CHORUS. III. Photometric and Spectroscopic Properties of Lyα Blobs at $z = 4.9–7.0$

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1. Introduction

Lyα emitters (LABs) are important objects to study the formation and evolution of star-forming galaxies (SFGs) at high redshifts where the redshifted Lyα emission becomes observable with ground-based telescopes (e.g., Ouchi et al. 2003, 2008). Previous narrowband imaging surveys have identified LABs with very luminous Lyα emission ($\log(L_{Ly\alpha}/[\text{erg s}^{-1}]) \geq 43.4$) and a large isophotal area ($\sim 150$ kpc$^2$) at $z \sim 2–7$. These luminous and spatially extended LABs are often referred to as Lyα blobs (LABs; e.g., Keel et al. 1999; Steidel et al. 2000; Francis et al. 2001; Matsuda et al. 2004). One well-known example of LABs is LAB1 (Steidel et al. 2000) at $z = 3.1$, while the most distant ones are Himiko (Ouchi et al. 2009) and CR7 (Sobral et al. 2015) at $z = 6.6$. LABs are important objects for studying massive galaxies and their circumgalactic medium (CGM) in the early universe. Although LABs have been analyzed individually by many studies, the relation between LABs at different epochs of $z \sim 3$ (e.g., LAB1) and $z \gtrsim 6$ (e.g., Himiko and CR7) is still unclear.

Following the identification of LABs, diffuse Lyα nebulae called Lyα halos (LAHs) are found ubiquitously around typical LAEs with $\log(L_{Ly\alpha}/[\text{erg s}^{-1}]) \sim 42–43$ at $z \sim 3–6$ and have been identified individually (e.g., Rauch et al. 2008; Wisotzki et al. 2016; Leclercq et al. 2017) or statistically by stacking analysis (e.g., Hayashino et al. 2004; Steidel et al. 2011; Matsuda et al. 2012; Feldmeier et al. 2013; Momose et al. 2014, 2016; Wisotzki et al. 2018). The typical isophotal area of LAHs is smaller than that of LABs at similar redshifts. However, the isophotal area measurement can be largely affected by both the detection limits and the surface brightnesses of LAHs and LABs.
At the same detection limit, faint LAHs show smaller isophotal areas than bright LABs if the radial profile shapes are the same, as the Lyα luminosities of LAHs are fainter than those of LABs by an order of magnitude. Nevertheless, it is still unclear whether LAHs and LABs at \( z \approx 5 \) have similar shapes of Lyα radial profiles to understand if LAHs and LABs at high \( z \) are distinct populations.

Although it is not clear if LAHs and LABs are distinct populations, there may be one difference between LAHs and LABs related to active galactic nuclei (AGNs). Konno et al. (2016) and Sobral et al. (2018) suggest that AGNs exist in LAEs brighter than a luminosity limit of \( \log (L_{\text{Ly}\alpha}/[\text{erg s}^{-1}]) \geq 43.4 \) at \( z \approx 2 - 3 \). Because most LABs exceed this luminosity limit, it is expected that LABs have AGN activities. Previously, AGNs have been identified in some LABs (e.g., LAB2 in Steidel et al. 2000; Basu-Zych & Scharf 2004), while no evidence of AGNs is found in other LABs (e.g., LAB1; Geach et al. 2007; Matsuda et al. 2007). Statistically, Geach et al. (2009) investigate 29 LABs at \( z = 3.09 \) and find that \( \approx 10\% - 30\% \) of the LABs contain AGNs.

To explain these observational results, there are two possibilities. One possibility is that all LABs intrinsically have AGNs, and that some AGNs are obscured or too faint to be identified. Another possibility is that there exist two kinds of LABs, with and without AGNs.

Related to the possible AGN activities in LABs, the extended Lyα emission can be explained by the several scenarios listed below.

1. **Fluorescence.** There exists some neutral hydrogen gas in the CGM around a galaxy that is heated by an AGN or star formation. The neutral hydrogen gas is photoionized by the ionizing photons from the galaxy center or UV background. Lyα photons are then emitted during the recombination process (e.g., Cantalupo et al. 2014; Prescott et al. 2015; Mas-Ribas & Dijkstra 2016).

2. **Resonant scattering.** Lyα photons escape to the CGM from a galaxy center and are resonantly scattered by the neutral hydrogen in the CGM. This process causes the galaxy to have Lyα emission more extended than the UV continuum (e.g., Hayes et al. 2011; Cen & Zheng 2013; Geach et al. 2014, 2016; Lake et al. 2015; Beck et al. 2016; Mas-Ribas et al. 2017).

3. **Gravitational cooling radiation.** Some inflow streams exist around a galaxy and accrete onto the galaxy center. Lyα photons are emitted by the collisional excitation of neutral hydrogen in the streams. In this radiation process, the streams release their gravitational potential energy (e.g., Haiman et al. 2000; Fardal et al. 2001; Dekel et al. 2009; Martin et al. 2015).

4. **Outflows.** Multiple supernova explosions in a galaxy produce hot gas outflows. The outflows drive shocked cooling shells that emit Lyα photons (e.g., Taniguchi & Shioya 2000; Bower et al. 2004; Mori et al. 2004; Wilman et al. 2005).

5. **Satellite galaxies.** A central galaxy is surrounded by multiple satellite galaxies that emit Lyα photons during star formation. In this scenario, a galaxy may exhibit both extended Lyα emission and extended UV continuum (e.g., Prescott et al. 2012; Francis et al. 2013; Geach et al. 2016; Mas-Ribas et al. 2017).

Because the different possible scenarios are expected to cause different shapes of Lyα radial profiles, various studies have tried to pinpoint the origin of extended Lyα emission by comparing Lyα radial profiles from models with those from observations (e.g., Lake et al. 2015; Mas-Ribas & Dijkstra 2016; Mas-Ribas et al. 2017). However, these studies target LAEs with fainter Lyα luminosities \( (\log (L_{\text{Ly}\alpha}/[\text{erg s}^{-1}]) < 43) \) than those of LABs. These models may not well explain the physical origin of the luminous and extended Lyα emission of LABs.

In this paper, we present the identification of two new LABs at \( z = 4.9 \) and 7.0. Including five LABs at \( z = 5.7 \) and 6.6 identified by previous studies, we investigate the photometric and spectroscopic properties of a total of seven LABs. We perform profile fitting to model the extended Lyα emission around LABs, and compare our best-fit models of LABs with those of LAHs in the literature. We investigate AGN activities in LABs with X-ray data and UV-line ratio diagnostics, and discuss the possible physical origins of the extended Lyα emission around LABs.

This paper is organized as follows. In Section 2, we describe the observations, data, and identification of two new LABs. In Section 3, we present the spectroscopic analysis of LABs. Our results are shown in Section 4, and the discussions are presented in Section 5. We summarize our findings in Section 6. Throughout this paper, we use AB magnitudes (Oke & Gunn 1983) and physical distances unless we indicate otherwise. A ΛCDM cosmology with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \) and \( h = 70 \) is adopted.

2. Observations, Data, and LAB Identification

In this paper, we study a total of seven LABs that include two new LABs from our observations and five LABs from previous studies. We use photometric and spectroscopic data either from our observations or in the literature.

2.1. New LABs Identified by the CHORUS Survey

2.1.1. Imaging Observations and Data Reduction

We carried out narrowband imaging observations with Subaru/Hyper Suprime-Cam (HSC; Furusawa et al. 2018; Kawanomoto et al. 2018; Komiyama et al. 2018; Miyazaki et al. 2018) in the course of project Cosmic Hydrogen Reionization Unveiled with Subaru (CHORUS; PI: A. K. Inoue). We used two narrow bands of NB718 (\( \lambda_c = 7170 \, \text{Å}, \) FWHM = 110 Å) and NB973 (\( \lambda_c = 9715 \, \text{Å}, \) FWHM = 100 Å). The central wavelengths of the NB718 and NB973 filters were chosen to detect redshifted Lyα emission at \( z = 4.9 \) and 7.0, respectively. The NB718 data were taken on 2017 February 25, March 23, and March 25, while the NB973 observations were conducted on 2017 January 26 and 28. The NB718 observations covered the COSMOS field, and the NB973 observations were carried out in the SXDS and COSMOS fields. The effective survey areas were 1.64 and 1.50 deg\(^2\) in the COSMOS and SXDS fields, respectively. The typical seeing sizes during observations were 0′′6–0′′9.

We reduce the NB718 and NB973 images with the HSC pipeline (Bosch et al. 2018) that uses codes from the Large Synoptic Survey Telescope (LSST) pipeline (Ivezic et al. 2019; Axelrod et al. 2010; Jurić et al. 2017). The astrometry and photometry are calibrated with the imaging data from the Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1; Schlafly et al. 2012; Tonry et al. 2012;
Magnier et al. (2013) survey. We do not use exposures with seeing sizes larger than 0″/9 during the reduction because these exposures were taken under bad weather conditions. The total integration times of the reduced NB718 and NB973 images are 6.3 hr and 14.7 hr, respectively. The typical 5σ limiting magnitudes in a 1″.5 diameter aperture are 26.2 in NB718 data and 24.9 in NB973 data.

During the reduction, in addition to the NB718 and NB973 images, we also use the ultra-deep layer data of broad bands (g, r, i, z, and y) from the Subaru Strategic Program (SSP) survey (PI: S. Miyazaki; Aihara et al. 2018) for source detection and forced photometry. Details of the source detection and forced photometry are described in Bosch et al. (2018). We do not use areas contaminated either by halos of bright stars (Coupon et al. 2018) or low signal-to-noise ratio pixels such as field edges. The catalogs produced in this procedure are referred to as source catalogs in the following sections.

2.1.2. Photometric Samples of LAEs at z = 4.9 and 7.0

To select LAEs at z = 4.9, we use source catalogs of the NB718, g, r, and i filters. We apply the following color criteria:

\[
\begin{align*}
ri - NB718 &> 0.7 \text{ and } r - i > 0.8 \text{ and } \\
ri - NB718 &> (ri - NB718)_{3σ}, \text{ and } \\
NB718ri &< NB718ri_{5σ} \text{ and } gri > gri_{3σ},
\end{align*}
\]

where the superscript “ap” indicates the aperture magnitude in a 2″/0 diameter, and no superscript corresponds to the total magnitude. The total magnitude is measured by the CModel photometry described in Bosch et al. (2018). The 2σ, 3σ, and 5σ subscripts stand for 2σ, 3σ, and 5σ detection limits, respectively. In Equation (1), \(r_i\) is calculated by the linear combination of the fluxes in the \(r\) band, \(f_r\), and \(i\) band, \(f_i\), following \(f_i = 0.3f_r + 0.7f_i\). The 3σ error of the \(r_i - NB718\) color is given by \((ri - NB718)_{3σ} = -2.5 \log(1 + 3 \sigma_r^2 f_r^2 + \sigma_i^2 f_i^2 f_{NB718} f_{NB718})\), where \(f_{err,r,i}\) and \(f_{err,NB718}\) are the 1σ errors in \(ri\) and NB718, respectively. These criteria allow us to choose LAEs with rest-frame Lyα equivalent widths (EW_{Lyα}) greater than 10 Å.

In total, 727 objects meet the color criteria. We then visually inspect these objects and exclude 586 spurious sources such as satellite trails. Finally, we obtain 141 LAE candidates at \(z = 4.9\). Figure 1 shows the color–magnitude diagram of our LAE candidates at \(z = 4.9\).

The selection of LAEs at \(z = 7.0\) is presented in Itoh et al. (2018). Briefly, Itoh et al. (2018) select LAEs with NB973 and broad bands (g, r, i, z, and y) following the criteria:

\[
\begin{align*}
(y < y_{5σ} \text{ and } y - NB973 > 1) \text{ or } y > y_{3σ} \text{ and } \\
(z < z_{5σ} \text{ and } z - y > 2) \text{ or } z > z_{3σ} \text{ and } \\
NB737 < NB737_{5σ} \text{ and } g > g_{3σ} \text{ and } \\
r > r_{3σ} \text{ and } i > i_{3σ},
\end{align*}
\]

where the meanings of the superscripts and subscripts are the same as in Equation (1).

Finally, there are 34 LAE candidates at \(z = 7.0\) after we conduct the color selection and visual inspection.

2.1.3. Identification of Two LABs

We select LAB candidates based on isophotal areas and narrowband magnitudes in a manner similar to the one in Shibuya et al. (2018). Figure 2 shows isophotal areas as a function of total narrowband magnitude for our LAE candidates at \(z = 4.9\) and 7.0. The isophotal area is defined as the area with a surface brightness above the 2σ detection limit. We estimate the isophotal area–magnitude relations of point sources using the point-spread functions (PSFs) in the NB718 and NB973 images. The isophotal areas of LAB candidates are larger than the 2.5σ confidence levels of the point sources. The narrowband magnitudes of the LAB candidates are brighter than 23.9 mag for NB718 and 24.1 mag for NB973. These two narrowband magnitudes, together with the 24.0 mag at \(z = 6\) that is used in Shibuya et al. (2018), correspond to a Lyα luminosity of \(1.6 \times 10^{43} \text{ erg s}^{-1}\) if we assume the UV continuum is negligible compared to the Lyα emission. We consider the changes of the luminosity distances and filter response curves in the calculation.

By the criteria of isophotal areas and narrowband magnitudes, nine and one LAB candidates are selected at \(z = 4.9\) and 7.0, respectively, as shown in Figure 2. The number densities of our LAB candidates are \(\sim 6.0 \times 10^{-6} \text{ and } 2.8 \times 10^{-7} \text{ Mpc}^{-3}\) at \(z = 4.9\) and 7.0, respectively, which are comparable to the number densities of \(\sim 10^{-7} \text{ and } 10^{-6} \text{ Mpc}^{-3}\) at \(z = 5.7\) and 6.6 in Shibuya et al. (2018). For the first step of our statistical study and follow-up spectroscopy, we select the brightest LAB candidates at \(z = 4.9\) and 7.0, which are named z49-1 (R.A. = 10h09m45.977, decl. = +2°02′44″28′′ [J2000]) and z70-1 (R.A. = 10h02m15.521, decl. = +2°40′33″23′′ [J2000]), respectively. The objects of z49-1 and z70-1 show large isophotal areas (157.5 and 42.2 physical kpc²) and bright Lyα luminosities (3.5 \times 10^{43} \text{ and } 2.6 \times 10^{43} \text{ erg s}^{-1}) that are distinguished from the other LAE candidates at each redshift. Snapshots of z49-1 and z70-1 are presented in Figure 3. The images of z49-1 and z70-1 from UltraVista (Y, J, H, and K bands) and Spitzer/IRAC (3.6 and 4.5 μm bands) are shown in Figure 4 and will be analyzed in Section 4.
2.1.4. Spectroscopic Observations

We carried out spectroscopic observations for z49-1 with Magellan/LDSS3 on 2017 May 28. The object of z49-1 was observed with an on-source exposure time of 1800 s. The observations were conducted in the long-slit mode with a slit width of 20. We used the OG590 filter with the VPH-Red grism (R = 680) to cover the expected Lyα emission line at z = 4.9.

Spectroscopic observations for z70-1 were performed with Keck/DEIMOS (Faber et al. 2003) on 2019 January 6. The total on-source exposure time was 3.7 hr. However, we only used the data in the last 1.7 hr because the data in the first 2 hr were taken under bad weather conditions. The slit width was 10 during the observations in the multiobject spectroscopy (MOS) mode. The OG550 filter and the 830 G grating (R ≈ 2900 at 9700 Å) were chosen to cover the wavelength where the Lyα emission line at z = 7.0 was expected.

2.2. LABs Identified in Previous Studies

From previous studies, we use five LABs including z57-1 and z57-2 (HSC J161927+551144 and HSC J161403+535701 in Shibuya et al. 2018) at z = 5.7, z66-1 (Himiko in Ouchi et al. 2009), z66-2 (CR7 in Sobral et al. 2015), and z66-3 (HSC J100334+024546 in Shibuya et al. 2018) at z = 6.6. Because these five LABs pass the LAB selection criteria in Shibuya et al. (2018) that are similar to ours, the LABs would also be selected by us if they fall in our survey. The imaging data are available from the SSP survey and shown in Figure 3. The spectra of z66-1, z66-2, and z66-3 are taken from Ouchi et al. (2009), Sobral et al. (2015), and Shibuya et al. (2018), respectively.

We carried out spectroscopic follow-up observations for z57-1 and z57-2 with Subaru/FOCAS on 2018 July 17. We chose a slit width of 08 in the MOS mode. The O58 filter and VPH900 grism (R = 1500) were used to cover the expected Lyα emission line at z = 5.7. Finally, we obtained data with an on-source exposure time of 1200 s for each target.

2.3. Summary of Our LAB Samples

Our final LAB samples include z49-1, z57-1, z57-2, z66-1, z66-2, z66-3, and z70-1, which are referred to as the seven LABs in the following sections. From the snapshots of the seven LABs in Figure 3, we can see that apparently all of the seven LABs are more extended in the narrowband images (NB718, NB816, NB921, and NB973) than the corresponding offband images (I, z, y, and y). Photometric properties of the seven LABs are summarized in Table 1. Details of spectroscopic observations of the seven LABs are presented in

![Figure 2. Isophotal area as a function of NB718 (top) and NB973 (bottom) magnitudes for LAEs (black filled circles) at z = 4.9 and 7.0, respectively. The dashed lines show the size–magnitude relations of point sources. The solid lines represent the selection criteria of LABs. The vertical solid lines correspond to magnitudes of 23.9 mag for NB718 and 24.1 mag for NB973. The diagonal solid lines show the 2.5σ confidence levels of isophotal areas of point sources. The magenta diamond boxes indicate LAB candidates selected with these criteria. The objects of z49-1 and z70-1 are shown as red filled circles.](image-url)

![Figure 3. Snapshots of the seven LABs. The size of each image is 5′ × 5′. HST corresponds to HST/WFC3 F814W, F125W, and F110W images for z49-1, z66-1 and z66-2, respectively.](image-url)

![Figure 4. Snapshots of z49-1 and z70-1 in the narrow band and Y, J, H, K, 3.6, and 4.5 μm bands. The size of each image is 5′ × 5′.](image-url)
Table 1
Photometric Properties of the Seven LABs

| ID    | Object Name | Redshift | NBtot (1) | BBtot (2) | log L495α (3) | EW0 (Å) (4) | δ |
|-------|-------------|----------|-----------|-----------|---------------|-------------|---|
| z49-1 | ...         | 4.9      | 22.66     | 23.89     | 43.54         | 47.5        | 5.68 |
| z57-1 | HSC J161927+551144a | 5.7     | 22.88     | 24.86     | 43.6          | 71.4        | 1.57 |
| z57-2 | HSC J161403+535701a | 5.7     | 23.53     | 25.32     | 43.2          | 20.6        | 4.14 |
| z66-1 | Himikob     | 6.6      | 23.55     | 25.00     | 43.40         | 78          | 2.09 |
| z66-2 | CR7c        | 6.6      | 23.24     | 24.92     | 43.93         | 211         | 0.62 |
| z66-3 | HSC J100334+024546d | 6.6    | 23.61     | 24.97     | 43.50         | 61.1        | 4.28 |
| z70-1 | ...         | 7.0      | 23.40     | 25.09     | 43.41         | 73          | 3.65 |

Notes.

a Column 1: total narrowband magnitude in units of mag. Column 2: total broadband magnitude in units of mag. Column 3: photometric Lyα luminosity in units of erg s⁻¹. Column 4: LAE overdensity described in Section 4.2.

b Shibuya et al. (2018).
c Shibuya et al. (2019).
d Ouchi et al. (2009).

Table 2. The spectroscopic data will be shown and discussed in the next section.

Table 2
Summary of Spectroscopy

| ID    | Instrument | Filter | Grism/Grating | Exp. Time (s) | Slit Width (") | zspec |
|-------|------------|--------|---------------|---------------|----------------|-------|
| z49-1 | Magellan/LDSS3 | OG590 | VPH-Red | 1800          | 2.0            | 4.888 |
| z57-1 | Subaru/FOCAS | O58   | VPH900       | 1200          | 0.8            | 5.709 |
| z57-2 | Subaru/FOCAS | O58   | VPH900       | 1200          | 0.8            | 5.733 |
| z66-1a | Keck/DEIMOS | GG495 | 830 G        | 10,800        | 1.0            | 6.595 |
| z66-2b | VLT/X-SHOOTER | ... | ...         | 8100          | 0.9            | 6.604 |
| z66-3c | Subaru/FOCAS | O58   | VPH900       | 6000          | 0.8            | 6.575 |
| z70-1 | Keck/DEIMOS | O550  | 830 G        | 6000          | 1.0            | 6.965 |

Notes.

a Ouchi et al. (2009).
b Sobral et al. (2015).
c Shibuya et al. (2018).

3. Spectroscopic Analysis

The spectrum of z70-1 is shown in Figure 5. Because the emission line at 9686 Å is partly overlapped by nearby sky lines, the line shape may be affected by the sky residual after sky subtraction. This emission line cannot be explained by an O II doublet, because the two peaks of an OII doublet at this wavelength would have a separation of ~8 Å that is broader than the line observed. We find no other emission lines between ~6000 and 10000 Å that indicate a foreground source. We conclude that z70-1 is not likely a low-z object but an LAB at z = 6.965.

Figure 6 presents the spectra of z49-1, z57-1, z57-2, z66-1, z66-2, and z66-3. The spectrum of z49-1 shows an emission line whose line center is at 7160 Å. The line center is measured by fitting a Gaussian function to the emission line. Additionally, on the spectrum, we find another emission line whose line center is at 9131 Å, as presented in Figure 7. These two emission lines can only be explained by an object emitting Lyα and C IV lines simultaneously at z = 4.888. The emission line at 7160 Å is asymmetric and has a red wing that is consistent with a high-z Lyα emission line. The object of z49-1 is confirmed as an LAB at z = 4.888. The Lyα and C IV fluxes of z49-1 measured from the spectrum are (1.52 ± 0.048) × 10⁻¹⁶ and (1.61 ± 0.29) × 10⁻¹⁷ erg s⁻¹ cm⁻², respectively.

Figure 8 shows the line-center offset Δλc and FWHM of the Lyα emission line as a function of positional offset Δd. Δd is the distance between the position of a measurement and a Lyα source center. By definition, the Lyα-source center is located at Δd = 0. The positive direction of Δd is from the blueshifted side to the redshifted side. Δλc is calculated following Δλc = λc(Δd) − λc(0). Because the Lyα emission line of z70-1 is affected by nearby sky lines as we discussed earlier, we do not include z70-1 in this analysis. In Figure 8, Δλc has a positive correlation with Δd although the correlation for z66-2 is weak. The correlation between Δλc and Δd indicates velocity gradients in the Lyα emission lines of our LABs. We notice that the FWHM also positively correlates with Δd. Clearly, z49-1 and z57-2 have larger velocity gradients and FWHMs than the other LABs.

4. Results

4.1. Lyα Surface Brightness Profiles

To make Lyα images of the seven LABs, we first match the PSFs of narrowband and offband images, and then subtract the offband images from the corresponding narrowband images. We use a PSF matching method similar to the one discussed in Aniano et al. (2011). The PSF matching procedure is briefly described below.
First, we extract the PSFs of narrowband and offband images by stacking 200–300 bright and unsaturated ($m_A^{AB} < 22$) point sources in each filter. These PSFs are referred to as initial PSFs. We choose the PSF with the largest FWHM among initial PSFs as the target PSF. Then, we calculate convolution kernels that are used to convolve the initial PSFs to the target PSF by

$$K = FT^{-1}\left(FT(PSF) \times \frac{1}{FT(PSF)}\right). \quad (3)$$

Figure 5. Two-dimensional (top) and one-dimensional (bottom) spectra that show the Ly$\alpha$ emission (black solid line) of z70-1. The vertical dashed line indicates the Ly$\alpha$ line center. The gray solid line presents the sky emission lines. The gray shades represent the wavelength ranges with strong sky emission.

Figure 6. Spectra of z49-1, z57-1, z57-2, z66-2, z66-1, and z66-3, which show Ly$\alpha$ emission lines (black solid lines). In each panel, the two-dimensional spectrum is shown in the top and the one-dimensional spectrum is presented in the bottom. The center (gray), side 1 (red), and side 2 (blue) components are measured at positions with $\Delta d < 0$, $\Delta d = 0$, and $\Delta d > 0$, respectively. The widths of the extraction slits are chosen arbitrarily to let the center, side 1, and side 2 components contain 50% ± 5%, 25% ± 5%, and 25% ± 5% of the total flux, respectively.

Figure 7. Same as Figure 5, but for the CIV emission of z49-1.

Figure 8. Line-center offset $\Delta \lambda_c$ (top) and FWHM (bottom) of the Ly$\alpha$ emission line as a function of positional offset $\Delta d$. The data of z66-1 are from Ouchi et al. (2009).
where \( K, FT, FT^{-1}, PSF_i, \) and \( PSF_t \) stand for the convolution kernel, Fourier transform, inverse Fourier transform, initial PSF, and target PSF, respectively. Finally, we convolve the narrowband and offband images of the seven LABs with the corresponding kernels to obtain PSF-matched images. The PSFs before and after matching are shown in Figure 9.

Figure 10 shows the \( \text{Ly} \alpha \) surface brightness profiles \( S_{\text{Ly} \alpha} \) of the seven LABs. To measure the scale lengths of the seven LABs, we perform a two-component (core and halo) fitting that is similar to the one adopted by Leclercq et al. (2017). Specifically, we decompose the surface brightness profiles into core and halo components, following

\[
S_{\text{cont}}(r) = \text{PSF} \ast A_1 \exp(-r/r_c) \quad \text{and} \quad S_{\text{Ly} \alpha}(r) = \text{PSF} \ast [A_2 \exp(-r/r_c) + A_3 \exp(-r/r_h)],
\]

where \( r_c \) and \( r_h \) are the scale lengths of the core and halo components, respectively. The “+” sign stands for convolution. The \( A_1, A_2, \) and \( A_3 \) are free parameters. The continuum profile \( S_{\text{cont}} \) is extracted from the offband images, while the \( \text{Ly} \alpha \) profile \( S_{\text{Ly} \alpha} \) is measured in the \( \text{Ly} \alpha \) images. We first fit \( S_{\text{cont}} \) with two free parameters \( A_1 \) and \( r_c \) to measure \( r_c \). Then, we use this \( r_c \) value to fit \( S_{\text{Ly} \alpha} \) with three free parameters \( A_2, A_3, \) and \( r_h \) to measure \( r_h \). The errors of \( S_{\text{cont}} \) and \( S_{\text{Ly} \alpha} \) are considered in the fitting.

Figure 10 shows the best-fit \( \text{Ly} \alpha \) surface brightness profiles of our LABs. Because there is an offset between the positions of the \( \text{Ly} \alpha \) and continuum centers of \( z57-2 \), we cannot perform the two-component fitting that requires the \( \text{Ly} \alpha \) and continuum centers to be the same. Instead, we use a one-component exponential function to fit the \( \text{Ly} \alpha \) profile of \( z57-2 \) in the halo region \(( r > 5 \text{ kpc})\), following

\[
S_{\text{Ly} \alpha}(r) = \text{PSF} \ast [A \exp(-r/r_h)],
\]

where the meanings of \( S_{\text{Ly} \alpha}, \text{PSF}, \) and the “*” sign are the same as in Equation (4). \( A \) is a free parameter. The fitting result of \( z57-2 \) is shown in Figure 11.

We estimate the uncertainties of the best-fit parameters with the Monte Carlo method. At each radius, we randomly add sky noise to the continuum and \( \text{Ly} \alpha \) profiles assuming a Gaussian distribution. After adding the sky noise, we fit the exponential function to the new profiles. We repeat this process (adding sky noise and profile fitting) for 100 times. We plot the histograms of the best-fit parameters and calculate the central 68.3% confidence intervals. We use these confidence intervals as the 1σ uncertainties of the best-fit parameters.

We compare the best-fit scale lengths as a function of \( \text{Ly} \alpha \) luminosities \( L_{\text{Ly} \alpha}, \text{Ly} \alpha \) rest-frame \( E_W \), continuum magnitudes \( M_{ \text{UV} } \), and redshifts \( z \) of the seven LABs with those of LAHs from Leclercq et al. (2017). As shown in Figures 12–14. When calculating the LAB average value, we do not use the best-fit \( r_h \) of \( z57-2 \) from the one-component exponential function fitting. In Figures 12 and 13, the relations between the scale lengths and galaxy properties including the \( L_{\text{Ly} \alpha}, EW_0, \) and \( M_{ \text{UV} } \) of our LABs are similar to those of MUSE LAHs. This suggests that our LABs and MUSE LAHs have similar connections between the extended \( \text{Ly} \alpha \) emission and host galaxies, and that our LABs are likely the bright version of MUSE LAHs. We also find that our LABs are consistent with a positive correlation between \( r_c \) as a function of \( M_{ \text{UV} } \) of MUSE LAHs, which is expected from the size evolution discussed in Shibuya et al. (2015, 2019).
4.2. Large-scale Structure around LABs

To investigate the large-scale structure around our LABs, we calculate the LAE overdensity $\delta$ at $z = 4.9, 5.7, 6.6, \text{and } 7.0$ in the same manner as in Harikane et al. (2019). The $\delta$ is defined as

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

where $n$ and $\bar{n}$ are the number and average number of LAEs in a cylinder, respectively. The radius of the cylinder is $\sim 10$ comoving Mpc (cMpc). This radius is the typical size of protoclusters whose masses grow to $\sim 10^{15} M_\odot$ at $z = 0$ in Chiang et al. (2013). The length of the cylinder is $\sim 40$ cMpc, consistent with the redshift range of LAEs selected by narrow bands. Figure 15 shows the overdensity maps of LAEs at $z = 4.9, 5.7, 6.6, \text{and } 7.0$. The maps are made by smoothing the calculated overdensities with a Gaussian kernel whose standard deviation $\sigma$ is $\sim 10$ cMpc at $z \sim 6$, in the same manner as Harikane et al. (2019). The $\delta$ of each LAB is presented in Table 1. Kikuta et al. (2019) show that most of their LABs reside in overdense regions at $z \sim 3$. Similarly, we find that all of the seven LABs are located in overdense regions, and six of the seven LABs have large overdensities above the $1\sigma$ significance levels.

Figure 16 shows $r_h$ as a function of the $\delta$ of our LABs. To test the correlation between $r_h$ and $\delta$, we calculate the Spearman’s rank correlation coefficient $\rho$ to be 0.43 with a $p$-value of 0.34. We do not consider the errors of $r_h$ and $\delta$ when calculating the $\rho$ and $p$-value. Although Matsuda et al. (2012) find a positive correlation between the halo scale length and LAE overdensity of LAEs at $z = 3.1$, our correlation test suggests that there is no significant correlation between the $r_h$ and $\delta$ of our LABs at $z = 4.9-7.0$. 

Figure 11. Same as Figure 6, but for z57-2. The red solid line represents the best-fit one-component exponential function.

Figure 12. Halo scale length as a function of Ly$\alpha$ luminosity (top) and Ly$\alpha$ rest-frame EW$_0$ (bottom) of the seven LABs (stars) and LAHs (filled circles) from Leclercq et al. (2017). The empty star represents z57-2, which does not have a two-component fitting result. The red filled square shows the average value of our LABs, with error bars indicating the rms. The MUSE LAHs at $z < 5$ and $z \geq 5$ are the blue and cyan filled circles, respectively. The average values of the MUSE LAHs are shown as black filled circles. The black horizontal error bar indicates the bin size, while the black vertical error bar is the rms. In the top panel, we slightly shift z49-1 (boxed star) along the horizontal axis by $+0.03$ to avoid overlaps.

Figure 13. Same as Figure 12, but for the core scale length (top) and halo scale length (bottom) as a function of continuum magnitude.

Figure 14. Halo scale length as a function of redshift. The MUSE LAHs with $M_{UV} \geq -20$ and $M_{UV} < -20$ are presented as cyan and blue filled circles, respectively. The meanings of stars and black filled circles are the same as in Figure 12. We use z66-1, z66-2, and z66-3 to calculate the LAB average value at $z = 6.6$ (red filled square). The objects of z57-2, z66-1, z66-2, and z66-3 are slightly shifted along the horizontal axis by $+0.05, -0.1, +0.1$, and $+0.03$ to avoid overlaps, respectively.
4.3. AGN Activity

Because the bright Lyα luminosities (>10^{43.4} erg s^{-1}) of the seven LABs make them possible hosts of AGNs, we investigate the AGN activities in LABs with X-ray and spectroscopic data. None of the seven LABs have X-ray counterparts in images and catalogs of XMM/Newton and

Figure 15. Overdensity maps of LAEs at z = 4.9, 5.7, 6.6, and 7.0. The red diamonds indicate our LABs, while the other LAEs are shown as black dots. The blue shaded regions present the overdensities of LAEs as indicated by the color bars. Dark blue regions have higher overdensities than the light blue regions.
The meanings of symbols are the same as those in Figure 12.

Figure 17. C IV EW_0 as a function of C IV/He II ratio. The object z49-1 is represented as a red filled circle. We show two AGN models with power-law indices of α = −2.0 (dotted line) and −1.2 (dashed line), and two SFG models of POPSTAR (solid line) and BPASS (dashed–dotted line) from Nakajima et al. (2018). The ionization parameters log U of the AGN and SFG models are −2.5 (yellow), −2.0 (green), −1.5 (cyan), −1.0 (sky blue), and −0.5 (blue). The black dashed line represents the threshold that distinguishes between AGNs and SFGs.

4.4. Stellar Population

We perform spectral energy distribution (SED) fitting on z49-1 and z70-1 using total magnitudes measured in Subaru HSC (g, r, i, z, y, NB816, and NB921), UltraVista (Y, J, H, and K), and Spitzer/IRAC (3.6 and 4.5 μm bands) images. In our SED fitting, we consider the contributions from both nebular and stellar populations. The nebular spectra (emission lines and continua) are calculated basically following Schaerer & de Barros (2009). We use the stellar population synthesis model GALAXEV (Bruzual & Charlot 2003) with Salpeter’s initial mass function (Salpeter 1955) to obtain stellar SEDs. A constant star formation history is assumed. Details of our SED fitting method are described in Ono et al. (2010). Because the 3.6 μm band is contaminated by Hα emission at z = 4.9, we do not use the photometry of the 3.6 μm band in our SED fitting of z49-1. The best-fit SEDs of z49-1 and z70-1 are shown in Figure 18. The SED models are presented by the red solid curves. The black filled circles are total magnitudes measured in the g, r, i, z, y, NB816, NB921, Y, J, H, K, 3.6, and 4.5 μm bands. The black open circle indicates the 3.6 μm band photometry that we do not use in the SED fitting of z49-1. The horizontal error bars represent the filter bandwidths. The vertical error bars show the 1σ errors in magnitude. The arrows indicate 3σ upper limits.

As we discussed in Section 1, AGNs have been identified in all of the LAEs with bright Lyα luminosities (log (L_\text{Ly}\alpha /[\text{erg s}^{-1}]) ≥ 43.4) at z ~ 2–3 in Konno et al. (2016) and Sobral et al. (2018). Similarly, Overzier et al. (2013) show that at least 63% of LABs at z ~ 2–3 are associated with luminous AGNs. On the other hand, no AGN has been confirmed to exist in LABs at z ≥ 5, including our LABs. This may suggest that typical LABs at z ≥ 5 are less likely to be powered by luminous AGNs than LABs at z ~ 2–3.

The spectra of the seven LABs do not show N V emission indicative of AGNs. Shibuya et al. (2018) investigate 21 bright LAEs that are not broad-line AGNs at z = 6–7 and find that the LAEs have Lyα line widths of ~200–400 km s^{-1}. Consistently, z57-1, z66-1, z66-2, z66-3, and z70-1 also show Lyα line widths of ~200–400 km s^{-1} in Figure 8, suggesting that z57-1, z66-1, z66-2, z66-3, and z70-1 are not broad-line AGNs. On the other hand, the Lyα line widths of z49-1 and z57-2 are systematically larger than 400 km s^{-1}. Because z49-1 has a very clear continuum center that z57-2 does not show in Figure 3, it is possible that a hidden AGN is the origin of the relatively large Lyα line width of z49-1. The large Lyα line width of z57-2 is not likely caused by an AGN, but by mergers or dense neutral hydrogen gas in the H I region.

In Section 3, we show that z49-1 has a C IV emission line with a line width of 317 ± 132 km s^{-1}. The rest-frame EW_0 of the C IV emission is 8.3 ± 1.5 Å. The spectrum shows no He II emission above the 2σ detection limit. We use the 2σ detection limit as an upper limit of the He II flux and find that the lower limit of the C IV to He II ratio is ∼1.2. We compare the C IV rest-frame EW_0 and C IV to He II ratio with the AGN and SFG models in Nakajima et al. (2018), and find that z49-1 is consistent with both the AGN and low-metallicity SFG models (Figure 17). This result indicates that z49-1 is a candidate of a high-z AGN, although the possibility of a low-metallicity SFG cannot be ruled out.
The upper object in the left panel is a foreground source. The RGB colors of z70-1 are presented by the 3.6 μm, y, and NB816 images, respectively. For z57-2, the RGB colors correspond to the y, z, and NB816 images, respectively. Because z57-2 does not show a clear center in the NB816 image, we smooth the y, z, and NB816 images of z57-2 with a Gaussian kernel whose sigma value is 0.1′′ before we make the pseudocolor image. The size of the images is 5″ × 5″. The length of 1″ is indicated as a white bar.

5. Discussion
5.1. Identification of the Most Distant LAB at z = 7.0

In this study, we have identified the most distant LAB found to date, z70-1 at z = 7.0. The composite pseudocolor image of z70-1 is presented in Figure 19, left. Figure 20 shows the Lyα and continuum profiles of z70-1. To test whether the Lyα profile of z70-1 is more extended than the continuum profile, we fit the exponential function shown in Equation (5) to the Lyα and continuum profiles. In the fitting, the errors of the profiles are considered. The best-fit scale lengths of the Lyα and continuum profiles are 1.43 ± 0.18 and 0.56 ± 0.41 kpc, respectively. We estimate the statistical significance of the difference between the scale lengths of the Lyα and continuum profiles assuming a normal distribution. We find that the Lyα and continuum profiles are different at the 87% confidence level. This suggests that the Lyα emission of z70-1 is extended beyond the continuum. Taken together with the identification of the Lyα emission line on the spectrum and the bright Lyα luminosity of z70-1, our result suggests that z70-1 is a real LAB at z = 7.0.

5.2. An Extremely Extended LAB at z = 5.7

The NB816 image of z57-2 in Figure 3 suggests that z57-2 has very extended Lyα emission presenting no clear center, which is apparently different from the other six LABs. The composite pseudocolor image of z57-2 is shown in Figure 19, right. Figure 21 displays the Lyα surface brightness profile of z57-2, together with the other six LABs and two model galaxies of Halo-11 and Halo-12 (Yajima et al. 2017; Arata et al. 2019) at z ∼ 6. Cosmological hydrodynamic and radiative transfer simulations produce Halo-11 and Halo-12, which have halo masses of 1.6 × 10^{14} and 7.5 × 10^{13} M_☉, respectively. As suggested by Behroozi et al. (2013), the halo masses of Halo-11 and Halo-12 correspond to stellar masses of

| ID   | Z (Z_⊙) | log M_⊙ (M_☉) | E(B − V)_⊙ (mag) | log(Age) (yr) | log(SFR) (M_☉ yr^{-1}) |
|------|---------|---------------|------------------|---------------|------------------------|
| z49-1| 0.004   | 9.0^{+2.7}_{-3.1} | 0.05             | 6.6^{+1.3}_{-1.5} | 2.4^{+1.3}_{-0.4} |
| z66-1a| 0.2     | 10.18^{+0.05}_{-0.07} | 0.15             | 8.26^{+0.05}_{-0.05} | 2.00^{+0.01}_{-0.01} |
| z66-2b| 0.005-0.2 | ∼10.3       | 0.0-0.5          | ∼8.8          | ∼1.4                  |
| z70-1| 0.02    | <9.1         | 0.10             | <7.7          | 2.6^{+1.8}_{-0.8} |

Notes.
- a Best-fit SED from Ouchi et al. (2013).
- b Best-fit SED from Sobral et al. (2015).

Figure 21. Lyα surface brightness profiles of z57-2 (red filled circles), the other six LABs (black filled circles), and two model galaxies of Halo-11 (green dashed-dotted line) and Halo-12 (blue dashed line). The black solid lines are the best-fit total models of the six other LABs in Figure 10. The cyan dotted line represents the PSF. The profiles of Halo-11 and Halo-12 are convolved with the PSF. All of the profiles are normalized at the radius of ∼0 kpc for comparison.
\( \sim 2.0 \times 10^9 \) and \( 1.4 \times 10^{10} M_\odot \) at \( z = 6.0 \), respectively, which are consistent with the stellar masses of our LABs estimated by the SED fitting (Section 4.4). In Figure 21, it is clear that z57-2 has a more extended Ly\( \alpha \) profile than the other six LABs. Moreover, model galaxies of Halo-11 and Halo-12 cannot explain the extremely extended Ly\( \alpha \) profile of z57-2.

The spectrum in Figure 6 shows that z57-2 has a Ly\( \alpha \) emission line with an FWHM of \( \sim 600 \) km s\(^{-1}\), which is broader than those of the other six LABs. It should be also noted that the Ly\( \alpha \) line of z57-2 shows multiple peaks. These features may be caused by dynamical systems, such as multiple components or mergers. Another possibility is that z57-2 has a nearly static cloud of thick HI gas that resonantly scatters components or mergers. Another possibility is that z57-2 has a Ly\( \alpha \) emission with a Ly\( \alpha \) luminosity of \( \sim 10^{43} \) erg s\(^{-1}\). The outflows have also been suggested by an observed Ly\( \alpha \) absorber that can be explained by a foreground hydrogen shell ejected by an LAB at \( z = 3.1 \). It should be noted that our LABs show similar Ly\( \alpha \) luminosities of \( \sim 10^{43} \) erg s\(^{-1}\) and that our LABs may have starbursts driven by possible mergers, as suggested by the multiple UV components in Figure 3.

Multiple supernova explosions are likely to happen in starbursts and drive outflows that produce the luminous and extended Ly\( \alpha \) emission of our LABs.

In Figure 3, the HST images of z49-1, z66-1, and z66-2 clearly show multiple UV continuum components. It is likely that having multiple UV continuum components is a common feature of high-\( z \) LABs (see also Prescott et al. 2012; Francis et al. 2013). The multiple components may correspond to multiple star-forming clumps in one galaxy, mergers, or satellite galaxies. It is possible that satellite galaxies are responsible for the large continuum size of LABs. On the other hand, if the satellite galaxies are the major contributors to the extended Ly\( \alpha \) emission, one would expect that the Ly\( \alpha \) and continuum profiles have similar shapes even if the satellite galaxies are not resolved. In Figure 10, it should be noted that the core component has the same shape as the continuum profile, and that the Ly\( \alpha \) profile cannot be explained by the single core component. However, the difference between the Ly\( \alpha \) and continuum profiles may be caused by satellite galaxies with high Ly\( \alpha \) EW\(_0\), such as the faint LAEs at \( z = 2.9-6.7 \) found in Maseda et al. (2018). It is possible that satellite galaxies with high Ly\( \alpha \) EW\(_0\) are the origin of the extended Ly\( \alpha \) emission around LABs.

In conclusion, all of the five scenarios of fluorescence, resonant scattering, gravitational cooling radiation, outflows, and satellite galaxies may contribute to the extended Ly\( \alpha \) emission around LABs.

### 6. Summary

In this study, we investigate the photometric and spectroscopic properties of seven LABs: two LABs at \( z = 4.888 \) (z49-1) and \( z = 6.965 \) (z70-1) identified by us, and five previously known LABs at \( z = 5.7-6.6 \) (z57-1, z57-2, z66-1, z66-2, and z66-3). Our results are summarized below.

1. We find that z70-1 has extended Ly\( \alpha \) emission with a scale length of \( 1.4 \pm 0.2 \) kpc that is about three times larger than the UV continuum. The object of z70-1 is the most distant LAB identified to date.
2. We show that z57-2 has Ly\( \alpha \) emission that is much more extended than the other six LABs. The origin of the extremely extended Ly\( \alpha \) emission of z57-2 is unclear and cannot be explained by cosmological hydrodynamic and radiative transfer simulations.
3. We measure the core and halo scale lengths of the Ly\( \alpha \) profiles of our LABs and show that the relations between
of the scale lengths and galaxy properties including the $L_{\text{Ly} \alpha}$, EW$_{\text{Ly} \alpha}$, and $M_{\text{UV}}$ of our LABs are similar to those of MUSE LAHs. This suggests that our LABs and MUSE LAHs have similar connections between the extended Ly$\alpha$ emission and host galaxies, and that our LABs are likely the bright version of high-$z$ LAHs.

4. We investigate the large-scale structure around our LABs by measuring the LAE overdensity. We find that all of the seven LABs are located in overdense regions, and six of the seven LABs have large overdensities above the 1$\sigma$ significance levels. Our LABs show no significant correlation between the halo scale length and LAE overdensity.

5. The seven LABs except z49-1 exhibit no AGN signatures such as X-ray emission, N V $\lambda$1240, or Ly$\alpha$ line broadening. The object of z49-1 has a strong C IV $\lambda$1548 emission line that suggests an AGN. We compare the C IV EW$_{\alpha}$ and C IV/He II ratio of z49-1 with the AGN and SFG models in Nakajima et al. (2018) and find that z49-1 is an AGN candidate, although the possibility of a young and low-metallicity SFG cannot be eliminated.

6. We find that all the Ly$\alpha$ emission lines of the seven LABs show velocity gradients on the spectra. The Ly$\alpha$ velocity gradients and line widths of z49-1 and z57-2 are larger than those of the other five LABs, which may be caused by an AGN (not likely for z57-2), mergers, or dense neutral hydrogen gas in the H I region.

7. We discuss the physical origin of the extended Ly$\alpha$ emission around our LABs. Fluorescence, resonant scattering, gravitational cooling radiation, outflows, and satellite galaxies can contribute to the extended Ly$\alpha$ emission.

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References
Aihara, H., Arimoto, N., Armstrong, R., et al. 2018, PASJ, 70, S4
Aniano, G., Draine, B. T., Gordon, K. D., & Sandstrom, K. 2011, PASP, 123, 1218
Arata, S., Yajima, H., Nagamine, K., Li, Y., & Khochfar, S. 2019, MNRAS, 488, 2629
