SILVERRUSH. VII. SUBARU/HSC IDENTIFICATIONS OF 42 PROTOCLUSTER CANDIDATES AT $z \sim 6 - 7$
WITH THE SPECTROSCOPIC REDSHIFTS UP TO $z = 6.574$:
IMPLICATIONS FOR COSMIC REIONIZATION

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ABSTRACT

We report fourteen and twenty-eight protocluster candidates at $z = 5.7$ and 6.6 over 14 and 19 deg$^2$ areas, respectively, selected from 2,230 (259) Ly$\alpha$ emitters (LAEs) photometrically (spectroscopically) identified with Subaru/Hyper Suprime-Cam (HSC) deep images (Keck, Subaru, and Magellan spectra and the literature data). Six out of the 42 protocluster candidates include 1 – 12 spectroscopically confirmed LAEs at redshifts up to $z = 6.574$. By the comparisons with the cosmological Ly$\alpha$ radiative transfer (RT) model reproducing LAEs with the reionization effects, we find that more than a half of these protocluster candidates are progenitors of the present-day clusters with a mass of $\gtrsim 10^{13}$M$_\odot$. We then investigate the correlation between LAE overdensity $\delta$ and Ly$\alpha$ rest-frame equivalent width $EW_{\text{Ly}\alpha}^{\text{rest}}$, because the cosmological Ly$\alpha$ RT model suggests that a slope of $EW_{\text{Ly}\alpha}^{\text{rest}}$–$\delta$ relation is steepened towards the epoch of cosmic reionization (EoR), due to the existence of the ionized bubbles around galaxy overdensities easing the escape of Ly$\alpha$ emission from the partly neutral intergalactic medium (IGM). The available HSC data suggest that the slope of the $EW_{\text{Ly}\alpha}^{\text{rest}}$–$\delta$ correlation does not evolve from the post-reionization epoch $z = 5.7$ to the EoR $z = 6.6$ beyond the marginally large statistical errors. There is a possibility that we would detect the evolution of the $EW_{\text{Ly}\alpha}^{\text{rest}}$–$\delta$ relation from $z = 5.7$ to 7.3 by the upcoming HSC observations providing large samples of LAEs at $z = 6.6 - 7.3$.

Keywords: galaxies: formation – galaxies: evolution – galaxies: high-redshift

1. INTRODUCTION

Studying the physical process of cosmic reionization is one of the important subjects in astronomy today.
regions, where many star-forming galaxies exist in a small volume of the universe (Furlanetto et al. 2006; Ouchi et al. 2012; Matthee et al. 2015; Ishigaki et al. 2016; Overzier 2016; Chiang et al. 2017). The cosmic reionization is expected to proceed from high- to low-density regions (see Iliev et al. 2008; Ouchi et al. 2012; Overzier 2016). This reionization process is called ‘inside-out scenario’. On the other hand, if major sources of cosmic reionization are X-ray emitting objects like AGNs, the scenario may be different. Due to the longer mean-free path of X-ray photons than that of UV photons from galaxies and the slow hydrogen recombination rate in the low-density region, cosmic reionization would not proceed from high-density, but low-density regions (see Miralda-Escudé et al. 2000; Nakamoto et al. 2001; McQuinn 2012; Mesinger et al. 2013). The physical process of cosmic reionization is tightly related to the major ionizing sources of cosmic reionization. Because no definitive observational evidence of ionized bubbles is found to date, identifying signatures of ionized bubbles around galaxy overdense regions, if any, is key to testing the inside-out scenario of cosmic reionization.

There is another importance of observations of galaxy overdensities near the EoR. Standard structure formation models predict that a large fraction of high-density regions evolve into massive galaxy clusters at redshifts near the EoR. There is another importance of observations of galaxy overdensities near the EoR. Standard structure formation models predict that a large fraction of high-density regions evolve into massive galaxy clusters at redshifts near the EoR. The IGM ionization state is studied with the Lyα/HI equivalent widths (EWs) of LAEs that depend on $z_{HI}$ (Dijkstra et al. 2011, 2016; Jensen et al. 2014; Franck & McGaugh 2016). It is popular that proto-clusters are identified with the distributions of the continuum-selected galaxies including dropout galaxies. However, there is a difficulty to find proto-clusters only with the continuum-selected galaxy samples due to the large redshift uncertainties of the continuum-selected galaxies. Instead, one can use LAEs to identify proto-clusters or galaxy overdensities in general, exploiting a small redshift uncertainty of LAEs. Here we investigate the LAE distribution and overdensity to identify proto-cluster candidates, and to investigate the IGM ionization state around galaxy overdensities. The IGM ionization state is studied with the Lyα equivalent widths (EWs) of LAEs that depend on $z_{HI}$ (Dijkstra et al. 2011, 2016; Jensen et al. 2014; Kakiichi et al. 2016). Having a number of galaxy overdensities, we statistically investigate proto-clusters and the IGM ionization states.

In this paper, we identify proto-cluster candidates at $z = 5.7$ and 6.6 based on the LAE samples of the SILVERRUSH project. SILVERRUSH is an on-going research project based on the Subaru/Hyper Suprime-Cam (HSC) Subaru Strategic Program (SSP: Aihara et al. 2017; Miyazaki et al. 2017; Komiyama et al. 2017; Furusawa et al. 2017). The SILVERRUSH project papers show various properties of LAEs in the EoR, clustering (Ouchi et al. 2017), photometry (Shibuya et al. 2017a), spectroscopy (Shibuya et al. 2017b), Lyα LFs (Konno et al. 2017), the ISM properties (Harikane et al. 2017), theoretical predictions (Inoue et al. 2018), and protoclusters (this work). This is the seventh publication in SILVERRUSH. SILVERRUSH is one of the twin programs devoted to scientific results on high redshift galaxies based on the HSC survey data. The other one is related to dropout galaxies, named Great Optically Luminous Dropout Research Using Subaru HSC (GOLDRUSH: Ouchi et al. 2017; Harikane et al. 2017; Toshikawa et al. 2017). Because we intend to enlarge our LAE samples, we include the LAE samples made in Ouchi et al. (2008) and Ouchi et al. (2010), which are previously obtained with Subaru/Suprime-Cam (SC: Miyazaki et al. 2002; see also Iye et al. 2004). We describe our photometric LAE samples with HSC and SC in Section 2. In Sections 3 and 4 we explain our spectroscopic LAE data and theoretical models of Inoue et al. (2018), respectively. We present the list of protocluster candidates at $z = 5.7$ and 6.6, and show the 3-dimensional LAE distributions of protocluster candidates (Section 5). In Section 6 we also discuss the physical process of cosmic reionization with the LAE distributions.

Throughout this paper, we use a cosmological parameter set of $\Omega_m = 0.3$, $\Omega_l = 0.7$, $\Omega_b = 0.04$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. The magnitudes are in the AB system.

2. DATA AND SAMPLES

2.1. Photometric Samples of HSC SSP Data

We calculate galaxy overdensity and identify protocluster candidates using photometric LAE samples of HSC SSP data. In our study, we use two-narrowband ($NB816$ and $NB921$) and five-broadband (grizy) imaging data, of the HSC SSP survey (Section 1) starting in March 2014. The HSC-SSP survey is an on-going program, for which 300 nights are allocated over 5 years. The HSC-SSP survey has three layers of the UltraDeep, Deep, and Wide, whose planned total survey areas are $\sim 4$ deg$^2$, $\sim 30$ deg$^2$, and $\sim 1400$ deg$^2$, respectively. The narrowband data are taken only in the UltraDeep and Deep layers. We use early datasets of the HSC-SSP survey taken until April 2016. In these datasets, HSC SSP has obtained $NB816$ data in two fields of the UltraDeep layer, UD-SXDS and UD-COSMOS, and two fields of the Deep layer, D-ELAIS-N1, and D-DEEP2-3. The data of $NB921$ have been taken in two fields of the UltraDeep layer, UD-SXDS and UD-COSMOS, and three fields of the Deep layer, D-ELAIS-N1, D-DEEP2-3, and D-COSMOS. The 5σ limiting magnitudes of the HSC imaging data are typically $\sim 25 - 25.5$ magnitudes in the narrowbands and $\sim 26 - 27$ magnitudes in the broadbands (Table 1 see also Shibuya et al. 2017a). The total survey areas of the early datasets are 13.8 deg$^2$ and 21.2 deg$^2$ in the fields with the $NB816$ and $NB921$ data, respectively. The $NB816$ and $NB921$ data allow us to identify strong $Ly\alpha$ emission lines of LAEs redshifted to $z = 5.726 \pm 0.046$ and $z = 6.580 \pm 0.056$, respectively, where the redshift ranges are defined with the FWHMs of the narrowbands. The total survey volumes for the early datasets are $1.2 \times 10^7$ Mpc$^3$ at $z = 5.7$.
and $1.9 \times 10^7 \text{Mpc}^3$ at $z = 6.6$. Note that these survey volumes are $\sim 2 - 50$ and $\sim 4 - 100$ times larger than those of previous studies for LAEs at $z = 5.7$ (e.g., Ouchi et al. 2008, Santos et al. 2016) and $z = 6.6$ (e.g., Ouchi et al. 2010, Kashikawa et al. 2011, Matthee et al. 2015), respectively.

The datasets are reduced by the HSC-SSP Collaboration with hscPipe (Bosch et al. 2017). hscPipe is a pipeline which is based on the Large Synoptic Survey Telescope (LSST) pipeline (Ivezic et al. 2008, Axelrod et al. 2010, Jurić et al. 2013). The astrometry and photometry of the datasets are calibrated based on the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) 1 imaging survey (Magnier et al. 2016).

Ouchi et al. (2008) and Ouchi et al. (2010) have carried out narrowband imaging with SC in 2003 and 2005-2007, respectively. The total areas of the narrowband imaging are $\sim 1$ deg$^2$ and $\sim 1.05$ deg$^2$ for the SC samples only. Ouchi et al. (2008) and Ouchi et al. (2010), in addition to the HSC LAE samples in Section 2.1, study $z = 5.7$ and $z = 6.6$ LAEs, respectively, in addition to the HSC samples. The color selection criteria to the objects in the HSC datasets are defined as

$$i - NB816 \geq 1.2 \text{ and } g > g3\sigma \text{ and } [(r \leq r3\sigma \text{ and } r - i \geq 1.0) \text{ or } (r > r3\sigma)]$$

for $z = 5.7$ and $6.6$ LAEs, respectively (see Shibuya et al. 2017a). We find 1,077 $z = 5.7$ LAEs and 1,153 $z = 6.6$ LAEs by photometry. Shibuya et al. (2017a) take spectra of 18 LAEs of the photometric samples, and confirm 13 LAEs at $z = 5.7$ and 6.6 by spectroscopy. Because the LAEs include faint sources that may not identify a signal with the depth of the spectroscopy, the contamination rate indicated by the spectroscopy is estimated to be $0 - 30\%$ in the $z = 5.7$ and $6.6$ LAEs in the photometric samples.

2.2. Photometric Samples of the SC Data

To select the spectroscopic targets of $z = 5.7$ and $6.6$ LAEs, we use photometric samples of Ouchi et al. (2008) and Ouchi et al. (2010), respectively, in addition to the HSC LAE samples in Section 2.1. Ouchi et al. (2008) and Ouchi et al. (2010) have carried out narrowband imaging with SC in 2003 and 2005-2007, respectively. The total areas of the narrowband imaging are $\sim 1$ deg$^2$ and $\sim 0.9$ deg$^2$ for $NB816$ and $NB921$ images, respectively. Ouchi et al. (2008) and Ouchi et al. (2010) detect objects in each narrowband image with SExtractor (Bertin & Arnouts 1996), and obtain SC LAE samples with the color selection criteria similar to the equations (1) and (2) that are defined as

$$i' - NB816 \geq 1.2 \text{ and } B > B2\sigma \text{ and } V > V2\sigma \text{ and } [(R \leq R2\sigma \text{ and } R - i' \geq 1.0) \text{ or } (R > R2\sigma)]$$

for $z = 5.7$ and $6.6$ LAEs, respectively.

3. SPECTROSCOPIC OBSERVATIONS AND SAMPLES

We conduct spectroscopic observations for the HSC and SC LAE samples. The spectroscopic observations for the HSC samples are presented in Shibuya et al. (2017a). Here we explain our spectroscopy for the SC samples that were conducted in 2007-2010.

3.1. Keck/DEIMOS Observation

We carried out spectroscopic follow-up observations for our $z = 5.7$ LAEs with Deep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on 2010 February 11. The sky was clear during the observations, and the seeing was $\sim 0''35$. We observed 22 out of the 401 SC LAEs at $z = 5.7$ (Ouchi et al. 2008) including very faint objects in each narrowband image with SExtractor (Bertin & Arnouts 1996), and obtain SC LAE samples with the color selection criteria similar to the equations (1) and (2) that are defined as

$$i - NB816 \geq 1.2 \text{ and } g > g3\sigma \text{ and } [(r \leq r3\sigma \text{ and } r - i \geq 1.0) \text{ or } (r > r3\sigma)]$$

and

$$i' - NB816 \geq 1.2 \text{ and } B > B2\sigma \text{ and } V > V2\sigma \text{ and } [(R \leq R2\sigma \text{ and } R - i' \geq 1.0) \text{ or } (R > R2\sigma)]$$

for $z = 5.7$ and $6.6$ LAEs, respectively.
Table 1
HSC Imaging Data

| Layer  | Field   | Area               | g      | r      | i      | z      | y      | NB816  | NB921  |
|--------|---------|--------------------|--------|--------|--------|--------|--------|--------|--------|
| UD     | SXDS    | 1.928 (1.873)     | 26.9   | 26.4   | 26.3   | 25.6   | 24.9   | 25.5   | 25.5   |
| UD     | COSMOS  | 1.965 (1.999)     | 26.9   | 26.6   | 26.2   | 25.8   | 25.1   | 25.7   | 25.6   |
| Deep   | COSMOS  | - (4.938)         | 26.5   | 26.1   | 26.0   | 25.5   | 24.7   | -      | 25.3   |
| Deep   | ELAIS-N1| 5.566 (5.599)     | 26.7   | 26.0   | 25.7   | 25.0   | 24.1   | 25.3   | 25.3   |
| Deep   | DEEP2-3 | 4.339 (3.100)    | 26.6   | 26.2   | 25.9   | 25.2   | 24.5   | 25.2   | 24.9   |

Note. — (1) Layer; (2) field; (3) effective area of the NB816 (NB921) image (deg²); (4)-(10) five sigma limiting magnitudes of the HSC g, r, i, z, y, NB816, and NB921 images in a circular aperture with a diameter of 1.′′5 (mag).

Table 2
Photometric Samples of the z = 5.7 and 6.6 LAEs

| Layer  | Field   | NB816 Full | NB816 < 24.5 | NB816 < 25.0 | NB921 Full | NB921 < 24.5 | NB921 < 25.0 |
|--------|---------|------------|--------------|--------------|------------|--------------|--------------|
| UD     | SXDS    | 224        | 83           | 164          | 58         | 21           | 43           |
| UD     | COSMOS  | 201        | 52           | 123          | 338        | 31           | 82           |
| Deep   | COSMOS  | -          | -            | -            | 244        | 91           | 196          |
| Deep   | ELAIS-N1| 229        | 140          | 166          | 349        | 142          | 258          |
| Deep   | DEEP2-3 | 423        | 127          | 319          | 164        | 104          | 82           |

Note. — (1) Layer; (2) field; (3) number of the z = 5.7 LAEs in the HSC photometric sample; (4)-(5) same as (3), but for z = 5.7 LAEs that are brighter than 24.5 and 25.0 mag in the NB816 band; (6) number of the z = 6.6 LAEs in the HSC photometric sample; (7)-(8) same as (6), but for z = 6.6 LAEs that are brighter than 24.5 and 25.0 mag in the NB921 band. a The NB816 image is not taken in Deep COSMOS.

Table 3
Spectroscopic Observations

| Layer  | Field   | Mask ID | Date     | Total Exposure | N_LAE  | Grism | CW | Filter |
|--------|---------|---------|----------|----------------|--------|-------|----|--------|
| Keck/DEIMOS |
| UD     | SXDS    | SXDS03  | 2010 Feb 11 | 36000         | 16     | 830   | 7900 | OG550  |

Note. — (1) Layer; (2) field; (3) mask ID; (4) date of observations; (5) total exposure time (sec); (6) numbers of the observed LAEs; (7) disperser name; (8) central wavelength of the grating setting (A); (9) filter name. a See also Lee et al. (2012) and Momcheva et al. (2013).
LAE candidates, and obtained 16 spectra in a good condition. During the observations, we took the standard stars G191B2B for the flux calibration. We used a mask with a slit width of 1″, the OG550 filter, and the 830 lines mm$^{-1}$ grating that is blazed at 8640 Å. The grating was tilted to be placed at a central wavelength of 7900 Å on the detectors. The spectral coverage and the spectral resolution were 4100 – 9400Å and $\lambda/\Delta\lambda \simeq 2400$, respectively.

We perform the data reduction using the spec2d IDL pipeline developed by the DEEP2 Redshift Survey Team [Davis et al. 2003]. The central wavelengths of Ly$\alpha$ emission were determined by Gaussian fitting. We detect 15 out of the 16 LAEs, and obtain Ly$\alpha$ line redshifts. The spectra of the example LAEs are shown in Figure 1.

3.2. Magellan/IMACS Observation

We conducted follow-up spectroscopy for 425 objects selected from the samples of $z = 5.7$ and $z = 6.6$ LAEs in Ouchi et al. (2008) and Ouchi et al. (2010), respectively. The observations were performed with the Inamori Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2006) on the Magellan I Baade Telescope in 2007 November 12 – 14, 2008 November 29 – December 2, 2008 December 18 – 19, and 2009 October 11 – 12. We chose GG455 filter and Grix-150-18.8 grism on 2007 November 12. In 2007 November 13 – 14, we change the filter from GG455 to GG570. For the rest of the IMACS observations, we used WB6300-9500 filter and grix-300-26.7 grism. The exposure time ranges from 15,300 s to 35,400 s with seeing sizes of 0.9′′ – 0.9′′.8. We used a 0.9′′ slit width that gives a spectral resolution of 1,000 – 2,000. We perform data reduction with the Carnegie Observatories System for MultiObject Spectroscopy (COSMOS) pipeline, and detect Ly$\alpha$ emission lines around 8160 Å. The equivalent widths are shown with the gray open circles. The exposure time ranges from 15,300 s to 35,400 s with seeing sizes of 0.9′′ – 0.9′′.8. We used a 0.9′′ slit width that gives a spectral resolution of 1,000 – 2,000. We perform data reduction with the Carnegie Observatories System for MultiObject Spectroscopy (COSMOS) pipeline, and detect Ly$\alpha$ emission lines around 8160 Å. The equivalent widths are shown with the gray open circles. The exposure time ranges from 15,300 s to 35,400 s with seeing sizes of 0.9′′ – 0.9′′.8. We used a 0.9′′ slit width that gives a spectral resolution of 1,000 – 2,000. We perform data reduction with the Carnegie Observatories System for MultiObject Spectroscopy (COSMOS) pipeline, and detect Ly$\alpha$ emission lines around 8160 Å. The equivalent widths are shown with the gray open circles.

3.3. Spectroscopic Samples and Catalogs

Adding to the SC spectroscopic sample of the LAEs confirmed with DEIMOS and IMACS in Sections 3.1 and 3.2, and the HSC spectroscopic sample of Shibuya et al. (2017) that includes LAEs in Ouchi et al. (2010), Sobral et al. (2013), and Hu et al. (2016), we use the redshift catalogs for the spectroscopically confirmed LAEs at $z = 5.7$ (6.6) taken from Ouchi et al. (2005), Ouchi et al. (2008), Mallery et al. (2012), Chanchaiworawit et al. (2017), and Guzmán et al. (in preparation). We make unified spectroscopic catalogs of LAEs at $z = 5.7$ and 6.6 Tables 4 and 5, respectively.

Note that, again, there are many LAEs in the SC spectroscopic sample that are not included in the HSC photometric sample. This is because the HSC photometric sample includes bright LAEs only down to ~25 mag in a narrowband, while the SC samples (spectroscopic and photometric samples) have faint LAEs down to ~26 mag in a narrowband (Section 2.2). Because the selection of the SC (and HSC) spectroscopic sample is heterogeneous, we use the homogeneous photometric sample of HSC LAEs to find protocluster candidates. The unified catalogs (the SC and HSC spectroscopic samples) are referred to confirm the redshifts of protocluster candidates in Section 5.1.4.

4. THEORETICAL MODEL

We compare our observational results with the cosmological simulation model of Inoue et al. (2018). Inoue et al. (2018) conduct the N-body simulations in a box size of 110$h^{-1}$ comoving Mpc (cMpc) length with 512$^3$ grids, which gives a spatial resolution of 214.8 comoving kpc. Inoue et al. (2018) present models of three reionization histories depending on the ionizing emissivity of halos: early, mid, and late, all of which are consistent with the latest Thomson scattering optical depth measurement (Planck Collaboration et al. 2016). Here we adopt the late model that explains the recent neutral hydrogen fraction measurements at $z \sim 6 - 7$. In
the model, a total of 4096 dark matter particles are used with a mass resolution of $7 \times 10^7 M_{\odot}$. Inoue et al. (2018) perform numerical radiative transfer calculations to reproduce cosmic reionization. In this model, LAEs are created with the relation of the Lyα photon production rate and halo mass determined by the radiation hydrodynamics (RHD) galaxy formation simulation of Hasegawa et al. (in preparation). Inoue et al. (2018) assume a total of 4096 dark matter particles are used with a mass resolution of $7 \times 10^7 M_{\odot}$. Inoue et al. (2018) perform numerical radiative transfer calculations to reproduce cosmic reionization. In this model, LAEs are created with the relation of the Lyα photon production rate and halo mass determined by the radiation hydrodynamics (RHD) galaxy formation simulation of Hasegawa et al. (in preparation). Inoue et al. (2018) assume

$$L_{\text{Ly} \alpha, \text{int}} = 10^{42} \times (1 - e^{-10M_{\odot}h}) \times M_{\odot}^{1.1} \times 10^{6\delta_{\text{Ly} \alpha}} \left[ \text{ergs}^{-1} \right],$$

where more massive haloes produce more Lyα photons due to the higher star-forming rate (SFR). Here, $M_{\odot}$ is the halo mass normalized by $10^{10} M_{\odot}$, and $\delta_{\text{Ly} \alpha}$ represents the fluctuation of the Lyα photon production. The ISM Lyα escape fraction is defined as

$$j_{\text{esc}, \alpha} = \exp(-\tau_{\alpha}),$$

where $\tau_{\alpha}$ is the Lyα optical depth. Inoue et al. (2018) assume the probability distribution of the Lyα optical depth as

$$P(\tau_{\alpha}) = \frac{\exp\{(\tau_{\alpha} - \langle \tau_{\alpha} \rangle)^2 / 2\langle \tau_{\alpha} \rangle\}}{\sqrt{2\pi\langle \tau_{\alpha} \rangle}}$$

and

$$\langle \tau_{\alpha} \rangle = \tau_{\alpha,10} \left( \frac{M_{\odot}}{10^{10} M_{\odot}} \right)^{p},$$

where $p$ indicates the halo mass dependence of $\langle \tau_{\alpha} \rangle$. Inoue et al. (2018) calibrate the parameter $\tau_{\alpha,10}$ with the $z = 5.7$ Lyα luminosity function (Komossa et al. 2017), and compare the model predictions with the various observational quantities of the Lyα luminosity functions at $z = 6.6$ and 7.3 (Komossa et al. 2017, 2014), the LAE angular auto-correlation functions at $z = 5.7$ and 6.6 (Ouchi et al. 2017), and the LAE fractions in Lyman break galaxies at $z = 5 - 7$ (Stark et al. 2011, Ono et al. 2012). In this paper, we use the model with the best parameter set ($\delta_{\text{Ly} \alpha} = 0$, $p = 1/3$, and $\tau_{\alpha,10} = 1.1$) that Inoue et al. (2018) conclude.

We select mock LAEs brighter than $10^{42.5}$ erg s$^{-1}$ in Lyα luminosity. Hereafter, we call these mock LAEs ‘LAE all’. We obtain 9574, 1415, and 55 mock LAEs at $z = 5.7$, 6.6, and 7.3, respectively, from the entire simulation box of the model.

For comparison with our observational results, we calculate overdensity $\delta$ of the mock LAEs that is defined as

$$\delta = \frac{n - \pi}{\pi},$$

where $n$ ($\pi$) is the total (average) number of LAEs found in a cylinder volume that mimics the observational volume for the $\delta$ measurements (Section 5.1.1). We choose the height of $\sim 40$ cMpc for the cylinder that corresponds to the redshift range of the narrowband observation LAE selection. The base area of the cylinder is defined by a radius of $10$ cMpc that corresponds to the inside-out scenario of cosmic reionization, $EW_{\text{Ly} \alpha}$ and $\delta$ in Inoue et al. (2018) for the universe with the neutral hydrogen fractions of $\log_{10} x_{\text{HI}} = -3.9$, -0.36 and -0.17 that are the average values of the simulation boxes at $z = 5.7$, 6.6, and 7.3, respectively. The relations of $EW_{\text{Ly} \alpha} - \delta$ are fit with a linear function, $EW_{\text{Ly} \alpha} = \alpha \delta + EW_{\delta=0}$, where $\alpha$ and $EW_{\delta=0}$ are the slope and the $EW_{\delta=0}$ value at $\delta = 0$, respectively. Figure 7 shows $\alpha$ as a function of $x_{\text{HI}}$ obtained by the model calculations. The slope $\alpha$ increases from the post reionization epoch ($\log_{10} x_{\text{HI}} = -3.9$) to the EoR ($\log_{10} x_{\text{HI}} = -0.36$ and -0.17). In the inside-out scenario of cosmic reionization, $EW_{\text{Ly} \alpha}$ values at high-overdensity regions would be higher than those at lower-overdensity regions. This is because the Lyα escape fraction is higher inside the ionized bubbles than outside the ionized bubbles. Thus, if cosmic reionization proceeds in the inside-out manner, a slope $\alpha$ is high at the EoR.

5. RESULTS AND DISCUSSION

5.1. Spatial Distribution of LAEs

5.1.1. Overdensity Measurements

We calculate LAE overdensities in each field with the HSC LAE samples. The definition of the LAE overdensity for our observational data is the same as the one for the model shown in Equation 9. We use a cylinder with
Overdensity Identifications

We find that δ values of the HSC LAEs in some regions significantly exceed beyond those expected by random distribution. These δ values are not explained by a random distribution of galaxies, but physical structures. We define a region with δ exceeding the 5σ level of the Poisson distribution as a high-density region (HDR). At z = 5.7 (6.6), δ = 9.7 (6.6) corresponds to the ∼ 5σ significance level. We find 14 (27) HDRs at z = 5.7 (6.6) with δ > 9.7 (6.6). There is an overdensity of z = 6.6 LAEs at R.A. = 34.64 deg and decl. = −4.56 whose δ is 6.1 slightly below the ∼ 5σ significance level. This overdensity is reported by Chanchariwarawit et al. [2017]. Although this does not meet the criterion of δ > 6.6, we include this overdensity to the sample of our HDRs. We thus obtain 14 (28) HDRs at z = 5.7 (6.6).

Halo Mass Estimates

From the theoretical model of Inoue et al. [2018], we obtain the halo mass M_h as a function of overdensity δ. Because the halo mass is strongly related with the structure formation tightly connected with the abundance of halos and galaxies, we use LAEs in the model of Inoue et al. [2018] whose abundance is the same as those of the HSC LAEs. We define M_h as the most massive halo found in a cylinder volume used for the δ calculation. Figure 8 shows M_h as a function of δ significance level at z = 5.7 (6.6). We fit the M_h - δ relation with a linear function, and obtain log_{10}(M_h/M_⊙) = 0.0326 + 11.79 (log_{10}(M_h/M_⊙) = 0.0326 + 11.54) at z = 5.7 (6.6).

We use the extended Press-Schechter model of Hamana et al. [2006] to estimate the present-day halo masses of the high-z (z = 5.7 and 6.6) halos. Based on the M_h - δ relation, we find that 60 (58)% of the z = 5.7 (6.6) M_h-halos in the HDRs are expected to evolve into present-day cluster haloes with a mass of > 10^{14} M_⊙ by z = 0. Because more than a half of the M_h-halos in the HDRs are progenitors of the present-day clusters, we regard the 14 (28) HDRs at z = 5.7 (6.6) as protocluster candidates. The 14 (28) protocluster candidates are listed in Table 3. Here we name the z = 5.7 (6.6) protocluster candidates as HSC-z6 (7) PCC.

We compare the abundance of the protocluster candidates with that of present-day clusters. The comoving survey volumes of the HSC observations are ∼ 1.2 × 10^7 Mpc^3 and ∼ 1.9 × 10^7 Mpc^3 at z = 5.7 and 6.6, respectively. Because there exists one present-day cluster with a mass of > 10^{14} M_⊙ in a volume of ∼ 5 × 10^5 Mpc^3 (Reiprich & Böhringer 2002), it is expected that our survey volumes at z = 5.7 and 6.6 include ∼ 20 and ∼ 40 present-day clusters, respectively. These numbers are comparable with those of our protocluster candidates, 14 and 28.

Three-Dimensional Distribution and Protocluster Candidates

Based on the follow-up spectroscopic observations in Section 3, we find 3 (3) protocluster candidates at z = 5.7 (6.6) which have (a) spectroscopically confirmed peaks of the overdensity is not always centered at the highest density region. This is because the position of the peak has an uncertainty on a scale of 0.07 deg.

5.1.2. Overdensity Identifications

Because some regions of the HSC narrowband data are not deep enough to calculate δ due to the data quality, we should not use the HSC LAEs found in the shallow regions for the density evaluation. The HSC imaging data are divided into 1.7 × 1.7 deg^2 rectangular tracts that are made of 0.2 × 0.2 deg^2 rectangular patches. We estimate a 5σ limiting magnitude of each patch in the NB816 (NB921) data for z = 5.7 (6.6) LAEs. We evaluate δ only in an area where the 5σ limiting magnitude of the NB816 (NB921) band is brighter than 24.5 (25.0) mag. These magnitude limits are determined to keep a high-detection completeness of LAEs. Komoo et al. [2017]. We assume that the number density of LAEs in the masked regions is the same as the mean number density of LAEs in all fields. We also do not evaluate δ for a cylinder, in which more than 50% of the area is masked. We show the HSC LAE sky distribution and the overdensity maps at z = 5.7 and 6.6 in Figures 8-16. The solid lines correspond to contours of δ from 5 (3)σ to 8 (7)σ significance levels with a step of 1σ at z = 5.7 (6.6). Note that the peak of the overdensity is not always centered at the highest density region. This is because the position of the peak has an uncertainty on a scale of 0.07 deg.

5.1.3. Halo Mass Estimates

From the theoretical model of Inoue et al. [2018], we obtain the halo mass M_h as a function of overdensity δ. Because the halo mass is strongly related with the structure formation tightly connected with the abundance of halos and galaxies, we use LAEs in the model of Inoue et al. [2018] whose abundance is the same as those of the HSC LAEs. We define M_h as the most massive halo found in a cylinder volume used for the δ calculation. Figure 8 shows M_h as a function of δ significance level at z = 5.7 (6.6). We fit the M_h - δ relation with a linear function, and obtain log_{10}(M_h/M_⊙) = 0.0326 + 11.79 (log_{10}(M_h/M_⊙) = 0.0326 + 11.54) at z = 5.7 (6.6).

We use the extended Press-Schechter model of Hamana et al. [2006] to estimate the present-day halo masses of the high-z (z = 5.7 and 6.6) halos. Based on the M_h - δ relation, we find that 60 (58)% of the z = 5.7 (6.6) M_h-halos in the HDRs are expected to evolve into present-day cluster haloes with a mass of > 10^{14} M_⊙ by z = 0. Because more than a half of the M_h-halos in the HDRs are progenitors of the present-day clusters, we regard the 14 (28) HDRs at z = 5.7 (6.6) as protocluster candidates. The 14 (28) protocluster candidates are listed in Table 3. Here we name the z = 5.7 (6.6) protocluster candidates as HSC-z6 (7) PCC.

We compare the abundance of the protocluster candidates with that of present-day clusters. The comoving survey volumes of the HSC observations are ∼ 1.2 × 10^7 Mpc^3 and ∼ 1.9 × 10^7 Mpc^3 at z = 5.7 and 6.6, respectively. Because there exists one present-day cluster with a mass of > 10^{14} M_⊙ in a volume of ∼ 5 × 10^5 Mpc^3 (Reiprich & Böhringer 2002), it is expected that our survey volumes at z = 5.7 and 6.6 include ∼ 20 and ∼ 40 present-day clusters, respectively. These numbers are comparable with those of our protocluster candidates, 14 and 28.
LAE(s). These are HSC-z6PCC1, HSC-z6PCC4, and HSC-z6PCC5 (HSC-z7PCC3, HSC-z7PCC9, and HSC-z7PCC28) at \( z = 5.7 \) (6.6). The three-dimensional distributions of HSC-z6PCC1, HSC-z6PCC4, HSC-z7PCC9, and HSC-z7PCC28 are shown in Figures 19, 20, 21, 22, respectively. Here we explain three examples of the protocluster candidates, HSC-z6PCC1, HSC-z7PCC9, and HSC-z7PCC28.

**HSC-z6PCC1** HSC-z6PCC1 (Figure 19) consists of \( z = 5.7 \) LAEs in the southern part of UD SXDS. Twelve spectroscopically confirmed LAEs exist within a distance of \( \sim 1 \) physical Mpc (pMpc). The redshift averaged over the spectroscopically-confirmed LAEs is \( z = 5.692 \). HSC-z6PCC1 is the same structure as Clump A that is a protocluster identified by Ouchi et al. (2005). Six out of the 12 spectroscopically confirmed LAEs are included in Clump A.

**HSC-z7PCC9** HSC-z7PCC9 at \( z = 6.6 \) (Figure 21) is located at the center of UD SXDS. HSC-z7PCC9 consists of five spectroscopically confirmed LAEs, including the giant Ly\( \alpha \) nebula ‘Himiko’ (Ouchi et al. 2009). The average redshift of the LAEs is \( z = 6.574 \). If all of the LAEs of HSC-z7PCC9 are spectroscopically confirmed, HSC-z7PCC9 could be one of the earliest protoclusters found to date.

**HSC-z7PCC28** HSC-z7PCC28 (Figure 22) is placed at the northern part of UD SXDS at \( z = 6.6 \). This is the protocluster candidate reported by Chanchaiworawit et al. (2017), although the overdensity of HSC-z7PCC28 is \( \delta = 6.1 \) slightly below the 5\( \sigma \) significance level (Section 5.1.2). There are five spectroscopically confirmed LAEs in a sphere with a radius of \( \sim 1 \) pMpc. The redshift averaged over the spectroscopically-confirmed LAEs is \( z = 6.534 \). Three out of the five spectroscopically confirmed LAEs are included in the mem-
Subaru/HSC Protoclusters at $z = 6 - 7$

5.2. Implications for Cosmic Reionization

5.2.1. Spatial Correlation between Bright LAEs and Overdensities

To study the origin of the bright-end excess of Ly$\alpha$ luminosity functions at $z = 5.7$ and 6.6 (Konno et al. 2017), we investigate the correlation between Ly$\alpha$ luminosity and overdensity. Figure 23 (24) shows the relation between Ly$\alpha$ luminosity $L_{\text{Ly}\alpha}$ and large-scale LAE overdensity $\delta_{LS}$ for $z = 5.7$ (6.6) LAEs. Here $\delta_{LS}$ is defined with a circle with a radius of 0.20 deg that corresponds to $\sim 30$ cMpc at $z \sim 6$ comparable with the size of typical ionized bubbles at this redshift predicted by Furlanetto et al. (2006) (cf. $\delta$ defined with a circular radius of 0.07 deg; see Section 5.1). With the results of Figures 23 and 24 we calculate a Spearman’s rank correlation coefficient $\rho$ and a p-value to test the existence of the correlation between $L_{\text{Ly}\alpha}$ and $\delta_{LS}$. We obtain $\rho = -0.017 (0.020)$ with p-value $= 0.75 (0.68)$ for $z = 5.7$ (6.6) LAEs, which suggest that there are no significant correlations between $L_{\text{Ly}\alpha}$ and $\delta_{LS}$. This result indicates that bright $L_{\text{Ly}\alpha}$ LAEs are not selectively placed at the overdensity and that there is no clear evi-
Figure 14. Same as Figure 8, but for the $z = 6.6$ LAEs in D-COSMOS field. The red-dashed line represents the region of the $z = 6.6$ LAE UD-COSMOS field that is shown in Figure 13.

dence connecting the bright-end LF excess and the ionized bubble. Because the statistical uncertainty of this analysis is still large, it is not a conclusive result. However, there is an increasing possibility that the ionized bubbles and the bright-end LF excess may not be related. For the other possible origins of the bright-end excess, Konno et al. (2017) discuss the AGN/low-$z$ contamination and the blended merging galaxies. We should discuss these other possibilities more seriously.

5.2.2. Correlation between Ly$\alpha$ EW and Overdensity

Figure 25 (26) presents $EW_{\text{rest}}^{\text{Ly} \alpha}$ as a function of $\delta$ at $z = 5.7$ (6.6). $EW_{\text{rest}}^{\text{Ly} \alpha}$ is estimated in the same manner as Shibuya et al. (2017a). We calculate $EW_{\text{rest}}^{\text{Ly} \alpha}$ of LAEs from the $NB816$ ($NB921$) and $z$ ($y$) band magnitudes. We use the subsamples of the LAEs in a range of $\delta$, and obtain a median value of $EW_{\text{rest}}^{\text{Ly} \alpha}$ at a given $\delta$. We perform chi-square fitting of the linear function to the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relations, and obtain the best-fit parameters, $\alpha$ and $EW_{\delta=0}^{\text{rest}}$, defined in Section 4. Because the theoretical model predicts that the value of $\alpha$ increases from $z = 5.7$ to 6.6 (Section 4), we show redshift evolution of the slope $\alpha$ of ‘HSC mock’ at $z = 5.7$ and 6.6. (In this model, the average neutral hydrogen fraction in the IGM at $z = 5.7$ and 6.6 are log $x_{\text{HI}} = -3.9$ and $-0.36$, respectively.) The model does not show the significant evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation beyond the statistical errors, which is consistent with those of the HSC LAE samples. The model suggests that the present HSC LAE samples are not large enough to test the existence of the ionized bubbles and the inside-out scenario of cosmic reionization. The HSC survey is underway, which will significantly enlarge the sample with the wider and deeper data for LAEs at $z = 5.7$ and 6.6 and make a new sample of LAEs at $z = 7.3$. There is a possibility that the evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation

5.2.3. Comparison with the Theoretical Model

We compare the results of Section 5.2.2 with the theoretical model of Inoue et al. (2018). We select mock LAEs which are brighter than 25.0 mag in narrowbands, which is the same magnitude limit as the HSC LAE $\delta$ estimates. We also apply the selection limits of the Ly$\alpha$ EW which are similar to those of the HSC LAE samples. We thus obtain 447 (80) mock LAEs for $z = 5.7$ (6.6) that are referred to as ‘HSC mock’. We derive the best-fit parameters and errors for HSC mock in the same way as Section 5.2.2. Note that we define the error of $EW_{\text{rest}}^{\text{Ly} \alpha}$ as the range of 68% distribution. Figure 27 presents redshift evolution of the slope $\alpha$ of ‘HSC mock’ at $z = 5.7$ and 6.6. (In this model, the average neutral hydrogen fraction in the IGM at $z = 5.7$ and 6.6 are log $x_{\text{HI}} = -3.9$ and $-0.36$, respectively.) The model does not show the significant evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation beyond the statistical errors, which is consistent with those of the HSC LAE samples. The model suggests that the present HSC LAE samples are not large enough to test the existence of the ionized bubbles and the inside-out scenario of cosmic reionization. The HSC survey is underway, which will significantly enlarge the sample with the wider and deeper data for LAEs at $z = 5.7$ and 6.6 and make a new sample of LAEs at $z = 7.3$. There is a possibility that the evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation

Figure 24. Figure 24 presents $EW_{\text{rest}}^{\text{Ly} \alpha}$ as a function of $\delta$ at $z = 5.7$ (6.6). $EW_{\text{rest}}^{\text{Ly} \alpha}$ is estimated in the same manner as Shibuya et al. (2017a). We calculate $EW_{\text{rest}}^{\text{Ly} \alpha}$ of LAEs from the $NB816$ ($NB921$) and $z$ ($y$) band magnitudes. We use the subsamples of the LAEs in a range of $\delta$, and obtain a median value of $EW_{\text{rest}}^{\text{Ly} \alpha}$ at a given $\delta$. We perform chi-square fitting of the linear function to the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relations, and obtain the best-fit parameters, $\alpha$ and $EW_{\delta=0}^{\text{rest}}$, defined in Section 4. Because the theoretical model predicts that the value of $\alpha$ increases from $z = 5.7$ to 6.6 (Section 4), we show redshift evolution of the slope $\alpha$ of ‘HSC mock’ at $z = 5.7$ and 6.6. (In this model, the average neutral hydrogen fraction in the IGM at $z = 5.7$ and 6.6 are log $x_{\text{HI}} = -3.9$ and $-0.36$, respectively.) The model does not show the significant evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation beyond the statistical errors, which is consistent with those of the HSC LAE samples. The model suggests that the present HSC LAE samples are not large enough to test the existence of the ionized bubbles and the inside-out scenario of cosmic reionization. The HSC survey is underway, which will significantly enlarge the sample with the wider and deeper data for LAEs at $z = 5.7$ and 6.6 and make a new sample of LAEs at $z = 7.3$. There is a possibility that the evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation

Figure 25 (26) presents $EW_{\text{rest}}^{\text{Ly} \alpha}$ as a function of $\delta$ at $z = 5.7$ (6.6). $EW_{\text{rest}}^{\text{Ly} \alpha}$ is estimated in the same manner as Shibuya et al. (2017a). We calculate $EW_{\text{rest}}^{\text{Ly} \alpha}$ of LAEs from the $NB816$ ($NB921$) and $z$ ($y$) band magnitudes. We use the subsamples of the LAEs in a range of $\delta$, and obtain a median value of $EW_{\text{rest}}^{\text{Ly} \alpha}$ at a given $\delta$. We perform chi-square fitting of the linear function to the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relations, and obtain the best-fit parameters, $\alpha$ and $EW_{\delta=0}^{\text{rest}}$, defined in Section 4. Because the theoretical model predicts that the value of $\alpha$ increases from $z = 5.7$ to 6.6 (Section 4), we show redshift evolution of the slope $\alpha$ of ‘HSC mock’ at $z = 5.7$ and 6.6. (In this model, the average neutral hydrogen fraction in the IGM at $z = 5.7$ and 6.6 are log $x_{\text{HI}} = -3.9$ and $-0.36$, respectively.) The model does not show the significant evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation beyond the statistical errors, which is consistent with those of the HSC LAE samples. The model suggests that the present HSC LAE samples are not large enough to test the existence of the ionized bubbles and the inside-out scenario of cosmic reionization. The HSC survey is underway, which will significantly enlarge the sample with the wider and deeper data for LAEs at $z = 5.7$ and 6.6 and make a new sample of LAEs at $z = 7.3$. There is a possibility that the evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation

Figure 26. Figure 26 presents $EW_{\text{rest}}^{\text{Ly} \alpha}$ as a function of $\delta$ at $z = 5.7$ (6.6). $EW_{\text{rest}}^{\text{Ly} \alpha}$ is estimated in the same manner as Shibuya et al. (2017a). We calculate $EW_{\text{rest}}^{\text{Ly} \alpha}$ of LAEs from the $NB816$ ($NB921$) and $z$ ($y$) band magnitudes. We use the subsamples of the LAEs in a range of $\delta$, and obtain a median value of $EW_{\text{rest}}^{\text{Ly} \alpha}$ at a given $\delta$. We perform chi-square fitting of the linear function to the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relations, and obtain the best-fit parameters, $\alpha$ and $EW_{\delta=0}^{\text{rest}}$, defined in Section 4. Because the theoretical model predicts that the value of $\alpha$ increases from $z = 5.7$ to 6.6 (Section 4), we show redshift evolution of the slope $\alpha$ of ‘HSC mock’ at $z = 5.7$ and 6.6. (In this model, the average neutral hydrogen fraction in the IGM at $z = 5.7$ and 6.6 are log $x_{\text{HI}} = -3.9$ and $-0.36$, respectively.) The model does not show the significant evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation beyond the statistical errors, which is consistent with those of the HSC LAE samples. The model suggests that the present HSC LAE samples are not large enough to test the existence of the ionized bubbles and the inside-out scenario of cosmic reionization. The HSC survey is underway, which will significantly enlarge the sample with the wider and deeper data for LAEs at $z = 5.7$ and 6.6 and make a new sample of LAEs at $z = 7.3$. There is a possibility that the evolution of the $EW_{\text{rest}}^{\text{Ly} \alpha}$ - $\delta$ relation
Figure 15. Same as Figure 8, but for the $z = 6.6$ LAEs in D-ELAIS-N1 field.

from $z = 5.7$ to 7.3 may be identified by the upcoming HSC observations providing the large samples of LAEs at $z = 5.7 - 7.3$. The ionized bubbles and the inside-out scenario should be tested in the forthcoming studies with the large samples of LAEs at $z = 5.7 - 7.3$.

6. SUMMARY

In this study, we study LAE overdensities at $z = 5.7$ and 6.6 with the early datasets of the HSC SSP survey based on the 2,230 LAEs obtained in the SILVERRUSH program. We identify the LAE overdensities and discuss cosmic reionization with the properties of LAEs, overdensity $\delta$, Ly$\alpha$ luminosity $L_{\text{Ly} \alpha}$, and the rest-frame Ly$\alpha$ equivalent width $EW_{\text{Ly} \alpha}^{\text{rest}}$. Our major results are listed below:

1. We calculate the LAE overdensity $\delta$ with the samples of the HSC LAEs at $z = 5.7$ and 6.6. We identify 14 (28) $z = 5.7$ (6.6) LAE overdensities with the $\gtrsim 5\sigma$ significance level, six out of which have 1 - 12 spectroscopically confirmed LAEs. We compare the LAE overdensities with the cosmological Ly$\alpha$ radiative transfer models, and find that more than a half of these LAE overdensities (60% and 58% of the LAE overdensities at $z = 5.7$ and 6.6) are progenitors of the present-day clusters with a mass of $\gtrsim 10^{14} M_\odot$. These 14 (28) LAE overdensities are thus protocluster candidates at $z = 5.7$ (6.6) that are listed in Table 6.

2. We investigate the correlation between $L_{\text{Ly} \alpha}$ and $\delta$ with the HSC LAEs. We obtain a Spearman’s rank correlation coefficient $\rho = -0.017$ (0.020) with p-value=0.75 (0.68) for $z = 5.7$ (6.6) LAEs, which indicate that there is no evidence of significant correlations between $L_{\text{Ly} \alpha}$ and $\delta$ beyond the observational uncertainties. Our result is related to the recent discussion about the bright-end excess of Ly$\alpha$
LFs at $z = 5.7$ and 6.6 such found in [Konno et al. (2017)]. For the physical reason of the bright-end excess, there is an idea that bright galaxies selectively existing in an overdensity region are placed near the center of the ionized bubbles that allow Ly$\alpha$ photons escape from the partly neutral IGM at the EoR. Because our results show no correlation between $L_{\text{Ly} \alpha}$ and $\delta$, there is no evidence supporting this idea.

3. We study the relations between $EW_{\text{Ly} \alpha}^{\text{rest}}$ and $\delta$ at $z = 5.7$ and 6.6. We fit a linear function to the $EW_{\text{Ly} \alpha}^{\text{rest}} - \delta$ data, and find that the slope (the relation) does not evolve (is not steepened) from $z = 5.7$ to 6.6 beyond the errors. The cosmological reionization model with the Ly$\alpha$ radiative transfer suggests that the slope is steepened towards the early EoR with a high neutral hydrogen fraction in the inside-out reionization scenario, because the ionized bubbles around galaxy overdensities ease the escape of Ly$\alpha$ emission from the partly neutral IGM at the EoR. Although the model suggests that the statistical accuracy of our HSC data is not high enough to investigate this steepening, so far we find no such steepening in the available HSC data. There is a possibility of detecting the evolution of the $EW_{\text{Ly} \alpha}^{\text{rest}} - \delta$ relation from $z = 5.7$ to 7.3 by the scheduled HSC narrowband observations that will make larger samples of LAEs at $z = 5.7 - 6.6$ as well as a new sample of LAEs at $z = 7.3$.

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Figure 19. Three-dimensional map of HSC-z6PCC1. The bottom panel presents the distribution of the LAEs projected on the sky. The top-left panel shows the distribution of the LAEs on the plane of transverse (east to west) vs. radial (redshift) directions. The black filled circles represent the HSC LAEs with $NB816 < 24.5$ used for the overdensity evaluation, while the yellow filled circles denote the spectroscopically-confirmed LAEs that include faint sources with $NB816 \approx 25 - 26$. The black solid lines in the bottom panel indicate the contours of the overdensity significance levels from 5σ to 6σ with a step of 1σ. The masked regions are shown with the gray regions. The top right panel shows the redshift distribution of the spectroscopically-confirmed LAEs. The black line indicates the mean expected number of LAEs in the region.

Figure 20. Same as Figure 19 but for HSC-z6PCC4.

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Figure 21. Same as Figure 19 but for HSC-z7PCC9. The black filled circles represent the HSC LAEs with $NB921 < 25.0$. The yellow circles indicate the spectroscopically-confirmed LAEs including sources with $NB921 \approx 25 - 26$.

Figure 22. Same as Figure 21 but for HSC-z7PCC28.

Figure 23. Lyα luminosity $L_{Ly\alpha}$ as a function of large-scale overdensity $\delta_{LS}$ for the HSC LAEs at $z = 5.7$ (gray circles). The red line indicates the best-fit linear function.
Figure 24. Same as Figure 23 but for the HSC LAEs at $z = 6.6$.

Figure 25. Lyα EW and overdensity $\delta$ for the HSC LAEs at $z = 5.7$ (gray crosses). The black circles with the error bars indicate the median values of the HSC LAEs at a given $\delta$. The red line represents the best-fit linear function. The gray region indicates the Lyα EW selection limit.

Figure 26. Same as Figure 25 but for the HSC LAEs at $z = 6.6$.

Figure 27. Redshift evolution of the slope $\alpha$. The red crosses denote the HSC LAEs, while the gray (black) circles show the model predictions with the samples of 'HSC mock' and LAE all', respectively. To avoid overlaps of the symbols, we slightly shift black and grey circles by 0.05 and 0.10 in redshift, respectively.

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### Table 4
Spectroscopic Sample of the $z = 5.7$ LAEs

| ID            | R.A. (J2000) | Decl. (J2000) | $z$   | Reference |
|---------------|--------------|---------------|-------|-----------|
| HSC J021714-050944 | 34.3104      | $-5.1456$     | 5.685 | This Study |
| HSC J021712-050748 | 34.3027      | $-5.1302$     | 5.699 | This Study |
| HSC J021728-051217 | 34.3678      | $-5.2047$     | 5.676 | This Study |
| HSC J021750-050203 | 34.4619      | $-5.0342$     | 5.708 | This Study |

Note. — Spectroscopically identified LAEs at $z = 5.7$. See the full sample catalog in the version published in ApJ. (1) Object ID; (2) right ascension; (3) declination; (4) spectroscopic redshift; (5) reference of the spectroscopic redshift. O05 = Ouchi et al. (2005), O08 = Ouchi et al. (2008), M12 = Mallery et al. (2012), and SH17 = Shibuya et al. (2017b).

### Table 5
Spectroscopic Sample of the $z = 6.6$ LAEs

| ID            | R.A. (J2000) | Decl. (J2000) | $z$   | Reference |
|---------------|--------------|---------------|-------|-----------|
| HSC J021703-0415619 | 34.2644      | $-4.3986$     | 6.589 | O10       |
| HSC J021820-0511109 | 34.5862      | $-5.1861$     | 6.575 | O10       |
| HSC J021819-050900 | 34.5808      | $-5.1502$     | 6.563 | O10       |
| HSC J021757-050844 | 34.4899      | $-5.1457$     | 6.595 | O10       |

Note. — Spectroscopically identified LAEs at $z = 6.6$. See the full sample catalog in the version published in ApJ. (1) Object ID; (2) right ascension; (3) declination; (4) spectroscopic redshift; (5) reference of the spectroscopic redshift. O10 = Ouchi et al. (2010), SO15 = Sobral et al. (2015), HU16 = Hu et al. (2016), SH17 = Shibuya et al. (2017b), and C&G17 = Chanchaiworawit et al. (2017) and Guzmán et al. (in preparation).
Table 6

Protocluster Candidates

| Name (1) | Layer (2) | Field (3) | R.A. (J2000) (4) | Decl. (J2000) (5) | overdensity $\delta$ (6) | significance (7) | $n_{\text{photo}}$ (8) | $n_{\text{spec}}$ (9) | $z_{\text{spec}}$ (10) |
|----------|-----------|-----------|------------------|-------------------|-------------------------|------------------|---------------------|------------------|----------------------|
| HSC-z6PCC3 | UD | SXDS | 34.26 | $-4.32$ | 9.7 | 5.4 | 5 | 4 (5) | 0 | - |
| HSC-z6PCC1 | UD | SXDS | 34.42 | $-5.54$ | 15.0 | 8.4 | 6 (7) | 12 | 5.692 |
| HSC-z6PCC4 | UD | SXDS | 35.16 | $-4.85$ | 9.7 | 5.4 | 4 (7) | 4 | 5.719 |
| HSC-z6PCC5 | UD | COSMOS | 149.94 | 1.60 | 9.7 | 5.4 | 4 (5) | 2 | 5.686 |
| HSC-z6PCC6 | Deep | ELAIS-N1 | 241.84 | 54.27 | 9.7 | 5.4 | 4 (4) | 0 | - |
| HSC-z6PCC7 | Deep | ELAIS-N1 | 242.32 | 53.77 | 9.7 | 5.4 | 4 (5) | 0 | - |
| HSC-z6PCC8 | Deep | ELAIS-N1 | 243.22 | 53.92 | 15.0 | 8.4 | 6 (8) | 0 | - |
| HSC-z6PCC9 | Deep | DEEP2-3 | 351.30 | 0.03 | 9.7 | 5.4 | 4 (4) | 0 | - |
| HSC-z6PCC10 | Deep | DEEP2-3 | 351.95 | $-0.10$ | 9.7 | 5.4 | 4 (6) | 0 | - |
| HSC-z6PCC11 | Deep | DEEP2-3 | 352.72 | 0.60 | 9.7 | 5.4 | 4 (4) | 0 | - |
| HSC-z6PCC12 | Deep | DEEP2-3 | 352.84 | 0.91 | 9.7 | 5.4 | 4 (6) | 0 | - |
| HSC-z6PCC13 | Deep | DEEP2-3 | 352.97 | 0.08 | 9.7 | 5.4 | 4 (4) | 0 | - |
| HSC-z6PCC14 | Deep | DEEP2-3 | 353.45 | $-0.10$ | 9.7 | 5.4 | 4 (4) | 0 | - |

$z = 5.7$

| Name (1) | Layer (2) | Field (3) | R.A. (J2000) (4) | Decl. (J2000) (5) | overdensity $\delta$ (6) | significance (7) | $n_{\text{photo}}$ (8) | $n_{\text{spec}}$ (9) | $z_{\text{spec}}$ (10) |
|----------|-----------|-----------|------------------|-------------------|-------------------------|------------------|---------------------|------------------|----------------------|
| HSC-z7PCC9 | UD | SXDS | 34.62 | $-5.13$ | 6.6 | 4.6 | 4 (4) | 3 | 6.574 |
| HSC-z7PCC28 | UD | SXDS | 34.64 | $-4.56$ | 6.1 | 3.8 | 3 (3) | 5 | 6.537 |
| HSC-z7PCC11 | UD | COSMOS | 149.35 | 2.41 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC15 | UD | COSMOS | 150.30 | 2.00 | 6.6 | 4.6 | 4 (6) | 0 | - |
| HSC-z7PCC16 | UD | COSMOS | 150.48 | 2.29 | 6.6 | 4.6 | 4 (8) | 0 | - |
| HSC-z7PCC1 | Deep | COSMOS | 148.96 | 1.02 | 10.5 | 7.2 | 6 (6) | 0 | - |
| HSC-z7PCC10 | Deep | COSMOS | 149.05 | 3.10 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC2 | Deep | COSMOS | 149.40 | 1.03 | 8.5 | 5.9 | 5 (5) | 0 | - |
| HSC-z7PCC12 | Deep | COSMOS | 149.41 | 3.54 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC13 | Deep | COSMOS | 149.67 | 2.79 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC14 | Deep | COSMOS | 149.97 | 1.45 | 6.6 | 4.6 | 4 (6) | 0 | - |
| HSC-z7PCC3 | Deep | COSMOS | 150.95 | 2.78 | 8.5 | 5.9 | 5 (5) | 1 | 6.575 |
| HSC-z7PCC17 | Deep | COSMOS | 151.15 | 3.49 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC18 | Deep | COSMOS | 151.16 | 3.13 | 6.6 | 4.6 | 4 (2) | 0 | - |
| HSC-z7PCC19 | Deep | ELAIS-N1 | 240.74 | 54.63 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC4 | Deep | ELAIS-N1 | 241.27 | 54.4 | 8.6 | 5.9 | 5 (5) | 0 | - |
| HSC-z7PCC20 | Deep | ELAIS-N1 | 241.58 | 56.33 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC21 | Deep | ELAIS-N1 | 241.92 | 55.66 | 6.6 | 4.6 | 4 (7) | 0 | - |
| HSC-z7PCC22 | Deep | ELAIS-N1 | 241.95 | 53.76 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC5 | Deep | ELAIS-N1 | 242.31 | 56.4 | 8.6 | 5.9 | 5 (5) | 0 | - |
| HSC-z7PCC23 | Deep | ELAIS-N1 | 242.38 | 55.03 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC24 | Deep | ELAIS-N1 | 242.47 | 53.48 | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC8 | Deep | ELAIS-N1 | 243.33 | 56.53 | 6.7 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC25 | Deep | ELAIS-N1 | 243.52 | 56.03 | 6.6 | 4.6 | 4 (5) | 0 | - |
| HSC-z7PCC6 | Deep | ELAIS-N1 | 243.73 | 55.13 | 8.6 | 5.9 | 5 (5) | 0 | - |
| HSC-z7PCC7 | Deep | ELAIS-N1 | 243.93 | 54.35 | 8.6 | 5.9 | 5 (5) | 0 | - |
| HSC-z7PCC26 | Deep | DEEP2-3 | 351.09 | $-0.77$ | 6.6 | 4.6 | 4 (4) | 0 | - |
| HSC-z7PCC27 | Deep | DEEP2-3 | 353.04 | 0.77 | 6.6 | 4.6 | 4 (4) | 0 | - |

Note. — (1) object ID; (2) layer; (3) field; (4) right ascension of the center of the member LAEs (deg); (5) declination of the center of the member LAEs (deg); (6)-(7) highest $\delta$ and the significance level in the protocluster candidates; (8) number of the HSC LAEs in a 0.07 deg radius from the center of the protocluster candidates; (9) number of the spectroscopically-confirmed LAEs in 10 cMpc from the center of the protocluster candidates; (10) average redshift value of the spectroscopically-confirmed LAEs.
