SILVERRUSH. II. First Catalogs and Properties of $\sim 2,000$ Ly$\alpha$ Emitters and Blobs at $z \sim 6 - 7$
Identified over the $14 - 21 \, \text{deg}^2$ Sky

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Abstract

We present an unprecedentedly large catalog consisting of $2,230 \gtrsim L^* \text{Ly} \alpha$ emitters (LAEs) at $z = 5.7$ and 6.6 on the 13.8 and 21.2 deg$^2$ sky, respectively, that are identified by the SILVERRUSH program with the first narrowband imaging data of the Hyper Suprime-Cam (HSC) survey. We confirm that the LAE catalog is reliable on the basis of 96 LAEs whose spectroscopic redshifts are already determined by this program and the previous studies. This catalogue is also available on-line. Based on this catalogue, we derive the rest-frame Ly$\alpha$ equivalent-width distributions of LAEs at $z \simeq 5.7 - 6.6$ that are reasonably explained by the exponential profiles with the scale lengths of $\simeq 120 - 170$ A, showing no significant evolution from $z \simeq 5.7$ to $z \simeq 6.6$. We find that 275 LAEs with a large equivalent width (LEW) of $> 240$ A are candidates of young-metal poor galaxies and AGNs. We also find that the fraction of LEW LAEs to all ones is 4% and 21% at $z \simeq 5.7$ and $z \simeq 6.6$, respectively. Our LAE catalog includes 11 Ly$\alpha$ blobs (LABs) that are LAEs with spatially extended Ly$\alpha$ emission whose profile is clearly distinguished from those of stellar objects at the $\gtrsim 3\sigma$ level. The number density of the LABs at $z = 6 - 7$ is $\sim 10^{-7} - 10^{-6}$ Mpc$^{-3}$, being $\sim 10 - 100$ times lower than those claimed for LABs at $z \simeq 2 - 3$, suggestive of disappearing LABs at $z \gtrsim 6$, albeit with the different selection methods and criteria for the low and high-$z$ LABs.

Key words: early universe — galaxies: formation — galaxies: high-redshift

1 Introduction

Ly$\alpha$ Emitters (LAEs) are one of important populations of high-$z$ star-forming galaxies in the paradigm of the galaxy formation and evolution. Such galaxies are thought to be typically young (an order of 100 Myr; e.g., Finkelstein et al. 2007; Gawiser et al. 2007; Finkelstein et al. 2007), compact (an effective radius of $< 1$ kpc; e.g., Catinoguchi et al. 2009; Bond et al. 2012), less-massive (a stellar mass of $10^8 - 10^9 M_\odot$; e.g., Ono et al. 2010; Guitaita et al. 2011), metal-poor ($\simeq 0.1$ of the solar metallicity; e.g., Nakanjima et al. 2012; Nakanjima & Ouchi 2014; Kojima et al. 2016), less-dusty than Lyman break galaxies (e.g., Blanc et al. 2011; Kusakabe et al. 2015), and a possible progenitor of Milky Way mass galaxies (e.g., Dressler et al. 2011). In addition, LAEs are used to probe the cosmic reionization, because ionizing photons escaped from a large number of massive stars formed in LAEs contribute to the ionization of intergalactic medium (IGM; e.g., Rhoads & Malhotra 2001; Malhotra & Rhoads 2006; Shimasaku et al. 2006; Kashikawa et al. 2006; Ouchi et al. 2008; Ouchi et al. 2010; Cowie et al. 2010; Hu et al. 2010; Kashikawa et al. 2011; Shibuya et al. 2012; Konno et al. 2014; Matthee et al. 2015; Matthee et al. 2015; Ota et al. 2017; Zheng et al. 2017).

LAEs have been surveyed by imaging observations with dedicated narrow-band (NB) filters for a prominent redshifted Ly$\alpha$ emission (e.g., Ajiki et al. 2002; Malhotra & Rhoads 2004; Kodaira et al. 2003; Taniguchi et al. 2005; Gronwall et al. 2007; Erb et al. 2011; Ciardullo et al. 2012). In large LAE sample constructed by the NB observations, two rare Ly$\alpha$-emitting populations have been identified: large equivalent width (LEW) LAEs, and spatially extended Ly$\alpha$ LAEs, Ly$\alpha$ blobs (LABs).

LEW LAEs are objects with a large Ly$\alpha$ equivalent width (EW) of $\gtrsim 240$ A which are not reproduced with the normal Salpeter stellar initial mass function (e.g., Malhotra & Rhoads 2002). Such an LEW is expected to be originated from complicated physical processes such as (i) photoionization by young and/or low-metallicity star-formation, (ii) photoionization by active galactic nucleus (AGN), (iii) photoionization by external UV sources (QSO fluorescence), (iv) collisional excitation due to strong outflows (shock heating), (v) collisional excitation due to gas inflows (gravitational cooling), and (vi) clumpy ISM (see e.g., Hashimoto et al. 2017). The highly-complex radiative transfer of Ly$\alpha$ in the interstellar medium (ISM) makes it difficult to understand the Ly$\alpha$ emitting mechanism (Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2008; Laursen et al. 2013; Laursen et al. 2009; Laursen & Sommer-Larsen 2007; Zheng et al. 2010; Yajima et al. 2012; Duval et al. 2013; Zheng & Wallace 2013).

LABs are spatially extended Ly$\alpha$ gaseous nebulae in the high-$z$ Universe (e.g., Steidel et al. 2000; Matsuda et al.
The origins of LABs (LAEs with a diameter ≃ 20 – 400 kpc) are also explained by several mechanisms: (1) resonant scattering of Lyα photons emitted from central sources in dense and extended neutral hydrogen clouds (e.g., Hayes et al. 2011), (2) cooling radiation from gravitationally heated gas in collapsed halos (e.g., Haiman et al. 2000), (3) shock heating by galactic superwind originated from starbursts and/or AGN activity (e.g., Taniguchi & Shioya 2000), (4) galaxy major mergers (e.g., Yajima et al. 2013), and (5) photoionization by external UV sources (QSO fluorescence; e.g., Cantalupo et al. 2005). Moreover, LABs have been often discovered in over-density regions at z ∼ 2 – 3 (e.g., Yang et al. 2009; Yang et al. 2010; Matsuda et al. 2011). Thus, such LABs could be closely related to the galaxy environments, and might be linked to the formation mechanisms of central massive galaxies in galaxy protoclusters.

During the last decades, Suprime-Cam (SCam) on the Subaru telescope has led the world on identifying such rare Lyα-emitting populations at z ≥ 6 (LEW LAEs; e.g., Nagao et al. 2008; Kashikawa et al. 2012; LABs; e.g., Ouchi et al. 2009; Sobral et al. 2015). However, the formation mechanisms of these rare Lyα-emitting populations are still controversial due to the small statistics. While LEW LAEs and LABs at z ∼ 2 – 5 have been studied intensively with a sample of ≥ 100 sources, only a few sources have been found so far at z ∼ 6. Large-area NB data are required to carry out a statistical study on LEW LAEs and LABs at z ≥ 6.

In March 2014, the Subaru telescope has started a large-area NB survey using a new wide field of view (FoV) camera, Hyper Suprime-Cam (HSC) in a Subaru strategic program (SSP: Aihara et al. 2017b). In the five-year project, HSC equipped with four NB filters of NB387, NB816, NB921, and NB101 will survey for LAEs at z ∼ 2.2, 5.7, 6.6, and 7.3, respectively. The HSC SSP NB survey data consist of two layers: Ultradep (UD), and Deep (D), covering 2 fields (UD-COSMOS, UD-SXDS), and 4 fields (D-COSMOS, D-SXDS, D-DEEP2-3, D-ELAIS-N1), respectively. The NB816, NB921, and NB101 images will be taken for the UD fields. The NB387, NB816, and NB921 observations will be conducted in 15 HSC-pointing D fields.

Using the large HSC NB data complemented by optical and NIR spectroscopic observations, we launch a research project for Lyα-emitting objects: Systematic Identification of LAEs for Visible Exploration and Reionization Research Using Subaru HSC (SILVERRUSH). The large LAE samples provided by SILVERRUSH enable us to investigate e.g., LAE clustering (Ouchi et al. 2017), LEW LAEs and LABs (this work), spectroscopic properties of bright LAEs (Shibuya et al. 2017b), Lyα luminosity functions (Konno et al. 2017), and LAE overdensity (R. Higuchi et al. in preparation). The LAE survey strategy is given by Ouchi et al. (2017). This program is one of the twin programs. Another program is the study for dropouts, Great Optically Luminous Dropout Research Using Subaru HSC (GOLDRUSH), that is detailed in Ono et al. (2017), Harikane et al. (2017), and Toshikawa et al. (2017).

This is the second paper in the SILVERRUSH project. In this paper, we present LAE selection processes and machine-readable catalogs of the LAE candidates at z ∼ 5.7 – 6.6. Using the large LAE sample obtained with the first HSC NB data, we examine the redshift evolutions of Lyα EW distributions and LAB number density. This paper has the following structure. In Section 2, we describe the details of the SSP HSC data. Section 3 presents the LAE selection processes. In Section 4, we check the reliability of our LAE selection. Section 5 presents Lyα EW distributions and LABs at z ∼ 6 – 7. In Section 6, we discuss the physical origins of LEW LAEs and LABs. We summarize our findings in Section 7.

Throughout this paper, we adopt the concordance cosmology with (Ωm, ΩΛ, h) = (0.3, 0.7, 0.7) (Planck Collaboration et al. 2016). All magnitudes are given in the AB system (Oke & Gunn 1983).
2 HSC SSP Imaging Data

We use the HSC SSP S16A data products of $g, r, i, z, \text{and } y$ broadband (BB; Kawanomoto 2017), $NB921$ and $NB816$ (Ouchi et al. 2017) images that are obtained in 2014-2016. It should be noted that this HSC SSP S16A data is significantly larger than the one of the first-data release in Aihara et al. (2017a). The $NB921$ ($NB816$) filter has a central wavelength of $\lambda_c = 9215\text{Å}$ ($8177\text{Å}$) and an FWHM of $\Delta \lambda = 135\text{Å}$ ($113\text{Å}$), all of which are the area-weighted mean values. The $NB921$ and $NB816$ filters trace the redshifted Ly$\alpha$ emission lines at $z = 6.580 \pm 0.056$ and $z = 5.726 \pm 0.046$, respectively. The NB filter transmission curves are shown in Figure 1. The central wavelength, FWHM, and the bandpass shape for these NB filters are almost uniform over the HSC FoV. The deviation of the $\lambda_c$ and FWHM values are typically within $\pm 0.3\%$ and $\pm 10\%$. 

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Fig. 2. Flow chart of the HSC LAE selection process. See Section 3 for more details.
The HSC pipeline performs CCD-by-CCD reduction, calibration for astrometry, and photometric zero point determination. The pipeline then conducts mosaic-stacking that combines reduced CCD images into a large coadd image, and creates source catalogs by detecting and measuring sources on the coadd images. The photometric calibration is carried out with the PanSTARRS1 processing version 2 imaging survey data (Magnier et al. 2013; Schlafly et al. 2012; Tonry et al. 2012). The details of the HSC SSP survey, data reduction, and source detection and photometric catalog construction are provided in Aihara et al. (2017a), Aihara et al. (2017b), and Bosch et al. (2017).

In the HSC images, source detection and photometry were carried out in two methods: unforced and forced. The unforced photometry is a method to perform measurements of coordinates, shapes, and fluxes individually in each band image for an object. The forced photometry is a method to carry out photometry by fixing centroid and shape determined in a reference band and applying them to all the other bands. The algorithm of the forced detection and photometry is similar to the double-image mode of SExtractor (Bertin & Arnouts 1996) that are used in most of the previous studies for high-z galaxies. According to which depends on magnitudes, S/N, positions, and profiles for detected sources, one of the BB and NB filter is regarded as a reference band. For merging the catalogs of each band, the object matching radius is not a specific value which depends on an area of regions with a $>5\sigma$ sky noise level. We refer the detailed algorithm to choose the reference filter and

![Fig. 3. Multi-band cutout images of our example LAEs and spurious sources. (a) LAEs at $z \approx 6.6$ (top) and $z \approx 5.7$ (bottom) in the forced LAE catalog. (b) LAEs at $z \approx 6.6$ (top) and $z \approx 5.7$ (bottom) in the unforced catalog. In the rightmost cutout images, the yellow solid and cyan dashed circles represent the central positions of the unforced LAEs in the NB and BB images, respectively. The diameters of the yellow solid and dashed circles in the cutout images of the unforced LAEs are 1'' and 0.5'', respectively. (c) Spurious sources with an NB magnitude-excess similar to that of LAE candidates (four panel sets at the top), 1: variable (e.g., supernova); 2: cosmic ray; 3: cross-talk artifact; 4: moving object (e.g., asteroids) and corresponding multi-epoch images (four panel sets at the bottom). The image size is 4'' × 4'' for the LAEs and spurious sources.](image-url)
filter priority to Bosch et al. (2017).

In the hscPipe detection and photometry, an NB filter is basically chosen as a reference band for the NB-bright and BB-faint sources such as LAEs. However, a BB filter is used as a reference band in the case that sources are bright in the BB image. The current version of hscPipe has not implemented the NB-reference forced photometry for BB-bright sources. In this specification, there is a possibility that we miss BB-bright sources with a spatial offset between centroids of BB and NB by using only the forced photometry. Thus, we combine the unforced or forced photometry for BB – NB colors to identify such BB-bright objects with a spatial offset between centroids of BB and NB (e.g., Shibuya et al. 2014a). See Section 3 for details of the LAE selection criteria.

We use cmodel magnitudes for estimating total magnitudes of sources. The cmodel magnitude is a weighted combination of exponential and de Vaucouleurs fits to light profiles of each object. The detailed algorithm of the cmodel photometry are presented in Bosch et al. (2017). To measure the S/N values for source detections, we use 1.5′-diameter aperture magnitudes.

## 3 LAE Selection

Using the HSC data, we perform a selection for LAEs at z ≃ 6.6 and z ≃ 5.7. Basically, we select objects showing a significant flux excess in the NB images and a spectral break at the wavelength of redshifted Lyα emission. In this study, we create two LAE catalogs: HSC LAE ALL (forced+unforced) catalog and HSC LAE forced catalog. The HSC LAE ALL catalog is constructed in a combination of the forced and unforced photometry. We use this HSC LAE ALL catalog for identifying objects with a spatial offset between centroids of BB and NB (see Section 2). On the other hand, the HSC LAE forced catalog consists of LAEs meeting only the selection criteria of the forced photometry. We use this HSC LAE forced catalog for statistical studies for LAEs (e.g., Lyα LF s). The HSC LAE forced catalog is a subsample of the ALL one. Figure 2 shows the flow chart of the LAE selection process. We carry out the following processes: (1) SQL selection, (2) visual inspections for the object images, (3) rejections of variable and moving objects with the multi-epoch images, and (4) forced selection. The details are described as below.

(1) **SQL selection:** We retrieve detection and photometric catalogs from PostgreSQL database tables. Using SQL scripts, we select objects meeting the following criteria of (i) magnitude and color selections and (ii) hscPipe parameters and flags.

(i) **Magnitude and color selection:** To identify objects with an NB magnitude excess in the HSC catalog, we apply the magnitude and color selection criteria that are similar to e.g., Ouchi et al. 2008; Ouchi et al. 2010:

\[
\begin{align*}
NB921_{\text{frc}}^{\text{unf}} &< NB921_{\text{frc}}^{\text{frc}} \\
\&\& (g_{\text{frc}} > g_{\text{frc}}^{\text{unf}} || g_{\text{frc}}^{\text{unf}} > g_{\text{frc}}^{\text{frc}}) \\
\&\& (r_{\text{frc}} > r_{\text{frc}}^{\text{unf}} || r_{\text{frc}}^{\text{unf}} > r_{\text{frc}}^{\text{frc}}) \\
\&\& (z_{\text{frc}} > z_{\text{frc}}^{\text{unf}} || z_{\text{frc}}^{\text{unf}} > z_{\text{frc}}^{\text{frc}}) \\
&\& (i_{\text{frc}} > i_{\text{frc}}^{\text{unf}} || i_{\text{frc}}^{\text{unf}} > i_{\text{frc}}^{\text{frc}}) \\
&\& (z_{\text{frc}} > z_{\text{frc}}^{\text{unf}} || z_{\text{frc}}^{\text{unf}} > z_{\text{frc}}^{\text{frc}}) \\
&\& (r_{\text{frc}} > r_{\text{frc}}^{\text{unf}} || r_{\text{frc}}^{\text{unf}} > r_{\text{frc}}^{\text{frc}}) \\
&\& (i_{\text{frc}} > i_{\text{frc}}^{\text{unf}} || i_{\text{frc}}^{\text{unf}} > i_{\text{frc}}^{\text{frc}}) \\
&\& (r_{\text{frc}} > r_{\text{frc}}^{\text{unf}} || r_{\text{frc}}^{\text{unf}} > r_{\text{frc}}^{\text{frc}}) \\
&\& (i_{\text{frc}} > i_{\text{frc}}^{\text{unf}} || i_{\text{frc}}^{\text{unf}} > i_{\text{frc}}^{\text{frc}}) \\
&\& (z_{\text{frc}} > z_{\text{frc}}^{\text{unf}} || z_{\text{frc}}^{\text{unf}} > z_{\text{frc}}^{\text{frc}}) \\
&\& (r_{\text{frc}} > r_{\text{frc}}^{\text{unf}} || r_{\text{frc}}^{\text{unf}} > r_{\text{frc}}^{\text{frc}}) \\
&\& (i_{\text{frc}} > i_{\text{frc}}^{\text{unf}} || i_{\text{frc}}^{\text{unf}} > i_{\text{frc}}^{\text{frc}}) \\
&\& (z_{\text{frc}} > z_{\text{frc}}^{\text{unf}} || z_{\text{frc}}^{\text{unf}} > z_{\text{frc}}^{\text{frc}}) \\
&\& (r_{\text{frc}} > r_{\text{frc}}^{\text{unf}} || r_{\text{frc}}^{\text{unf}} > r_{\text{frc}}^{\text{frc}}) \\
&\& (i_{\text{frc}} > i_{\text{frc}}^{\text{unf}} || i_{\text{frc}}^{\text{unf}} > i_{\text{frc}}^{\text{frc}})
\end{align*}
\]

for \(z \approx 6.6\), and

\[
\begin{align*}
NB816_{\text{frc}}^{\text{unf}} &< NB816_{\text{frc}}^{\text{frc}} \\
\&\& (g_{\text{frc}} > g_{\text{frc}}^{\text{unf}} || g_{\text{frc}}^{\text{unf}} > g_{\text{frc}}^{\text{frc}}) \\
\&\& (i_{\text{frc}} > i_{\text{frc}}^{\text{unf}} || i_{\text{frc}}^{\text{unf}} > i_{\text{frc}}^{\text{frc}}) \\
&\& (r_{\text{frc}} > r_{\text{frc}}^{\text{unf}} || r_{\text{frc}}^{\text{unf}} > r_{\text{frc}}^{\text{frc}}) \\
&\& (i_{\text{frc}} > i_{\text{frc}}^{\text{unf}} || i_{\text{frc}}^{\text{unf}} > i_{\text{frc}}^{\text{frc}}) \\
&\& (r_{\text{frc}} > r_{\text{frc}}^{\text{unf}} || r_{\text{frc}}^{\text{unf}} > r_{\text{frc}}^{\text{frc}}) \\
&\& (i_{\text{frc}} > i_{\text{frc}}^{\text{unf}} || i_{\text{frc}}^{\text{unf}} > i_{\text{frc}}^{\text{frc}})
\end{align*}
\]

for \(z \approx 5.7\), where the indices of frc and unf represent the forced and unforced photometry, respectively. The subscript of 5σ (3σ) indicates the 5σ (3σ) limiting magnitude for a given filter. The values with and without a superscript of ap indicate the aperture and total magnitudes, respectively. These magnitudes are derived with the hscPipe software (see Section 2; Bosch et al. 2017). The limits of the \(i − NB816\) and \(z − NB921\) colors are the same as those of Ouchi et al. (2008) and Ouchi et al. (2010), respectively. To exploit the survey capability of HSC identifying rare objects, we use the 3σ \(g\) and \(r\) limiting magnitude (instead of the value of 2σ used in Ouchi et al. 2008) for the criteria of Lyman break off-band nondetection. In the process (4), we replace 3σ with 2σ for the \(g\) and \(r\) magnitude criteria for the consistency with the previous studies.

Note that we do not apply the flags_pixel_bright_object[center/any] masking to the LAE ALL catalog in order to maximize LAE targets for future follow-up observations (Aihara et al. 2017a). These flags for the object masking are used in the process (4).

(ii) **Parameters and flags:** Similar to Ono et al. (2017), we set several hscPipe parameters and flags in the HSC catalog to exclude e.g., blended sources, and objects affected by saturated pixels, and nearby bright source halos. We also mask regions where exposure times are relatively short by using the countinputs parameter, \(N_c\), which denotes the number of exposures at a source position for a given filter. Table 2 summarizes the values and brief explanations of the hscPipe parameters and flags used for our LAE selection. The full details of these parameters and flags are presented in Aihara et al. (2017a). To search for LAEs in large areas of the HSC fields, we do not apply the countinputs parameter to the BB images.
Table 1. Properties of the HSC SSP S16A NB Data

| Field          | R.A. (J2000) | Dec. (J2000) | Area (deg²) | $T_{\text{exp}}$ (hour) | $m_{\text{lim}}(5\sigma, 1.5''\phi)$ (mag) | $N_{\text{LAE,ALL}}$ | $N_{\text{LAE,F}}$ |
|----------------|--------------|--------------|-------------|-------------------------|------------------------------------------|----------------------|-------------------|
| UD-COSMOS      | 10:00:28     | +02:12:21    | 2.05        | 11.25                  | 25.6                                     | 338                  | 116               |
| UD-SXDS        | 02:18:00     | -05:00:00    | 2.02        | 7.25                   | 25.5                                     | 58                   | 23                |
| D-COSMOS       | 10:00:60     | +02:13:53    | 5.31        | 2.75                   | 25.3                                     | 244$^a$              | 47$^a$            |
| D-DEEP2-3      | 23:30:22     | -00:44:38    | 5.76        | 1.00                   | 24.9                                     | 164                  | 35                |
| D-ELAIS-N1     | 16:10:00     | +54:17:51    | 6.08        | 1.75                   | 25.3                                     | 349                  | 48                |
| **Total**      |              |              | 21.2        | 24.00                  |                                          | 1153                 | 269               |

| Field          | R.A. (J2000) | Dec. (J2000) | Area (deg²) | $T_{\text{exp}}$ (hour) | $m_{\text{lim}}(5\sigma, 1.5''\phi)$ (mag) | $N_{\text{LAE,ALL}}$ | $N_{\text{LAE,F}}$ |
|----------------|--------------|--------------|-------------|-------------------------|------------------------------------------|----------------------|-------------------|
| UD-COSMOS      | 10:00:28     | +02:12:21    | 1.97        | 5.50                    | 25.7                                     | 201                  | 176               |
| UD-SXDS        | 02:18:00     | -05:00:00    | 1.93        | 3.75                    | 25.5                                     | 224                  | 188               |
| D-DEEP2-3      | 23:30:22     | -00:44:38    | 4.37        | 1.00                    | 25.2                                     | 423                  | 282               |
| D-ELAIS-N1     | 16:10:00     | +54:17:51    | 5.56        | 1.00                    | 25.3                                     | 229                  | 130               |
| **Total**      |              |              | 13.8        | 11.25                   |                                          | 1077                 | 776               |

(1) Field.
(2) Right ascension.
(3) Declination.
(4) Survey area with the HSC SQL parameters in Table 2.
(5) Total exposure time of the NB imaging observation.
(6) Limiting magnitude of the NB image defined by a $5\sigma$ sky noise in a $1.5''$ diameter circular aperture.
(7) Number of the LAE candidates in the ALL (unforced+forced) catalog.
(8) Number of the LAE candidates in the forced catalog.

$^a$ The value of $N_{\text{LAE,ALL}}$ ($N_{\text{LAE,F}}$) includes 30 (7) LAEs selected in UD-COSMOS.

Table 2. HSC SQL Parameters and Flags for Our LAE Selection

| Parameter or Flag         | Value | Band | Comment |
|---------------------------|-------|------|---------|
| detect_is_tract_inner    | True  | —    | Object is in an inner region of a tract and not in the overlapping region with adjacent tracts |
| detect_is_patch_inner    | True  | —    | Object is in an inner region of a patch and not in the overlapping region with adjacent patches |
| countinputs              | $\geq 3$ | NB   | Number of visits at a source position for a given filter. |
| flags_pixel_edge         | False | grizy,NB | Locate within images |
| flags_pixel_interpolated_center | False | grizy,NB | None of the central $3 \times 3$ pixels of an object is interpolated |
| flags_pixel_saturated_center | False | grizy,NB | None of the central $3 \times 3$ pixels of an object is saturated |
| flags_pixel_cr_center    | False | grizy,NB | None of the central $3 \times 3$ pixels of an object is masked as cosmic ray |
| flags_pixel_bad          | False | grizy,NB | None of the pixels in the footprint of an object is labelled as bad |

The number of objects selected in this process is $n_{\text{SQL}} \simeq 121,000$.

(2) **Visual inspections for object images:** To exclude cosmic rays, cross-talks, compact stellar objects, and artificial diffuse objects, we perform visual inspections for the BB and NB images of all the objects selected in the process (1). Most spurious sources are diffuse components near bright stars and extended nearby galaxies. The hscPipe software conducts the cmodel fit to broad light profiles of such diffuse sources in the NB images, which enhances the $BB - NB$ colors. For this reason, the samples constructed in the current SQL selection are contaminated by many diffuse components. Due to the clear difference of the appearance between LAE candidates and diffuse components, such spurious sources can be easily excluded through the visual inspections. The number of objects selected in this process is $n_{\text{vis}} \simeq 10,900$.

The visual inspection processes are mainly conducted by one of the authors. For the reliability check, four authors in this paper have individually carried out such visual inspections.
Fig. 4. (Top) Color of $z - NB921$ as a function of $NB921$ magnitude for the LAEs at $z \simeq 6.6$ in the UD (left) and D (right) fields. The filled red and open magenta circles denote the forced and unforced LAEs, respectively. For the LAEs undetected in the $z$-band images, the $z$-band magnitudes are replaced with the $2\sigma$ limiting magnitudes. The $x$-axis denotes the forced (unforced) $z - NB921$ colors for the forced (unforced) LAEs. The horizontal dashed and dotted line shows the color criteria of $z - NB921 > 1.0$ and $z - NB921 > 1.8$, respectively. The gray dots present objects detected in the $NB921$ images. The solid curves show the $3\sigma$ error tracks of $z - NB921$ color for each field. The $3\sigma$ error tracks are derived by Equation 3. (Bottom) Color of $i - NB816$ as a function of $NB816$ magnitude for the LAEs at $z \simeq 5.7$. The definitions of symbols, curves, and lines are the same as those of the top panels.

For $z \simeq 5.300$ objects in the UD-COSMOS $NB816$ fields, and compare the results of the LAE selection. The difference in the number of selected LAEs is within $\pm 5$ objects. Thus, we do not find a large difference in our visual inspection results.

(3) Rejection of variable and moving objects with multi-epoch images: We exclude variable and moving objects such as supernovae, AGNs, satellite trails, and asteroids using multi-epoch NB images. The NB images were typically taken a few months - years after the BB imaging observations. For this reason, there is a possibility that sources with
an NB flux excess are variable or moving objects which happened to enhance the luminosities during the NB imaging observations. The NB images are created by coadding $\simeq 10 - 20$ and $\simeq 3 - 5$ frames of 15 minute exposures for the current HSC UD and D data, respectively. Using the multi-epoch images, we automatically remove the variable and moving objects as follows. First, we measure the flux for individual epoch images, $f_{\text{1 epoch}}$, for each object. Next, we obtain an average, $f_{\text{ave}}$, and a standard deviation, $\sigma_{\text{epoch}}$, from a set of the $f_{\text{1 epoch}}$ values after a $2\sigma$ flux clipping. Finally, we discard an object having at least a multi-epoch image with a significantly large $f_{\text{1 epoch}}$ value of $f_{\text{1 epoch}} \geq f_{\text{ave}} + A_{\text{epoch}} \times \sigma_{\text{epoch}}$. Here we tune the $A_{\text{epoch}}$ factor based on the depth of the NB fields. The $A_{\text{epoch}}$ value is typically $\simeq 2.0 - 2.5$. Figure 3 shows examples of the spurious sources.

We also perform visual inspections for multi-epoch images to remove contaminants which are not excluded in the automatic rejection above. We refer the remaining objects after this process as the LAE ALL catalog.

**Forced selection:**

In the selection criteria of Equations (1) and (2), the HSC LAE ALL catalog is obtained in the combination of the forced and unforced colors. In this process, we select LAEs only with the forced color excess to create the forced LAE subsamples from the HSC LAE ALL catalog. In addition, the $3\sigma$ limit is replaced with $2\sigma$ for the criteria of $g$ and $r$ band non-detections.

Here we also adopt a new stringent color criterion of $z - NB921 > 1.8$ for $z \simeq 6.6$ LAEs. Due to the difference of the $z$ band transmission curves between SCam and HSC, the criterion of $z - NB921 > 1.0$ in Equation (1) do not allow us to select LAEs whose $EW_{0,Ly\alpha}$ is similar to those of previous SCam studies. The $BB - NB$ color crite-

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**Fig. 5.** Surface number density (SND) of the HSC LAEs at $z \simeq 6.6$ (five panels at the left) and $\simeq 5.7$ (four panels at the right) in each UD and D field. The filled red and open magenta circles indicate the LAEs in the forced and ALL catalog, respectively. The error bars are given by Poisson statistics from the number of LAEs. The gray crosses represent the LAEs in Ouchi et al. (2010) for $z \simeq 6.6$ and Ouchi et al. (2008) for $z \simeq 5.7$. The data points of the gray crosses are identical in all the fields for each redshift. The SND slightly declines in the HSC LAEs at NB $\gtrsim 24.5$ mag would be originated from the incompleteness of the LAE detection and selection. The completeness-corrected SNDs are presented in Konno et al. (2017). The data points of the HSC LAEs are slightly shifted along x-axis for clarity.
Fig. 6. Surface number density (SND) as a function of NB magnitude for the LAEs at $z \sim 6.6$ (left) and $\sim 5.7$ (right) in the HSC LAE forced catalog. The colored symbols denote the LAEs in each UD and D field (green circles: UD-SXDS; magenta squares: UD-COSMOS; cyan triangles: D-ELAIS-N1; light-red inverse-triangles: D-DEEP2-3; orange diamonds: D-COSMOS). The error bars are given by Poisson statistics from the number of LAEs. The gray crosses represent the LAEs in Ouchi et al. (2010) for $z \sim 6.6$ and Ouchi et al. (2008) for $z \sim 5.7$. The SND slight declines in the HSC LAEs at $NB > 24.5$ mag would be originated from the incompleteness of the LAE selection. The completeness-corrected SNDs are presented in Konno et al. (2017). The data points of the HSC LAEs are slightly shifted along x-axis for clarity.

Table 3. Photometric properties of example LAE candidates

| Object ID      | NB (mag) | g (mag) | r (mag) | i (mag) | z (mag) | y (mag) |
|----------------|----------|---------|---------|---------|---------|---------|
| HSC J021601−041442 | 23.85 ± 0.10 | 26.89 ± 0.45 | 27.03 ± 0.62 | 26.65 ± 0.63 | 25.28 ± 0.31 | 25.29 ± 0.53 |
| HSC J021754−051454 | 24.01 ± 0.12 | > 27.6 | > 27.3 | > 26.9 | 26.09 ± 0.57 | 25.21 ± 0.50 |
| HSC J021702−050604 | 24.64 ± 0.21 | > 27.6 | > 27.6 | > 26.9 | > 26.5 | > 25.8 |
| HSC J021638−043228 | 24.74 ± 0.23 | > 27.6 | > 27.3 | > 26.9 | 26.17 ± 0.60 | > 25.8 |
| HSC J021609−050236 | 24.90 ± 0.26 | 27.53 ± 0.72 | 27.29 ± 0.75 | > 26.9 | 26.32 ± 0.67 | > 25.8 |

(1) Object ID.
(2)-(7) Total magnitude of NB-, g-, r-, i-, z, and y-bands.
The 2$\sigma$ limits of the total magnitudes for the undetected bands.
(The complete machine-readable catalogs will be available on our project webpage at http://cos.icrr.u-tokyo.ac.jp/rush.html.)

Lya in the forced selection correspond to the rest-frame Lya EW of $EW_{\text{Ly}α} > 14$ Å and $> 10$ Å for $z \sim 6.6$ and $z \sim 5.7$ LAEs, respectively. These $EW_{\text{Ly}α}$ limits are comparable to those of the previous SCam studies (e.g., Ouchi et al. 2010). The relation between $EW_{\text{Ly}α}$ and $BB − NB$ colors is described in Konno et al. (2017) in details. Moreover, we remove the objects in masked regions defined by the flags_pixel_bright_object_[center/any] parameters (Aihara et al. 2017a).

We refer the set of the remaining objects after this process as
the forced LAE catalog. This forced LAE catalog is used for studies on LAE statistics such as measurements of Lyα EW scale lengths.

The LAE candidates selected in this forced selection are referred to as the forced LAEs. On the other hand, we refer to the remaining LAE candidates in the HSC LAE ALL catalog as the unforced LAEs. The examples of forced and unforced LAEs are shown in Figure 3. As shown in the top-right panels of Figure 3, the unforced LAEs have a ≃ 0.2 − 0.3 spatial offset between centroids in NB and BB.

In total, we identify 2,230 and 1,045 LAE candidates in the HSC LAE ALL and forced catalogs, respectively. Table 1 presents the numbers of LAE candidates in each field. The machine-readable catalogs of all the LAE candidates will be provided on our project webpage at http://cos.icrr.u-tokyo.ac.jp/rush.html. The photometric properties of example LAE candidates are shown in Table 3.

As shown in Table 1, the number of $z \simeq 5.7$ LAEs in D-DEEP2-3 appears to be large compared to that of the other $z \simeq 5.7$ fields. This may be because the seeing of the NB816 images of D-DEEP2-3 is better than that of the other $z \simeq 5.7$ fields. Similarly, the small number of $z \simeq 6.6$ LAEs in UD-SXDS may be affected by the seeing size. The number density of LAEs is discussed in the next section. Note that edge regions of UD-COSMOS is overlapped with a flanking field, D-COSMOS (Aihara et al. 2017b). We find that 30 (7) LAEs in UD-COSMOS are also selected in the HSC LAE ALL (forced) sample of D-COSMOS. To analyze the D field independently in the following sections, we include the overlapped LAEs in the D-COSMOS sample.

Figure 4 shows the color-magnitude diagrams for the LAE candidates. The solid curves in the color magnitude diagrams indicate the 3σ errors of $BB - NB$ color as a function of the NB flux, $f_{NB}$, given by

$$\pm 3\sigma_{BB-NB} = -2.5 \log_{10} \left(1 \pm 3 \sqrt{\frac{f_{z\text{NB}}^2 + f_{z\text{BB}}^2}{f_{NB}}} \right), \quad (3)$$

where $f_{z\text{NB}}$ and $f_{z\text{BB}}$ are the 1σ flux error in the $z$ and $NB921$ ($i$ and $NB816$) bands for $z \simeq 6.6$ ($z \simeq 5.7$), respectively. As shown in Figure 4, the LAE candidates have a significant NB magnitude excess.

4 Checking the Reliability of Our LAE Selection

Here we check the reliability of our LAE selection.

4.1 Spectroscopic Confirmations

We have conducted optical spectroscopic observations with Subaru/FOCAS and Magellan/LDSS3 for 18 bright LAE candidates with $NB \lesssim 24$ mag. In these observations, we have confirmed 13 LAEs. By investigating our spectroscopic catalog of Magellan/IMACS, we also spectroscopically identify 8 LAEs with $NB \lesssim 24$ mag. In addition, we find that 75 LAEs are spectroscopically confirmed in literature (Murayama et al. 2007; Ouchi et al. 2008; Taniguchi et al. 2009; Ouchi et al. 2010; Mallery et al. 2012; Sobral et al. 2015; Higuchi et al. in preparation). In total, 96 LAEs have been confirmed in our spectroscopy and previous studies. Using the spectroscopic sample whose number of observed LAEs is known, we estimate the contamination rate to be ≃ 0 − 30%. The details of the spectroscopic observations and contamination rates are given by Shibuya et al. (2017b).

4.2 LAE Surface Number Density

Figure 5 shows the surface number density (SND) of our LAE candidates and LAEs identified in previous Subaru/SCam NB surveys, SCam LAEs (e.g., Ouchi et al. 2008; Ouchi et al. 2010). We find that the SNDs of the forced LAEs are comparable to those of SCam LAEs. On the other hand, the SNDs of unforced LAEs at $z \simeq 6.6$ are higher than that of SCam LAEs. The high SND of the unforced LAEs is mainly caused by the color criterion for the HSC LAE ALL catalog of $z - NB921 > 1.0$ that is less stringent than $z - NB921 > 1.8$ (see Section 3). We also identify SND humps of our forced LAEs at $z \simeq 6.6$ at the bright-end of $NB \simeq 23$ mag in UD-COSMOS. The presence of such a SND hump has been reported by $z \simeq 6.6$ LAE studies (e.g., Matthee et al. 2015). The significance of the bright-end hump existence in Lyα LFs is ≃ 3σ, which are discussed in Konno et al. (2017). The slight declines in SNDs at a faint NB magnitude of $NB \gtrsim 24.5$ mag would be originated from the incompleteness of the LAE detection and selection. Konno et al. (2017) present the SND corrected for the incompleteness.

Figure 6 compiles the SNDs of all the HSC UD and D fields. We find that our SNDs show a small field-to-field variation, but typically follow those of the SCam LAEs.

4.3 Matching Rate of HSC LAEs and SCam LAEs

The UD-SXDS field has been observed previously by SCam equipped with the NB921 and NB816 filters (Ouchi et al. 2008; Ouchi et al. 2010). We compare the catalogs of our selected HSC LAE candidates and SCam LAEs, and calculate the object matching rates as a function of NB magnitudes. The object matching radius is 1″. The object matching rate between the HSC LAEs and SCam LAEs is ≃ 90% at a bright NB magnitude of $\lesssim 24$ mag. The high object matching rate indicates that we adequately identify LAEs in our selection processes. However, the matching rate decreases to ≃ 70% at a faint magnitude of $\simeq 24.5$ mag. This is due to the shallow depth of the HSC NB fields compared to the SCam ones. Konno et al. (2017) discuss the detection completeness of faint LAEs.
Fig. 7. Lyα EW distribution for the HSC LAEs at $z \simeq 6.6$ (left) and $z \simeq 5.7$ (right). The top and bottom panels show the UD and D fields, respectively. The thin gray histograms with error bars denote the Lyα EW distributions for the forced LAEs. The error bars are given by Poisson statistics from the number of sample LAEs. The red solid and blue dashed lines present the best-fit exponential and Gaussian functions of Equations (4) and (5), respectively, which are obtained from MC simulations with the $EW_{0, Ly\alpha}$ uncertainties (see Section 5.1 for more details).

5 Results

Here we present the Lyα EW distributions (Section 5.1) and LABs selected with the HSC data (Section 5.2). For the consistency with previous LAE studies, we use the forced LAE sample in the following analyses, if not specified.

5.1 Lyα EW Distribution

We present the Lyα EW distributions for LAEs at $z \simeq 5.7 - 6.6$. In a method described in Section 8, we calculate the rest-frame Lyα EW, $EW_{0,Ly\alpha}$, for the LAEs. The $y(z)$ band magnitudes are used for the rest-frame UV continuum emission of $z \simeq 6.6$ ($z \simeq 5.7$) LAEs. Figure 7 shows the observed Lyα EW distributions at $z \simeq 5.7 - 6.6$ in the UD and D fields. To quantify these Lyα EW distributions we perform Monte Carlo (MC) simulations. The procedure of the MC simulations is similar to that of e.g., Shimasaku et al. (2006), Ouchi et al. (2008) and Zheng et al. (2014). First, we generate artificial LAEs in a Lyα luminosity range of $\log L_{Ly\alpha}/\text{erg s}^{-1} = 42 - 44$ according to $z \simeq 5.7 - 6.6$ Lyα LFs of Konno et al. (2017). Next, we assign Lyα EW and BB magnitudes to each LAE by assuming that the Lyα EW distributions are the exponential and Gaussian functions (e.g., Gronwall et al. 2007; Kashikawa et al. 2011; Oyarzún et al. 2016):

$$\frac{dN}{dEW} = N \exp \left( - \frac{EW}{W_e} \right),$$

(4)

and,

$$\frac{dN}{dEW} = N \frac{1}{\sqrt{2\pi}\sigma_g^2} \exp \left( - \frac{EW^2}{2\sigma_g^2} \right),$$

(5)

where $N$ is the galaxy number, $W_e$ and $\sigma_g$ are the Lyα EW scale lengths of the exponential and Gaussian functions, respectively. By changing the intrinsic $W_e$ and $\sigma_g$ values, we make samples of artificial Lyα EW distributions. We then select LAEs based on NB and BB limiting magnitudes and $BB - NB$ colors corresponding to Lyα EW limits which are the same as those of our LAE selection criteria (Section 3). Finally, the best-fit Lyα EW scale lengths are obtained by fitting to the artificial Lyα EW distribution to the observed ones.

Figure 7 presents the Lyα EW distributions obtained in the MC simulations. As shown in Figure 7, we find that the Lyα
EW distributions are reasonably explained by the exponential and Gaussian profiles. The best-fit scale lengths are summarized in Table 5. The best-fit exponential (Gaussian) Ly\(\alpha\) scale lengths are, on average of the UD and D fields, 153 \(\pm\) 18 Å and 154 \(\pm\) 15 Å (146 \(\pm\) 24 Å and 139 \(\pm\) 14 Å) at \(z \approx 5.7\) and \(z \approx 6.6\), respectively. As show in Table 5, there is no large difference in the Ly\(\alpha\) EW scale lengths for the UD and D fields. This no large \(EW_{0,\text{Ly}\alpha}\) difference indicates that the results of our best-fit Ly\(\alpha\) EW scale lengths does not highly depend on the image depths and the detection incompleteness. In Section 6.1, we discuss the redshift evolution of the Ly\(\alpha\) EW scale lengths.

We investigate LEW LAEs whose intrinsic Ly\(\alpha\) EW value, \(EW_{0,\text{Ly}\alpha}^{\text{int}}\), exceeds 240 Å (e.g., Malhotra & Rhoads 2002; Dawson et al. 2004). To obtain \(EW_{0,\text{Ly}\alpha}^{\text{int}}\), we correct for the IGM attenuation for Ly\(\alpha\) using the prescriptions of Madau (1995). In the HSC LAE ALL sample, we find that 45 and 230 LAEs have a LEW of \(EW_{0,\text{Ly}\alpha}^{\text{int}} > 240\) Å, for \(z \approx 6.6\) and \(z \approx 5.7\), respectively. These LEW LAEs are candidates of young-metal poor galaxies and AGNs. The fraction of the LEW LAEs in the sample is 21% for \(z \approx 5.7\). The fraction of LEW LAEs at \(z \approx 5.7\) is comparable to that of previous studies on \(z \approx 5.7\) (e.g., \(\sim 25\%\) at \(z \approx 5.7\) in Ouchi et al. 2008; \(\sim 30 \sim 40\%\) at \(z \approx 5.7\) in Shimasaku et al. 2006). In contrast, the fraction of LEW LAEs at \(z \approx 6.6\) is 4% which is lower than that at \(z \approx 5.7\). The low fraction at \(z \approx 6.6\) might be due to the neutral hydrogen IGM absorbing the Ly\(\alpha\) emission. Out of the LEW LAEs, 32 and 150 LAEs at \(z \approx 6.6\) and \(z \approx 5.7\) exceed \(EW_{0,\text{Ly}\alpha}^{\text{int}} = 240\) beyond the 1\(\sigma\) uncertainty of \(EW_{0,\text{Ly}\alpha}^{\text{int}}\).
respectively.

5.2 LABs at \( z \simeq 5.7 - 6.6 \)

We search for LABs with spatially-extended Ly\( \alpha \) emission. To identify LABs, we measure the NB isophotal areas, \( A_{iso} \), for the forced LAEs. In this process, we include an unforced LAE, Himiko, which is an LAB identified in a previous SCam NB survey (Ouchi et al. 2009). First, we estimate the sky background level, and obtain the \( \sigma_{iso} \) values as pixels with fluxes brighter than the 2\( \sigma \) sky fluctuation. Note that the NB magnitudes include both fluxes of Ly\( \alpha \) and the rest-frame UV continuum emission. Instead of creating Ly\( \alpha \) images by subtracting the flux contribution of the rest-frame UV continuum emission, we here simply use the NB images for consistency with previous studies (e.g., Ouchi et al. 2009).

Using \( A_{iso} \) and NB magnitude diagrams, we select LABs which are significantly extended compared to point sources. This selection is similar to that of Yang et al. (2010). Figure 8 presents \( A_{iso} \) as a function of total NB magnitude. We also plot star-like point sources which are randomly selected in HSC NB fields. The \( A_{iso} \) and NB magnitude selection window is defined by a 2.5\( \sigma \) deviation from the \( A_{iso} \)-NB magnitude distribution for the star-like point sources. The value of 2.5\( \sigma \) is applied for fair comparisons with previous studies of e.g., Yang et al. (2009) and Yang et al. (2010) who have used \( z \simeq 2 - 4\sigma \). We perform visual inspections for the NB cutout images to remove unreliable LABs which are significantly affected by e.g., diffuse halos of nearby bright stars.

In total, we identify 11 LABs at \( z \simeq 5.7 - 6.6 \). Figure 9 and Table 4 present multi-band cutout images and properties for the LABs, respectively. As shown in Figure 9, these LABs are spatially extended in NB. Our HSC LAB selection confirms that CR7 and Himiko have a spatially extended Ly\( \alpha \) emission. Six out of our 11 LABs have been confirmed by our spectroscopic follow-up observations (Shibuya et al. 2017b) and previous studies (Ouchi et al. 2009; Mallery et al. 2012; Sobral et al. 2015). In Section 6.2, we discuss the redshift evolution of the LAB number density.

| Object ID          | \( \alpha \) (J2000) | \( \delta \) (J2000) | \( NB_{tot} \) (mag) | \( UV_{tot} \) (mag) | \( \log L_{Ly\alpha} \) (erg s\(^{-1}\)) | \( EW_{Ly\alpha} \) (\AA) | \( z_{spec} \)  |
|-------------------|---------------------|---------------------|---------------------|---------------------|--------------------------------|----------------------|------------|
| HSC J100058+014815\(^a\) | 10:00:58.00 +01:48:15.14 | 23.25 24.48 43.9\(^e\) | 211 \(\pm\) 20\(^e\) | 6.604\(^e\) |
| HSC J021757−050844\(^b\) | 02:17:57.58 −05:08:44.64 | 23.50 25.40 43.4\(^e\) | 78\(^{+8}_{-6}\) | 6.595\(^b\) |
| HSC J100334+024566\(^c\) | 10:03:34.66 +02:45:46.56 | 23.61 24.97 43.5\(^e\) | 61 \(\pm\) 20\(^e\) | 6.575\(^e\) |

\( NB_{tot} \) (z \simeq 6.6)

| Object ID          | \( \alpha \) (J2000) | \( \delta \) (J2000) | \( NB_{tot} \) (mag) | \( UV_{tot} \) (mag) | \( \log L_{Ly\alpha} \) (erg s\(^{-1}\)) | \( EW_{Ly\alpha} \) (\AA) | \( z_{spec} \)  |
|-------------------|---------------------|---------------------|---------------------|---------------------|--------------------------------|----------------------|------------|
| HSC J100129+014929 | 10:01:29.07 +01:49:29.81 | 23.47 25.87 43.4 | 95\(^{+40}_{-19}\) | 5.707\(^d\) |
| HSC J100109+021513 | 10:01:09.72 +02:15:13.45 | 23.13 25.77 43.6 | 257\(^{+172}_{-76}\) | 5.712\(^d\) |
| HSC J100123+015600 | 10:01:23.84 +01:56:00.46 | 23.94 26.43 43.3 | 106\(^{+70}_{-27}\) | 5.726\(^d\) |
| HSC J095946+013208 | 09:59:46.73 +01:32:08.45 | 24.16 26.12 43.1 | 52\(^{+25}_{-13}\) | — |
| HSC J100139+015428 | 10:01:39.94 +01:54:28.34 | 24.11 26.58 43.2 | 100\(^{+60}_{-30}\) | — |
| HSC J161927+551144 | 16:19:27.73 +55:11:44.70 | 22.88 24.86 43.7 | 89\(^{+33}_{-20}\) | — |
| HSC J161403+535701 | 16:14:03.82 +53:57:01.25 | 23.53 25.32 43.4 | 51\(^{+23}_{-12}\) | — |
| HSC J232924+003600 | 23:29:24.85 +00:36:00.34 | 23.62 26.48 43.4 | 55\(^{+45}_{-14}\) | — |

(1) Object ID.
(2) Right ascension.
(3) Declination.
(4) Total magnitudes of \( NB_{tot} \)- and \( NB_{816} \)-bands for \( z \simeq 6.6 \) and \( z \simeq 5.7 \), respectively.
(5) Total magnitudes of \( y \)- and \( z \)-bands for \( z \simeq 6.6 \) and \( z \simeq 5.7 \), respectively.
(6) Ly\( \alpha \) luminosity.
(7) Rest-frame equivalent width of Ly\( \alpha \) emission line.
(8) Spectroscopic redshift.
\(^a\) CR7 in Sobral et al. (2015).
\(^b\) Himiko in Ouchi et al. (2009).
\(^c\) Spectroscopically confirmed in Shibuya et al. (2017b).
\(^d\) Spectroscopically confirmed in Mallery et al. (2012).
\(^e\) Spectroscopic measurements from the literature.

\( NB_{816} \) (z \simeq 5.7).

Table 4. Properties of the LABs selected in the HSC NB Data.
6 Discussion

6.1 Redshift Evolution of Lyα EW Distribution

We discuss the redshift evolution of the Lyα EW scale lengths in a compilation of the results from literature (Zheng et al. 2014; Ouchi et al. 2008; Nilsson et al. 2009; Hu et al. 2010; Kashikawa et al. 2011; Cowie et al. 2011; Ciardullo et al. 2012). Figure 10 shows the redshift evolution of the Lyα EW scale lengths at z ≃ 0 − 7. Our best-fit Lyα scale lengths are comparable to that of Kashikawa et al. (2011) and/or Zheng et al. (2014) at z ≃ 5.7 − 6.6. The high Lyα EW scale lengths at higher z would indicate that metal-poor and/or less-dusty galaxies with a strong Lyα emission is more abundant at higher-z (e.g., Stark et al. 2011). In addition, Zheng et al. (2014) have found that the Lyα EW scale length increases towards high-z following a (1+z)-form. Our Wα and σα values for z ≃ 5.7 − 6.6 are also roughly comparable to Zheng et al.’s (1+z)-form evolution. However, no significant evolution in the Lyα EW scale lengths from z ≃ 5.7 to z ≃ 6.6 is identified in our HSC LAE data, although a possible decline in σα in the UD fields is found. A slight decrease both in Wα and σα from z ≃ 5.7 to z ≃ 6.6 has been found by Kashikawa et al. (2011). This sudden decline in the Lyα scale lengths at z ≃ 6.6 may be caused by the increasing hydrogen neutral fraction in the epoch of the cosmic reionization at z ≫ 7. Note that the Lyα EW scale length measurements would largely depend on BB and NB depths and Lyα EW cuts. Using deeper NB and BB images from the future HSC data release, we will examine the redshift evolution of Lyα scale lengths accurately.

6.2 Redshift Evolution of LAB Number Density

We discuss the redshift evolution of the LAB number density, NLAB. Figure 11 shows NLAB at z ≃ 0 − 7 measured by this study and the literature (Keel et al. 2009; Yang et al. 2009; Yang et al. 2010; Matsuda et al. 2009; Saito et al. 2006). For the plot of the NLAB, Yang et al. (2010) have compiled NLAB measurements down to an NB surface brightness (SB) limit of 5 × 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2}. The SB limits of our HSC NB data are ≃ 5 × 10^{-18} and ≃ 8 × 10^{-18} erg s^{-1} cm^{-2} for the UD and D fields, respectively. Our HSC NB images at least for the UD fields are comparably deep, allowing for fair comparisons with Yang et al.’s NLAB plot. Our NLAB values are 1.4 × 10^{-6} and 2.9 × 10^{-7} Mpc^{-3} (2.6 × 10^{-7} and 1.1 × 10^{-7} Mpc^{-3}) at z ≃ 5.7 and z ≃ 6.6 in the UD (D) fields, respectively. The number density at z ≃ 6 − 7 is ≃ 10 − 100 times lower than those claimed for LABs at z ≃ 2 − 3 (e.g., Matsuda et al. 2004; Yang et al. 2009; Yang et al. 2010). As shown in Figure 11, there is an evolutional trend that NLAB increases from z ≃ 7 to ≃ 3 and subsequently decreases from z ≃ 3 to ≃ 0. This trend of the LAB number density evolution is similar to the Madau-Lilly plot of the cosmic SFR density (SFRD) evolution (e.g., Madau et al. 1996; Lilly et al. 1996). Similar to Shibuya et al. (2016), we fit the Madau-Lilly plot-type formula,

\[ N_{LAB}(z) = a \times \frac{(1+z)^b}{1 + [(1+z)/c]^d}, \]  

where a, b, c, and d are free parameters (Madau & Dickinson 2014).
2014) to our $N_{\text{LAB}}$ evolution. For the fitting, we exclude Matsuda et al. (2009)’s data point which has been obtained in a overdense region, SSA22. The best-fit parameters are $a = 9.1 \times 10^{-8}$, $b = 2.9$, $c = 5.0$, and $d = 11.7$.

The similarity of the cosmic SFRD and LAB evolution might indicate that the origin of LABs are related to the star formation activity. As described in Section 1, LABs are thought to be formed in physical mechanisms that are connected with the star formation, e.g., the cold gas accretion and the galactic superwinds. The cold gas accretion could produce the extended Ly$\alpha$ emission powered by the gravitational energy (e.g., Momose et al. 2016; Mas-Ribas & Dijkstra 2016; Mas-Ribas et al. 2017). On the other hand, the superwinds induced by the starbursts in the central galaxies would blow out the surrounding neutral gas, and form extended Ly$\alpha$ nebulae (e.g., Mori & Umemura 2006). The cold gas accretion rate and the strength of galactic superwinds are predicted to evolve with physical quantities related to the cosmic SFRD (e.g., Dekel et al. 2009; Keréş et al. 2009). The comparisons of the cosmic SFRD and LAB evolutions would provide useful hints that LABs are formed in these scenarios.

However, it should be noted that the LAB selection method is not homogeneous in our comparison of $N_{\text{LAB}}$ at $z \approx 0 - 7$. There is a possibility that the $N_{\text{LAB}}$ evolution from $z \approx 7$ to $z \approx 3$ is caused by the cosmological surface brightness dimming effect at high-$z$. The cosmological surface brightness dimming would significantly affect the detection and selection completeness for LABs at high-z. To confirm the $N_{\text{LAB}}$ evolution and quantitatively compare with the cosmic SFRD, we need to homogenize the selection method for LABs at $z \approx 2 - 7$ in the future HSC NB data.

7 Summary and Conclusions

We develop an unprecedentedly large catalog consisting of LAEs at $z = 5.7$ and 6.6 that are identified by the SILVERRUSH program with the first NB imaging data of the Subaru/HSC survey. The NB imaging data is about an order of magnitude larger than any other surveys for $z \approx 6 - 7$ LAEs conducted to date.

Our findings are as follows:

- We identify $2,230 > L^*$ LAEs at $z = 5.7$ and 6.6 on the 13.8 and 21.2 deg$^2$ sky, respectively. We confirm that the LAE catalog is reliable on the basis of 96 LAEs whose spectroscopic redshifts are already determined by this program (Shibuya et al. 2017b) and the previous studies (e.g., Mallery et al. 2012). The LAE catalog is presented in this work, and published online.
• With the large LAE catalog, we derive the rest-frame Ly\(\alpha\) EW distributions of LAEs at \(z \approx 5.7\) and \(\gtrsim 6.6\) that are reasonably explained by the exponential profile. The best-fit exponential (Gaussian) Ly\(\alpha\) scale lengths are, on average of the Ultradeep and Deep fields, 153 ± 18 Å and 154 ± 15 Å (146 ± 24 Å and 139 ± 14 Å) at \(z \approx 5.7\) and \(z \approx 6.6\), respectively, showing no significant evolution from \(z \approx 5.7\) to \(z \approx 6.6\). We find 45 and 230 LAEs at \(z \approx 6.6\) and \(z \approx 5.7\) with a LEW of \(EW_{9.17} > 240\) Å corrected for the IGM attenuation for Ly\(\alpha\). The fraction of the LEW LAEs to all LAEs is \(\approx 4\)% and \(\approx 21\)% at \(z \approx 6.6\) and \(z \approx 5.7\), respectively. These LEW LAEs are candidates of young-metal poor galaxies and AGNs.

• We search for LABs that are LAEs with spatially extended Ly\(\alpha\) emission whose profile is clearly distinguished from those of stellar objects at the \(\gtrsim 3\sigma\) level. In the search, we identify 11 LABs in the HSC NB images down to a surface brightness limit of \(\gtrsim 5 - 8 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) which is as deep as data of previous studies. The number density of the LABs at \(z \approx 6 - 7\) is \(\approx 10^{-7} - 10^{-6}\) Mpc\(^{-3}\) that is \(\approx 10 - 100\) times lower than those claimed for LABs at \(z \approx 2 - 3\), suggestive of disappearing LABs at \(z \gtrsim 6\), although the selection methods are different in the low and high-\(z\) LABs.

It should be noted that Ly\(\alpha\) EW scale length derivation methods and the LAB selections are not homogeneous in a redshift range of \(z \approx 0 - 7\). Using the future \(z \approx 2.2, 5.7, 6.6\), and 7.3 HSC NB data, we will systematically investigate the redshift evolution of Ly\(\alpha\) EW scale lengths and \(N_{\text{LAB}}\) at \(z \approx 2 - 7\) in homogeneous methods.

8 Appendix: Calculation of Ly\(\alpha\) EW

In this section, we describe the method to calculate the \(EW_{9.17,\text{Ly}\alpha}\) values. The procedures and the assumption of this method are similar to those of e.g., Malhotra & Rhoads (2002), Dawson et al. (2004), Gronwall et al. (2007), Kashikawa et al. (2011). For the calculation of \(EW_{9.17,\text{Ly}\alpha}\), we assume that LAEs have a \(\delta\) function-shaped Ly\(\alpha\) line and the flat rest-frame UV continuum emission (i.e. \(\beta_\nu = 0\), where \(\beta_\nu\) is the UV spectral slope per unit frequency). In such an LEE spectrum, the magnitude, \(m\), for a waveband filter with a transmission curve, \(T_\nu\), is described as follows:

\[
f_c = \frac{A_{BB} f_{BB}}{B_{BB} + R_{BB}} = f_{BB} \quad \text{(14)}
\]

\[
f_t = \frac{A_{NB}(B_{BB} + R_{BB}) - A_{BB}(B_{NB} + R_{NB})}{B_{BB} + R_{BB}} \quad \text{(15)}
\]

\[
a = \frac{T_{BB}(\nu_{\alpha}) - B_{BB}(\nu_{\alpha})}{T_{BB}(\nu_{\alpha}) - R_{BB}(\nu_{\alpha})} \quad \text{(16)}
\]

\[
b = \frac{B_{BB}(\nu_{\alpha}) - R_{BB}(\nu_{\alpha})}{T_{BB}(\nu_{\alpha}) - R_{BB}(\nu_{\alpha})} \quad \text{(17)}
\]

Note that \(B_{BB} + R_{BB} = A_{BB}\) due to the negligible IGM absorption at the wavelengths of BB filters. Here we define \(a\) and \(b\) as

\[
a = \frac{A_{NB}}{T_{NB}(\nu_{\alpha})} \quad \text{(18)}
\]

\[
b = \frac{B_{NB} + R_{NB}}{T_{NB}(\nu_{\alpha})} \quad \text{(19)}
\]
For the HSC $NB921$ and $NB816$ filters, the sets of the values are calculated to be $(a, b) \simeq (4.7, 2.3) \times 10^{12}$ and $(a, b) \simeq (5.2, 2.7) \times 10^{12}$, respectively. Using $f_c$ and $f_l$, we calculate the $EW_{0, Ly\alpha}$ values via

$$EW_{0, Ly\alpha} = \frac{f_l}{f_c} \frac{c}{\beta} \frac{1}{1 + z}.$$ (20)

To obtain the median values and uncertainties for $EW_{0, Ly\alpha}$, we perform Monte Carlo (MC) simulations in a method similar to that of e.g., Shimasaku et al. (2006). In the simulation, we randomly generate a flux density value, $f_{MC}$, following a Gaussian probability distribution with an average of $\bar{f}$ and a dispersion of the $1\sigma$ sky background noise, $\sigma_{sky}$, for the NB and BB bands. Here we also randomize $\beta_c$ and $\nu_c$ in Gaussian probability distributions with $1\sigma$ dispersions of $\Delta \beta$ and $\Delta \nu$ = $FWHM_{NB}/2.35$, respectively, where $FWHM_{NB}$ is the FWHM of the NB filters. The dispersion of $\Delta \beta = 0.2$ is typical for high-$z$ galaxies (Bouwens et al. 2014). In the manner that are the same as described in this section, we calculate a $EW_{0, Ly\alpha}$ value using $f_{MC}$ for NB and BB. In this process, negative values of $f_c$, $f_l$, and $EW_{0, Ly\alpha}$ are forced to be zero. Such a process is performed 1,000 times for each object. During the iteration, a simulated $EW_{0, Ly\alpha}$ value is discarded in the case that a $BB - NB$ color does not meet the selection criteria of Equations (1) and (2). Using the set of $EW_{0, Ly\alpha}$ values obtained from the MC simulations, we calculate the median values and the 16- and 84-percentile errors for $EW_{0, Ly\alpha}$.

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References

Aihara, H., et al. 2017a, arXiv:1702.08449
—. 2017b, arXiv:1704.05858
Arrigoni Battaia, F., Hennawi, J. F., Prochaska, J. X., & Cantalupo, S. 2015a, ApJ, 809, 163
Arrigoni Battaia, F., Yang, Y., Hennawi, J. F., Prochaska, J. X., Matsuda, Y., Yamada, T., & Hayashino, T. 2015b, ApJ, 804, 26
Axelrod, T., Kantor, J., Lupton, R. H., & Pierfederici, F. 2010, An open source application framework for astronomical imaging pipelines
Bertin, E., & Arnouts, S. 1996, A&As, 117, 393
Blanc, G. A., et al. 2011, ApJ, 736, 31
Bond, N. A., Gawiser, E., Guaita, L., Padilla, N., Gronwall, C., Ciardullo, R., & Lai, K. 2012, ApJ, 753, 95
Bosch, J., et al. 2017, ArXiv e-prints
Bouwens, R. J., et al. 2014, ApJ, 793, 115
Cai, Z., et al. 2017, ApJ, 837, 71
Cantalupo, S., Arrigoni-Battaia, F., Prochaska, J. X., Hennawi, J. F., & Madau, P. 2014, Nature, 506, 63
Cantalupo, S., Porciani, C., Lilly, S. J., & Miniati, F. 2005, ApJ, 628, 61
Ciardullo, R., et al. 2012, ApJ, 744, 110
Cowie, L. L., Barger, A. J., & Hu, E. M. 2010, ApJ, 711, 928
Cowie, L. L., Hu, E. M., & Songaila, A. 2011, ApJL, 735, L38
Dawson, S., et al. 2004, ApJ, 617, 707
Dekel, A., et al. 2009, Nature, 457, 451
Dressler, A., Martin, C. L., Henry, A., Sawicki, M., & McCarthy, P. 2011, ApJ, 740, 71
Duval, F., Schaar, D., Östlin, G., & Laursen, P. 2013, ArXiv e-prints
Erb, D. K., Bogosavljević, M., & Steidel, C. C. 2011, ApJL, 740, L31
Finkelstein, S. L., Rhoads, J. E., Malhotra, S., Grogin, N., & Wang, J. 2008, ApJ, 678, 655
