Lyα emitters at \( z = 6.5 \) in the SSA22 field: An area more neutral or void at the end of the reionization epoch

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ABSTRACT

We present results of a survey of Lyman α emitters (LAEs) at \( z = 6.5 \) which is thought to be the final epoch of the cosmic reionization. In a \( \approx 530 \) arcmin\(^2\) deep image of the SSA22 field taken through a narrowband filter NB912 installed in the Subaru/Suprime-Cam, we have found only 14 LAEs candidates with \( L_{\alpha} \gtrsim 3 \times 10^{42} \) erg s\(^{-1}\). Even applying the same colour selection criteria, the number density of the LAE candidates is a factor of 3 smaller than that found at the same redshift in the Subaru Deep field (SDF). Assuming the number density in the SDF is a cosmic average, the probability to have a number density equal to or smaller than that found in the SSA22 field is only 7% if we consider fluctuation by the large-scale structure (i.e. cosmic variance) and Poisson error. Therefore, the SSA22 field may be a rare void at \( z = 6.5 \). On the other hand, we have found that the number density of \( i' - \) drop galaxies with \( 25.5 < z' < 26.0 \) in the SSA22 field agrees well with that in the SDF. If we consider a scenario that a larger neutral fraction of intergalactic hydrogen, \( x_{HI} \), in the SSA22 field obscures a part of Lyα emission, \( x_{HI} \) in the SSA22 field should be about 2 times larger than that in the SDF. This can be translated into \( x_{HI} < 0.9 \) at \( z = 6.5 \) in the SSA22 field. A much larger survey area than previous ones is required to overcome a large fluctuation reported here and to obtain a robust constraint on \( x_{HI} \) at the end of the reionization from LAEs.

Key words: cosmology: observations — galaxies: high-redshift — intergalactic medium

1 INTRODUCTION

Survey of Lyα emitters (LAEs) at \( z \gtrsim 6 \) has been significantly developing in the last decade since the initial discovery papers (Hu, McMahon, & Cowie 1999; Rhoads & Malhotra 2000; Kodaira et al. 2003; Iye et al. 2004). At \( z \approx 5.7 \), many LAE surveys with the Subaru/Suprime-Cam (S-Cam; Miyazaki et al. 2002) have been made so far (Hu et al. 2004; Ajiki et al. 2003, 2006; Shimasaku et al. 2006; Murayama et al. 2007; Ouchi et al. 2008). In particular, Shimasaku et al. (2006) have performed a deep LAE survey at \( z = 5.7 \) in the Subaru Deep Field (SDF) and present a seminal luminosity function (LF) of Lyα emission at the redshift. Murayama et al. (2007) have performed a very wide (\( \approx 2 \) deg\(^2\)) survey in the COSMOS field and found no evidence of a large-scale clustering of bright (\( L_{\alpha} \gtrsim 1 \times 10^{43} \) erg s\(^{-1}\)) LAEs at \( z = 5.7 \). Finally, Ouchi et al. (2008) have reported results of a wide (\( \approx 1 \) deg\(^2\)) and deep survey in the Subaru/XMM-Newton Deep Survey (SXDS) field and confirmed the LF by Shimasaku et al. (2006). In addition, Ouchi et al. (2008) report a factor of 5 variation of the number density of LAEs among their 5 fields of view of S-Cam.

On the other hand, few surveys had been reported to date at \( z \approx 6.5 \) (Taniguchi et al. 2003; Hu et al. 2003; Hu & Cowie 2003), and a significant improvement is arising (Ouchi et al. 2010; Hu et al. 2010). A largest sample of LAEs at \( z = 6.5 \) reported so far is the one in the SDF presented by Taniguchi et al. (2003). Based on this sample, Kashikawa et al. (2006) have constructed the Lyα LF at the redshift and found that a significant reduction at the bright-end relative to the \( z = 5.7 \) LF by Shimasaku et al. (2006). They interpret this reduction as a signature of the end epoch of the cosmic reionization.

The cosmic reionization is one of the most drastic events in the history of the universe and it happened at \( z \approx 10 \) (Dunkley et al. 2009). The reionization was probably trig-
gered by the first-generation of stars and galaxies. Thus, the event contains the information of the structure formation in the early universe. The subsequent galaxy formation proceeded in the reionized universe and was significantly affected by the ionizing background radiation. This is a complex astrophysical process (or feedback) which is one of the most important issues to be resolved in observational cosmology (e.g., Loeb & Barkana 2001).

The discovery of the Gunn-Peterson trough (Gunn & Peterson 1965) in spectra of QSOs and a GRB at $z \sim 6$ (Becker et al. 2003; Totani et al. 2006) marks the end of the reionization epoch (e.g., Fan, Carilli, & Keating 2006). Furthermore, Kashikawa et al. (2006) argue that the evolution of Ly$\alpha$ LF between $z = 5.7$ and $z = 6.5$ which they found is another signature of the end epoch; since the measurements of ultraviolet (UV) LF of the LAEs agree very well between the two redshifts, the apparent faintness of Ly$\alpha$ emission of $z = 6.5$ LAEs is caused by an increase of attenuation by neutral hydrogen remained in the intergalactic medium (IGM) at $z > 6$.

A significant variation in the IGM transmission found in the spectra of $z = 6$ QSOs suggests inhomogeneous reionization (Djorgovski, Bogosavljevic, & Mahabal 2006). Numerical simulations also show inhomogeneity of the reionization process (e.g., Ciardi, Stoehr, & White 2003). This means that there may be a large variation in the end epoch of the reionization among lines of sight. If it is true, the number density of $z = 6.5$ LAEs may vary significantly among different survey fields. Indeed, Hu & Cowie (2006) report such a large variation between two fields of view of S-Cam. Therefore, another survey of $z = 6.5$ LAEs similar to Taniguchi et al. (2005) is indispensable to discuss such a field-to-field variation.

This paper presents a photometric sample of $z = 6.5$ LAEs found in the archival imaging data taken with S-Cam towards the SSA22 field. Some of the LAEs have been confirmed by spectroscopy in Hu et al. (2010). Then, we compare the number density of the LAEs in the SSA22 field with that in the SDF in order to discuss the field-to-field variation quantitatively. The structure of the rest of this paper is as follows; first, we describe the imaging data used in this paper in §2. Then, we present the photometric sample of $z = 6.5$ LAEs in the SSA22 in §3. In §4, we compare the Ly$\alpha$ LF derived in the SSA22 with that in the SDF, and also compare the number density of $i'$-drop galaxies in the two fields. In §5, we discuss the cause of the small number of LAEs in the SSA22. The final section provides the conclusions of this paper.

The cosmology adopted in this paper is a flat ACDM cosmology with $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. All magnitudes are described by the AB system: $AB = -2.5 \log f_v - 48.60$, where $f_v$ in unit of erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ (Oke 1974).

2 IMAGING DATA

We have collected imaging data of the SSA22 field ($\alpha = 22^\mathrm{h} 17^\mathrm{m} 34^\mathrm{s}, \delta = +00^\circ 17' 00''$; J2000) taken with Subaru/Suprime-Cam (S-cam; Miyazaki et al. 2002) from the archive data system, SMOKA (Subaru-Mitaka-Ookayama-Kiso Archive System; Baba et al. 2002). The collected broadband data are $B$, $V$, $R$, $i'$, and $z'$. In order to select $z \simeq 6.5$ LAEs, we use the imaging data through a narrowband NB912 (central wavelength of 9.139 Å and full width at half maximum [FWHM] of 134 Å) whose efficiency curve is shown in Figure 1. Table 1 is a summary of the imaging data.

All the data were reduced using sfdred (Yagi et al. 2002, Ouchi et al. 2004) and IRAF with the standard manner. In this paper, we selected only frames taken under a good seeing condition. Then, FWHMs of stellar objects in the final images are relatively good as summarised in Table 1, except for $R$ band. The relative accuracy in astrometry in the final images is less than 0.5 pix (pixel scale is 0."202). The flux density calibrations of $z'$ and NB912 images were done by a photometric standard star GD 50 and a spectroscopic standard star G 93-48, respectively. The calibrations of other broadband images were done so as that the colour distributions of $z'$ around 25.5 AB objects in the SSA22 agree with those in the SDF reported by Kashikawa et al. (2004), after the correction of the Galactic dust extinction based on Schlegel, Finkbeiner, & Davis (1998).

The data of $z'$ and NB912 were taken with two position angles with a difference of 90°. While the S-cam has a field of view of $34' \times 27'$, therefore, the area with a good homogeneous quality in the final co-added image is reduced to $22.7' \times 23.6'$ for the two filters. We use only this area to search for LAEs at $z \simeq 6.5$. The limiting magnitudes of $z'$ and NB912 in Table 1 are also measured in this area. The co-moving depth of our survey is 41.6 $h_0^{-1}$ Mpc since NB912 effectively captures Ly$\alpha$ emission line between $z = 6.46$ and $z = 6.57$. Finally, our survey volume is $1.3 \times 10^5 h_0^{-2} $ Mpc$^3$ in co-moving unit.

As a comparison field, we adopt the SDF ($\alpha = 13^\mathrm{h} 24^\mathrm{m} 39^\mathrm{s}, \delta = +27^\circ 29' 25''$; J2000). Kashikawa et al. (2004) published the reduced and calibrated images of $B$, $V$, $R$, $i'$, $z'$, and two narrowband NB816 and NB921. The NB921 has the central wavelength of 9.196 Å and FWHM of the transmission of 132 Å, which are quite similar to those of NB912 as shown in Figure 1. Taniguchi et al. (2003) and Kashikawa et al. (2006) reported their results of LAE survey using NB921 in the SDF. We use these images and photometric catalogue reported in Kashikawa et al. (2004) and in
that the colour excess deviates from a flat density ratio of $z$.

We have found an excellent agreement in 22 field with that in the SDF. The result is shown in Figure 2.

Before selecting LAEs, we should confirm the accuracy of our flux calibration in the SSA22 field. For this aim, we compare the flux calibration of our data in the SSA22 field. For candidates in the SSA22 field in Taniguchi et al. (2005) for a comparison with our LAE can-

didates in the SSA22 field in §4.

First, we made object detection in the final NB912 image by SExtractor (Bertin & Arnouts 1996) with the criterion of "5 connected pixels above 2-$\sigma$". We detected 64,787 objects. Then, we selected objects satisfying all the following criteria:

(a) $22.00 < NB912 < 26.04$ (5$\sigma$),
(b) $z' - NB912 > 1.0$,
(c) $z' - NB912 > -2.5\log_{10}(1 - 3\sigma[F_{\nu}/F_{NB912}])$,
(d) $i' - z' > 1.3$ or $i' > 27.53$ (2$\sigma$),
(e) $B > 27.89$, $V > 27.66$, and $R > 27.03$ (3$\sigma$),

where $\sigma$ indicates 1-$\sigma$ uncertainty of photometry in each band and $\sigma[F_{\nu}/F_{NB912}]$ means 1-$\sigma$ uncertainty of the flux density ratio of $z'$ and NB912. The criterion (c) ensures that the colour excess deviates from a flat $F_{\nu}$ spectrum by more than 3-$\sigma$ of the flux density ratio. These criteria are equivalent with those in the SDF applied by Taniguchi et al. (2005), but our $B$, $V$, $R$, and $i'$ depths are 0.2–0.8 AB shallower than those in the SDF. The resulting number of objects is 12, after visual check to remove objects evidently affected by spiders of bright foreground stars. We show the colour-magnitude diagram, the spatial distribution, and thumbnail images of the LAE candidates in Figures 3, 4, and 5, respectively. The coordinate and photometric measurements of these objects are summarised in Table 2.

In addition, we found one object which may be a LAE at $z \approx 6.5$ in a careful visual checking of hundreds objects satisfying the magnitude and colour cuts (criteria [a]–[c]) but not the drop-out criteria ([d] and [e]). The photometry in shorter wavelengths of this object is probably affected by a bright neighbour as found in Figure 5 second line from the bottom. If the effect by the neighbour was removed, this object would satisfy all the selection criteria.

Furthermore, we add another object as No.14 in the LAE list. This object is reported in Hu et al. (2010) as a drop-out object and was added as an additional LAE candidate and one spectroscopic LAE whose photometry is affected by a neighbouring object.

### Table 1. Imaging data of the SSA22 field used in this paper.

| Filter | Observed year (P.I.) | Exposure time (h) | PSF FWHM (") | 1-$\sigma$ limit (AB)* |
|--------|----------------------|------------------|---------------|------------------------|
| $B$    | 2008 (Y. Nakamura)   | 2.6              | 0.78          | 29.08                  |
| $V$    | 2002 (T. Hayashino), 2003 (P. Capak), 2008 (Y. Nakamura) | 2.1 | 0.82 | 28.85 |
| $R$    | 2000, 2001 (E. Hu)   | 2.9              | 1.06          | 28.22                  |
| $i'$   | 2001 (P. Capak)      | 1.4              | 0.78          | 28.28                  |
| $z'$   | 2001 (Y. Komiyama), 2002, 2003 (P. Capak) | 2.9 | 0.77 | 27.77 |
| NB912  | 2002, 2003 (P. Capak) | 12.7            | 0.77          | 27.79                  |

* Aperture diameter is twice of the PSF FWHM. The Galactic dust extinction is corrected based on Schlegel et al. (1998).

Figure 2. $z'$ number counts in the SSA22 field (plus) and SDF (cross).

Figure 3. Colour-magnitude diagram between $z' - NB912$ and NB912 in the SSA22 field. All objects detected in NB912 are shown by small dots. The dot-dashed and dashed lines show the applied colour and magnitude cuts and 3-$\sigma$ uncertainty in the flux density ratio of $z'$ and NB912, respectively. The selected LAE candidates are shown by filled squares. The open squares are one additional LAE candidate and one spectroscopic LAE whose photometry is affected by a neighbouring object.
Table 2. Observed properties of $z \simeq 6.5$ LAE candidates in the SSA22 field.

| Object          | RA (J2000) | Dec (J2000) | $i'$ $^a$ | $z'$ $^a$ | NB912 $^a$ | Remarks               |
|-----------------|------------|-------------|-----------|-----------|------------|-----------------------|
| SSA22-z6p5-1    | 22:17:42.84 | +00:18:08.5  | > 28.28   | 26.57     | 25.16      | HC221742-001808 ($z_{\mathrm{sp}} = 6.4692$) |
| SSA22-z6p5-2    | 22:16:44.62 | +00:05:54.8  | 27.77     | > 27.77   | 25.39      |                       |
| SSA22-z6p5-3    | 22:18:10.79 | +00:04:02.0  | > 28.28   | 27.77     | 25.51      |                       |
| SSA22-z6p5-4    | 22:17:40.13 | +00:08:14.1  | 27.61     | 27.22     | 25.74      |                       |
| SSA22-z6p5-5    | 22:16:45.15 | +00:12:38.3  | > 28.28   | 27.72     | 25.76      |                       |
| SSA22-z6p5-6    | 22:16:51.72 | +00:04:53.5  | 27.60     | 27.32     | 25.77      |                       |
| SSA22-z6p5-7    | 22:18:07.05 | +00:07:26.9  | > 28.28   | > 27.77   | 25.81      |                       |
| SSA22-z6p5-8    | 22:17:57.12 | +00:18:19.4  | > 28.28   | 27.21     | 25.81      |                       |
| SSA22-z6p5-9    | 22:17:22.73 | +00:21:44.2  | 28.23     | > 27.77   | 25.84      |                       |
| SSA22-z6p5-10   | 22:17:23.69 | +00:10:23.0  | > 28.28   | 27.55     | 25.84      |                       |
| SSA22-z6p5-11   | 22:18:01.65 | +00:22:21.1  | > 28.28   | > 27.77   | 25.91      | HC221801-002220 ($z_{\mathrm{sp}} = 6.5360$) |
| SSA22-z6p5-12   | 22:17:38.28 | +00:09:09.1  | 28.23     | 27.77     | 25.85      |                       |

$^a$ Magnitudes measured within a circular aperture diameter of twice of PSF FWHM of each band. Magnitudes below the 1-σ limit are denoted by the lower limit.

$^b$ Photometry of this object is affected by a neighbouring object.

Figure 4. Spatial distribution of candidates of galaxies at $z \gtrsim 6$ in the SSA22 field. The filled squares are $z \simeq 6.5$ LAE candidates and the open squares are one additional candidate and one spectroscopic LAE whose photometry is affected by a neighbouring object. The circles are $i'$-drop galaxies with 25.5 < $z'$ < 26.0. The dashed line shows the survey area.

spectroscopic LAE. As shown in Figure 5 bottom line, this object has a close neighbour which is probably low-$z$ object. The separation is very close ($\simeq 1''$), so that we missed finding it. The colour excess $z' - $NB912 of this object satisfies with the criterion (b) shown in Figure 3 (fainter open square).

In our photometric LAE sample, there are 4 objects confirmed to be LAEs at $z = 6.5$ by Hu et al. (2010) spectroscopically. We note their redshift in Table 2. Other objects are possibly foreground objects like [O III], [O II], or Hα emitters. Indeed, Kashikawa et al. (2006) have found one [O III] emitter and five unidentified single emission line objects among 22 LAE candidates which they took the spectra. The five single emission line objects are either LAE or [O II] emitter. The contamination fraction in our LAE candidates would be similar to that in the SDF sample because the selection criteria are essentially the same. However, this issue should be confirmed by a follow-up spectroscopy in future.

4 COMPARISON WITH SUBARU DEEP FIELD

We have found 14 candidates of LAE at $z \simeq 6.5$ in the SSA22 field. In this section, we compare statistics of our LAE candidates with those in another large survey in the SDF by Taniguchi et al. (2005) and Kashikawa et al. (2006).

4.1 Lyα luminosity function

First, we compare the cumulative LFs of the LAE candidates in the SSA22 field and in the SDF. While we found only 14 candidates in the SSA22, Taniguchi et al. (2005) reported 57 candidates in the SDF. Among their 57 objects, one object was found to be a foreground [O III] emitter by follow-up spectroscopy and other five objects may be also foreground contaminations (Taniguchi et al. 2005; Kashikawa et al. 2006). However, we compare our 14 candidates with their 57 candidates because we may also have foreground contamination in our 14 photometric samples.

We estimate Lyα flux by the same method adopted in Taniguchi et al. (2005):

$$f_{\lambda_{\mathrm{Ly}\alpha}} = f_{\lambda_{\mathrm{obs}}}(\mathrm{NB912}) \Delta \lambda_{\mathrm{NB912}} / f_{\lambda_{\mathrm{cont}}} \Delta \lambda_{\mathrm{NB912}} / 2,$$

where $f_{\lambda_{\mathrm{obs}}}(\mathrm{NB912})$ is the observed NB912 flux density (per Å), $f_{\lambda_{\mathrm{cont}}}$ is the continuum flux density, and $\Delta \lambda_{\mathrm{NB912}} = 134$ Å is FWHM of the NB912 efficiency curve. The division by 2 accounts for the continuum break at the shortward of Lyα emission line because of intergalactic attenuation. The continuum flux density is estimated from

1 They published 58 objects but one object, No.22, has $z' - $NB921 = 0.87 which does not satisfy their criterion $z' - $NB921 > 1.0. Thus, we remove this object from discussions in this paper.
$\Delta f_{\text{width}}$ = \{ $f_{\text{obs}}^{(\text{z'})} \Delta \lambda_{\text{z'}} - f_{\text{obs}}^{(\text{NB912})} \Delta \lambda_{\text{NB912}} \} / \Delta \lambda_{\text{eff}}$, (2)

where $f_{\text{obs}}^{(\text{z'})}$ is the observed z’ flux density, $\Delta \lambda_{\text{z'}}$ = 1180 Å is the band-width of the z’ filter, and $\Delta \lambda_{\text{eff}}$ = 450 Å is an effective band-width for the continuum, which is the width between the longward edges of z’ and NB912 band-widths. Note that we omit a numerical factor multiplied to $f_{\text{obs}}^{(\text{NB912})} \Delta \lambda_{\text{NB912}}$ in [Tuniguchi et al. (2003)] because it is actually the efficiency of the z’ filter at Lyα wavelength relative to the average efficiency of the filter and about unity. Although this modification is not very important, we re-calculate Lyα fluxes of the LAE candidates in the SDF. When the estimated $f_{\text{Lyα}}^{\text{cont}}$ is less than its 1-σ uncertainty estimated from an error propagation in equation (2), we set $f_{\text{Lyα}}^{\text{cont}} = 0$ in equation (1). Finally, we converted $f_{\text{Lyα}}$ into Lyα luminosity which are summarised in Table 3. In the table, we also list the continuum luminosity density and the observed equivalent width of Lyα for which we adopted the estimated 1-σ uncertainty as an upper or lower limit.

Figure 6 shows the cumulative LF’s of Lyα of the LAE candidates in the SSA22 field and in the SDF. There is a clear difference. As summarised in Table 4, the number density of the z ≲ 6.5 LAE candidates with $L_{\text{Lyα}} > 3 \times 10^{42}$ erg s$^{-1}$ in the SSA22 is a factor of 2.5 smaller than that in the SDF. The number ratio (SDF/SSA22) is 3.5 for $L_{\text{Lyα}} > 5 \times 10^{42}$ erg s$^{-1}$ and 3.4 for $L_{\text{Lyα}} > 7 \times 10^{42}$ erg s$^{-1}$. In Figure 6, the SSA22 LF seems to be reproduced if the number density of the SDF LF is reduced by a factor of 0.3. On the other hand, a factor of 0.6 reduction of $L_{\text{Lyα}}$ in the SDF LF also provides an agreement with the SSA22 LF. The reduction of $L_{\text{Lyα}}$ corresponds to a scenario with a different neutral fraction of hydrogen in the two fields. We will discuss this point more in section 5.2.

**Table 3.** Estimated properties of z ≲ 6.5 LAE candidates in the SSA22 field.

| Object                | $L_{\text{Lyα}}$ $^{a}$ (10$^{42}$ erg s$^{-1}$) | $L_{\text{UV}}$ $^{b}$ (10$^{28}$ erg s$^{-1}$ Hz$^{-1}$) | EW$_{\text{obs}}$ $^{c}$ (10$^{2}$ Å) |
|-----------------------|-----------------------------------------------|-------------------------------------------------|----------------------------------|
| SSA22-z6p5-1          | 5.74                                          | 8.5                                             | 2.4                              |
| SSA22-z6p5-2          | 5.91                                          | < 4.8                                          | > 4.5                            |
| SSA22-z6p5-3          | 5.26                                          | < 4.8                                          | > 4.0                            |
| SSA22-z6p5-4          | 4.25                                          | < 4.8                                          | > 3.2                            |
| SSA22-z6p5-5          | 4.20                                          | < 4.8                                          | > 3.2                            |
| SSA22-z6p5-6          | 4.15                                          | < 4.8                                          | > 3.1                            |
| SSA22-z6p5-7          | 3.99                                          | < 4.8                                          | > 3.0                            |
| SSA22-z6p5-8          | 3.69                                          | < 4.8                                          | 2.3                              |
| SSA22-z6p5-9          | 3.89                                          | < 4.8                                          | > 2.9                            |
| SSA22-z6p5-10         | 3.89                                          | < 4.8                                          | > 2.9                            |
| SSA22-z6p5-11         | 3.85                                          | < 4.8                                          | > 2.9                            |
| SSA22-z6p5-12         | 3.66                                          | < 4.8                                          | > 2.8                            |
| SSA22-z6p5-13 $^{d}$  | 8.16                                          | < 16                                           | > 1.9                            |
| SSA22-z6p5-14 $^{d}$  | 8.49                                          | < 12                                           | > 2.6                            |

$^{a}$ Lyα luminosity estimated by equation (1).

$^{b}$ UV continuum luminosity estimated by equation (2).

$^{c}$ Observed equivalent width of Lyα.

$^{d}$ The derived UV luminosities are an upper limit because z’ flux densities are contaminated by a neighbouring object.

**Table 4.** The observed number density in unit co-moving volume of z ≲ 6.5 LAE candidates in SSA22 and SDF.

| $L_{\text{Lyα}}$ (10$^{42}$ erg s$^{-1}$) | N(SSA22)$^{a}$ (10$^{-5}$ Mpc$^{-3}$) | N(SDF)$^{a}$ (10$^{-5}$ Mpc$^{-3}$) |
|-----------------------------------------|-------------------------------------|-------------------------------------|
| > 10                                    | 0$^{+1.6}_{-1.4}$                    | 2.3$^{+1.6}_{-1.0}$                   |
| > 7                                     | 1.5$^{+2.0}_{-1.9}$                  | 5.1$^{+2.0}_{-1.9}$                   |
| > 5                                     | 3.7$^{+2.5}_{-2.1}$                  | 12.9$^{+2.9}_{-2.4}$                 |
| > 3                                     | 10.4$^{+3.6}_{-2.7}$                 | 25.8$^{+3.9}_{-3.4}$                 |

$^{a}$ 1-σ uncertainties are based on Poisson statistics (Gehrels 1986).
4.2 Number density of $i'$-drop galaxies

Here we compare the number densities of $i'$-drop galaxies in the SSA22 and in the SDF. This comparison may be useful to resolve the reason why the number of $z \simeq 6.5$ LAE candidates in the SSA22 is so small relative to that in the SDF. Namely, the small number of the LAE candidates in the SSA22 may suggest that the field is just a void-like region at $z \simeq 6.5$. If so, the number density of $i'$-drop galaxies may be also small. However, we should be cautious about the difference of completeness along the line of sight for sampling $i'$-drop galaxies and the LAE candidates: $\sim 250$ $h^{-1}_0$ Mpc for $i'$-drop galaxies but $42$ $h^{-1}_0$ Mpc for the LAE candidates.

To select $i'$-drop galaxies among objects detected in the $z'$ band, we adopt the following criteria for the SSA22 (SDF):

(a) $25.50 < z' < 26.00$ ($5\sigma$),
(b) $i' - z' > 1.5$ or $i' > 27.53$ (27.84) ($2\sigma$),
(c) $B > 27.89$ (28.38), $V > 27.66$ (27.69), and $R > 27.03$ (27.76) ($3\sigma$),

where $\sigma$ indicates $1$-$\sigma$ uncertainty of photometry in each band and the values in parentheses for the SDF. These criteria are similar to those in Nagao et al. (2004) and Ota et al. (2005). We do not have near-infrared data and cannot adopt any rest-frame UV colour criteria as done by Bouwens et al. (2003) and Shimasaku et al. (2005). Thus, our sample of the $i'$-drop objects is contaminated by Galactic M/L/T dwarfs. However, the contamination is less than 10% for $z' > 25.5$ AB (Ota et al. 2003). The survey area in the SSA22 is the same as the LAE candidates.

The resultant numbers of the $i'$-drop galaxies are 25 in the SSA22 and 36 in the SDF. The surface densities are $0.047 \pm 0.009$ arcmin$^{-2}$ in the SSA22 and $0.036 \pm 0.006$ arcmin$^{-2}$ in the SDF both of which are consistent with that in the SXDS field by Ota et al. (2005). Therefore, the number density of $i'$-drop galaxies in the SSA22 is 'normal'. This may suggest that a large difference of the number densities of the LAE candidates in the two fields is not caused by different number densities of dark matter haloes. However, we should caution ourselves that the sampling redshift of the $i'$-drop selection is different from that of the LAE selection. On the other hand, the spatial distribution of the $i'$-drop galaxies in the SSA22 seems to be well correlated to that of the LAE candidates as shown in Figure 3. This may indicate a similar redshift range of the $i'$-drop galaxies to the LAE candidates, while we should wait for spectroscopic confirmations to reach the final conclusion.

4.3 Effect of smaller aperture size

Because of finer FWHMs in our final images, the aperture sizes in our photometry are smaller than those in the SDF. This difference may affect the estimation of Ly$\alpha$ luminosity and the resultant LF unless the Ly$\alpha$ emissions are point-like in our image. Indeed, some LAE candidates seem to be spatially extended as found in Figure 4. To examine this issue, we have performed the LAE selection again in the images convolved with a Gaussian kernel so that FWHMs of point-like sources become 1.0$''$. This was the same in the SDF images. The selection criteria are the same as §3, but the limiting magnitudes are $\sim 0.3$ mag shallower. The photometry was made within a diameter of twice of the FWHM (i.e., 2.0$''$). After removing objects affected by spiders of bright stars, we have found 6 objects with NB912 < 25.76 (5-$\sigma$) and 4 objects with $L_{Ly\alpha} > 5 \times 10^{42}$ erg s$^{-1}$. This number is consistent with 3 objects found in the finer FWHM images other than the objects SSA22-z6p5-13 and -14 whose photometry affected by a foreground object. Therefore, the smaller aperture sizes due to finer FWHMs do not affect our conclusion.

5 DISCUSSIONS

5.1 Cosmic variance

We have found a large difference in the number densities of $z \simeq 6.5$ LAE candidates in the SSA22 and in the SDF. Here we examine if this difference can be explained by variance of the number density of dark matter haloes, i.e., cosmic variance. For this aim, we assume the SDF LF to be representative.

First, we calculate the expected number of $z \simeq 6.5$ LAE candidates in the SSA22 from the observed number in the SDF. As shown in the third column of Table 5, the expected numbers, $N_{\text{exp}}$, are a factor of about 3 larger than the observed numbers, $N_{\text{obs}}$. Next, we estimate a fractional standard deviation by cosmic variance, $\sigma_{cv}$, according to Somerville et al. (2004). As summarised in the fourth column of Table 5, the $\sigma_{cv}$ values become smaller for less luminous LAE candidates because the bias parameters are smaller. The survey volume of our SSA22 survey is smaller than that of the SDF, and thus, the resultant $\sigma_{cv}$ values are
Table 5. Number of $z \simeq 6.5$ LAE candidates in the SSA22 survey expected from the SDF luminosity function and cosmic variance.

| $L_{\text{Ly}{\alpha}}$ (10^{42} \text{ erg s}^{-1}) | $N_{\text{obs}}$ | $N_{\text{exp}}$ | $\sigma_{\text{cv}}$ | $P(\leq N_{\text{obs}})$ |
|----------------|-------------|-------------|-------------|------------------|
| > 10           | 0           | 3.1         | 49          | 12               |
| > 7            | 2           | 6.8         | 46          | 14               |
| > 5            | 5           | 17.4        | 41          | 6.5              |
| > 3            | 14          | 34.7        | 36          | 6.6              |

a Observed number of the LAE candidates in the SSA22 survey.
b Number of the LAE candidates found in the SSA22 survey expected from the SDF result.
c Fractional standard deviation by cosmic variance estimated by the method in Somerville et al. (2004) based on the observed number density in the SDF and the SSA22 survey volume.
d Probability to have a number equal to or smaller than the observed number. This is estimated from the expected number by a Monte-Carlo simulation taking into account the Gaussian cosmic variance and Poisson error.

larger than those estimated in Kashikawa et al. (2006) for the SDF. Although we adopted the lines for $z = 6$ in figure 3 of Somerville et al. (2004) which are the closest to $z = 6.5$, the uncertainty caused by the redshift difference would be small.

In order to examine the statistical significance of the smallness of the observed numbers, we have performed a Monte-Carlo simulation as follows: Assuming the cosmic variance to be Gaussian, we first draw a random number from the Gaussian distribution with its mean of $N_{\text{exp}}$ and the standard deviation of $N_{\text{exp}} \sigma_{\text{cv}}$. Then, we draw another random number from the Poisson distribution with its parameter of the first random number and store the second random number as the “expected observed number”, $N'_{\text{obs}}$. We repeat this procedure 100,000 times for each Ly$\alpha$ luminosity bin. Finally, we count the realizations whose $N'_{\text{obs}}$ is equal to or smaller than the real observed number $N_{\text{obs}}$. The resultant probabilities are listed in the last column of Table 5. We find that the probability to have $N_{\text{obs}}$ of LAE candidates with $L_{\text{Ly}{\alpha}} > 5 - 3 \times 10^{42}$ erg s$^{-1}$ as small as in the SSA22 field is less than 7%, while the probability is higher for more luminous LAEs due to a larger Poisson error. From the Monte-Carlo simulation, we may conclude that the SSA22 field is a rare void at $z \simeq 6.5$.

However, we find no significant difference of the number density of i’-drop galaxies in the SSA22 and the SDF. Indeed, the number of i’-drop galaxies in the SSA22 expected from that in the SDF is consistent as summarised in Table 6. Note that the $\sigma_{\text{cv}}$ for this case is smaller than those in the LAE case because the survey volume is larger. On the other hand, the survey depth along the line of sight for i’-drop galaxies is about 6 times larger than that for LAEs. This point may explain the consistency of the number density of i’-drop galaxies even if there is a void at $z \simeq 6.5$ traced by LAEs.

Table 6. Same as Table 4 but for i’-drop galaxies.

| $z'$ | $N_{\text{obs}}$ | $N_{\text{exp}}$ | $\sigma_{\text{cv}}$ | $P(\geq N_{\text{obs}})$ |
|------|-------------|-------------|-------------|------------------|
| 1–0.6 | 25          | 19.5        | 27          | 23               |

5.2 Difference of neutral fraction and implications for reionization

As an alternative scenario, if neutral hydrogen remains more in the SSA22 than in the SDF at $z = 6.5$, Ly$\alpha$ emission is more heavily obscured in the SSA22, and thus, the number density of the observable LAEs decreases in the SSA22. As found in Figure 6, the cumulative LF in the SSA22 is almost reproduced if the Ly$\alpha$ luminosity in the SDF is reduced by a factor of 0.6. According to Santos (2004), the Ly$\alpha$ transmission through the IGM is roughly proportional to $1/x_{\text{HI}}$, where $x_{\text{HI}}$ is the hydrogen neutral fraction in the IGM. Therefore, the factor of 0.6 reduction of Ly$\alpha$ luminosity can be interpreted as a factor of about 2 larger $x_{\text{HI}}$ in the SSA22 than in the SDF.

Kashikawa et al. (2006) have already found a significant reduction of the Ly$\alpha$ luminosity at $z = 6.5$ relative to $z = 5.7$ in the SDF and argue that the IGM is more neutral at $z = 6.5$ than $z = 5.7$. Their estimation based on Santos (2004) model is $x_{\text{HI}} < 0.45$ at $z = 6.5$. In the SSA22, there may be a further factor of ~2 reduction of Ly$\alpha$ luminosity. This is translated into $x_{\text{HI}} < 0.9$ at $z = 6.5$ in the SSA22. Therefore, more than half hydrogen may be still neutral at $z = 6.5$ in the SSA22 field.

The furthest known LAE is IOK-1 at $z = 6.96$ found in the SDF by Iye et al. (2006), Ota et al. (2008) have constrained $x_{\text{HI}}$ at $z = 7$ in the SDF based on this one object: $x_{\text{HI}} = 0.1–0.6$. The Ly$\alpha$ luminosity of this object is $1.1 \times 10^{43}$ erg s$^{-1}$. On the other hand, we could not find any LAE candidates with $L_{\text{Ly}{\alpha}} > 1 \times 10^{43}$ erg s$^{-1}$ at $z = 6.5$ in the SSA22. The number density of $z = 7$ LAE in the SDF is $\sim 3 \times 10^{-6}$ Mpc$^{-3}$ for $L_{\text{Ly}{\alpha}} > 1 \times 10^{43}$ erg s$^{-1}$ which may match with an extrapolation of the SSA22 LF shown in Figure 6. This may imply that the SSA22 at $z = 6.5$ is as neutral as the SDF at $z = 7$.

If the $z = 6.5$ IGM in the SSA22 field is more neutral than that in the SDF and Ly$\alpha$ luminosity in the SSA22 field is reduced, an effect may appear in the Ly$\alpha$ EW distribution. Figure 7 shows the observed Ly$\alpha$ EW as a function of UV luminosity for $z = 6.5$ photometric LAE samples in the SSA22 field and in the SDF. Although we expect that the EWs of the SSA22 sample are systematically smaller than those of the SDF sample, we can not find such a trend. On the other hand, the UV luminosities in the SSA22 field may be systematically smaller than those in the SDF, which may indicate that the small number of the LAEs in the SSA22 field is due to a cosmic variance. However, in any case, we can not extract any conclusion due to the small statistics of the SSA22 sample. A future work with a much larger sample is required.

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3 Kashikawa et al. (2006) obtained an upper limit on $x_{\text{HI}}$. The Ly$\alpha$ luminosity reduction (or IGM transmission of Ly$\alpha$) could be accounted for by almost ionized IGM if there is no galactic wind (see Fig. 25 in Santos 2004).
reduction puts a constraint on the neutral fraction at $z$ by Taniguchi et al. (2005) and Kashikawa et al. (2006). On dates is a factor of 3 smaller than that in the SDF reported is only 14. The co-moving number density of the LAE candidates $\approx 530$ arcmin. Indeed, a factor of about 2 reduction in the SSA22 than in the SDF, a part of Ly$\alpha$ from the LAE candidates.

$\frac{1}{5}$ in the SSA22. This is similar to

$\frac{1}{5}$ LAEs among 5 fields-of-view of the S-Cam. Therefore, we need a much wider survey area than the surveys reported here and previously in order to obtain a robust mean LF of $z = 6.5$ LAEs and a robust mean neutral fraction in the IGM at the redshift.

6 CONCLUSIONS

This paper presents results of a deep survey of $z = 6.5$ LAE candidates in the SSA22 field based on the imaging data collected with Subaru/S-Cam. We have selected the LAE candidates by the standard technique based on a narrowband excess by an emission line and drop-outs at shorter wavelengths. The adopted narrowband is NB912 which can collect Ly$\alpha$ emission at $z = 6.46 - 6.57$. We have also selected $i'$-drop galaxies for a comparison. These galaxies exist at a similar high redshift to but more extended range than the LAE candidates.

A summary of the observational findings is as follows; The number of the LAE candidates with $L_{\text{Ly}\alpha} > 3 \times 10^{42}$ erg s$^{-1}$ in the observed area of $530$ arcmin$^2$ in the SSA22 field is only 14. The co-moving number density of the LAE candidates is a factor of 3 smaller than that in the SDF reported by [Taniguchi et al. (2005)] and [Kashikawa et al. (2006)]. On the other hand, the number densities of $i'$-drop galaxies in the two fields agree within the Poisson error.

We have considered two possibilities accounting for the small number density of the LAE candidates in the SSA22: (1) fluctuation due to the large-scale structure (i.e. so-called cosmic variance) and (2) fluctuation of the neutral fraction of hydrogen in the IGM. In the cosmic variance scenario, the probability to have the small number density as in the SSA22 field is 7% if we assume the SDF to be the cosmic average. Therefore, the SSA22 field at $z = 6.5$ may be a rare void. However, there is no evidence of such a void in the $i'$-drop galaxies although their redshift range is different from the LAE candidates.

If the neutral fraction in the IGM is higher in the SSA22 than in the SDF, a part of Ly$\alpha$ emission is more heavily obscured in the SSA22. Indeed, a factor of about 2 reduction of Ly$\alpha$ luminosity in the SDF provides a good fit of the SSA22 Ly$\alpha$ LF. This is interpreted as a factor of about 2 higher neutral fraction in the SSA22 field than in the SDF. Even in the SDF, $z = 6.5$ Ly$\alpha$ LF indicates a factor of 2 reduction of Ly$\alpha$ luminosity relative to $z = 5.7$. Therefore, we may obtain $x_{\text{HI}} < 0.45$ [Kashikawa et al. 2006]. Therefore, we may obtain $x_{\text{HI}} < 0.9$ at $z = 6.5$ in the SSA22 field.

In any case, the smallness of the number density of the $z = 6.5$ LAE candidates in the SSA22 clearly shows that there is a large fluctuation of the LAE number density at this high redshift as already suggested by [Hu et al. (2004), 2002; Hu & Cowie (2006); Hu et al. (2010)]. [Ouchi et al. (2008)] also reports a factor of 5 variation in the number densities of $z = 5.7$ LAEs among 5 fields-of-view of the S-Cam. Therefore, we need a much wider survey area than the surveys reported here and previously in order to obtain a robust mean LF of $z = 6.5$ LAEs and a robust mean neutral fraction in the IGM at the redshift.

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