Spatial inhomogeneity is one of the important features for understanding the reionization process; however, it has not yet been fully quantified. To map this inhomogeneous distribution, we simultaneously detect Ly$\alpha$ emitters (LAEs) and Lyman-break galaxies (LBGs) at $z \sim 6.6$ from the Subaru/Hyper Suprime-Cam large-area ($\sim 1.5$ deg$^2 = 34,000$ cMpc$^2$) deep survey. We estimate the neutral fraction, $x_{\text{HI}}$, from the observed number density ratio of LAEs to LBGs, $n(\text{LAE})/n(\text{LBG})$, using numerical radiative transfer simulations, in which model galaxies are selected to satisfy the observed selection function. While the average $x_{\text{HI}}$ within the field of view is found to be $x_{\text{HI}} < 0.4$, which is consistent with previous studies, the variation of $n(\text{LAE})/n(\text{LBG})$ within the field of view for every 140 pMpc$^2$ area is found to be as large as a factor of 3. This may suggest a spatially inhomogeneous topology of reionization, but it also leaves open the possibility that the variation is based on the inherent large-scale structure of the galaxy distribution. Based on the simulations, it may be difficult to distinguish between the two from the current survey. We also find that LAEs in the high-LAE-density region are more numerous at high EW$_{\alpha}$, supporting the fact that the observed $n(\text{LAE})/n(\text{LBG})$ is more or less driven by the neutral fraction, though the statistical significance is not high.

Unified Astronomy Thesaurus concepts: High-redshift galaxies (734); Reionization (1383); Early universe (435)

1. Introduction

The reionization process is the transition of the intergalactic medium (IGM) from a neutral to an ionized state. One of the important features of reionization is spatial inhomogeneity, the topology of which is closely related to the distributions of the ionizing sources, the escape fraction of ionizing photons, the clumpiness of the IGM, and the ionizing photon energy, and so on. Strong radiation from the first stars and galaxies ionized their surrounding neutral intergalactic medium, creating a sphere of ionized atomic hydrogen, a H II bubble (e.g., McQuinn 2016). The multiplication and progressively larger sizes of these H II bubbles resulted in the reionization of nearly all of the available neutral primordial gas, completing the process of cosmic reionization around $z \sim 6$. Therefore, we expect a spatially inhomogeneous distribution of neutral and ionized IGM, whose characteristic physical scales and topology depend on the histories of the clustering and luminosity of the reionizing sources. There is active debate over whether faint galaxies (e.g., Finkelstein et al. 2019) or bright (e.g., Naidu et al. 2020) galaxies should play a more significant role in the reionization photon budget, but the reionization topology will vary greatly depending on which one contributes more. Previous studies have reported some observational evidence of spatially inhomogeneous reionization, primarily from the observations of large scatter of the IGM transmission on the background quasars (e.g., Fan et al. 2006; Becker et al. 2015; Bosman et al. 2018; Yang et al. 2020). Recent observations continue to provide indirect evidence of large H II bubbles (e.g., Zheng et al. 2017; Castellano et al. 2018; Meyer et al. 2020; Tilvi et al. 2020; Hu et al. 2021).

The Ly$\alpha$ fraction $X_{\text{Ly} \alpha}$ is one of the most widely used methods for assessing the neutrality of the IGM at the epoch of cosmic reionization (e.g., Stark et al. 2010; Curtis-Lake et al. 2012; Ono et al. 2012; Schenker et al. 2014; Tilvi et al. 2014; Cassata et al. 2015; see also a review by Ouchi et al. 2020).
These studies derive $X_{\text{Ly}\alpha}$, the as fraction of Lyman-break galaxies (LBGs) that show Ly$\alpha$-emission lines at $4 < z < 9$, suggesting the trend that the Ly$\alpha$ fraction abruptly drops from $z = 6$ to $z = 7$ in contrast to its monotonic increase from $z = 4$ to $z = 6$. This can be caused by resonant scattering by intervening neutral hydrogen in IGM during the reionization epoch. In addition to the decrease in the Ly$\alpha$ fraction, the decline in the Ly$\alpha$ equivalent width (EW) at $z > 6$ has been observed in previous studies, suggesting the suppression of Ly$\alpha$ visibility (e.g., Treu et al. 2012, 2013; Hoag et al. 2019; Mason et al. 2019; Jung et al. 2020). However, identifying the Ly$\alpha$ emission lines generally requires spectroscopic observations of LBGs, which is too expensive to enlarge the sample size and survey area. Previous studies have limited the survey area to a maximum of about 0.1 deg$^2$ and the number of targets to about 70 (Stark et al. 2011; Schenker et al. 2014). Therefore, these studies are unable to depict the spatial variation of the neutral fraction $x_{\text{HI}}$ and only put constraints on the average value over the survey volume.

To overcome this difficulty, we use a data set of large-area (∼1.5 deg$^2$) images from Subaru/Hyper Suprime-Cam (HSC; Furusawa et al. 2018; Kawanomoto et al. 2018; Komiyama et al. 2018; Miyazaki et al. 2018). The large field of view (FoV) of HSC enables us to efficiently detect Ly$\alpha$ emitters (LAEs) and LBGs and to illustrate the spatial inhomogeneity of reionization. In contrast to the previous studies, we detect LAEs based only on the photometric observations and construct LBG and LAE samples separately. Though the limiting luminosity of the LAE and LBG samples is not necessarily the same, we use a ratio of the number density of LAEs to that of LBGs, $n(\text{LAE})/n(\text{LBG})$, as a proxy for the Ly$\alpha$ fraction. The same selection criteria as in the observation is applied to the model to consider the difference in limiting magnitude between the two populations when generating the model prediction of $x_{\text{HI}}$ from $n(\text{LAE})/n(\text{LBG})$.

One key importance here is that LBGs and LAEs must be simultaneously detected at almost the same redshift to measure $n(\text{LAE})/n(\text{LBG})$. For this purpose, we have installed a new intermediate-band filter, IB945, whose central wavelength is 9462 Å, with an FWHM of 330 Å. IB945 can detect LBGs at $z \sim 6.6$, whose redshift range ($\Delta z = 0.4$) is narrower than that of typical Lyman-break selection ($\Delta z = 1.0$). With the wide FoV and the new filter, HSC is the only instrument in the world capable of carrying out this study.

In this paper, we use the imaging data taken by the HSC Subaru Strategic Program (SSP; Aihara et al. 2018a) and the Cosmic Hydrogen Reionization Unveiled with Subaru (CHORUS) project (Inoue et al. 2020). This paper is constructed as follows. Section 2 describes the observational data we use. Sample selection is explained in Section 3. We show the distribution of the LAEs and LBGs and draw the $n(\text{LAE})/n(\text{LBG})$ map in Section 4. Section 5 describes the reionization simulation and discusses the neutral fraction and its spatial variation. We summarize this paper in Section 6.

Throughout this paper, we use the AB magnitude system (Oke & Gunn 1983). We adopt a ΛCDM cosmology with $h = 0.7$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$, which is consistent with recent Planck observations (Planck Collaboration et al. 2020).

### 2. Observational Data

We use the HSC-SSP S18A UltraDeep internal data release product of $g$, $r$, $i$, $z$, and $Y$ broadband (BB) and NB921 images taken from 2014 to 2018. The details of the SSP observations are described in Aihara et al. (2018a). We refer to Aihara et al. (2018b, 2019) for the data analysis and the catalog construction. NB921 (Ouchi et al. 2018) has a central wavelength of 9215 Å and an FWHM of 135 Å. Figure 1 shows the transmission curves of the filters.

The IB945 images are taken from the CHORUS project (Inoue et al. 2020). We have carried out deep imaging observation with IB945 in the COSMOS field, which is one of the UltraDeep layers of the HSC-SSP. The HSC data are reduced with HSC pipeline version 6.7 (Bosch et al. 2018), which is based on the Large Synoptic Survey Telescope (LSST) pipeline (Jurić et al. 2017; Bosch et al. 2019; Ivezic et al. 2019). The astrometry and photometric calibration are performed based on the data from Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1; Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013; Chambers et al. 2016). The final seeing size is $0^\prime.66$. The survey area is divided into tracts, and each tract is divided into $9 \times 9$ patches (Aihara et al. 2018a). Table 1 summarizes the details of the imaging data.

In our analysis, we use forced catalogs, in which photometry is measured at a fixed position in all band images. We use convolved flux to measure the magnitude after smoothing as a source has the same PSF sizes in all the filters.

![Figure 1](https://hsc.mtk.nao.ac.jp/ssp/)

**Figure 1.** Filter transmission curves of the BB, NB, and IB filters. The blue and red lines show the NB921 and IB945 filters, respectively. The black solid lines represent the $g$, $r$, $i$, $z$, and $\text{y}$-band filters from left to right.

| Filter | 5σ Limiting Magnitude$^a$ | PSF ($^b$) |
|--------|--------------------------|------------|
| $g$    | 27.9                     | 0.84       |
| $r$    | 27.6                     | 0.74       |
| $i$    | 27.5                     | 0.70       |
| $z$    | 27.0                     | 0.65       |
| $Y$    | 26.9                     | 0.77       |
| NB921  | 26.3                     | 0.68       |
| IB945  | 25.0                     | 0.66       |

**Notes.**

$^a$ The 5σ limiting magnitude with a $1''5$ aperture in the patch (4, 4).

$^b$ PSF size averaged over the entire FoV.

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16 https://hsc.mtk.nao.ac.jp/ssp/
The aperture diameter and the PSF size are 1.5 and 0.84, respectively.

We use hscPipe parameters and flags to exclude objects affected by saturated or bad pixels and by nearby bright stars. To ensure the images are sufficiently deep, we limit the survey field by using the countinput parameter. The bright-object mask is automatically generated in the pipeline (Coupon et al. 2018). Because the brightobject mask is not enough around the brightest stars, we visually check the images and add mask regions where the image is affected by the bright objects. The effective survey area of the IB945 image is 1.46 deg² as shown in Figure 2. Table 2 indicates the detail of the flags and parameters.

The limiting magnitude in each patch is calculated in the same way as in Inoue et al. (2020). We distribute ~5000 apertures with a 1.5 diameter per patch, avoiding the masked regions and detected sources, and derive the limiting magnitude by fitting the flux distribution with a Gaussian function. Sky subtraction is performed using the median in an annulus of 1.5 width and 2.5 inner diameter around the aperture. The spatial variations in the 1.5 aperture limiting magnitudes are shown in Figure 3.

3. Selection

3.1. LAE Selection

We construct a z ∼ 6.6 LAE catalog using the HSC data. The selection of LAEs is based on flux excess in NB compared to adjacent BB filters. We apply the color selection criteria similar to those in Shibuya et al. (2018a):

\[
\begin{align*}
&\text{NB921 < NB921}_{1.5} \\
&\text{& } z - \text{NB921} > 1.8 \\
&\text{& } g > g_{s} \\
&\text{& } r > r_{s} \\
&\text{& } (z < z_{3} \text{ & } i - z > 1.3) \\
&\text{or } z > z_{3} \\
\end{align*}
\]  

where \(NB921_{1.5}\), \(g_{s}\), \(r_{s}\), and \(z_{3}\) represent the 5σ or 3σ limiting magnitude in each filter. To remove low-z contaminants, we impose nondetection in a shorter wavelength than the Lyman limit and the existence of the Lyman break between the \(i\) and \(z\) bands for sources detected in the \(z\) band above the 3σ level. The criteria for nondetection in the \(g\) and \(r\) bands are relaxed to 5σ from 2σ cut of Shibuya et al. (2018a) because the 2σ cut significantly removes plausible LAE candidates. Because the \(g\)- or \(r\)-band image is very deep, if a very small 2σ level is used as the detection criterion, there are many cases where a small amount of noise is enough to cause the object to be judged as detected. In our dropout sample, the detection of the Lyman break is guaranteed by relaxing the criterion for nondetection. Relaxing the criteria may increase the low-z contaminants, but spectroscopic follow-up observations are necessary to quantitatively evaluate the contamination. The \(z - NB\) color threshold corresponds to the rest-frame Lyα \(EW_{0}\) of 14 Å. The limiting magnitude in NB921 corresponds to the Lyα luminosity of \(2 \times 10^{42} \text{ergs}^{-1}\). We also consider the 3σ error of the \(z - NB921\) color as a function of the NB921 flux \(f_{NB}:\)

\[
z - \text{NB921} > -2.5 \log \left(1 + 3 \frac{f_{z,1.5}^2 + f_{NB,1.5}^2}{f_{NB}}\right),
\]

where \(f_{z,1.5}\) and \(f_{NB,1.5}\) are the 1σ flux error in the \(z\) band and NB921, respectively. The 1114 objects are selected by color–magnitude selection.

We visually inspect the images of LAE candidates to remove cosmic rays, false detections in NB, and sources that are apparently detected at shorter wavelengths but are considered as nondetection. In total, the number of LAE candidates is 189. Though the survey area is an order of magnitude larger than in previous studies (e.g., Stark et al. 2011; Schenker et al. 2014), the number of objects does not increase much as the survey depth is shallower by about one magnitude. Figure 4 shows the color–magnitude diagram of the LAE candidates.

The LAE candidates can be contaminated by low-z line emitters with a faint continuum, e.g., H\(\alpha\), [O\(\text{II}\)], and [O\(\text{III}\)] emitters. NB-detected H\(\alpha\) emitters, which are not detected at short wavelengths, must have rest-frame \(EW_{0} > 160\) Å, which is exceptionally large (Fumagalli et al. 2012). To meet the color selection of \(z - \text{NB} > 1.8\), the \(EW_{0}\) of the [O\(\text{I}\)] and [O\(\text{III}\)] emitters must be greater than 150Å and 270Å, respectively, but this EW is also extremely large (Khostovan et al. 2016; Reddy et al. 2018). Therefore, we can expect that the contamination of such low-z line emitters is negligible. Shibuya et al. (2018b) estimate contamination rates in the HSC LAE candidates from spectroscopic confirmations. The contamination rates are \(\simeq 33\%\) and \(\simeq 44\%\) for bright (NB < 24 mag) and all LAE candidates, respectively. Given that we are using the same \(z - \text{NB921}\) color cut as theirs, we expect the contamination rates in our sample are similar, though different criteria for non-detection of \(g\) and \(r\) bands may increase the contamination rate. Ono et al. (2021) construct an LAE sample from the same data set. They use the \(z - \text{NB921} > 1.0\) color cut. They select LAE candidates with machine-learning techniques instead of via visual inspection. Our LAE catalog includes some fainter objects than theirs due to the difference in the measurement of the limiting magnitude. The number of our LAE candidates that
meet their limiting magnitude is 60, and 31 out of the 60 LAE candidates are also included in their LAE catalog. Most of the LAE candidates that do not appear in their catalog are fainter objects.

3.2. LBG Selection

We construct a z ~ 6.6 LBG catalog based on the Lyman-break color selection technique, which is efficient for selecting sources with a sharp Lyman break and a blue UV continuum. Selection criteria are as follows:

\[
\begin{align*}
Y &< Y_{5\sigma} \quad (7) \\
& g > g_{5\sigma} \quad (8) \\
& r > r_{5\sigma} \quad (9) \\
& z - Y > 1.2 \quad (10) \\
& IB945 - Y < 1.0 \quad (11) \\
& z - IB945 > 1.0. \quad (12)
\end{align*}
\]

To derive these criteria, we use the spectral energy distribution (SED) models from CIGALE (Boquien et al. 2019). In this modeling, we use the Bruzual & Charlot (2003) single stellar population model and the Salpeter initial mass function (Salpeter 1955). Model parameters are a constant star formation history with ages of 50, 100, 200, and 400 Myr; metallicity of Z/Z_\odot = 0.2; the Calzetti extinction law with E(B-V) = 0.0–0.4 (Calzetti et al. 2000); and the IGM absorption of Meiksin (2006), which is the default IGM model of CIGALE. Figure 5 shows the evolutionary track of the model SED on the IB945 − Y versus z − Y plane. The limiting magnitude of the Y-band almost corresponds to the rest-frame UV absolute magnitude (M_{UV}) of M_{UV} < −20.5 when assuming a flat continuum slope. By using IB945, the redshift distribution of LBGs can be made narrower than the typical z-dropout selection (see Figure 9). We further explore the redshift distribution of our samples in Section 3.3.

The 589 objects are selected from the color selection. We carry out visual inspections to exclude false detection in the Y band and sources that are apparently detected at shorter wavelengths but are considered as nondetection. Finally, the number of LBG candidates is 179. Unlike LAEs, cosmic rays are rarely contaminated, as it requires that they be detected in at least two Y and IB945 bands. The color–color diagram of the LBG candidates is shown in Figure 5. Seven LBG candidates are also included in the LAE catalog, which demonstrates that we detect LBGs at a similar redshift to the LAEs. The reason for the small number of sources selected for both LAEs and LBGs is that the limiting magnitudes of both samples are not the same. When calculating the neutral fraction from the sample, we take this difference into account and apply these selection criteria to the simulation model.

Because the z − Y color of low-z galaxies is small, as shown in Figure 5, the contamination rate is expected to be low. However, as in the case of LAE selection, the 5σ limiting magnitude is used as a criterion for nondetection in the g and r bands, which may lead to increased contamination. The quantitative evaluation of the contamination rate is difficult unless we conduct systematic spectroscopic follow-up observations of the IB945-selected galaxies. Harikane et al. (2021) detect 27 z ~ 7 LBGs in the same field using a z − Y color criterion. Eighteen of their samples are also included in our LBG sample. Our LBG catalog contains more LBGs than their sample because of the differences in the color selection criteria and the measurement of the limiting magnitude.

3.3. Completeness

We estimate the detection and selection completeness of our samples by the following Monte Carlo simulation. Here, the detection completeness is defined as the fraction of mock galaxies that are detected in the detection band, while the selection completeness is defined as the fraction of mock galaxies that satisfy the color selection criteria, which also take detection completeness into account. To generate a mock-LBG catalog, we use the same SED model as described in Section 3.2. In contrast to the mock-LBG catalog, we generate the SED model of LAEs with a simple assumption of a δ-function-shaped Lyα emission line, a flat (f_α = const.) UV continuum, and the IGM attenuation of Madau (1995). The mock LAEs have EWs of 10 < EW_{Lyα} < 200 following the EW distribution obtained from Shibuya et al. (2018a). The redshift of the mock LAEs ranges from 6.50 to 6.66 with an interval of Δz = 0.02.

We randomly distribute the mock galaxies on the g, r, i, z, and Y-band, NB921, and IB945 images using BALROG (Suchyta et al. 2016). We consider the total magnitude of the mock galaxies in the range of 23 ≤ m ≤ 27 with a 0.5 magnitude step in the Y-band and NB921 for LBGs and LAEs, respectively. We assume a Sérsic profile with an index of 1.5 and a half-light radius of 0.4 pkpc, which are consistent with
Figure 3. The 5σ limiting magnitudes in the 15" aperture and their spatial variation. The patches are overlapping due to the definition of the tracts and patches around DEC = 1.5°. The four red squares show the patches (4, 4), (5, 3), (6, 6), and (7, 7) from left to right.
Figure 4. The color–magnitude diagram of the LAE candidates. The blue points represent the LAE candidates. The horizontal blue line indicates the color criterion, $z - \text{NB921} = 1.8$. The vertical blue line shows the limiting magnitude in the patch (4, 4). The black solid curve shows the 3σ error of the $z - \text{NB921}$ color given by Equation (6). The gray dots represent all objects detected in NB921.

Figure 5. The color–color diagram of the LBG candidates. The red points represent the LBG candidates that pass the visual inspection. For sources fainter than the 1σ level in the $z$ band, $z$-band magnitudes are replaced with the 1σ limiting magnitude. The red solid line shows the LBG selection criteria. The black solid, dashed, and dotted lines show the track of LBG model SED constructed by CIGALE with $E(B-V) = 0.0$, 0.2, and 0.4, respectively. The black circles indicate their redshift from $z = 5.5$ to $z = 7.0$ with a $\Delta z = 0.1$ step. The green points indicate dwarf stars taken from Knapp et al. (2004), and the blue pluses show stars from Gunn & Stryker (1983). The dashed gray line shows the typical track of elliptical, Sbc, Scd, and irregular galaxies (Coleman et al. 1980) from $z = 0$ to 2.

Shibuya et al. (2015, 2019) at $z \sim 6.6$. BALROG makes use of GALSIM (Rowe et al. 2015) to simulate the profile of the objects and convolve it with the PSF size. The PSF model is constructed with PSFX (Bertin 2011) from cutout images at each detection processed with SExtractor (Bertin & Arnouts 1996). We detect and measure the mock galaxies using hscPipe version 6.7 in the same way as described in Section 2.

The detection completeness is defined as the number fraction of the mock galaxies that are successfully detected in the detection band images ($Y$ and NB921 for LBGs and LAEs, respectively). We regard sources that are detected within 6σ from the positions of the mock galaxies and with a difference of 0.5 mag or less from the input magnitude as successfully detected objects (Inoue et al. 2020). We apply the same selection to the mock galaxies as described in Sections 3.1 and 3.2 and calculate the selection completeness of our LAE and LBG samples. The selection completeness is defined as the number ratio of the mock galaxies satisfying the selection criteria to all mock galaxies. The LAE selection function considers the $z - \text{NB}$ color. Because the wavelength ranges of the filter transmission of the $z$ band and NB921 overlap, emission lines detected in NB do not necessarily satisfy the $z - \text{NB}$ color selection. It is important to consider the selection completeness for LAEs. The uncertainty of the completeness takes into account the Poisson errors of the numbers of the embedded and recovered mock galaxies.

As shown in Figure 3, the spatial variation of the limiting magnitude in the survey area is approximately circularly symmetric, and the limiting magnitude becomes gradually shallow toward the edge of the FoV. We divide the survey area into four regions with respect to the distance from the center and assume that the completeness is constant in each region. We use the patches (4, 4), (5, 3), (6, 6), and (7, 7), which are 0′, 16′, 32′, and 48′ away from the center of the FoV (Figure 3). We carry out this simulation in the four patches to estimate the spatial variation of completeness in the FoV. Figure 6 shows the detection completeness for LBGs and LAEs. This figure shows slightly lower completeness at the edge of the FoV. The detection completeness is less than unity even on the bright end. This is because the embedded mock galaxies overlap with the bright objects in the image. Figure 7 shows the selection completeness as a function of magnitude and redshift for LBGs and LAEs in the patch (4, 4).

In Section 5.1.2, we sample model galaxies in the same redshift range as the observation to make comparisons. For this purpose, we derive the redshift distribution without taking detection incompleteness into account, which we call the selection function. We define the selection function as the selection completeness divided by the detection completeness. In each patch, we derive the selection function for each magnitude. The amplitude of the selection function of LAE strongly depends on the NB magnitude because the fainter objects have a larger uncertainty in the observed color, while the selection function of LBGs has almost no changes in terms of the magnitude. We average the selection functions over the magnitude weighted with the observed number count. The error of the selection function is calculated from the uncertainty of the detection and selection completeness. Figure 8 shows the selection function of LAEs and LBGs. We do not find any systematic variations of the selection function in the four patches. The selection function should be less than or equal
to unity, but there is one point that is greater than unity in the LBG selection function, which is just caused by the calculation. The selection completeness is calculated in each magnitude and redshift, while the detection completeness is averaged over redshift. Thus, the selection completeness is not necessarily smaller than the detection completeness. We also show in Figure 8 the redshift distribution of model galaxies (Section 5.1.1) selected with the same color selection criteria. The redshift ranges are similar to the selection functions while the peaks of the distribution are shifted to lower redshift. This is because higher-redshift galaxies are more difficult to detect due to their fainter magnitude. In Figure 9, we compare the selection function of the samples. While the width of the LBG selection function is broader than that of LAEs, it is narrower than that of the typical z-dropout selection. This confirms that IB945 allows us to detect LBGs at a similar redshift to LAEs. The remaining difference in the selection function between LBGs and LAEs is taken into account in the model galaxies to be compared, along with the difference in the limiting magnitude, so as to have exactly the same selection function as the observation (Section 5.1.2).

4. Results

4.1. Surface Density

Applying the selection criteria described in Section 3, we obtained 179 LBGs and 189 LAEs at \( z \sim 6.6 \). Figures 10 and 11 show the surface densities of LBGs and LAEs as a function of magnitude, respectively. Because the redshift range (\( \Delta z \)) of our LBG selection is different from that of Bouwens et al. (2015), we correct it by the width of the selection function estimated in Section 3.3. The surface densities of LBGs and LAEs corrected by the detection completeness are found to be consistent with those of previous studies. The surface density of LAEs is lower than that of Ouchi et al. (2010), though this is because the MAG_AUTO of SEXTRACTOR, which they use as the total magnitude, is biased toward brighter magnitudes. By integrating the surface density corrected by the detection completeness down to the limiting magnitudes, we obtain \( n(\text{LAE})/n(\text{LBG}) = 0.76 \pm 0.10 \) as an average of the entire FoV. In this calculation, we only consider the Poisson error and the error of the completeness as the uncertainty of \( n(\text{LAE})/n(\text{LBG}) \).

To evaluate the scatter of \( n(\text{LAE})/n(\text{LBG}) \), we distribute \( \sim 5000 \) apertures of 10’–30’ radii on the survey area and count the number of LAEs and LBGs within them. We exclude apertures where the masked regions cover more than 20% of the apertures. Figure 12 shows the median and scatter of \( n(\text{LAE})/n(\text{LBG}) \) as a function of aperture radii. There is deviation from the value calculated for the entire FoV (\( n(\text{LAE})/n(\text{LBG}) = 0.76 \pm 0.10 \)) even with 30’ apertures. This is because the number ratio in the entire FoV is derived by integrating the number density down to the limiting magnitude, which is a little different from counting the numbers in the apertures. Both approaches would give consistent results, but the difference in procedure for counting and completeness correction may cause slightly different results.

To see the spatial variation of \( n(\text{LAE})/n(\text{LBG}) \) over the field, we use a 20’ (\( \sim 50 \) cMpc) radius aperture in the following analysis. In general, using a small aperture (\( r_{\alpha} < 15’ \)) will result in a larger variation of \( n(\text{LAE})/n(\text{LBG}) \), as expected, because fewer objects are contained in the aperture. On the other hand, an aperture of \( > 25’ \) radius, which is too large compared to the FoV of HSC, is not appropriate for the study of spatial inhomogeneity. With the 20’ radius, the field-averaged \( n(\text{LAE})/n(\text{LBG}) \) is \( 0.84^{+0.23}_{-0.27} \). Because this calculation takes the spatial variation of \( n(\text{LAE})/n(\text{LBG}) \) between the apertures into account, the uncertainty is larger than that described above. The difference between the maximum and minimum values is as large as a factor of 3. In the following, we use this value as our result for \( n(\text{LAE})/n(\text{LBG}) \).

4.2. Spatial Distribution

We calculate the density distribution using the Gaussian kernel density estimation. The surface density at a coordinate

---

\( r_{\alpha} < 15’ \)
where the integration is calculated over the effective area of the 

\[ K(X, X_i) = \frac{1}{2\pi \lambda^2} \exp \left( -\frac{r_i^2}{2\lambda^2} \right). \]

where \( r_i \) is the projected separation between \( X \) and \( X_i \), and \( \lambda \) is the bandwidth parameter. The optimal bandwidth is calculated by maximizing the likelihood cross-validation (LCV; Hall 1982) in the same way as Chartab et al. (2020). The LCV is defined as

\[ LCV(\lambda) = \frac{1}{N} \sum_{k=1}^{N} \log \sigma_{\text{LAE}}(X_k), \]

where \( N \) is the total number of objects and \( \sigma_{\text{LAE}}(X_k) \) is the surface density at the position \( X_k \) calculated excluding the 4th object. The optimized values are 3.63 and 3.75 for LBGs and LAEs, respectively. We adopt 4.00 as the common bandwidth for LBGs and LAEs to compare them under the same condition. The spatial inhomogeneity of the depth is corrected by the detection completeness by assuming the circularly symmetric variation as described in Section 3.3.

Because the survey area is limited and has masked regions, correcting the boundary effect is necessary. The true density distribution is estimated as (see Chartab et al. 2020; Jones 1993)

\[ \sigma_{\text{true}}(X) = \frac{\sigma(X)}{\int_{\mathcal{S}} K(X, X_i) dS}, \]

where the integration is calculated over the effective area of the survey field (\( \mathcal{S} \)).

We define the overdensity \( \delta \) as

\[ \delta = \frac{\sigma - \bar{\sigma}}{\bar{\sigma}}, \]

where \( \bar{\sigma} \) is the mean density averaged over the entire effective survey area after the completeness correction and the boundary correction. Figures 13 shows the density distribution of LBGs and LAEs, respectively. The LAE overdensity regions located slightly south of the center of the FoV are consistent with the results reported in Higuchi et al. (2019) and Zhang et al. (2020).

Using the whole sample of LBGs and LAEs, we draw the map of \( n(\text{LAE})/n(\text{LBG}) \). From Figure 14, we interpret that the reionization is proceeding in the high-LAE-density region, while it is delayed in the low-LAE-density region, though the intrinsic distribution of these galaxy populations must also be taken into account, which is discussed in Section 5.1.5.

5. Discussion

5.1. Neutral Fraction

5.1.1. Reionization Simulation

We carry out a reionization simulation to predict the neutral fraction \( x_{\text{HI}} \) from \( n(\text{LAE})/n(\text{LBG}) \) based on Inoue et al. (2018). Simulating star formation and ionizing photon escape requires high-resolution radiative hydrodynamical (RHD) simulations. However, an RHD simulation in a large-scale (>100 cMpc) box is not feasible because of the huge numerical costs. Therefore, we divide the simulation into the following two steps. First, we conduct a high-resolution RHD simulation to model galaxies and the IGM in a 20 cMpc box. The RHD simulation takes into account radiative feedback, which regulates star formation. Then, the recipe constructed in the first step is used for solving the radiative transfer of ionizing photons in a large-scale \( N \)-body simulation in a box of (162 cMpc). Inoue et al. (2018) present several models in terms of the production rate and the escape fraction of Ly\( \alpha \) photons to simulate the LAE SED. They find that Model G reproduces the observed luminosity function, autocorrelation function, and LAE fraction; therefore, we adopt Model G. In Model G, the Ly\( \alpha \) photon production rate is determined as a function of halo mass without any fluctuations. The Ly\( \alpha \) escape fraction in Model G depends on halo mass with a fluctuation to model the stochasticity in the transfer of Ly\( \alpha \) photons. The reionization simulation assumes two models, the Late and Mid reionization models. The mean neutral fractions of the Late and Mid reionization models at \( z \sim 6.6 \) are 0.4 and 0.0, respectively. The details of this simulation are described in Inoue et al. (2018). We generate 20 (10 for the Late reionization and the other 10 for Mid reionization) light-cone outputs from


\[ z = 5.5 \text{ to } z = 9 \text{ by randomly shifting and rotating the snapshots of the simulation box. Each light-cone output has a } \sim 1 \text{ deg}^2 \text{ FoV.} \]

\[ x_{\text{HI}} = 0.4 \text{ and } x_{\text{HI}} = 0.0 \text{ at } z = 6.6. \text{ To obtain the continuous relation over a wide range of } x_{\text{HI}}, \text{ we shift the selection function along the redshift axis with } \Delta z = 0.1 \text{ steps in a range of } 6 < z < 8 \text{ without changing the shape, and we sample the model LAEs and LBGs at each redshift. We assume little evolution of both galaxy populations over } 6 < z < 8. \text{ We show in Figure 15 the relation between } n(\text{LAE})/n(\text{LBG}) \text{ and } x_{\text{HI}}. \text{ Though the relation flattens out in the range of } x_{\text{HI}} < 0.25 \]

\[ \text{Figure 8. The selection function of the LAEs (left) and the LBGs (right). Colors indicate the patches, the same as in Figure 6. Gray histograms show the redshift distribution of the model LAEs and LBGs selected from the simulation box (Section 5.1.1). The amplitudes of the histograms are scaled for clarity.} \]

\[ \text{Figure 9. Normalized selection functions of the samples. The blue solid and the orange dashed line represent the LAEs and LBGs, respectively. We also show the selection function of } z \text{-dropout galaxies from Ono et al. (2018) with the green dotted line for comparison.} \]

\[ \text{Figure 10. Surface number density of LBGs at } z \sim 6.6 \text{ as a function of } Y \text{-band magnitude. Filled and open circles represent the raw and the detection-completeness-corrected surface densities of our } z \sim 6.6 \text{ LBGs (} \Delta z = 0.4\text{), respectively. Black crosses and green pluses indicate the surface densities of } z \sim 6 \text{ (} \Delta z = 0.8\text{) and } 7 \text{ (} \Delta z = 1.0\text{) galaxies of Bouwens et al. (2015), respectively.} \]
Figure 11. Surface density of LAEs at \( z = 6.6 \) as a function of NB921 magnitude. Filled and open circles represent the raw and the detection-completeness-corrected surface densities of our \( z \sim 6.6 \) LAEs, respectively. For comparison, we also plot results of Shibuya et al. (2018a) and Ouchi et al. (2010). The points are slightly shifted horizontally for clarity.

Figure 12. The median and 68th percentile range of \( n(\text{LAE})/n(\text{LBG}) \) in the FoV as a function of aperture size.

because most LAEs reside in ionized bubbles, and their \( \text{Ly} \alpha \) lines are less sensitive to the neutral gas in the highly ionized universe.

5.1.3. Field-averaged Neutral Fraction and Comparisons with Previous Studies

In Section 4.1, we obtain \( n(\text{LAE})/n(\text{LBG}) = 0.84^{+0.23}_{-0.17} \) as the average of the entire FoV. Using the relation shown in Figure 15, we estimate the neutral fraction averaged over the survey field to be \( x_{\text{HI}} \leq 0.4 \) in the \( 1 \sigma \) range of \( n(\text{LAE})/n(\text{LBG}) \). In addition to the large scatter in \( n(\text{LAE})/n(\text{LBG}) \) in the simulation data, the observed scatter in \( n(\text{LAE})/n(\text{LBG}) \) is large, due to the shallow depth of the observation. The constraint for \( x_{\text{HI}} \) is only given as an upper limit. Deeper observations are required to more strictly constrain \( x_{\text{HI}} \).

Because the faintest objects, the completeness of which is low (~0.5), have a dominant contribution to the total number of objects, this could be prone to uncertainty. To address this problem, we use the objects that are 0.5 mag brighter than the limiting magnitude and derive \( x_{\text{HI}} \) in the same way as described above. When calculating the \( n(\text{LAE})/n(\text{LBG}) \) relation from the simulation model, we also use a 0.5 mag brighter selection criterion for the model LBGs. We raise the lower limit of the \( \text{Ly} \alpha \) luminosity of the model LAE selection by 1.6 (corresponding to 0.5 mag brighter) because, in the model, LAE selection is not based on photometric magnitude. The numbers of the model LBGs and LAEs decrease by factors of 0.3 and 0.4 with the 0.5 mag brighter selection criterion, respectively. This is consistent with the surface density of the observed LBGs and LAEs (Figures 10 and 11). The same result is obtained in this analysis; therefore, the \( x_{\text{HI}} \) estimate is found to be robust. In the Appendix, we describe the other selection procedures to further explore the robustness of our results.

In the previous studies, the \( \text{Ly} \alpha \) fraction \( X_{\alpha, \text{obs}} \) is defined as the fraction of LBGs that show a \( \text{Ly} \alpha \) emission line. These studies spectroscopically confirm the \( \text{Ly} \alpha \) emission lines among their photometric LBG sample. On the other hand, the redshift range and the limiting magnitude of our LAEs and LBGs are not exactly the same because we detect them separately. To compare our result with the \( \text{Ly} \alpha \) fraction estimates of previous studies, \( X_{\alpha, \text{est}}^{25} \), we additionally constrain the LAE to be detected in the \( Y \) band with a 5\( \sigma \) significance \((Y < Y_{S\alpha})\). The \( Y \)-band magnitude is a proxy for the rest-frame UV continuum flux, and \( Y_{S\alpha} \) corresponds to \( M_{\text{UV}} < -20.3 \), which is similar to the depth of the LBG sample. We also limit LAEs with \( \text{EW}_0 > 25 \, \text{A} \). The \( \text{EW}_0 \) is calculated from the photometry in NB921 and the \( Y \) band. The number of LAEs that satisfy \( Y < Y_{S\alpha} \) and \( \text{EW}_0 > 25 \, \text{A} \) is 15. Because the redshift range is different between LBGs and LAEs, we correct the difference by multiplying the ratio of the widths of the selection functions described in Section 3.3. Figure 16 shows the comparison of \( X_{\alpha, \text{est}}^{25} \) with those in previous studies. Overall, our measurement of the field-averaged \( n(\text{LAE})/n(\text{LBG}) \) is consistent with the \( X_{\alpha, \text{est}}^{25} \) estimates of the previous studies within the error.

5.1.4. Spatial Inhomogeneity of the Neutral Fraction in the Simulation Box

As shown in Figure 14, we find the spatial variation of \( n(\text{LAE})/n(\text{LBG}) \). The \( n(\text{LAE})/n(\text{LBG}) \) map could be converted to the \( x_{\text{HI}} \) map using Figure 15 to see the possible spatial inhomogeneity in the reionization process. However, because the two are almost uncorrelated for \( x_{\text{HI}} < 0.25 \) and the relation has a large scatter, it may be difficult to draw the \( x_{\text{HI}} \) map from the observed data. Thus, we will use only the simulated data to see the spatial correlation between \( n(\text{LAE})/n(\text{LBG}) \) and \( x_{\text{HI}} \).

We average \( x_{\text{HI}} \) over a redshift slice of 6.54 < \( z < 6.63 \). The \( X_{\alpha, \text{est}}^{25} \) and \( x_{\text{HI}} \) maps in the same way as described in Section 4.2. Figure 17 shows the \( x_{\text{HI}} \) and \( n(\text{LAE})/n(\text{LBG}) \) map at \( z = 6.6 \) in one of the light-cone models. We find a moderate correlation (correlation coefficient \( r = -0.25 \) and the \( p \)-value \( p < 0.001 \)) between \( x_{\text{HI}} \) and \( n(\text{LAE})/n(\text{LBG}) \) when we divide the map into a grid with a side of 1' (2.5 cMpc) as shown in Figure 18. The apertures near the edge of the simulation box have less effective area overlapping with the simulation box, increasing the uncertainty of the relation. When we limit to the central region with a square of 80 cMpc per side, where the
boundary effect is small, the correlation becomes strong ($r = -0.47$ and $p < 0.001$). The result, at least in the simulation, demonstrates that the spatial variation of $n({\text{LAE}})/n({\text{LBG}})$ seen in Figure 14 implies a patchy reionization topology, i.e., reionization is proceeding in the high-LAE-density region, while it is delayed in the low-LAE-density region. The high-LAE-density regions could correspond to H II bubbles at $z \sim 6.6$.

### 5.1.5. Is the Observed Inhomogeneity Caused by Patchy Reionization or Intrinsic LSS?

In the previous section, we discuss a possible reionization topology from the spatial variation of $n({\text{LAE}})/n({\text{LBG}})$ we observed, although the number ratio of LAEs and LBGs, $n({\text{LAE}})/n({\text{LBG}})$, could also depend on their intrinsic distribution, the large-scale structure (LSS). To distinguish the reionization topology from the LSS, we estimate the intrinsic scatter of $n({\text{LAE}})/n({\text{LBG}})$ without IGM attenuation from the simulation data. The simulation calculates three kinds of Ly$\alpha$ luminosities: intrinsic, escaped from a halo, and transmitted through the IGM. The third one is the Ly$\alpha$ luminosity with IGM absorption and the second one is that without IGM absorption ($x_{HI} = 0$). We compare the scatter of $n({\text{LAE}})/n({\text{LBG}})$ using the two Ly$\alpha$ luminosities in selecting LAEs. The reionization inhomogeneity further increases the scatter of $n({\text{LAE}})/n({\text{LBG}})$ in addition to the intrinsic scatter due to the LSS. Therefore, if we can confirm that the scatter with IGM is larger than that without IGM, we can conclusively distinguish between the two. Because in the Mid reionization model ($x_{HI} = 0.0$ at $z = 6.6$) the difference between the two Ly$\alpha$ luminosities is negligible, we use the Late reionization model ($x_{HI} = 0.4$ at $z = 6.6$) in this analysis.
We select LAEs and LBGs in the same way as Section 5.1.2, but we adopt the top-hat redshift distribution of $\Delta z = 0.1$ for LAEs and LBGs at $z = 6.6$ (see the Appendix). The number of LBGs does not change with or without IGM absorption, while the number of LAEs with IGM absorption is smaller by a factor of 0.6 than that without IGM absorption. In this comparison, the number of objects in both cases with and without IGM absorption should be comparable because we need to compare the scatter of both cases, as distinct from the difference in Poisson errors. Therefore, we randomly choose LAEs with a probability of 0.6 in the case of no IGM attenuation. In the case of IGM absorption, the Ly$\alpha$ attenuation depends on the neutral fraction, and random choosing enables a uniform reduction in the number of LAEs without being affected by IGM absorption. Choosing randomly increases the uncertainty, but its effect is negligibly small. We distribute $\sim 5000$ apertures on the FoV and calculate the $n(\text{LAE})/n(\text{LBG})$ within them. When the area overlapping with the simulation box is less than 80% of the aperture, we exclude the aperture, which degrades the result due to the large Poisson error. Varying the aperture radius from $5'$ to $30'$ (corresponding to 1.6–10 pMpc), we show in Figure 19 the scatter of $n(\text{LAE})/n(\text{LBG})$ with and without IGM absorption. There is no difference between them, probably due to the small number of the sample or the low neutral fraction at $z \sim 6.6$; therefore, we conclude that distinguishing the reionization topology from the LSS may be difficult at this survey depth.

To investigate how deep an observation is required for this goal, we carry out the same analysis including fainter objects in the simulation. We change the limiting Ly$\alpha$ luminosity down to $L_{\text{Ly} \alpha} > 2.5 \times 10^{41}$ ergs$^{-1}$ with a 0.2 dex interval and the limiting rest-frame UV absolute magnitude down to $M_{\text{UV}} < -17.5$ mag with a 0.5 mag step. To match the expected number

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**Figure 16.** Ly$\alpha$ fraction $X_{\text{Ly} \alpha}^{25}$ as a function of redshift. The previous results are taken from Stark et al. (2010), Schenker et al. (2014), Tilvi et al. (2014), Ono et al. (2012), Curtis-Lake et al. (2012), and Cassata et al. (2015).

**Figure 17.** $x_{\text{HI}}$ map and $n(\text{LAE})/n(\text{LBG})$ distribution in a simulation box of the Late reionization model. The green color shows the $x_{\text{HI}}$, and the contours indicate the $n(\text{LAE})/n(\text{LBG})$.

**Figure 18.** The relation between $x_{\text{HI}}$ and the $n(\text{LAE})/n(\text{LBG})$ in the simulation box when dividing the map in Figure 17 into a grid with side of $1'$ (2.5 cMpc). The blue points show the whole region shown in the map, and the orange points are from the central region with a square of 80 cMpc per side (25% of the total area of the simulation box).

**Figure 19.** The median and 1$\sigma$ scatter of $n(\text{LAE})/n(\text{LBG})$ as a function of aperture size in the Late reionization model. Blue and orange indicate whether or not IGM absorption is assumed, respectively. The absolute value of $n(\text{LAE})/n(\text{LBG})$ is different from that in Figures 12 and 15 because LAEs and LBGs are both selected with the top-hat redshift distribution of $\Delta z = 0.1$. 

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of LAEs with and without the IGM absorption, we randomly choose LAEs without the IGM absorption as described above. Figure 20 shows the scatter of \( n(\text{LAE})/n(\text{LBG}) \) within the apertures with a 20' radius between those with and without the IGM absorption as a function of limiting Ly\( \alpha \) luminosity. The error bars are calculated by bootstrapping the model galaxies before calculating \( n(\text{LAE})/n(\text{LBG}) \) within the apertures. When we include the fainter objects, the scatter of \( n(\text{LAE})/n(\text{LBG}) \) becomes smaller. However, we cannot find a significant difference between those with and without IGM absorption in the simulation even with observations 2 mag deeper (limiting luminosity \( L_{\text{Ly}\alpha} \sim 4 \times 10^{41} \text{ ergs}^{-1} \)) than the current survey.

At \( z = 6.6 \), IGM absorption hardly decreases the number of faint objects because the neutral fraction is not that high \( \chi_{\text{HI}} \sim 0.4 \). This seems to be one of the reasons why we cannot see a significant difference between those with and without IGM absorption. We carry out the same analysis at \( z = 8.0 \) \( \chi_{\text{HI}} \sim 0.8 \) to verify that the comparison of \( n(\text{LAE})/n(\text{LBG}) \) can distinguish between reionization topology and the LSS. Because the number of objects declines at higher redshift, we use \( \Delta z = 0.4 \) at \( z = 8.0 \). In the same way as \( z = 6.6 \), we derive the scatter of \( n(\text{LAE})/n(\text{LBG}) \) as a function of limiting Ly\( \alpha \) luminosity. We might be able to detect a difference between the scatter of \( n(\text{LAE})/n(\text{LBG}) \) with and without IGM absorption seen in Figure 20 by assuming deep observations (limiting luminosity \( L_{\text{Ly}\alpha} \sim 4 \times 10^{41} \text{ ergs}^{-1} \)) while the difference is small. This suggests that observation at an earlier phase of reionization may be able to detect a spatially inhomogeneous nature in the universe with a sufficient amount of neutral hydrogen.

The scatter of \( n(\text{LAE})/n(\text{LBG}) \) relative to the median value as a function of limiting Ly\( \alpha \) luminosity in the Late reionization model. Colors are the same as in Figure 19. The dashed (solid) lines show the result of \( z = 6.6 \) \( (8.0) \). The gray dotted line shows the current survey depth. The error bars are estimated by bootstrapping the model galaxies before calculating \( n(\text{LAE})/n(\text{LBG}) \) within apertures.

The scatter of \( n(\text{LAE})/n(\text{LBG}) \) relative to the median value as a function of limiting Ly\( \alpha \) luminosity in the Late reionization model. Colors are the same as in Figure 19. The dashed (solid) lines show the result of \( z = 6.6 \) \( (8.0) \). The gray dotted line shows the current survey depth. The error bars are estimated by bootstrapping the model galaxies before calculating \( n(\text{LAE})/n(\text{LBG}) \) within apertures.

Figure 20. The scatter of \( n(\text{LAE})/n(\text{LBG}) \) relative to the median value as a function of limiting Ly\( \alpha \) luminosity in the Late reionization model. Colors are the same as in Figure 19. The dashed (solid) lines show the result of \( z = 6.6 \) \( (8.0) \). The gray dotted line shows the current survey depth. The error bars are estimated by bootstrapping the model galaxies before calculating \( n(\text{LAE})/n(\text{LBG}) \) within apertures.

still exceeds the variance from \( x_{\text{HI}} \) at \( z = 6.6 \) (Figure 20). If we can make this observation deeper at higher \( z \) to study the earlier stage of reionization, we may be able to detect the spatial variation of \( x_{\text{HI}} \). However, this is only a validation using this simulation; other simulations based on different reionization scenarios may give different results, and it is not clear if this is the case in the real universe. Although this simulation model reproduces each observation well in terms of the evolution of the Ly\( \alpha \) luminosity function, the autocorrelation function, and the Ly\( \alpha \) fraction, it may be beyond the scope of this simulation model to reproduce the variance as well. Further investigation of the model is necessary.

5.2. Equivalent-width Distribution

The rest-frame Ly\( \alpha \) EW distribution could also be a plausible probe of reionization (Treu et al. 2012, 2013; Jung et al. 2020). We calculate the EW\( _0 \) of the LAEs in the same way as Shibuya et al. (2018a). In this analysis, we exclude sources undetected in the \( Y \) band, which would cause large uncertainties in the EW\( _0 \) measurements. The EW\( _0 \) distribution of our LAE sample is similar to that in Shibuya et al. (2018a). The Kolmogorov–Smirnov test does not find any significant difference between the two distributions \( (p\text{-value } p = 0.36) \). To investigate the relation between the EW\( _0 \) and the neutrality, we divide the sample into high- and low-LAE-density regions based on the \( n(\text{LAE})/n(\text{LBG}) \) shown in Figure 14 at the positions of the LAEs. When we compare the EW\( _0 \) distribution between the top and bottom quartiles of \( n(\text{LAE})/n(\text{LBG}) \), as shown in Figure 21, the LAEs in the high-LAE-density region are more populous at EW\( _0 > 100 \) \( \text{Å} \), though the statistical significance is not high. We compare the EW\( _0 \) distribution with the model prediction of Dijkstra et al. (2011) as shown in Figure 22. While the error bar is large, a low-\( n(\text{LAE})/n(\text{LBG}) \) environment might indicate a high neutral fraction, implying that the LAEs in the highest-\( n(\text{LAE})/n(\text{LBG}) \) environment are surrounded by ionized bubbles. It is in line with the relation that increasing the neutral fraction reduces \( n(\text{LAE})/n(\text{LBG}) \). While we assume a flat UV continuum when calculating the EW\( _0 \), the uncertainty of the UV slope affects the EW\( _0 \). However, considering the uncertainty is difficult because most
of our LAEs are detected only in the $Y$ band redward of the Ly$\alpha$. The UV slope might depend on the environment, and it will be investigated by future observations.

6. Summary

In this paper, we, for the first time, attempt to quantify the spatially inhomogeneous reionization from the wide-field survey with Subaru HSC.

1. We simultaneously detect 189 LAEs and 179 LBGs at $z \sim 6.6$ in the COSMOS field with large-FoV ($\sim 1.5$ deg$^2$) HSC observations. The newly installed filter IB945 makes it possible to detect LAEs at a similar redshift to LBGs. The surface number densities of our LAE and LBG samples are consistent with those in previous studies.

2. Based on the state-of-the-art simulation of reionization, the observed $n$(LAE)/$n$(LBG), 0.84$-^{0.23}_{+0.27}$, puts a constraint on the average neutral fraction in the FoV of $x_{\text{HI}} < 0.4$, which is consistent with previous studies.

3. By comparing the density distribution of LAEs and LBGs, we detect a spatial variation over a factor of 3 in $n$ (LAE)/$n$(LBG). Our model predicts that the spatial variation of $n$(LAE)/$n$(LBG) corresponds to the spatial variation of the neutral fraction, i.e., the patchy reionization topology. This implies reionization is proceeding in the high-LAE-density region in our observation, while it is delayed in the low-LAE-density region.

4. Based on the model, we conclude that the observed large scatter of $n$(LAE)/$n$(LBG) can either be explained by the reionization topology or the intrinsic LSS, and it may be difficult to distinguish them at the current survey depth.

5. LAEs in the high-LAE-density regions are found to be more populous at high EW$_0$. This result supports the fact that the observed $n$(LAE)/$n$(LBG) is more or less driven by the neutral fraction, though the statistical significance is not high.

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Software: astdex (https://github.com/ymao/adstex), Astropy (Astropy Collaboration et al. 2013, 2018), Datashtader (https://datashader.org/), Jupyter (Kluyver et al. 2016), Matplotlib (Hunter 2007), Numpy (Harris et al. 2020), pandas (Reback et al. 2021; McKinney 2010), SciPy (Virtanen et al. 2020), uncertainties (http://pythonhosted.org/uncertainties/).
The colors are the same as Figure 15.

Relation between $\Delta z$ and $n(\text{LAE})/n(\text{LBG})$ in the simulation data with the $\Delta z = 0.1$ top-hat selection function for LAEs and $\Delta z = 0.3$ for LBGs. The colors are the same as Figure 15.

Appendix

Robustness of the Relation between $n(\text{LAE})/n(\text{LBG})$ and $x_{\text{HI}}$

In Section 5.1, we derive the relation between the number ratio $n(\text{LAE})/n(\text{LBG})$ and the neutral fraction $x_{\text{HI}}$ using the observed selection functions described in Section 3.3. To see the robustness of the trend, here we make a simpler assumption that our results are robust.

In the simulation data, we select LAEs and LBGs with the top-hat selection and photometric selection in the same way as in the observational data. We use the ratio of the number of the objects with the top-hat selection to that with photometric selection as the correction factor between the simulation and the observation. We derive the observed $n(\text{LAE})/n(\text{LBG})$ with the top-hat selection by multiplying the correction factor to the observed number of objects, and derive the neutral fraction in the same way as in Section 5.1. The neutral fraction is $x_{\text{HI}} < 0.4$, which is consistent with the result of Section 5.1. We confirm that the effect of the difference in selection methods is negligible and that our results are robust.

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