging and spectroscopy survey of $z = 7$–7.1 LAEs for this purpose. We did this survey in 2003, using the Subaru Telescope Faint Object Camera And Spectrograph (FOCAS, Kashikawa et al. 2002) and a narrowband filter, NB980 ($\lambda_c \sim 9800$ Å, FWHM $\sim 100$ Å; see Figure 1) as a groundwork for our subsequent larger $z = 7$ LAE surveys in 2005–2010 by Iye et al. (2006) and Ota et al. (2008, 2010a). Since no detailed information about $z \sim 7$ galaxies was available in 2003, we selected LAE candidates with tentative color criteria and conducted spectroscopy of them. In this paper, we re-analyze the NB980 data, refine the color criteria based on recent knowledge of $z \gtrsim 7$ galaxies, select $z = 7$–7.1 LAE candidates and see if their spectra were taken in 2003 to derive a contamination-free result.

In Section 2, we describe our imaging data. We perform selection of LAE candidates in Section 3. In Section 4, we explain the result of follow-up spectroscopy. In Section 5, we compare our NB980 survey with previously derived $z \gtrsim 7$ Lyα photometric LFs. We conclude in Section 6. Throughout we use an $(\Omega_m, \Omega_b, h) = (0.3, 0.7, 0.7)$ cosmology and 2″ aperture AB magnitudes, unless otherwise specified.

### 2 IMAGING OBSERVATION AND DATA

#### 2.1 Broadband and Narrowband Images

The NB980 survey targeted the Subaru Deep Field (SDF, Kashikawa et al. 2004) and the sky region around a galaxy cluster MS1520.1+3002 (hereafter, MS1520). For the SDF, broadband $BVRi'z'$ and narrowband NB816 ($\lambda_c = 8150$ Å, FWHM = 120 Å) and NB921 ($\lambda_c = 9196$ Å, FWHM = 132 Å) images were taken with the Subaru Telescope Suprime-Cam (Miyazaki et al. 2002) by the SDF project and NB973 ($\lambda_c = 9755$ Å, FWHM = 200 Å) image by Iye et al. (2006). All the SDF images were convolved to have a common point spread function (PSF) of $0''$.98. Limiting magnitudes at 3σ with 2″ diameter apertures are $(B, V, R, i', z') = (29.45, 27.74, 27.80, 27.43, 26.62, 26.63, 26.54, 25.47)$. The $i'$ and $z'$ images of MS1520 were also taken by the Suprime-Cam and have PSFs of $0''.66$ and $0''.83$ and limiting magnitudes (2″ aperture, 3σ) of 27.33 and 25.74.

#### 2.2 NB980 Imaging and Data Reduction

We imaged the SDF and MS1520 with NB980 and FOCAS on 2003 May 7–8. The seeing was $0''.7$–1''.2. The 600 sec exposures were dithered with a simple pattern to minimize loss of the survey area. First, every time each exposure was taken, the pointing was shifted by 2″ in the RA direction. After repeating this 8 (5) times for the SDF (MS1520), the pointing was returned to the original position in the RA direction but moved by 3″ in the DEC direction. We repeated this procedure 3 times. The total integration times were 4 (SDF) and 2.7 (MS1520) hours.

We reduced the NB980 data in the same manners as in Takata et al. (2003). The dithered exposures were registered and combined to produce final stacked images of the SDF and MS1520 (hereafter NB980-SDF and NB980-MS1520) as shown in Figure 2. This reduced the fringing, but slight residual remained in the stacked images. The standard star HD144 (Oke 1990) was imaged during the observations to calibrate the photometric zeropoints. They were NB980 = 30.27 mag ADU$^{-1}$ for both NB980-SDF and NB980-MS1520. The PSFs and 2″ aperture 3σ limiting magnitudes of NB980-SDF and NB980-MS1520 were 23.25 and 23.27, and NB980 = 24.67 and 24.44, respectively. Assuming the minimum detectable rest frame Lyα EW of $W_{\text{rest}}^{\text{Ly}\alpha} = 20$ Å (see Section 2.2), these magnitudes correspond to Lyα flux limits of $F_{\text{Ly\alpha}} \sim 1.2$ and $1.4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ or Lyα luminosity.
3 LAE CANDIDATE SELECTION

3.1 Photometry

We first matched astrometry and pixel scales of all the Suprime-Cam images to those of NB980-SDF and NB980-MS1520. Also, we convolved PSFs of the z'-band images to those of NB980-SDF and NB980-MS1520 to calculate $z' - NB980$ color by measuring $z'$ and NB980 magnitudes with the same aperture to select LAE candidates in Section 3.2. Then, we performed source detection and photometry with the SExtractor (Bertin & Arnouts 1996). The pixel scale of the NB980 images is $0.4''$ 1083 pixel$^{-1}$. We regarded an area larger than 5 contiguous pixels with a flux greater than 2σ as an object. We detected objects in NB980-SDF and NB980-MS1520 and did photometry in other wavebands, using the double-imaging mode. The 2'' diameter aperture magnitudes were measured with the MAG_AUTO parameter and total magnitudes the MAG_AUTO. Finally, combining the photometry in all the wavebands, we constructed the NB980-detected object catalogs for the SDF and MS1520.

3.2 LAE Criteria and Candidate Selection

Figure 1 shows that the NB980 band is located at the red side of the $z'$ band. If the Lyman break of an LBG is redshifted into NB980, it results in a significant excess of $z' - NB980$. If the spectrum has Lyα emission, the excess is more significant. We used this characteristic to isolate $z \sim 7$ LBGs/LAEs. We examined the expected $z' - NB980$ colors of $z \sim 7$ LBGs/LAEs and derived candidate selection criteria. We first created model spectra of LBGs having the power law continua $f_{\lambda} \propto \lambda^\beta$ with several different slopes $\beta = -3, -2.5, -2, -1.5, -1, 0$ and then model spectra of LAEs by adding Lyα emission with rest frame EWs of $W_{\text{Ly}\alpha}^\text{rest} = 20, 50, 100, 150$ and 300Å. We did not assume any specific line profile or velocity dispersion. Instead, we simply added the total line flux value to the spectra at 1216Å. Then, we redshifted the spectra to $z = 0-8$ and applied Lyα absorption by IGM, using the prescription of Madau (1995).

Colors of LBGs/LAEs were calculated using the model spectra and transmission curves of $z'$ and NB980 and plotted as a function of redshift in Figure 2. For comparison, we also calculated the colors of E (elliptical), Sbc, Scd and Im (irregular) galaxies using the Coleman, Wu & Weedman (1980) template spectra. As clearly seen, LBGs ($W_{\text{Ly}\alpha}^\text{rest} = 0$) and LAEs ($W_{\text{Ly}\alpha}^\text{rest} > 20$Å) are expected to produce significant excess in NB980 against $z'$ at $z \sim 7-7.1$. Also, $z \sim 1-3$ ellipticals show modest excess due to the 4000Å Balmer break. We adopted $z' - NB980 > 2.5$ as a criterion that selects $z \sim 7-7.1$ LBGs/LAEs avoiding ellipticals. We used the following criteria to select LBG/LAE candidates.

\[
NB980 \leq 3\sigma \text{ limiting magnitude}
\]
Table 1. Photometry of MS1520-A.

| RA(J2000) | DEC(J2000) | i' | z' | NB980 | NB980 |
|-----------|------------|----|----|-------|-------|
| 15:22:11.8 | +29:50:40.3 | >28.52 | >26.94 | 23.87 | 23.42 |

NOTE: The columns 3–5 (6) are 2'' aperture (total) magnitudes. The limits are 1σ.

4. FOLLOW-UP SPECTROSCOPY

In our previous NB980 survey in 2003, we had selected more candidates with more inclusive criteria \( z' \sim NB980 > 1.3 \) and 2σ limiting magnitudes. Then, we had conducted spectroscopy on 2003 June 22–23 with multi-object slits and FOCAS. We confirmed that MS1520-A selected in Section 4.2 had been also observed in 2003. At that time, we had used VPH950 grism (grating of 1095 lines mm\(^{-1}\) and resolution of \( \sim 2500 \)) with Os8 order-cut filter (coverage of 580–1000 nm) and Os8 slits. Integration time was 4 hours comprising six 2400 seconds exposures dithered along the slit by \( \pm 1'' \). The spectra of the standard star Feige 34 [Oka 1990] had been also obtained and used for flux calibration. The data reduction was performed in the same standard manners as in Iye et al. [2006]. We inspected the sky-subtracted stacked spectrum of MS1520-A and could identify neither Ly\(\alpha\) emission, a UV continuum nor any other spectral features.

4.1 Possibility of the Candidate Being an LAE

To see if we had enough depth to detect Ly\(\alpha\), we compared the sky background RMS of the stacked spectrum with Ly\(\alpha\) flux estimated from NB980 magnitude. If we assume \( z = 7 \) and a rest frame Ly\(\alpha\) EW as low as \( W_{Ly\alpha}^{\text{rest}} = 20\AA\) for the most severe case, \( \sim 76\% \) of the NB980 flux comes from Ly\(\alpha\) line, and total NB980 magnitude of MS1520-A, 23.42 converts to Ly\(\alpha\) flux, \( F_{Ly\alpha} = 3.7 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \). Ota et al. [2010b] estimated that slit loss of the flux in the FOCAS spectroscopy of a \( z = 6.96 \) LAE 10K-1 [Iye et al. 2004] is \( \sim 35\% \) with a 0.8'' slit under a seeing of 1''. We also used 0.8'' slits for our spectroscopy, and the seeing was also \( \sim 1'' \). If we apply this slit loss, the flux is \( F_{Ly\alpha}^{NB} = 2.4 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \). Meanwhile, we used binning of 4 pixels (equivalent to 0.4'', smaller than the seeing of \( \sim 1'' \)) in the spatial direction to extract one dimensional spectrum of MS1520-A. Calculating the variance in unbinned pixels in the dispersion direction at 9750–9850\AA\ (NB980 passband) in this spectrum, we estimated the sky RMS to be \( 8.8 \times 10^{-19} \text{erg s}^{-1} \text{cm}^{-2} \). The FWHM of Ly\(\alpha\) line, for example, of a \( z = 6.6 \) LAE varies from 55 to 14.6\AA\ [Kashikawa et al. 2004; Taniguchi et al. 2005]. If we assume the FWHMs of \( z = 7 \) LAEs are similar, the Ly\(\alpha\) flux is \( F_{Ly\alpha}^{spec} = (0.48–1.3) \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \). This is 2–5 times fainter than \( F_{Ly\alpha}^{NB} \), deep enough to detect Ly\(\alpha\). Thus, MS1520-A is unlikely an LAE.

4.2 Possibility of the Candidate Being an LBG

Another possible origin of MS1520-A is a \( z \sim 7 \) LBG. However, we could neither see any faint continuum by eye on the 2 dimensional spectrum nor in the 1 dimensional one after the 4 pixel binning in the spatial direction. To see if we had enough depth to detect the continuum, we compared the sky RMS of the stacked spectrum with the UV continuum flux density estimated from NB980 magnitude. If we assume \( z = 7.05 \) Lyman break (i.e., all the NB980 flux are from the UV continuum at the red half of NB980 and zero flux otherwise), total NB980 magnitude of MS1520-A, 23.42 and 35% slit loss converts to a UV continuum flux density, \( F_{\lambda, UV}^{NB} = 6.4 \times 10^{-19} \text{erg s}^{-1} \text{cm}^{-2} \). The sky RMS of the 1 dimensional spectrum, \( 8.8 \times 10^{-19} \text{erg s}^{-1} \text{cm}^{-2} \), is 1.4 times shallower than \( F_{\lambda, UV}^{NB} \), not enough to detect the continuum. Our spectroscopy does not reveal if MS1520-A is a \( z \sim 7 \) LBG.

Another way is to see if our NB980 imaging was deep enough to detect \( z \sim 7 \) LBGs. Ouchi et al. [2009] recently detected 22 \( z \sim 7 \) LBG candidates in the SDF and the GOODS-N fields to the UV luminosity \( M_{UV} = -21 \). If we assume that all the NB980 flux is from the UV continuum and that \( z = 7 \), our depths, NB980 = 24.67 (SDF) and 24.44 (MS1520), convert to \( M_{UV} \sim -22.3 \) and \(-22.5 \). To these limits, Ouchi et al. [2009] did not detect any LBGs. Hence, MS1520-A is unlikely a \( z \sim 7 \) LBG.

4.3 Other Possibilities

The other possible origin of MS1520-A is a late-type star, a variable/transient object or a noise. In case of a late-type star, the spectrum could show no signal if the continuum is fainter than our spectroscopy limit. Because we have only one image blueward of Ly\(\alpha\) (\( i' \)-band), the null detection criterion only on this band might not be strict enough to remove a faint late-type star. In case of a variable/transient
object, it could have been fainter than our detection limit at the time of i’-band imaging and the spectroscopy while it might have been bright at the time of NB980 imaging. Meanwhile, MS1520-A is unlikely a low-z line emitter. If it was, its line flux would be as bright as the $F_{\text{Ly} \alpha}$ estimated in Section 4.1 and detectable by the spectroscopy.

The purpose of this study is to obtain a contamination free result for $z \sim 7$ LAEs, including null detection. We can safely conclude that we detect no $z \sim 7$ LAE in our survey volume and to our detection limit. We used this information to assess $z \gtrsim 7$ photometric Lyα LF in the literatures.

5 DISCUSSION

We compared our null detection with the expected detection number of LAEs estimated from a variety of $z = 7$ and 7.7 photometric Lyα LFs to check their consistency with the current contamination free result.

5.1 Comparison with $z = 7$ Lyα LFs

In Table 2, we calculated and listed expected detection number of LAEs in our NB980 survey volume by integrating or interpolating Lyα LFs from four recent $z = 7$ LAE surveys (Ota et al. 2008, 2010a; Hibon et al. 2011, 2012) to our survey limits. The errors include Poisson error for small number statistics and cosmic variance (see the footnote of Table 2 for details). For comparison, we also calculated the expected number in the case of no neutral hydrogen attenuation of Lyα emission (i.e., Lyα transmission to neutral hydrogen $T_{\text{Ly} \alpha}^{\text{IGM}} = 1$) by integrating such a $z = 7$ Lyα LF predicted by a recent LAE evolution model of Kobayashi et al. (2007) to our survey limits. The expected numbers estimated using LFs from Ota et al. (2008, 2010a) and one of the Hibon et al. (2012) survey fields (D33) are consistent with the null detection. Conversely, the number estimated using Hibon et al. (2011) LF indicates the detection of 3.0$^{\pm 1.2}_{\pm 2.0}$ LAEs. Also, though consistent with null detection within the error, the number, 1.1$^{+1.0}_{-1.6}$, estimated from another LF (D41) of Hibon et al. (2012) is larger than those estimated from other $z = 7$ LFs. This implies that LAE candidates detected by Hibon et al. (2011, 2012) might include some degree of contaminations. We compared Ota et al. (2008, 2010a) and Hibon et al. (2011, 2012) surveys and investigated what causes the discrepancy.

Ota et al. (2008, 2010a) obtained the narrowband NB973 images of the SDF and the SXDS (Furusawa et al. 2008) fields with one pointing of the Subaru Suprime-Cam each, reaching limiting magnitudes NB973 = 24.9 and 25.4 ($5\sigma$, 2′ aperture). Meanwhile, Hibon et al. (2012) imaged two fields called D33 and D41 with the same NB973 filter and one Suprime-Cam pointing each and reached limiting magnitudes NB973 = 24.3 and 24.7 ($5\sigma$, 2′ aperture). Though Hibon et al. (2012) images are shallower than Ota et al. (2008, 2010a), they detected 7 and 7 LAE candidates in the D33 and the D41, while Ota et al. (2008, 2010a) detected 1 and 3 in the SDF and the SXDS (see Table 2). Moreover, Hibon et al. (2011) imaged the COSMOS field with their narrowband NB9680 ($\lambda_c = 9680\AA$, FWHM$\sim 90\AA$) to detect 6 LAE candidates, though their limit and volume are shallower and smaller than those of Ota et al. (2008, 2010a).

Meanwhile, Kobayashi et al. (2007) $z = 7$ LF with $T_{\text{Ly} \alpha}^{\text{IGM}} = 1$ predicts the detection of 5.6$^{\pm 2.7}_{\pm 2.7}$ LAEs even if the neutral fraction at $z = 7$ is 0%. Because Hibon et al. (2011, 2012) LFs predict 1.1$^{+1.0}_{-1.6}$-3.0$^{+3.2}_{-2.0}$ detections whether or not neutral fractions is 0%, the expected in the LF number between Hibon et al. (2011, 2012) and Ota et al. (2008, 2010a) cannot be explained by field-to-field variation of the degree of Lyα attenuation by neutral hydrogen. In addition, since Hibon et al. (2011, 2012) and Ota et al. (2008, 2010a) surveyed similar and very large volumes, cosmic variance and Poisson error are not the cause of difference, either. Moreover, because Ota et al. (2010a) probed to much deeper limit than Hibon et al. (2011, 2012), if difference in dust extinction of all the $z = 7$ LAEs in different sky fields is $E(B-V) < 0.06$ (equivalent to difference in survey depth), dust extinction is also unlikely the reason. For example, Ono et al. (2012) constrained dust extinction of a spectroscopically confirmed z = 7.213 LAE to be $E(B-V) \sim 0.05$. Though it is one example, dust extinction of individual $z = 7$ LAEs seem to be modest. Thus difference in dust extinction among $z = 7$ LAEs could be even smaller. One remaining factor that causes the discrepancy between Ota et al. (2008, 2010a) and Hibon et al. (2011, 2012) is different LAE selection criteria.

5.1.1 Effect of Selection Criteria on Detection Number

Hibon et al. (2011, 2012) did not consider the redshift evolution of narrowband excess of galaxies, while Ota et al. (2008, 2010a) did. The NB980 and NB973 they used have FWHMs of 90Å and 200Å, and located at the red edge of $\lambda$-band. This makes $z < 7$ LAEs/LBGs also selected as candidates. In the case of NB973, $z \gtrsim 6.4$ Lyα emission with EWs of even $W_{\text{Ly} \alpha}^{\text{rest}} \lesssim 20\AA$ can produce significant excess of $\lambda \sim NB973 > 0.7$, according to Figure 3 of Ota et al. (2008) that plots redshift evolution of $z' - NB973$ colors of model LAEs/LBGs generated with Bruzual & Charlot (2003) population synthesis models. The same Figure also shows that a $z = 7$ LAE/LBG is expected to have $z' - NB973 > 1.9$. We also calculated $z' - NB973$ color versus redshift similar to Figure 3 in the present paper, using spectra $f_{\lambda} \propto \lambda^\beta$ with $\beta = -3$ to 0 and $W_{\text{Ly} \alpha}^{\text{rest}} = 0$ to 300Å and found that a $z = 7$ LAE/LBG is expected to have $z' - NB973 > 2.2$. For example, a spectroscopically confirmed $z = 6.96$ LAE (10K-1, Iye et al. 2006) has a color of $z' - NB973 > 2.44$. Ota et al. (2008, 2010a) adopted slightly less strict criterion $z' - NB973 > 1.72$, considering the effects of photometric errors and possible diversity of $z = 7$ LAEs on the color. This criterion in principle selects $z \gtrsim 6.5$ LAEs/LBGs. Hence, Ota et al. (2008, 2010a) imposed an additional criterion, a null detection in the narrowband NB921 ($\lambda_c = 9196\AA$, FWHM = 132Å) to avoid $z = 6.5-6.6$ LAEs/LBGs. Hence, their criteria select $z \gtrsim 6.7$ LAEs/LBGs.

Meanwhile, Hibon et al. (2012) used even more inclusive criterion $z' - NB973 > 0.65$, which selects $z \gtrsim 6.4$ LAEs/LBGs, and they did not have NB921 images to avoid $z = 6.5-6.6$ LAEs. Their sample include 4 and 6 candidates with $z' - NB973 \sim 1.5$ in the D33 and the D41 fields. Some of them might be $z = 6.5-6.6$ LAEs, which Ota et al. (2008, 2010a) did not select. In fact, Ota et al.
Table 2. Expected detection number of LAEs in the NB980 survey estimated from $z = 7$ and 7.7 Lyα LFs.

| Authors              | Volume$^{a}$ (10$^4$ Mpc$^3$) | Lyα flux limit$^{a}$ (10$^{-17}$ erg s$^{-1}$ cm$^{-2}$) | #LAE candidates$^{d}$ detected | Expected #LAEs in NB980 survey$^{c}$ |
|----------------------|---------------------------------|-----------------------------------------------------------|---------------------------|----------------------------------------|
|                      |                                 |                                                           |                           | SDF                         | MS1520          | SDF+MS1520             |
| $z = 7$ LAEs         |                                 |                                                           |                           |                           |                 |                       |
| This study           | 1.0                             | 1.2–1.4                                                   | 0                         | $-^{+1.9}$                     | $-^{+1.8}$       | $-^{+1.8}$             |
| Ota et al. (2008)    | 32                              | 1.5$^b$                                                   | 1                         | $0.3^{+0.3}$                   | $0.2^{+0.2}$     | $0.3^{+0.3}$           |
| Ota et al. (2010a)   | 30                              | 0.97$^b$                                                  | 3                         | $0.1^{+0.1}$                   | $0.07^{+0.07}$   | $0.1^{+0.1}$           |
| Hibon et al. (2011)  | 7.2                             | 1.8$^c$                                                   | 6                         | $2.0^{+2.8}$                   | $1.5^{+1.9}$     | $3.0^{+3.2}$           |
| Hibon et al. (2012)  | D33$^f$                         | 2.7$^b$                                                   | 7                         | $0.5^{+1.9}$                   | $0.2^{+0.2}$     | $0.5^{+1.9}$           |
| Hibon et al. (2012)  | D41$^f$                         | 1.9$^b$                                                   | 7                         | $1.1^{+2.3}$                   | $0.5^{+1.9}$     | $1.1^{+2.2}$           |
| Kobayashi et al. (2007) | —                              | —                                                         | —                         | $0.4^{+0.4}$                   | $0.3^{+0.3}$     | $0.6^{+0.5}$           |
| $z = 7.7$ LAEs       |                                 |                                                           |                           |                           |                 |                       |
| Hibon et al. (2010)  | 6.3                             | 0.83                                                      | 7                         | $0.3^{+1.9}$                   | $0.2^{+1.8}$     | $0.3^{+1.8}$           |
| Tilvi et al. (2010)  | 1.4                             | 0.60                                                      | 4                         | $0.7^{+1.3}$                   | $0.4^{+0.4}$     | $0.8^{+0.7}$           |
| Krug et al. (2012)   | 2.8                             | 0.80                                                      | 4                         | $0.5^{+1.9}$                   | $0.4^{+0.4}$     | $0.7^{+0.6}$           |

$^{a}$The survey volume and limit of the papers in the column 1. $^{b}$Lyα fluxes converted from their limiting NB973 magnitudes (5σ, 2" aperture), assuming a rest frame Lyα EW of 20A and $z = 7$. $^{c}$The Lyα flux directly converted from the NB9680 magnitude of their faintest LAE candidate. $^{d}$The number of LAE candidates the authors detected in their survey volumes and to their survey limits. $^{e}$The expected detection number of LAEs in our NB980 survey estimated using the Lyα LFs from the papers in the column 1. For Ota et al. (2008), we integrated the inferred $z = 7$ Lyα LF in Figure 10 of their paper. Ota et al. (2010a) Lyα LF is based on $L_{Lyα}$ directly converted from Lyα fluxes of their candidates. Ota et al. (2010a) estimated that ~77% of NB973 total flux of $a = 6.96$ LAE (I0K-1) is from Lyα. Hence, we interpolated Ota et al. (2010a) Lyα LF attenuated by 0.77 × $L_{Lyα}$ to our NB980 survey limits to obtain the expected number of LAEs. For Hibon et al. (2010, 2011, 2012), we integrated the Schechter (1976) LFs best-fitted to their observed data by them. For Kobayashi et al. (2007), we interpolated their Lyα LFs to our NB980 survey limits. The errors include Poisson errors for small number statistics (Gehrels, 1986) and cosmic variance $σ_v$. We combined these errors quadratically and if the lower limit was a negative value, we adjusted it to zero. We calculated $σ_v$'s using the bias $b = 3.4$ obtained for LAEs by Ouchi et al. (2004) and the dark matter halo variances $σ_{DM}$'s at $z = 6$ predicted by the analytic model of Somerville et al. (2004) and our survey volumes. The $σ_v$'s are ~48% (~54%) for the survey volume equivalent to one (two) FOCAS field of views. $^{f}$The Schechter parameters $Φ$'s and $L_*$ for LFs derived from the D33 and the D41 fields in Table 4 in Hibon et al. (2012) paper was found to be mistakenly listed. They are switched with each other (P. Hibon 2012, private communication). We used their Schechter LFs with correct parameters to estimate the expected LAE numbers.

(2008) reported that if they did not impose null detection in NB921, they selected a spectroscopically confirmed $z = 6.6$ LAE IOK-3 with $z' \sim NB973 \sim 1.41$ as a candidate. Besides, Hibon et al. (2011) adopted NB680 – $z' \sim -0.75$ without examining redshift evolution of this color of LAEs. For the same reason as the case of NB973, Hibon et al. (2011) sample might potentially include some lower redshift LAEs/LBGs. If Hibon et al. (2011, 2012) candidates really include some such contaminations, their real $z = 7$ Lyα LFs after corrected for the contaminations could show evolution from $z = 6$ and predict more consistent number of LAEs in our NB980 survey.

5.2 Comparison with $z = 7.7$ Lyα LFs

In Table 2 we also listed the expected number of LAEs in our survey estimated using 3 $z = 7.7$ Lyα LFs (Hibon et al. 2010, Tilvi et al. 2010, Krug et al. 2012) under the assumption that LF does not evolve from $z = 7$ to 7.7. All the expected numbers are consistent with null detection within errors. Nonetheless, the average value 0.7–0.8 of the expected number (0.7$^{+2.5}_{-0.8}$ – 0.8$^{+2.5}_{-0.8}$ LAEs) estimated from the LFs of Tilvi et al. (2010) and Krug et al. (2012) is close to a single detection that means evolution of LF from $z = 7$ to 7.7. Actually, these authors and even Hibon et al. (2010) claim that if their candidates are all real $z = 7.7$ LAEs, their LFs imply a trend opposite to the decline of Lyα LF from $z = 5.7$ to 6.6 and 7 found by Kashikawa et al. (2011), Ouchi et al. (2010a and Ota et al. 2008, 2010a), Tilvi et al. (2010) and Krug et al. (2012) also performed Monte Carlo simulations to estimate the expected number of LAEs in their surveys and concluded that even if 1 or 2 candidates in their samples are real $z = 7.7$ LAEs, it implies no evolution of Lyα LF from $z = 6.5$ to 7.7. There are two possible scenarios that explain the situation.

One is that $z = 7.7$ LAEs might be somehow brighter than $z = 6.5$ LAEs in Lyα luminosity. In this case, $z = 7.7$ LF is observed to be similar to or higher than $z = 6.5$ LF even if attenuated by neutral hydrogen. There are two factors potentially supporting this. First, stellar population studies of $z \sim 6$ massive ($\sim 10^{10} M_⊙$) LBGs suggest that they could have had substantially high star formation rates in the past at $z \sim 7$–8 to assemble their high masses and could be very bright at $z \gtrsim 7$ (Yan et al. 2006, Eyles et al. 2007). Also, narrowband selected LBGs tend to be the lower and younger age extension of LBG population and might be at the earlier stage of the evolution of LBGs (Lai et al. 2008, Pirzkal et al. 2007). If $z = 7.7$ LBGs are the progenitors of $z = 6$ massive LBGs, they might be intrinsically very bright. Second, Hayes et al. (2011) estimated Lyα escape fractions $f_{esc}^{Lyα}$ at $z \sim 0.7$–7.7 using observed data in literatures and found that $f_{esc}^{Lyα}$ increases with redshift.
when they fitted a power law to $f_{\text{esc}}$ at $z \sim 0.6$. If $f_{\text{esc}}$ is higher in LAEs at $z = 7.7$ than 6.5, $z = 7.7$ LAEs are observed to be brighter.

Another scenario is that all the LAE candidates of Tilvi et al. (2010) and Krug et al. (2012) and all/some of Hibon et al. (2010) LAE candidates are not $z = 7.7$ LAEs. This agrees with the decline of Ly$\alpha$ flux from $z = 5.7$ to 6.6–7 found by Kashikawa et al. (2011), Ouchi et al. (2010) and Ota et al. (2008, 2010a). This scenario is supported by another $z = 7.7$ LAE survey by Clement et al. (2011) who did not detect any candidates. As mentioned earlier, the drop in fraction of Ly$\alpha$ emitters LBGs at $z > 6$ (Ono et al. 2012; Pentericci et al. 2011; Schenker et al. 2012) could be also a support.

6 CONCLUSION

We conducted the Subaru FOCAS NB980 imaging and spectroscopy survey of $z = 7$–7.1 LAEs in the SDF and MS1520 and detected no LAEs to a 3$\sigma$ Ly$\alpha$ flux limit of $\sim 1.4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ in a comoving volume of $\sim 10^4$ Mpc$^3$.

We estimated the expected number of LAEs in our survey from $5 \leq z \leq 7$ and $3 \leq z \leq 7.7$ photometric Ly$\alpha$ LFs. Seven agree with null detection within errors but average LAE numbers predicted by one $z = 7.7$ LAE are similar to or higher than lower-$z$ LAEs. For $z = 7$, the discrepancy likely comes from different LAE selection criteria. For $z = 7.7$, there are 2 possibilities. (1) If $z = 7.7$ LAEs are brighter than lower-$z$ LAEs, $z = 7.7$ LF is similar to or higher than lower-$z$ LFs even if attenuated by neutral hydrogen. (2) If all the $z = 7.7$ candidates are not real, Ly$\alpha$ LF declines from $z \sim 6$ to 7.7.

Evaluation of $z \gtrsim 7$ Ly$\alpha$ LFs in this study relies on an indirect method. The direct and best way is secure spectroscopy of all the candidates. Future powerful telescopes such as JWST or TMT will facilitate this and reveal the real nature of Ly$\alpha$ LFs at the epoch of reionization.

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