Observations of the Lyman-α Universe

Masami Ouchi,1,2,3 Yoshiaki Ono,2 and Takatoshi Shibuya4

1National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; email: ouchims@icrr.u-tokyo.ac.jp
2Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8582, Japan
3Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8583, Japan
4Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido 090-8507, Japan

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Abstract
Hydrogen Lyman-α (Lyα) emission has been one of the major observational probes for the high redshift universe, since the first discoveries of high-z Lyα emitting galaxies in the late 1990s. Due to the strong Lyα emission originated by resonant scattering and recombination of the most-abundant element, Lyα observations witness not only HII regions of star formation and AGN but also diffuse HI gas in the circum-galactic medium (CGM) and the inter-galactic medium (IGM). Here we review Lyα sources, and present theoretical interpretations reached to date. We conclude that: 1) A typical Lyα emitter (LAE) at z ≥ 2 with a $L^*$ Lyα luminosity is a high-z counterpart of a local dwarf galaxy, a compact metal-poor star-forming galaxy (SFG) with an approximate stellar (halo) mass and star-formation rate of $10^8 - 10^9 M_\odot$ and $1 - 10 M_\odot$ yr$^{-1}$, respectively; 2) High-z SFGs ubiquitously have a diffuse Lyα emitting halo in the CGM extending to the halo virial radius and beyond; 3) Remaining neutral hydrogen at the epoch of reionization makes a strong dimming of Lyα emission for galaxies at z > 6 that suggest the late reionization history. The next generation large telescope projects will combine Lyα emission data with HI Lyα absorptions and 21cm radio data that map out the majority of hydrogen (HII+Hi) gas, uncovering the exchanges of i) matter by outflow/inflow and ii) radiation, relevant to cosmic reionization, between galaxies and the CGM/IGM.
1. Introduction

Hydrogen Lyα emission is a critical probe for understanding the high-redshift universe. Due to the abundant hydrogen and the atomic electron transition between the lowest energy levels, from the $n = 2$ state to the ground ($n = 1$) state, Lyα is one of the strongest emission lines produced in the universe. Although Lyα has a physical nature of resonance line whose photons have more chances of dust attenuation in gaseous nebulae in the process of resonant scattering, the short wavelength (1216˚A) of Lyα emission allows us to pinpoint faint high-$z$ objects by optical and near-infrared (NIR) observations very efficiently. Lyα is used as an excellent probe of high-$z$ objects near the observational redshift frontier.

Historically, Partridge & Peebles (1967) first predict an importance of a high-$z$ galaxy that emits a strong Lyα line. Partridge & Peebles (1967) argue that an early galaxy produces strong Lyα emission by the recombination process in the inter-stellar medium (ISM) heated by young massive stars, and that up to 6-7% of the total galaxy luminosity can be converted to a Lyα luminosity that is as bright as $\sim 2 \times 10^{45}$ erg s$^{-1}$ at $z \sim 10 – 30$. Moreover, Partridge & Peebles (1967) claim a possibility of strong free-electron scattering in ionized gas of the inter-galactic medium (IGM) that smears radiation from young galaxies. Although recent studies do not agree with the extremely bright Lyα luminosity and the notable smearing of the radiation in the ionized IGM, Partridge & Peebles (1967) is an excellent imaginative theory paper (published more than a half century ago) suggesting that strong Lyα emission of high-$z$ galaxies is physically related to early galaxies and the ionization state of the IGM that are two major topics discussed today with strong Lyα emission, namely galaxy formation and cosmic reionization.

After the theoretical predictions of Partridge & Peebles (1967), a number of programs searched for high-$z$ galaxies with strong Lyα emission by observations. However, no such objects were found until the mid-1990s, due to the limited sensitivities of the available telescopes. Finally, by the operation starts of large (8-10m class) ground-based telescopes

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1 Because a chance of electron’s staying at the ground state is very high, due to a short-time scale required for ground-state transitions, Lyα photons are resonantly scattered by hydrogen.
and Hubble Space Telescope (HST), a few high-z galaxies with strong Lyα emission were successfully identified by narrowband (NB) imaging and spectroscopy on the sky around QSO BR2327-0607 at \( z = 4.55 \) (Hu & McMahon 1996) and a radio galaxy 53W002 at \( z = 2.39 \) (Pascarelle et al. 1996) as well as in the blank field (Cowie & Hu 1998). Subsequently, a number of deep observation programs have been conducted for Lyα emitting objects at \( z \geq 2 \), including the Hawaii Survey (Cowie & Hu 1998), the Large Area Lyman Alpha Survey (Rhoads et al. 2000), the Subaru surveys (Ouchi et al. 2003), and the Multi-wavelength Survey by Yale-Chile (Gawiser et al. 2007), the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) Pilot Survey (Adams et al. 2011), and Very Large Telescope (VLT) /Multi Unit Spectroscopic Explorer (MUSE) survey (Bacon et al. 2017). Moreover, Lyα emitting objects in the local and low-z universe are investigated by space-based UV observations such by the HST program of Lyman-Alpha Reference Sample (Östlin et al. 2014) and the Galaxy Evolution Explorer (GALEX) grism programs (Deharveng et al. 2008; Cowie et al. 2011). Lyα emitting galaxies with no AGN, thus found, have a Lyα luminosity of \( 10^{41} - 10^{44} \, \text{erg s}^{-1} \), more than an order of magnitude fainter than the one predicted by Partridge & Peebles (1967).

Lyα emitting objects are called Lyα emitters (LAEs). Conventionally, LAEs are defined as objects with a rest-frame Lyα equivalent width (EW) of

\[
\text{EW}_0 \gtrsim 20 \, \text{Å}
\] (1)

This Lyα \( \text{EW}_0 \) limit corresponds to that of the samples made by classical observations for LAEs with a NB whose wavelength transmission width is a \( \sim 1\% \) of the central wavelength. It is known that LAEs are young star-forming galaxies (SFGs) or AGNs (Section 3). Figure 1 is an illustration of a conceptual LAE with spectroscopic properties that are detailed in Section 2.

Because Lyα photons are resonantly scattered by neutral hydrogen \( \text{H} \), Lyα is unfortunately thought to be a poor probe of galaxy dynamics or the ionizing photon budget. However, the distribution and dynamics of \( \text{H} \) gas are encoded to Lyα emission via the resonant scattering. The resonantly scattered Lyα photons allow us to investigate \( \text{H} \) gas in and around high-z objects that is generally hard to be probed by observations. The circum-galactic medium (CGM) of high-z SFGs are characterized by diffuse Lyα emission extending over \( > 10 \) physical kpc (pkpc) even to the large scale reaching the IGM (Kakuma et al. 2019). Interestingly, such diffuse Lyα emission of high-z galaxies cover the entire sky in any observational lines of sight (Wisotzki et al. 2018). Figure 1b, d illustrate Lyα emission traveling in the CGM and the IGM. Theoretical models predict that some fractions of Lyα photons are produced by cold accretion, outflow, and unresolved faint satellites (Section 2) especially in the CGM and the IGM. At the epoch of reionization (EoR), the ionized fraction and distribution of \( \text{H} \) in the IGM are imprinted in the observed Lyα emission (Section 9). Lyα is an important probe for gas of the CGM and the IGM for characterizing galaxies and cosmic reionization.

\[\text{cMpc}: \text{comoving megaparsec}\]
\[\text{pkpc}: \text{physical kiloparsec}\]
Figure 1
Conceptual figure of an LAE with a moderately high mass. In panel b, the LAE is located at the central node of the filamentary structure surrounded with satellite galaxies. The white dashed circle represents the virial radius of the host dark matter halo of the LAE. Panel d is a zoom-in of the LAE. Possible origins of Lyα emission are labeled: a) star formation (SF), b) AGN, c) cold accretion, d) outflow, and e) satellite galaxies. In the LAE with outflowing gas, the wavy lines (① – ③) indicate three light paths for the observed Lyα lines. Panels e and c present spectra that are dominated by the contributions of the light paths of ① + ② and ③, respectively, with the observed spectrum (black line) and error (gray region) and the best-fit models (red line). The light paths of ② and ③ indicate that Lyα photons are resonantly scattered in the outflowing gas. In panel a, the continuum spectrum of the LAE with a metal absorption line is shown. The spectral data are adapted with permission from [Hashimoto et al. 2015] and [Sugahara et al. 2019].
2. Physical Picture of LAEs

2.1. Origins of Lyα emission

Lyα emission from galaxies have five major origins. In the ISM near the central region of a galaxy, Lyα emission can be originated from recombinations of hydrogen atoms that are ionized mainly by two sources: 1) young massive stars (star formation) and 2) an AGN if any. In the CGM and the outer region, Lyα can be emitted from three origins: 3) outflow that can collisionally excite H\textsc{i} atoms (shock heating), 4) infalling gas (cold accretion), which is predicted to release a significant amount of its gravitational energy in Lyα through collisional excitation (gravitational cooling), and 5) fluorescence from hydrogen in the CGM and IGM photoionized by UV background radiation powered by energetic sources such as QSOs. In addition, star formation in unresolved faint satellite galaxies can also contribute. Note that no Lyα sources dominated by gravitational cooling have been definitively identified so far (Sections 6 and 7).

Another important physical process for Lyα emission is resonant scattering, since H\textsc{i} gas in typical galaxies is optically thick to Lyα. The cross section of Lyα for a collection of moving atoms can be obtained by convolving the single atom cross section with their velocity distribution. Assuming a Maxwellian velocity distribution and introducing the dimensionless frequency variable

$$x = \frac{(\nu - \nu_0)}{\Delta \nu_D},$$

where \(\nu_0\) is the line center frequency and \(\Delta \nu_D\) is the Doppler width, the average cross section is

$$\sigma_x(\nu, T) = \frac{3\lambda_0^2 a_v}{2\sqrt{\pi}} H(a_v, x) \simeq 5.9 \times 10^{-14} \left(\frac{T}{10^4 K}\right)^{-1/2} H(a_v, x) \text{ cm}^2, \quad (2)$$

where \(\lambda_0\) is the Lyα wavelength, \(a_v\) is the Voigt parameter, and \(H(a_v, x)\) is the Voigt function,

$$H(a_v, x) = \frac{a_v}{\pi} \int_{-\infty}^{\infty} e^{-\frac{y^2}{(y-x)^2 + a_v^2}} dy \approx \left\{ \begin{array}{ll}
    e^{-x^2} & \text{central resonant core,} \\
    a_v \sqrt{\pi x^2} & \text{damping wing.}
\end{array} \right. \quad (3)$$

The transition between the core and wing happens at around \(e^{-x^2} = a_v/(\sqrt{\pi} x^2)\). Based on these equations, H\textsc{i} gas is optically thick to Lyα at the line center (hereafter referred to as “optically thick”) when the H\textsc{i} column density is higher than \(N_{\text{HI}} = 1/\sigma_x(\nu_0, T) \simeq 2 \times 10^{13} (T/10^4 \text{K})^{1/2} \text{ cm}^{-2}\), which is much lower than those of typical galaxies. Although this resonance nature of Lyα makes it difficult to pinpoint the original Lyα source position, it enables investigations of the distribution and the kinematics of H\textsc{i} gas via theoretical modeling.

2.2. Modeling Lyα Emission

One of the key issues to modeling Lyα emission from galaxies is its complicated radiative transfer due to the resonance nature of Lyα. Analytical solutions have been obtained only in very limited cases. In the simple case of an optically thick dust-free static slab with

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5 In the case of collisional excitation, the Lyα to H\textsc{a} flux ratio can be higher than that of the case B recombination (Figure 7 of Dijkstra 2017).

6 A detailed derivation of this equation is given in Section 6.4 of Dijkstra (2017).

7 In other words, Lyα photons scatter multiple times in the optically thick line core before diffusing into the wings, where they finally escape.
a central plane source emitting Lyα, the emergent Lyα line profile is given by Harrington (1973) as

\[ J(x) = \frac{\sqrt{6}}{24\sqrt{\pi}a\tau_0} x^2 \cosh \left( \sqrt{\frac{x^2 - x^2_c}{2a\tau_0}} \right), \tag{4} \]

where \( \tau_0 \) is the optical depth at the line center from the center to the boundary of the slab. The spectral shape is symmetric around \( x = 0 \) and double peaked at \( x \approx \pm 1.1(a\tau_0)^{1/3} \). The peaks are more separated with higher \( \tau_0 \), because Lyα photons need to shift their velocities more into the wings to escape.

For more general cases, there are some theoretical models, such as the expanding shell (ES) model (Ahn 2004; Verhamme et al. 2006), that adopt the Monte Carlo radiative transfer technique, which successfully explain the diversity of observed Lyα profiles with a relatively small number of physical parameters. The ES model assumes a simple geometry where a Lyα source is located at the center of a spherically symmetric expanding shell of homogeneous and isothermal HI gas, modeling a galaxy-scale supershell made by multiple supernovae in star-forming regions (Figure 1d).

To explain the basic idea of the ES model, Figure 1 shows the predictions of observed Lyα emission line profiles for three different light paths (1○−3○). Lyα photons along the light path (1○) directly come from the central Lyα source penetrating the shell. Along the light path (2○), Lyα photons escape from the shell approaching the observer via scattering, although some of them are absorbed by HI in the shell, resulting in a red component escaping the red wing of Lyα absorption in the blueshifted shell and a small blue component escaping the blue wing of the Lyα absorption. Figure 1f shows the Lyα spectrum that is dominated by these two components (1○+2○). The velocity shift of the red component relative to the systemic redshift is small, because a small number of Lyα photons escape from the far side of the shell blowing away by scattering that is referred to as backscattering. Lyα photons tracking the light path (3○) experience the backscattering at the shell. In this case, the Lyα spectrum can have a peak at \( \sim 2V_{\text{exp}} \), where \( V_{\text{exp}} \) is the radial expansion velocity or the outflow velocity (see Figure 1f). The \( \sim 2V_{\text{exp}} \) shift of the peak is given by an effect similar to that of a reflection in a moving mirror; the Lyα photons enter the shell experiencing a Doppler shift by \( V_{\text{exp}} \) and are then backscattered to the observer being further Doppler shifted by \( V_{\text{exp}} \). This simple model has successfully reproduced observed Lyα profiles of LAEs as well as of Lyman break galaxies (LBGs) at both low and high redshifts (Section 6).

Combining with Monte Carlo radiative transfer calculations, some theoretical studies have conducted cosmological hydrodynamic simulations including dust attenuation effects to investigate possible descendants of high-z LAEs as well as their physical properties. Yajima et al. (2012) have found that progenitors of a present-day Milky Way (MW) like galaxy with a halo mass \( \sim 10^{12} \, M_\odot \) show bright Lyα emission at high redshifts comparable to Lyα \( L^* \) (\( L_{\text{Ly}\alpha}^* \)) of LAEs at \( z \sim 2 - 6 \). The left panel of Figure 2 shows the distributions of gas and stars of the most massive progenitor of a MW-like galaxy as well as the Lyα surface brightness (SB) at different redshifts. The right panel of Figure 2 represents the evolution of Lyα properties of the 60 most massive progenitors. As shown in the bottom right panel of Figure 2, most of the galaxies at high redshifts are classified as LAEs, and

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8See also Equation 3.51 and the footnote on p.29 of Laursen (2010).
9Such galaxy-scale expanding supershells are found in nearby starbursts (Marlowe et al. 1995).
Figure 2

Left: Snapshots of a MW-like galaxy at different redshifts in a cosmological hydrodynamic simulation. From left to right, the distributions of gas and stars as well as the SB of Ly\(\alpha\) are shown. The box size is 200 pkpc. Right: Evolution of the Ly\(\alpha\) properties of the 60 most massive progenitors. From top to bottom, the Ly\(\alpha\) luminosity, the escape fraction of Ly\(\alpha\) photons over whole solid angle, and Ly\(\alpha\) EW\(0\) are presented. The red filled circle corresponds to the most massive progenitor at each redshift. The blue filled circles represent the median value of the 60 galaxies. Note that observational effects of reionization, Ly\(\alpha\) dimming in the IGM (Section 9), are not included in the models. Adapted from Yajima et al. (2012) with permission.

3. Ly\(\alpha\) Emitter Observations

As introduced in Section 1, LAEs have been identified by many observational studies. The successful classical technique to find LAEs is NB imaging. In this technique, LAEs are selected based on their NB excesses compared to broadbands (Figure 3). Imaging surveys with wide-field cameras such as Subaru Suprime-Cam have constructed large samples of LAEs and their follow-up spectroscopic campaigns have confirmed the validity of the NB imaging technique with low fractions of contaminants. The recent advent of new wide-field cameras including Hyper Suprime-Cam (HSC) now allows LAE surveys over cosmological
volumes ($\sim 0.5$ comoving Gpc$^2$; Ouchi et al. 2018).

Another successful technique is blind spectroscopy. In particular, the integral field spectrograph of VLT/MUSE has recently yielded complementary results to those of the NB imaging. Thanks to the wider wavelength coverage and higher spectral resolution, MUSE is suitable to search for LAEs over a wide redshift range down to a flux limit fainter than the NB observations (Drake et al. 2017), although the field-of-view of MUSE is small. Another remarkable effort is made by a wide-field fiber spectrograph survey, HETDEX (Hill et al. 2008), to cover a $\sim 400$ deg$^2$ sky via a blind search for relatively bright LAEs. Because strong Ly$\alpha$ emission from high-z galaxies is redshifted in a wavelength range of optical and NIR where deep spectroscopic data can be obtained, Ly$\alpha$ emission has been detected in many galaxies by spectroscopy at the high-redshift frontier. Table 1 presents the list of galaxies identified, to date, at a spectroscopic redshift $z_{\text{spec}} > 7.2$. Some high-z galaxies are found only with the Ly$\alpha$ continuum break (Oesch et al. 2016) or [OIII]88$\mu$m emission (Tamura et al. 2019). Previously it was thought that Ly$\alpha$ photons cannot escape from galaxies especially at the early EoR due to the resonant scattering effect in the neutral IGM. However, as summarized in Figure 4, a majority of galaxies, found to date, show Ly$\alpha$ emission even at $z \sim 9$, beyond the heart of reionization, suggesting a patchy nature of reionization where relatively luminous ionizing sources such as the spectroscopically confirmed galaxies are located in large ionized bubbles in the IGM, which allow Ly$\alpha$ photons to escape from the neutral IGM.

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Table 1  List of spectroscopically identified galaxies at $z_{\text{spec}} > 7.2$

| ID          | R.A. (J2000)  | Decl. (J2000) | $z_{\text{spec}}$ | $M_{UV}$ (mag) | $\text{Ly}_\alpha$ EW ($\AA$) | Probe Lines | Other Reference |
|-------------|---------------|---------------|-------------------|----------------|-------------------------------|-------------|-----------------|
| GN-z11      | 12:36:25.46   | +62:14:31.4   | 11.09             | $-22.1 \pm 0.2$ | Lyman break                   | O16         |
| MACS1149-JD | 11:49:33.59   | +22:44:45.80  | 9.3096            | $-22.0$        | 28                            | Ly$\alpha$  |
| EGS-2008b   | 14:20:08.50   | +52:53:26.60  | 8.6843            | 11.1           | Ly$\alpha$                    | L17         |
| AzTE4-YD2   | 00:14:24.9    | -30:22:56.1   | 8.382             | 10.7 $\pm$ 2.7 | Ly$\alpha$                    | L17         |
| MACS0416-Y1 | 04:16:09.40   | -24:05:35.5   | 8.3118            | 11.4           | Ly$\alpha$                    | T19         |
| EGS-z8-1    | 14:20:34.89   | +53:00:15.4   | 7.7302            | 21.4           | Ly$\alpha$                    | Z15         |
| z7-GND-3811 | 03:32:32.01   | -27:45:37.1   | 7.6037            | 15.6 $^2$ $(^0)$ | Ly$\alpha$                    | S16         |
| MACS1423-z7p64 | 12:36:25.46 | +62:14:31.4   | 11.09             | $-22.1 \pm 0.2$ | Lyman break                   | O16         |
| EGS-z8-2    | 14:20:12.09   | +53:00:26.97  | 7.4770            | 20.2           | Ly$\alpha$                    | B16, S17    |
| GS2-148     | 03:33:09.14   | -27:51:55.47  | 7.452             | 140.3 $\pm$ 19.0 | Ly$\alpha$                    | L18         |
| SDF-01106-2 | 13:24:35.418  | +27:27:37.84  | 7.268             | 1.99 $\pm$ 0.37 | Ly$\alpha$                    | S12         |
| SXDF-01106-2 | 02:18:44.518 | -19:15:58.79  | 7.215             | 21.52 $\pm$ 0.18 | Ly$\alpha$                    | S12, S17    |
| GJ-10806    | 12:36:22.08   | +62:08:07.7   | 7.213             | 21.8           | Ly$\alpha$                    | O12         |

Note: (1) Object ID. (2) Right ascension. (3) Declination. (4) Spectroscopic redshift. (5) Intrinsic UV absolute magnitude. (6) Ly$\alpha$ EW in the rest-frame. (7) Emission lines used for spectroscopic redshift determination. (8) Other detected emission lines. (9) Reference: F13 = Finkelstein et al. (2013), H18 = Hashimoto et al. (2018), Ho17 = Hoang et al. (2017), Ho18 = Hoang et al. (2018), Hu19 = Hu et al. (2019), H16 = Inoue et al. (2016), J19 = Jung et al. (2019), L17 = Laporte et al. (2017), L18 = Larson et al. (2018), O12 = Oesch et al. (2012), O15 = Oesch et al. (2015), O16 = Oesch et al. (2016), RB16 = Roberts-Borsani et al. (2016), S12 = Shibuya et al. (2012), S16 = Song et al. (2016), S17 = Stark et al. (2017), T19 = Tamura et al. (2019), and Z15 = Zitrin et al. (2015).

Figure 4
UV absolute magnitude, $M_{UV}$, as a function of redshift for spectroscopically confirmed galaxies at $z_{\text{spec}} > 7$ taken from Table 1 and the literature. The red and black circles represent galaxies with and without Ly$\alpha$ detection, respectively. In particular, galaxies with Ly$\alpha$ $EW > 20\AA$ are shown with the red filled circles.
In total, thanks to the successful selection techniques and intensive spectroscopic follow-up campaigns, until now >1,000 (>20,000) LAEs have been spectroscopically identified (photometrically selected) in the literature (e.g., Drake et al. 2017; Sobral et al. 2018; Shibuya et al. 2019). As shown in the bottom right panel of Figure 3, LAEs tend to have faint sub $L_{\text{UV}}^* \sim 0.1L_{\text{UV}}^*$ luminosities, UV-continuum luminosities fainter than the characteristic luminosity $L_{\text{UV}}^*$ of SFGs (Reddy & Steidel 2009) at similar redshifts by about an order of magnitude. The numerous LAEs with faint UV continua can be understood by the observational fact that a UV-continuum faint SFG has a Ly$\alpha$ emitting galaxy fraction higher than the one of a UV-continuum bright SFG (Figure 5), which is known as the Ando effect (Ando et al. 2006).

**Figure 5**
Fraction of spectroscopically confirmed galaxies at $z = 3.0–6.2$ emitting strong Ly$\alpha$ lines (Ly$\alpha$ $EW_0 > 50$ Å) as a function of $M_{\text{UV}}$. The black vertical dashed line denotes the $\simeq 90\%$ detection completeness limit. The red dashed lines are the best-fit lines of the first-order polynomials in the ranges of $-22.0 < M_{\text{UV}} < -20.5$ and $-20.0 < M_{\text{UV}} < -18.5$. Adapted from Stark et al. (2010) with permission.

One of the most fundamental observational quantities to characterize galaxy properties is the luminosity function (LF). The left panels of Figure 6 compile Ly$\alpha$ LF measurements for LAEs over a wide redshift range of $z \sim 0.3–7.3$. The Ly$\alpha$ LF is often parameterized with a Schechter function (Schechter 1976),

$$\phi(L_{\text{Ly}}\alpha)dL_{\text{Ly}}\alpha = \phi^* \left( \frac{L_{\text{Ly}}\alpha}{L_{\text{Ly}}\alpha}^* \right)^{\alpha} \exp \left( -\frac{L_{\text{Ly}}\alpha}{L_{\text{Ly}}\alpha}^{*} \right) d\left( \frac{L_{\text{Ly}}\alpha}{L_{\text{Ly}}\alpha} \right),$$

(5)

Throughout this review, the UV continuum indicates the continuum emission at the rest-frame $\simeq 1500$ Å. No extinction corrections are applied unless otherwise specified.
where $L_{\text{Ly}\alpha}$ is the observed Ly$\alpha$ luminosity, $L^*_{\text{Ly}\alpha}$ is the characteristic Ly$\alpha$ luminosity, $\phi^*$ is the normalization, and $\alpha$ is the faint-end slope. A Schechter function is also expressed with a Ly$\alpha$ luminosity in the logarithmic form,

$$
\Phi(\log L_{\text{Ly}\alpha}) = (\ln 10) \phi^* 10^{(\alpha+1)(\log L_{\text{Ly}\alpha} - \log L^*_{\text{Ly}\alpha})} \exp\left(-10^{(\log L_{\text{Ly}\alpha} - \log L^*_{\text{Ly}\alpha})}\right).
$$

The best-fit Schechter functions derived in the literature are also plotted in the left panels of Figure 6 and their best-fit Schechter parameters are summarized in Table 2. The right panels of Figure 6 show the 1$\sigma$ and 2$\sigma$ confidence intervals for the combinations of the Schechter parameters of $L^*_{\text{Ly}\alpha}$ and $\phi^*$, where the $\alpha$ values are fixed at fiducial values of $-1.8$ for low redshifts (top) and $-2.5$ for high redshifts (bottom).

Figure 6
Left: Ly$\alpha$ LFs from $z = 0.3$ to $z = 5.7$ (top) and from $z = 5.7$ to $z = 7.3$ (bottom). The colored curves are their best-fit Schechter functions. Right: 1$\sigma$- and 2$\sigma$-level error contours of their Schechter parameters, $L^*_{\text{Ly}\alpha}$ and $\phi^*_{\text{Ly}\alpha}$. The references of the data are summarized in Table 2.

Ly$\alpha$ LFs show three evolutionary trends: a monotonic increase from $z \sim 0$ to $z \sim 3$, no evolution from $z \sim 3$ to $z \sim 6$, and a rapid drop beyond $z \sim 6$. First, at $z \sim 0 - 3$, the Ly$\alpha$ LFs show a strong increase with increasing redshift (Deharveng et al. 2008; Cowie et al. 2010). The rise of Ly$\alpha$ LFs is much larger than that of UV-continuum LFs based on
Table 2  Schechter parameters for Lyα LFs of LAEs

| redshift | $L_{\text{Ly}\alpha}$ (10^{42} \text{ erg s}^{-1}) | $\phi^*$ (10^{-3} \text{ Mpc}^{-3}) | $\alpha$ | Reference |
|----------|---------------------------------|---------------------------------|--------|-----------|
| 0.3      | 0.71^{+1.22}_{-0.29}            | 1.12^{+2.47}_{-0.61}           | -1.8 (fixed) | Cowie et al. (2010), Konno et al. (2016) |
| 2.2      | 4.87^{+1.83}_{-0.68}            | 3.37^{+0.80}_{-0.66}           | -1.8 (fixed) | Konno et al. (2016) |
| 3.1      | 8.45^{+1.65}_{-0.74}            | 3.90^{+1.27}_{-0.90}           | -1.8 (fixed) | Ouchi et al. (2008), Konno et al. (2016) |
| 5.7      | 9.09^{+3.47}_{-2.70}            | 4.44^{+4.04}_{-2.95}           | -1.8 (fixed) | Ouchi et al. (2008), Konno et al. (2016) |
| 5.7      | 16.4^{+21.6}_{-6.2}             | 0.849^{+0.771}_{-0.57}         | -2.56 ± 0.43 | Ouchi et al. (2018) |
| 6.6      | 16.6^{+4.0}_{-6.9}              | 0.467^{+14.44}_{-0.442}        | -2.49 ± 0.50 | Konno et al. (2018) |
| 7.0      | 15.0^{+4.2}_{-3.1}              | 0.45^{+0.26}_{-0.18}           | -2.5 (fixed) | Itoh et al. (2018) |
| 7.3      | 5.5^{+9.45}_{-3.3}              | 0.94^{+12.03}_{-0.93}          | -2.5 (fixed) | Konno et al. (2014), Itoh et al. (2018) |

the comparisons of Lyα luminosity densities (LDs), i.e.,

$$\rho_{\text{Ly}\alpha} = \int_{L_{\text{Ly}\alpha}^{\text{lim}}}^{\infty} L_{\text{Ly}\alpha} \phi_{\text{Ly}\alpha}(L_{\text{Ly}\alpha})dL_{\text{Ly}\alpha},$$  \hspace{1cm} (7)

where $L_{\text{Ly}\alpha}^{\text{lim}}$ is the limiting Lyα luminosity, and the UV-continuum LDs,

$$\rho_{\text{UV}} = \int_{L_{\text{UV}}^{\text{lim}}}^{\infty} L_{\text{UV}} \phi_{\text{UV}}(L_{\text{UV}})dL_{\text{UV}},$$  \hspace{1cm} (8)

where $\phi_{\text{UV}}$, $L_{\text{UV}}$, and $L_{\text{UV}}^{\text{lim}}$ are the UV-continuum LF, the UV-continuum luminosity, and the limiting UV-continuum luminosity, respectively. The top panel of Figure 4 (Konno et al. 2016) presents the comparison of the Lyα and UV-continuum LD evolution, and indicates that the rise of the Lyα LD is larger than the one of the UV LD from $z \sim 0$ to 3. Second, from $z \sim 3$ to $z \sim 6$, the Lyα LFs show no significant evolution (Ouchi et al. 2008), while the UV LFs decrease strongly in the volume number density at $M_{\text{UV}} = -21$ mag by a factor of about 5 (Bouwens et al. 2015). These differences of the evolutionary trends can be explained by the fact that the escape fraction of Lyα photons and/or the ionizing photon production rate from galaxies increase with increasing redshift from $z \sim 0$ to $z \sim 6$ (Hayes et al. 2011). See Section 6 for more details. The Lyα escape fraction is defined as

$$f_{\text{esc}} = \frac{L_{\text{Ly}\alpha}}{L_{\text{Ly}\alpha}^{\text{int}}},$$  \hspace{1cm} (9)

where $L_{\text{Ly}\alpha}^{\text{int}}$ is the intrinsic Lyα luminosity that can be estimated from a star-formation rate (SFR), $L_{\text{Ly}\alpha}^{\text{int}} [\text{erg s}^{-1}] = 1.1 \times 10^{42} \text{ SFR} [M_\odot \text{ yr}^{-1}]$, under the assumption of the case B recombination (Footnote 11 of Henry et al. 2015) and the relation between the Hα luminosity and SFR (i.e., a constant ionizing photon production rate; Kennicutt 1998). The bottom panel of Figure 7 presents evolution of the cosmic average $f_{\text{esc}}^{\text{Ly}\alpha}$ values that are estimated with the Lyα and UV LFs via eq. (9). The cosmic average $f_{\text{esc}}^{\text{Ly}\alpha}$ monotonically increases by two orders of magnitude with increasing redshift from $z \sim 0$ to $z \sim 6$. Lastly, the Lyα LD appears to drop faster than the UV LD from $z \sim 6$ to a higher redshift (Figure 7). Because this evolutionary trend at $z \gtrsim 6$ is closely related to cosmic reionization, we discuss this evolutionary trend thoroughly in Section 9.
Figure 7
Top: Lyα LDs and UV LDs as a function of redshift. The red symbols indicate Lyα LDs. The orange (blue) symbols and shaded area denote the UV LDs and the errors, respectively, corrected for (no) dust extinction. The gray area is the evolutionary trend of the dust-corrected UV LDs scaled to the Lyα LD at $z \sim 3$. Bottom: Cosmic average Lyα escape fraction, $f_{\text{Ly}}^{\text{esc}}$, as a function of redshift. The red filled (open) symbols are $f_{\text{Ly}}^{\text{esc}}$ estimated from the observed Lyα LDs and the dust-corrected UV LDs without (with) considering the effect of IGM absorption. The blue symbols are those corrected for dust extinction in the case of no Lyα resonant scattering, which are discussed in the text of Section 6 regarding Lyα escape fraction. The magenta solid line represents the best-fit function for the Lyα escape fraction evolution from $z = 0$ to 6. Adapted from Konno et al. (2016) with permission.

Another notable feature in Lyα LFs is the shape of the bright end. At $z \sim 2–3$, the significant bright-end LF excesses beyond the Schechter functions are found and explained by AGNs by the multiwavelength analysis (Konno et al. 2016) and spectroscopy (Sobral et al. 2018). At redshifts higher than $z \sim 2–3$, such bright-end LF excess features are not clearly found, probably because the number densities of AGNs decrease with increasing...
redshift. Interestingly, at the EoR $z \sim 7$, some studies have reported possible bright-end LF excess detections, arguing that bright LAEs are presumably surrounded by large ionized bubbles (Matthee et al. 2015; Zheng et al. 2017). However, with the great statistical accuracy, the Subaru HSC survey has recently claimed that the Ly$\alpha$ LF at $z \sim 7$ can be explained by the Schechter functional form with no significant bright-end LF excess but with a steep slope of $\alpha \sim -2.5$ (Komoo et al. 2018; Itoh et al. 2018). The shape of the bright-end LF is under debate (Hu et al. 2019).

Although the previous studies have successfully characterized the overall evolution of Ly$\alpha$ LFs, there is still a fundamental but important open question: What is the lowest mass of dark matter halos of SFGs that can emit Ly$\alpha$? The previous observations are not deep enough to detect very faint LAEs. In fact, as can be seen in Table 2, most of the previous studies do not obtain good constraints on the faint end slope $\alpha$ and thus have fixed $\alpha$ at a fiducial value in the Schechter function fitting. From the theoretical point of view, the LF is expected to have a turnover at a faint luminosity, because it is difficult for very low-mass halos to host SFGs due to inefficiency of gas cooling (Liu et al. 2016).

4. Morphological Properties

A compact nature of LAEs has been known by HST observations since the early discoveries of LAEs (Pascarelle et al. 1996). Deep HST extra-galactic legacy data have indicated that LAEs have half light radii of $r_e \sim 1$ pkpc on average in the rest-frame UV and optical stellar continua (Malhotra et al. 2012; Paulino-Afonso et al. 2018; Shibuya et al. 2019). Although sub-structures are found in some cases, the main stellar components of LAEs basically have a disk-like radial SB profile with a S´ersic index of $n_s \sim 1$ (Gronwall et al. 2011; Taniguchi et al. 2009) similar to LBGs (left panel of Figure 8). This typical radial SB profile of LAEs is not largely changed over cosmic time similar to other SFG populations (Paulino-Afonso et al. 2018; Shibuya et al. 2019).

Early HST studies have reported that the UV morphology of LAEs shows the nearly no $r_e$ evolution over cosmic time (Malhotra et al. 2012; Paulino-Afonso et al. 2018). However, it is claimed that the no $r_e$ evolution results may be obtained by the bias raised by heterogeneous LAE samples in luminosity over the redshift range (Shibuya et al. 2019). Note that the UV continuum morphology of LAEs follows the $r_e$-luminosity relation similar to the one of LBGs. The $r_e$-luminosity relation indicates that faint continuum LAEs have a small $r_e$ (Leclercq et al. 2017; Shibuya et al. 2019). If sample selections at different redshifts are not well controlled, observers identify many faint LAEs at low $z$ that has a small $r_e$, which diminishes a trend of $r_e$ evolution. Comparing bias-controlled and uncontrolled samples, Shibuya et al. (2019) find that the no $r_e$ evolution of LAEs is mistakenly concluded, due to the existence of the $r_e$-luminosity relation and the sample bias. With the bias-controlled samples, the median $r_e$ values of LAEs monotonically evolve as $r_e \sim (1 + z)^{-1.37}$ similar to those of SFGs and LBGs at a given UV-continuum luminosity (Shibuya et al. 2019; right panel of Figure 8).

The spatial offset between Ly$\alpha$ and stellar continuum emission peaks, referred to as the Ly$\alpha$ spatial offset or $\delta_{\text{Ly} \alpha}$, is an important clue to physical properties of LAEs (Ouchi et al. 2013; Jiang et al. 2013). Statistical studies suggest that LAEs with a low Ly$\alpha$ EW$_0$ typically have a large $\delta_{\text{Ly} \alpha}$ value (Shibuya et al. 2014; Hoag et al. 2019). This Ly$\alpha$ EW$_0 - \delta_{\text{Ly} \alpha}$ anti-correlation implies that Ly$\alpha$ photons are selectively attenuated by dust, due to the long mean-free path of Ly$\alpha$ photons by resonant scattering in abundant HI gas of low-Ly$\alpha$
EW$_0$ galaxies that makes large δ$_{\text{Ly} \alpha}$ values.

In summary, the disk-like radial SB profile and the $r_e$ values indicate that LAEs have stellar components similar to that of LBGs at a given UV continuum luminosity. This morphological similarity suggests that the Ly$\alpha$ escape is not strongly related to the morphology of stellar components, but instead, is governed by the column density, geometry, kinematics, and/or ionization states of the ISM and CGM. This interpretation is also supported by the δ$_{\text{Ly} \alpha}$ measurements. This physical picture is explained by the theoretical models of the viewing angle effect where Ly photons easily escape in the direction of disk face-on (Zheng & Wallace 2014) Verhamme et al. 2012). Of course, the morphology of LAEs may not be a simple disk, but a disk-like shape with sub-structures on < 1 pkpc scales that are poorly understood. Clumpy structures are identified in various high-z galaxies including some LAEs (Shibuya et al. 2016) Cornachione et al. 2018 Ritondale et al. 2019). Further studies are needed to test the viewing angle effect of the Ly$\alpha$ escape.

![Figure 8](image.png)

Left: Radial SB profiles of continuum in the rest-frame UV wavelength for LAEs (red curve) and LBGs (blue curve) at $z \sim 3 - 4$ (Shibuya et al. 2019). The shaded regions associated with the red and blue curves show the 1σ uncertainties of the radial SB profiles. The solid and dashed black lines depict the best-fit Sérsic profiles with $n_s = 1$ and $n_s = 4$, respectively. The gray line denotes a point spread function (PSF) of the imaging data. Right: Redshift evolution of $r_e$ for LAEs (red diamonds; Shibuya et al. 2019) and SFGs/LBGs (small and large blue filled circles; Shibuya et al. 2015) in the $L_{\text{UV}}$ range of $0.12 - 1 L_{\ast, z=3}$, where $L_{\ast, z=3}$ is the characteristic UV luminosity at $z \sim 3$ (Steidel et al. 1999). The red filled diamonds with and without an open circle represent $r_e$ measured in the rest-frame optical and UV wavelengths, respectively. The red open diamonds are observational estimates of $r_e$ for the luminosity range of $L_{\text{UV}} = 0.12 - 1 L_{\ast, z=3}$ (see Shibuya et al. 2019). The magenta region and blue line present the best-fit $(1 + z)^\alpha$ functions for the LAEs and SFGs/LBGs, respectively, where $\alpha$ is the power-law index. The black symbols denote measurements of LAEs summarized in Shibuya et al. (2019).

5. Stellar Population

Studying the stellar population of LAEs is important to understand their physical nature and to reveal the relationship between LAEs and other high-z galaxies at similar redshifts. Stellar populations of galaxies are characterized with physical properties such as stellar mass and stellar age, and can be investigated from comparisons between their observed spectral energy distributions (SEDs) with those of stellar population synthesis models. Since LAEs
are typically faint in the continuum, it is not easy to derive their SEDs on an individual basis, and thus many studies have performed stacking analyses of low spectral-resolution broadband photometry to obtain their typical SEDs with a high signal-to-noise ratio.\footnote{There are two major stacking methods, i.e., average and median, and each method has its pros and cons. In general, average stacking can consider all objects in a sample yielding a good representative value, unless the sample includes outliers such as very bright AGN and/or low-z emission line galaxy contaminants. Median stacking is less likely to be affected by such contaminants, although it does not take into account the fluxes of all objects in a sample. Thus, one should check the consistency of the results with these two methods. Note that, although these two stacking methods mostly give reasonable results for typical values, no stacking method can identify the large dispersion of properties in a sample if any (Vargas et al. 2014).}

Early studies have demonstrated that the rest-frame UV to optical SEDs of high-z LAEs can be obtained from the combination of deep optical data with NIR images such taken with the Spitzer Space Telescope (Gawiser et al. 2007; Lai et al. 2008). Since typical LAEs host star formation, their SEDs of broadband photometry are expected to be characterized with not only stellar emission but also nebular emission from their star-forming regions. In fact, deep NIR spectroscopy results targeting $z \sim 2 - 3$ LAEs have revealed the presence of strong nebular emission lines in the rest-frame optical wavelength such as Hα and [Oiii]5007 (Guaita et al. 2013; Nakajima et al. 2013). A study of local LAEs indicates that a majority of LAEs have Hα $EW_{\alpha}$ of $\sim 50 - 1000$ Å (Cowie et al. 2010). To include the influence of nebular emission on the determination of stellar population parameters, Ono et al. (2010b) have fitted stellar population synthesis models with and without nebular emission to averaged SEDs of $z \sim 6 - 7$ LAEs by adopting the prescription for nebular emission suggested by Schaerer & de Barros (2009). Ono et al. (2010b) have shown that the best-fit parameters in these two cases are extremely different for the LAEs, mainly because strong nebular lines mimic a substantial Balmer break feature.\footnote{It is confirmed that flux ratios of [Oiii]/Hα in best-fit SED+nebular emission models are consistent with those directly obtained by spectroscopy (Figure 9 of Harikane et al. 2018).} For example, the best-fit stellar mass (age) in the case of considering nebular emission is about an order (two orders) of magnitude smaller than that without nebular emission, which is more serious than the case of the continuum-bright LBGs (Schaerer & de Barros 2009). It is critical for including the effect of nebular emission in stellar population analyses of LAEs.

Subsequent results including the effect of nebular emission have led to a general consensus that typical LAEs are low-mass (stellar mass $\sim 10^{8-9} M_\odot$), young stellar age ($\sim 10$ Myr)\footnote{This young stellar age can be found, probably due to intermittent star formation.} SFGs with a SFR of $\sim 1 - 10 M_\odot$ yr$^{-1}$ (Figure 9; Nakajima et al. 2012 see also Hagen et al. 2013), suggesting that typical LAEs are high-z counterparts of local dwarf galaxies, i.e. high-z analogs of local dwarf galaxies. The right panel of Figure 9 shows compilations of stellar mass and SFR estimates for LAEs at $z \sim 2$ (Hagen et al. 2016) as well as photo-z selected SFGs at similar redshifts (Santini et al. 2017). At fixed stellar masses of $M_* \sim 10^9 M_\odot$, where the completeness for the NB-selected LAEs is high enough for fair comparisons of LAEs and SFGs, LAEs have higher SFRs than the average values of the SFGs, indicating that LAEs have higher specific SFRs than typical SFGs due to the young stellar ages of LAEs.
6. Inter-Stellar Medium (ISM)

In this section, we review four topics of the ISM of LAEs. In the first three topics, we introduce three ISM properties of LAEs: gas kinematics and neutral hydrogen column density, dust extinction, and metallicity. All of these properties are explained by the nature of LAEs that have a Lyα escape fraction higher than the other galaxy population, which are detailed in the fourth topic. In the fourth topic, we present that LAEs are sources of ionizing photons with distinguished ISM features, i.e. a high ionization state.

Gas Kinematics and Neutral Hydrogen Column Density — Analyses of emission and absorption lines suggest that LAEs show a strong gas outflow and a low neutral hydrogen column density $N_{\text{HI}}$. The gas kinematics is evaluated from the velocity offset of the low-ionization interstellar (LIS) UV metal absorption lines $\Delta v_{\text{IS}}$ with respect to the systemic redshift $z_{\text{sys}}$. Deep NIR spectroscopic observations have found that the LIS UV metal absorption lines are typically blueshifted from $z_{\text{sys}}$ by $\sim 200$ km s$^{-1}$ for LAEs [Hashimoto et al. 2013, Shibuya et al. 2014a] Figure 1], suggesting that there exists a notable gas outflow with an outflow velocity of $V_{\text{exp}} \sim 200$ km s$^{-1}$ in LAEs that is similar to LBGs, majority of which are SFGs with weak/no Lyα emission [Steidel et al. 2010]. Another important tool
characterizing the gas kinematics is a Lyα emission line. Observations of Lyα emission find various shapes of Lyα profiles, a Lyα emission velocity offset (redshift) from the systemic velocity and double Lyα emission line peaks. Several studies have measured the Lyα velocity offset $\Delta v_{\text{Ly}\alpha}$ for LAEs (McLinden et al. 2011; Guaita et al. 2013), and have identified an anti-correlation between Lyα $EW_0$ and $\Delta v_{\text{Ly}\alpha}$ (Hashimoto et al. 2013; Shibuya et al. 2014a; Erb et al. 2014). As shown in the left panel of Figure 10, LAEs have a Lyα velocity offset of $\Delta v_{\text{Ly}\alpha} \sim 200$ km s$^{-1}$ (see a typical spectrum in Figure 1e), which is systematically smaller than $\Delta v_{\text{Ly}\alpha} \sim 400$ km s$^{-1}$ of LBGs (Steidel et al. 2010; see a typical spectrum in Figure 1b). According to the observational results, LAEs have, on average, a Lyα velocity offset comparable with the outflow velocity, $\Delta v_{\text{Ly}\alpha} \sim V_{\text{exp}} \sim 200$ km s$^{-1}$, while LBGs show $\Delta v_{\text{Ly}\alpha} \sim 2V_{\text{exp}} \sim 400$ km s$^{-1}$.

If the ES model (Section 2.2) is applicable to LAEs and LBGs, various profiles of the observed Lyα emission lines including the Lyα velocity offsets and double peaks can be beautifully explained. The ES models best-fit to the observational data are presented with red lines in Figure 1, e. Moreover, the Lyα $EW_0 - \Delta v_{\text{Ly}\alpha}$ anti-correlation can be interpreted by the difference in $N_{\text{HI}}$ between LAEs and LBGs. In the ES model, the relation of $\Delta v_{\text{Ly}\alpha} \sim V_{\text{exp}}$ is obtained, if the backscattered Lyα emission is weak due to the small H$\text{I}$ column density of the shell, $N_{\text{HI}} \lesssim 10^{20}$ cm$^{-2}$. In contrast, $\Delta v_{\text{Ly}\alpha} \sim 2V_{\text{exp}}$ is reproduced, if the amount of Lyα back scattering is large in the case of a high H$\text{I}$ column density in the shell, $N_{\text{HI}} \gtrsim 10^{20}$ cm$^{-2}$. The interpretation based on the ES model suggests that LAEs have a H$\text{I}$ column density of the shell lower than those of LBGs, which are quantitatively concluded by ES model fitting results (Hashimoto et al. 2015). This difference in $N_{\text{HI}}$ would

Figure 10
Left: Lyα $EW_0$ as a function of Lyα velocity offset $\Delta v_{\text{Ly}\alpha}$ (Nakajima et al. 2018). The data points are the compilation of the literature data (red, orange, and magenta: LAEs at $z \sim 2 - 3$; blue: LBGs at $z \sim 2 - 3$; green: green pea galaxies at $z \sim 0.3$). Adapted from Nakajima et al. (2018) with permission. Right: Lyα escape fraction as a function of color excess, $E(B-V)$ (Atek et al. 2014). The data points represent measurements of SFGs at $z \sim 0 - 0.3$ taken from the literature (see also Section 3). The differences of the data-point colors indicate differences of the references. The black line and the yellow shade present the best-fit linear function and its 1σ fitting uncertainty, respectively. The red dashed line denotes the MW extinction law for a foreground-screen case that ignores Lyα resonant scattering. Note that a similar relation is also found for LAEs at $z = 2 - 4$ (Blanc et al. 2011). Adapted from Atek et al. (2014) with permission.
produce the Ly$\alpha$ EW$\mathrm_0 - \Delta v_{\text{Ly} \alpha}$ anti-correlation.

The low HI column density for LAEs is also explained with measurements of the covering fraction, $f_c$, of LIS gas estimated from the depth of LIS metal absorption lines. Medium-high resolution spectroscopy find a possible anti-correlation between Ly$\alpha$ EW$_0$ and $f_c$ [Jones et al. 2013; Shibuya et al. 2014a]. Because $f_c$ positively correlates with the HI gas density on average, the Ly$\alpha$ EW$_0 - f_c$ anti-correlation supports the idea that a large EW$_0$ (i.e. a large Ly$\alpha$ escape) is given by the low $N_{\text{HI}}$ gas clouds.

**Dust extinction** — LAEs are known as dust poor galaxies. The stellar and nebular extinction values are estimated to be $E(B-V) \sim 0 - 0.2$ for majority of LAEs by stellar-population synthesis model fitting and Balmer decrement analyses, respectively [Ono et al. 2010a; Kojima et al. 2017]. The dust-poor nature of LAEs is confirmed with measurements of the UV-continuum spectral slope $\beta$ that is defined by the power-law approximation of the UV-continuum flux, $f_\lambda \propto \lambda^\beta$. LAEs have typically a blue UV-continuum spectrum of $\beta \sim -2$ that is systematically smaller than those of LBGs in the same UV magnitude range [Stark et al. 2010], supporting the fact that LAEs are dust poor.

The dust extinction law of a galaxy can be evaluated by combining $\beta$ and the IRX ratio,

$$IRX = \frac{L_{\text{IR}}}{L_{\text{UV}}}, \quad (10)$$

where $L_{\text{IR}}$ and $L_{\text{UV}}$ are the total infrared and UV luminosities, respectively. Recent studies using Spitzer and Herschel have revealed that LAEs at $z \sim 2$ have typically low IRX values at a given $\beta$ value similar to that of the Small Magellanic Cloud (SMC) or even below those of Calzetti’s local starbursts [Wardlow et al. 2014; Kusakabe et al. 2015]. This low IRX values are consistent with results that LAEs at $z > 5$ have faint far-infrared (FIR) continua at the observed-frame 1mm band found by Atacama Large Millimeter/sub-millimeter Array (ALMA) observations [Knudsen et al. 2016]. These IRX and FIR studies also confirm that LAEs have the low dust extinction.

**Metallicity** — LAEs have a gas-phase metallicity lower than SFGs with a low Ly$\alpha$ EW on the basis of deep spectroscopy and two kinds of metallicity estimates, strong line and direct electron temperature $T_e$ methods. The strong line method using, e.g., H$\alpha$, H$\beta$, [O iii]5007,4959, is widely applied to LAEs at $z \sim 2 - 3$. Observational studies have estimated the typical gas-metallicity to be $Z \sim 0.1 - 0.5Z_\odot$ for LAEs at $z \sim 2 - 3$ with the N2 and R23 indices [Finkelstein et al. 2011; Nakajima et al. 2012]. These metallicity measurements are comparable to or lower than those of the galaxy mass metallicity relation at $z \sim 2 - 3$ [Finkelstein et al. 2011], and consistent with the SFR-mass metallicity relation [Nakajima et al. 2012]. Similarly low metal abundances, $Z \sim 0.1 - 0.3Z_\odot$, are obtained for $z \sim 2 - 4$ LAEs by the $T_e$ methods with the successful detections of faint $T_e$-sensitive emission lines, [O iii]4363 [Trainor et al. 2016] and O iii]1661,1666 [Kojima et al. 2017]. These studies of strong line and direct $T_e$ methods indicate that the gas-phase metallicity of typical LAEs falls in a range of $Z \sim 0.1 - 0.5Z_\odot$ that is similar to or slightly lower than the typical metallicity of LBGs with the same UV-continuum luminosity [Steidel et al. 2014].

LAEs with a large Ly$\alpha$ EW$_0$ are thought to be candidates of metal-free, i.e. pop III, galaxies. A large Ly$\alpha$ EW$_0$ of $\gtrsim 240$ ˚A cannot be reproduced by recombination processes in a normal SFG with the solar metallicity and a Salpeter initial mass function (IMF;
Figure 11

Left: Lyα EW₀ as a function of stellar age for models of stellar evolution and photoionization (Schaerer 2003). The three blue dashed lines indicate pop III (Z = 0) instantaneous starburst models for a Salpeter IMF with mass ranges of 50 – 500 M☉ (top), 1 – 500 M☉ (middle), and 1 – 100 M☉ (bottom). The blue solid (dotted) lines are the same as the blue dashed lines, but for a metallicity of Z = 10⁻⁷ (10⁻⁵). The cyan dashed lines represent instantaneous starbursts of Salpeter IMF 1 – 100 M☉ models with Z = 0.0004, 0.001, 0.004, 0.008, 0.020, and 0.040 from top to bottom. The three squares denote constant SFR models of the 50 – 500 M☉ Salpeter IMF with metallicities of Z = 0, 10⁻⁷, and 10⁻⁵ from top to bottom, where the stellar ages are arbitrary. The red triangles (green circles) are the same as the squares, but for the mass range 1 – 500 M☉ (1 – 100 M☉). The green lines are the same as the green circles but for metallicities of Z = 0.0004, 0.001, 0.004, 0.008, 0.020, and 0.040 from top to bottom. Right: Same as the left panel, but for Hei1640 EW₀. Adapted from Schaerer (2003) with permission.

Malhotra & Rhoads (2002). The left panel of Figure 11 presents theoretical predictions for Lyα EW₀ of young galaxies including pop III galaxies. The large Lyα EW₀ can be accomplished by a young extremely metal poor galaxy with a top heavy IMF that efficiently produces ionizing photons for strong Lyα via recombination (Schaerer 2003). Large-area imaging and deep spectroscopic observations have identified a large number of large-Lyα EW sources (Hashimoto et al. 2017; Shibuya et al. 2018b). A strong Hei1640 emission line is another useful tool to distinguish pop III galaxies from pop II SFGs, because a production of Hei line requires metal-poor massive stars emitting high-energy (> 54 eV) photons that ionize He⁺. The right panel of Figure 11 shows Hei1640 EW₀ as a function of stellar age for models of young galaxies including pop III galaxies, and indicates that a moderately strong Hei1640 (EW₀ ≥ 5Å) line can be observed in a young extremely metal poor galaxy with a top heavy IMF. Although Hei1640 emission can be also found in AGNs and SFGs with a notable amount of Wolf-Rayet stars, such objects, except type 2 AGNs and high-mass X-ray binaries, can be removed by a presence of their broad line (≥ 1000Å) component of Hei emission. There are several reports of detecting such strong and narrow Hei1640 emission in large-Lyα EW sources (Prescott et al. 2009; Sobral et al. 2015). However, subsequent spectroscopy and multi-wavelength studies suggest that these objects are not pop III galaxies, due to the detections of metal lines or the lack of evidence on the strong Hei1640 emission (Prescott et al. 2015; Shibuya et al. 2018a; Bowler et al.).
Lyα Escape Fraction — As described above, LAEs have the ISM with \( N_{\rm HI} \), \( E(B - V) \), and \( Z \) lower than those of other types of galaxies with a low Lyα EW at the similar redshift. These characteristics of the ISM are plausibly related to the high Lyα escape fraction \( f_{\mathrm{Ly}\alpha}\); Section 3 of LAEs. The low \( N_{\rm HI} \) and \( E(B - V) \) allow Lyα photons to easily escape from the ISM of LAEs due to a small number of the Lyα resonant scattering and absorption. Here, the low \( Z \) is necessary for the low \( E(B - V) \).

The connection between \( f_{\mathrm{Ly}\alpha} \) and the ISM properties has been understood on the individual and statistical bases. The Lyα escape fraction has been estimated individually for LAEs at \( z \sim 0 - 4 \) (Atek et al. 2014; Blanc et al. 2011). The right panel of Figure 10 presents that \( f_{\mathrm{Ly}\alpha} \) anti-correlates with \( E(B - V) \), indicating that Lyα photons are heavily absorbed in a dusty galaxy. On the other hand, as discussed (shown) in Section 3 (Figure 7), the cosmic average \( f_{\mathrm{Ly}\alpha} \) values increase monotonically from \( z \sim 0 \) to \( z \sim 6 \) by two orders of magnitude (Hayes et al. 2010; Konno et al. 2016). The strong (two orders of magnitude) increase in \( f_{\mathrm{Ly}\alpha} \) is explained neither by 1) IGM absorption, 2) stellar population, 3) outflow velocity, 4) clumpy ISM, nor 5) dust extinction of a simple screen dust model (Konno et al. 2016).

Historically, it was often discussed that the large \( f_{\mathrm{Ly}\alpha} \) found in SFGs at high redshift was explained by the scenario of selective dust attenuation for Lyα and UV-continuum in the clumpy ISM (a.k.a. Neufeld’s effect; Neufeld 1991). In the clumpy ISM, Lyα photons are resonantly scattered on the surface of clumpy gas clouds with a negligible dust absorption (see Figure 1 of Neufeld 1991). By the resonance scattering, the total number of Lyα photons is conserved. On the other hand, UV-continuum photons penetrate multiple clumpy gas clouds in the foreground whose centers have dusty molecular gas, being heavily absorbed by the dust. The difference of Lyα and UV-continuum extinction produces a high Lyα \( EW_\lambda \). The validity of the Neufeld’s effect had not been tested in realistic ISM conditions, but only in a simple case of the static and very clumpy/dusty ISM since the publication of Neufeld (1991). Recent radiative transfer simulations have conducted extensive calculations with various physical parameters, and found that the Neufeld’s effect exists, but emerges only under special physical conditions, a low outflow velocity, very high extinction, and an extremely clumpy gas distribution (most gas is locked up in clumps), many of which do not agree with the observed properties of LAEs (Laursen et al. 2013; Duval et al. 2014). The clumpy ISM scenario is probably not the reason of the high \( f_{\mathrm{Ly}\alpha} \) values at high redshift.

Although the physical origin of the strong increase in \( f_{\mathrm{Ly}\alpha} \) has not been definitively concluded, the rise in \( f_{\mathrm{Ly}\alpha} \) is probably caused by another scenario, 6) the decrease of \( \HI \) column density towards high-z that reduces the resonant scattering and thus dust attenuation of Lyα. This scenario can explain the increase of \( f_{\mathrm{Ly}\alpha} \) by two orders of magnitude (Konno et al. 2016).

Ionization State — Recent optical and NIR spectroscopy find that LAEs have ionizing states significantly different from those of other galaxy populations. The left panel of Figure 12 shows that the \( O32 \) ratio \( ^{14} \), the line flux ratio of [OIII]5007 to [OII]3727, of \( z \sim 2 - 3 \) LAEs
Figure 12

Left: Diagram of $O_{32}$ vs. $R_{23}$ indices for high-z and local galaxies (Nakajima & Ouchi 2014; Nakajima et al. 2016). The red and blue symbols represent LAEs and LBGs at $z \sim 2 - 4$, respectively. The orange data points indicate Lyman-continuum leaders. The green triangle denotes a green pea galaxy. The gray shade shows SDSS local galaxies. The large open symbols and the cross indicate average measurements. This figure is reproduced and provided by K. Nakajima. Right: Conceptual figure for ionization-bounded (top) and density-bounded (bottom) nebulae (Zackrisson et al. 2013). Adapted from Zackrisson et al. (2013) with permission.

is $\sim 10 - 100$ times higher than those of local galaxies and even higher than those of LBGs at the similar redshifts (Nakajima & Ouchi 2014). Based on comparisons with photoionization models in the $O_{32}$ vs. $R_{23}$ diagram, the high $O_{32}$ ratios of LAEs indicate high ionization parameters, $q_{\text{ion}} = 1 - 9 \times 10^8$ cm s$^{-1}$. Detections of high ionization lines of C$\text{iii}]$1907,1909 and C$\text{iv}$1548 also indicate that the ionization state of LAEs is very high (Stark et al. 2014). On the other hand, recent ALMA studies have suggested that the [C$\text{ii}]$158$\mu$m emission of LAEs are systematically fainter than the local SFR-$L_{\text{CII}}$ relation (Ouchi et al. 2013; Harikane et al. 2018, cf. Carniani et al. 2018). Although a faint [C$\text{ii}]$158$\mu$m luminosity for a given SFR could be explained by a presence of AGN or the collisional de-excitation of C$^+$, LAEs show neither AGN activity nor gas density high enough for the collisional de-excitation.

The two properties of the high $q_{\text{ion}}$ and weak [C$\text{ii}]$158$\mu$m emission may be consistently explained by the ISM of density-bounded nebula (Nakajima & Ouchi 2014). The right panel of Figure 12 shows a conceptual diagram of density-bounded and ionization-bounded nebulae. In the density-bounded (ionization-bounded) nebula, the size of ionized regions are determined by the amount of gas around ionizing sources (the number of ionizing photons). In contrast with the ionization-bounded nebula, the density-bounded nebula has a small outer shell of ionized gas emitting low-ionization lines including [O$\text{ii}$]3727, while

$$R_{23} \equiv \frac{f([\text{OII}][5007] + [\text{OII}][4959])}{f(H\beta)}.$$
the density-bounded nebula has a well-developed inner core of highly ionized gas producing high-ionization lines (e.g., [C\text{iii}]1907,1909, [O\text{iii}]5007,4959, and [O\text{ii}]88\mu m). In this case, [C\text{ii}]158\mu m-emitting photo-dissociation region (PDR) does not exist. More realistically, a non-zero $\sim 10\%$ covering fraction of PDR can explain both small [C\text{ii}]158\mu m/SFR and large [O\text{ii}]88\mu m/SFR ratios found in high-$z$ SFGs, a majority of which are LAEs (Harikane et al. 2019a). Moreover, the density-bounded nebula would help ionizing photons escape from the ISM of LAEs, contributing to the cosmic reionization (Nakajima & Ouchi 2014; Jaskot & Oey 2014; see Section 9).

There are many open questions about the ISM of LAEs. Although the density-bounded nebula is an interesting scenario, no direct evidence of density-bounded nebulae has been obtained. Another problem of the ISM is that some LAEs have an extremely low IRX value for a given UV slope $\beta$ even below the SMC’s dust extinction curve (Capak et al. 2015). It is unclear how such a low IRX value is reproduced, because realistic dust sizes cannot make the flat IRX-$\beta$ relation. Besides these detailed physical questions, one should push high Ly$\alpha$ EW LAE searches \textsuperscript{16} for a promising candidate of pop III galaxy whose identification is key for understanding the first stage of galaxy formation.

7. Circum-Galactic Medium (CGM) and the Large-Scale Structures Traced by Diffuse Ly$\alpha$

This section presents the diffuse and spatially extended Ly$\alpha$ emission around SFGs from a small scale to a large scale that are known as Ly$\alpha$ halos (LAHs), Ly$\alpha$ blobs (LABs), enormous Ly$\alpha$ nebulae (ELANe), and the large-scale Ly$\alpha$ emission in the IGM. The extended Ly$\alpha$ emission has a large diversity in size, ranging from $\sim 1$ pkpc to $\gtrsim 1,000$ pkpc, which are summarized in Figure 13. Note that LAHs, LABs, and ELANe are not clearly defined by physical quantities, but roughly classified by the Ly$\alpha$ luminosity and size. Although the physical origins of the extended Ly$\alpha$ emission are poorly understood, there are six scenarios for the extended Ly$\alpha$ emission: 1) resonant scattering of Ly$\alpha$ emission from central star-forming regions and/or AGNs, 2) photoionization/recombination in unresolved dwarf satellite galaxies, 3) outflowing gas, 4) infalling gas, 5) fluorescence, and 6) galaxy mergers. In the following paragraphs, we review properties and possible physical origins of the extended Ly$\alpha$ emission.

\textsuperscript{16}See the text of the metallicity topic in this Section.
Lyα scale length $r_n$ or extent $r_{\text{ext}}$ of extended Lyα emission as a function of Lyα luminosity. The blue, green, and red symbols denote LAHs, LABs, and ELANs, respectively, taken from the literature (Leclercq et al. 2017; Wisotzki et al. 2016; Steidel et al. 2011; Momose et al. 2014, 2016; Xue et al. 2017; Matsuda et al. 2011; Zhang et al. 2019; Borisova et al. 2016; Cantalupo et al. 2014; Hennawi et al. 2015; Cai et al. 2016), while the definitions of $r_{\text{ext}}$ and Lyα luminosity depend on various studies in the literature. Here, the $r_{\text{ext}}$ values are converted from the end-to-end Lyα extent (Borisova et al. 2016) multiplied by a factor of 0.5 to mitigate the difference in measurement techniques. The top three images show sample snapshots of an LAH (Leclercq et al. 2017), LAB (Matsuda et al. 2011), and ELAN (Cantalupo et al. 2014) from left to right that are adapted with permission.

The parameter of $r_n$ is the Lyα halo scale length, quantifying

\[ L_{\text{Ly}\alpha}/\text{erg s}^{-1} \]

\[ r_{\text{ext}} \text{[pkpc]} \]

\[ \log L_{\text{Ly}\alpha}/\text{erg s}^{-1} \]

\[ r_n \quad \text{or} \quad r_{\text{ext}} \text{[pkpc]} \]

\[ \text{MAMMOTH-1} \quad \text{LAB1} \quad \text{Slug} \quad \text{Jackpot} \quad \text{Himiko} \]

\[ 42 \quad 44 \quad 45 \]

\[ \text{Figure 13} \]

\[ \text{Although the exponential profile is an empirical model, a Ly\alpha radial SB profile similar to the exponential profile can be derived on the basis of a physical picture of Ly\alpha resonant scattering in} \]

\[ 24 \quad \text{Ouchi et al.} \]
Top panels (a)-(d): Images, spectrum, and radial SB profiles of a galaxy with an LAH at $z = 3.61$ that are taken from Leclercq et al. (2017) with permission. (a) UV-continuum image. (b) Lyα spectrum. (c) Lyα image. (d) Radial Lyα SB profile. In the panel (d), the black circles with the error bars present the observed Lyα SB profile, while the (red) green and blue curves indicate the best-fit Lyα SB profiles of (total) core and LAH components, respectively. Bottom: Cross-correlation functions of Lyα emission with SDSS BOSS quasars at $z \sim 2-4$ (blue pentagons; Croft et al. 2018) and with LAEs (red diamonds: $z = 5.7$; red circles: $z = 6.6$; Kakuma et al. 2019). The curves represent radial Lyα SB profiles of an ELAN (cyan solid line; Cantalupo et al. 2014), radio-quiet quasars (blue dashed line; Borisova et al. 2016), and galaxies at $z \sim 3$ (orange solid line; Steidel et al. 2011) orange dashed line; Leclercq et al. 2017) and at $z \sim 6$ (red dashed line; Leclercq et al. 2017). The two black dashed lines are power law functions of $\xi \propto r^{-1.5}$ that are shown for references.

---

a gaseous halo with a simple power-law distribution of HI gas, $f_c \propto r^{-\gamma}$, where $\gamma$ is a power-law
the extent of LAHs. Several studies find that $r_n$ correlates with physical properties of LAEs, providing useful hints for physical origins of LAHs. In SFGs, the Lyα halo scale length decreases with increasing the Lyα luminosity of the central part of the SFGs at $r < 8$ pkpc ($L_{\text{cent},\text{Lyα}}$; Momose et al. 2016), indicating that a large Lyα halo is found in $L_{\text{cent},\text{Lyα}}$-faint galaxies. (In other words, Lyα halos are small in LAEs whose central < 8 pkpc part of Lyα luminosity is bright.) The $L_{\text{cent},\text{Lyα}}$-faint galaxies may be explained by strong Lyα resonant scattering (scenario 1) in the thick H$\text{I}$ clouds near the galaxy center, which eventually produce a largely extended Lyα halo. On the other hand, radiative transfer and hydrodynamical simulations suggest that the Lyα resonant scattering effect (scenario 1) cannot reproduce the largely-extended Lyα SB profiles of LAHs, while the cooling radiation (scenario 4) may be needed to explain Lyα emission at the outer part of LAHs (Lake et al. 2015). In contrast with the Lyα emission, UV-continuum emission is not spatially extended in observational data (Momose et al. 2014; Leclercq et al. 2017). This compact UV-continuum emission would rule out a significant contribution from unresolved dwarf satellite galaxies (scenario 2). Recently, stacked ALMA data reveal that SFGs at $z \sim 5$–7 have a 10 pkpc-scale extended carbon [C$\text{II}$]158$\mu$m emission whose SB profile shape is very similar to the one of the Lyα emission (Fujimoto et al. 2019). The existence of the extended emission of [C$\text{II}$] similar to Lyα might suggest that LAHs are originated from the neutral gas expelled by outflows that are carbon enriched (scenario 3). Deep observations identify that the $r_n$ value is almost constant over the redshift range of $z \sim 2$–6, perhaps suggesting no significant redshift evolution of physical properties of LAHs at $z < 6$ (Momose et al. 2014; Leclercq et al. 2017). There is a hint of an increase of $r_n$ towards the reionization epoch of $z = 6.6$, but the increase is found only at the 1σ level (Momose et al. 2014).

— Ly$\alpha$ blobs (LABs) are spatially extended Ly$\alpha$ nebulae with a physical scale of $\sim 10$–100 pkpc and a Ly$\alpha$ luminosity of $\sim 10^{44}$ erg s$^{-1}$ (Steidel et al. 2000; Matsuda et al. 2004; Shibuya et al. 2018b). Such extended Ly$\alpha$ emission has been found around various types of sources: e.g., SFGs (Steidel et al. 2000; Ouchi et al. 2009), radio-loud galaxies (McCarthy et al. 1987; van Ojik et al. 1997), and radio-quiet QSOs (Borisova et al. 2016).

Physical properties of LABs have been investigated by multi-wavelength observational and theoretical studies. Deep X-ray observations find that a majority of LABs show no clear AGN activity, while $\sim 20\%$ of LABs host an AGN (Basu-Zych & Scharf 2004; Geach et al. 2009). Similarly, $\sim 30\%$ of LABs are detected at radio wavelengths (Ao et al. 2017). These X-ray and radio results would indicate that AGNs contribute to the extended Ly$\alpha$ emission in some LABs via Ly$\alpha$ resonant scattering and/or fluorescence (scenarios 1 and 5). A tangential polarization signal up to 20$\%$ is detected in the Ly$\alpha$ emission around an LAB (Hayes et al. 2011), which might suggest that LABs are produced by Ly$\alpha$ resonant scattering (scenario 1; Dijkstra & Loeb 2008; Trebitsch et al. 2016). According to theoretical studies (Pardal et al. 2001; Dijkstra & Loeb 2009; Goerdt et al. 2010), the extended Ly$\alpha$ emission of LABs can be reproduced by the cooling radiation (scenario 4). However, LABs have a moderately large Ly$\alpha$ velocity offset from the systemic velocity, several hundreds km s$^{-1}$ (Yang et al. 2014), that may be evidence for strong outflow (scenario 3). HST observations reveal that some high-$z$ LABs have multiple stellar components (Ouchi et al. 2013; Sobral et al. 2015), which suggests that starbursts caused by galaxy mergers (scenario 6) create the extended Ly$\alpha$ emission. The galaxy merger
scenario might be supported by the fact that LABs reside in galaxy overdense regions (Matsuda et al. 2004; Yang et al. 2010; Kikuta et al. 2019).

— Enormous Lyα nebulae (ELANe) are extended Lyα emission harboring QSOs (Cantalupo et al. 2014; Hennawi et al. 2015; Cai et al. 2016). The Lyα emission of ELANe extends to a scale of several hundreds pkpc (> 400 pkpc for some ELANe) that is larger than a virial radius of a dark-matter halo hosting the QSOs. The existences of energetic QSOs suggest that ELANe are fluorescently illuminated (scenario 5). However, very high density clumps are needed to produce the observed high Lyα SB of \( \sim 10^{-18} \) to \( 10^{-16} \) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) (Cantalupo et al. 2014). Alternatively, the Lyα resonant scattering may be also important in ELANe (scenario 1). Distinguishing the two scenarios of 1) and 5), one should observe non-resonant hydrogen recombination lines such as Hα in ELANe as demonstrated by Leibler et al. (2018).

NB imaging observations and the Keck/Palomar Cosmic Web Imagers (KCWI/PCWI) spectroscopy find that ELANe tend to reside in galaxy overdense regions (Cai et al. 2017, 2018). The environments of ELANe indicate that ELANe would exist in progenitors of massive galaxy clusters.

— The large-scale Lyα emission extending to \( \sim 1 \) – \( 15 \) comoving Mpc (cMpc) is identified by the cross-correlation Lyα intensity mapping technique (bottom panel of Figure 14). The cross-correlation Lyα intensity mapping technique is to obtain the spatial cross correlation between objects with known redshifts (e.g., galaxies and QSOs) and faint Lyα emission below a detection limit of imaging/spectroscopic data, and to detect the faint Lyα emission, where the spatial cross correlation analysis systematically removes signals unrelated to the objects. Croft et al. (2018) report the detection of a very faint Lyα emission around QSOs at a large scale of \( \sim 1 \) – \( 15 \) cMpc by Lyα intensity mapping of cross correlation between SDSS BOSS QSOs at \( z \sim 2 \) – \( 3.5 \) and Lyα emission in a large number of SDSS spectra (with no Lyα detections on individual basis). The radial SB profile of these large-scale Lyα emission is smoothly connected to the one of ELANe at \( r \sim 1 \) cMpc (bottom panel of Figure 14). The connection with ELANe indicates that the large-scale Lyα emission may be produced by the fluorescent radiation from QSOs (scenario 5). In addition to QSOs, Kakuma et al. (2019) conduct Lyα intensity mapping of cross correlation between LAEs at \( z \sim 6 \) and Lyα emission in NB image pixels, and identify extremely faint Lyα emission around LAEs at a spatial scale beyond a virial radius of the LAE hosting dark-matter halo (\( \sim 0.15 \) cMpc) up to \( \sim 1 \) cMpc. This cross-correlation signals of LAEs are consistent with the extrapolation of Lyα radial SB profiles of LAHs (Leclercq et al. 2017) bottom panel of Figure 14. Comparisons with numerical simulations suggest that the large-scale Lyα emission is not fully explained by the combination of resonant scattering (scenario 1) and unresolved dwarf satellite galaxies (scenario 2), but contributed by Lyα emission created by other mechanisms that possibly includes the cold accretion.

Due to the diverse physical properties, it is still under debate how the extended Lyα emission is produced in LAHs, LABs, and ELANe. It is also unclear whether the possible increase in \( r_n \) to the epoch of reionization truly exists (see the topic of LAHs), which is thought to be an indicator of the IGM neutral hydrogen fraction increase (Jeeson-Daniel et al. 2012).
8. Clustering of LAEs

Distant cosmic structures including primeval large-scale structures and progenitors of galaxy clusters (a.k.a. protoclusters) are investigated with LAEs. LAEs are advantageous to map out the spatial distribution of high-$z$ galaxies efficiently by NB imaging and spectroscopic surveys (Ouchi et al. 2005a; Yamada et al. 2012b). Figure 15 is the map of LAEs at $z \sim 6$ over the scale of $1.5\,\text{deg}^2$ corresponding to $\sim 200\,\text{cMpc}$, showing primeval galaxy clusters, filaments, and voids.

The systematic large-scale structure survey is being conducted by HETDEX (Section 3). HETDEX is a cosmology survey investigating cosmic structures at $z \sim 2 - 3$, measuring...
the baryon acoustic oscillation on the scale of ~100 cMpc for understanding the equation state of dark energy.

In the scale of galaxy clusters, LAEs are tracers of the galaxy distribution, which is the concept same as the one of the HETDEX cosmology survey. The overdensity \( \delta \) is defined as

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

where \( n (\bar{n}) \) is the (average) number density of LAEs in a volume or an area. Because LAEs are low-mass galaxies (Section 5), LAEs show overdensity regions whose \( \delta \) values are smaller than those of LBG and submillimeter-galaxy (SMG) overdensity regions. However, overdensity regions of mass distribution are pinpointed with an LAE sample, if the LAE sample is large enough to provide \( \delta \) measurements with a high statistical accuracy distinguishing the overdensity regions from the field.

Theoretical models suggest that LAE overdensities with large \( \delta \) values are progenitors of clusters, i.e. protoclusters (Chiang et al. 2013). Protoclusters of LAE overdensities are identified at \( z \sim 2 - 7 \) by blank-field surveys such as large-area NB observations (Ouchi et al. 2005a; Yamada et al. 2012b; Harikane et al. 2019b). Table 3 summarizes the spectroscopically-confirmed protoclusters identified by the LAE blank-field surveys, and compares protoclusters identified with the other types of galaxies such as LBGs and SMGs.

Clustering properties of LAEs are quantified with correlation functions in two or three-dimensional space. The top left panel of Figure 16 presents the two-dimensional space correlation functions \( \omega (\theta) \), i.e. the angular correlation functions (ACFs), of \( \gtrsim L^* \) LAEs at \( z = 5.7 \) and 6.6 (Ouchi et al. 2018). Clearly, the ACFs of the LAEs are stronger than those of underlying dark matter \( \omega_{DM} (\theta) \) predicted by the linear theory of the \( \Lambda \)CDM model (top left panel of Figure 16). In the \( \Lambda \)CDM framework, the excess of \( \omega (\theta) \) above \( \omega_{DM} (\theta) \) is

![Table 3 - List of Protoclusters](https://www.annualreviews.org/doi/abs/10.1146/annurev-astro-081915-011018)

Note: Spectroscopically-confirmed protoclusters having \( > 10 \) galaxies with spectroscopic redshifts. The protoclusters are listed in order of redshift. This table is the abstract of Table 3 of Harikane et al. (2019b). (1) Protocluster name. (2) Redshift. (3) Number of member galaxies confirmed by spectroscopy. (4) Galaxy overdensity. Note that the length scales of the overdensity measurements differ. (5) Types of member galaxies so far identified. (6) Total (expected) mass of the overdensity at the redshift (\( z = 0 \)) in units of solar masses. (7) Reference: C17,19 = Chanciaworawit et al. 2017, 2019; D16 = Dey et al. 2016; H19 = Hiuchi et al. 2019; H18 = Harikane et al. 2018; J18 = Jiang et al. 2018; L14 = Lee et al. 2014; L13 = Lemle et al. 2013; M04 = Miley et al. 2004; M05 = Matsuda et al. 2005; M18 = Miller et al. 2018; O05 = Ouchi et al. 2005; Ov08 = Overzier et al. 2008; O18 = Oke et al. 2018; S00 = Steidel et al. 2000; S19 = Shi et al. 2019; T04 = Toshikawa et al. 2014; T18 = Umezawa et al. 2018; V07 = Veneramo et al. 2007; Y12 = Yamada et al. 2012; Z05 = Zirns et al. 2005;
Figure 16

Left: ACF and bias of \( \gtrsim L^* \) LAEs at \( z = 5.7 \) (Ouchi et al. 2018) that are shown in the top and bottom panels, respectively. The data points indicate the ACFs (top) and bias (bottom) of the LAEs. In the top panel, the solid line presents the best-fit HOD model. The 1-halo and 2-halo terms of the best-fit HOD model are shown with the dashed lines that overlap with the solid line at the small and large scales, respectively. The dotted line denotes the underlying dark matter predicted by the linear theory. In the bottom panel, the horizontal line represents the average bias of the LAEs. The top axis denotes the projected distance in comoving megaparsecs. Right: Bias of \( \gtrsim L^* \) LAEs as a function of redshift (Ouchi et al. 2018). The data points represent the bias of the LAEs at \( z = 2 - 7 \). The solid lines indicate bias of dark-matter halos with a halo mass of \( 10^8 \), \( 10^9 \), \( 10^{10} \), \( 10^{11} \), and \( 10^{12} M_\odot \) in the case of one-to-one correspondence between galaxies and dark-matter halos. The gray region shows the dark-matter halo mass range of \( 10^{10} - 10^{12} M_\odot \) where the bias of LAEs at \( z = 2 - 7 \) fall, while the number-weighted average mass is \( 10^{10} - 10^{11} M_\odot \). The dotted lines are evolutionary tracks of bias in the case of the galaxy-conserving model.

The definition of the bias is also given by

\[
b^2 \equiv \frac{\omega(\theta)}{\omega_{DM}(\theta)}\]  

The average bias of \( L^* \) LAEs is \( b \sim 1 - 2 \) at \( z \sim 2 - 3 \) and \( b \sim 4 - 5 \) at \( z \sim 6 - 7 \) (Ouchi et al. 2018). This increase of bias towards high \( z \) is explained by the physical picture that a galaxy forms only at a rare peak of density fluctuations, where dark-matter halos are made, at the early stage of the cosmic structure formation (Bardeen et al. 1986). Based on the average bias evolution of Figure 16, the low bias values indicate that LAEs at \( z \sim 2 - 3 \) may be progenitors of today’s Milky-Way like galaxies (Gawiser et al. 2007), while the high bias values suggest that LAEs at \( z \sim 5 - 7 \).
are progenitors of present-day massive elliptical galaxies (Ouchi et al. 2010).

There are large scatters in the bias measurements of LAEs obtained to date (see the right panel of Figure 16). The scatters would be larger than the statistical uncertainties. It is suggested that the large scatters are made by the sample variance, a.k.a. cosmic variance, originated by the small survey volumes (Kusakabe et al. 2018). Although the survey volumes of LAEs are generally small, \(10^6\) cMpc\(^3\) or less, on-going Subaru HSC and HETDEX observations are providing the measurements of bias with negligibly small cosmic variance effects.

The correlation function is modeled by the power law or the halo occupation distribution (HOD) model. The power law is the empirical relation that has been used since the early measurements of local galaxy correlation functions were obtained (Totsuji & Kihara 1969). The HOD model is the parameterized model providing the relation between observed galaxies and hosting dark-matter halos of the \(\Lambda CD M\) structure formation (Cooray & Sheth 2002). The parameters of the HOD model define the occupation of galaxies in a dark-matter halo as a function of mass, including the dark-matter halo mass limit for hosting a galaxy and the power-law slope (and the scatter) of the occupation number depending on dark-matter halo mass. Once the occupation of galaxies in a dark-matter halo is determined, a correlation function and abundance of galaxies can be predicted with the HOD model. The correlation function consists of two components, 1-halo and 2-halo terms in small (\(\lesssim 1\) comoving Mpc; cMpc) and large (\(\gtrsim 1\) cMpc) scales, respectively (top left panel of Figure 16). The 1-halo term signal is originated from clustering of galaxies within one dark-matter halo, while the 2-halo term signal is made by clustering of galaxies hosted by different dark-matter halos. The correlation function and the abundance of galaxies, thus predicted, are compared with those of observational results, which determine the HOD model best-fit parameters. The HOD model with the best-fit parameters reveals properties of dark-matter halos hosting LAEs, and indicates that the average mass of dark-matter halos \(\langle M_h \rangle\) are moderately small, \(\langle M_h \rangle = 10^{10} - 10^{11} M_\odot\) for the LAEs (top left panel of Figure 16; Ouchi et al. 2018). Because this is the average value of the dark-matter halo masses, there should exist more LAEs with masses higher and lower than the average mass in overdensity (i.e. proto-cluster) and underdensity regions, respectively.

Once the mass of the hosting dark-matter halos is constrained by HOD modeling, the number density of the hosting dark-matter halos \(n_{DMH}\) can be estimated with the \(\Lambda CD M\) model. The \(n_{DMH}\) value can be compared with the number density of the observed LAEs \(n_{Ly\alpha}\). The Ly\(\alpha\) duty cycle of LAEs, \(DC_{Ly\alpha}\) is defined as the ratio of \(n_{Ly\alpha}\) to \(n_{DMH}\),

\[
DC_{Ly\alpha} = \frac{n_{Ly\alpha}}{n_{DMH}}
\]

\(DC_{Ly\alpha}\) is the fraction of the Ly\(\alpha\) emitting galaxies to the dark-matter halos for a given mass. In the physical picture of LAEs, the Ly\(\alpha\) duty cycle is determined by two effects, the intermittent star-formation activity and time-dependent Ly\(\alpha\) escape. Observational results suggest that \(DC_{Ly\alpha}\) is about 1\% (Gawiser et al. 2007; Ouchi et al. 2010) that is comparable with the predictions of the numerical simulations, \(DC_{Ly\alpha} \sim 1 - 10\%\) (Nagamine et al. 2010). As detailed in this section, clustering measurements of LAEs are not only useful to probe the cosmic structures, but also to understand the physical properties of LAEs, hosting dark-matter halos and Ly\(\alpha\) duty cycles.
9. Cosmic Reionization and Lyα

Deep observations for galaxies have reached the EoR at $z \geq 6$, when the neutral hydrogen of the IGM is ionized (Fan et al. 2006) left panel of Figure 17.

Lyα photons from a galaxy are scattered by the partly neutral hydrogen at the EoR. Lyα lines are redshifted from the systemic velocity of a galaxy by $\sim 100 - 200$ km s$^{-1}$ on average (Section 6), avoiding the extremely strong resonant scattering at the rest-frame 1216Å in the partly neutral IGM. However, the redshifted Lyα is still scattered by the

Figure 17
Left: Conceptual diagram of observations for LAEs at the EoR in the expanding universe. The purple and black colors indicate the neutral and ionized IGM, respectively. LAEs in the ionized IGM (i.e. ionized bubbles) emit Lyα photons that are scattered by the neutral hydrogen IGM. The Lyα photons emitted in the large ionized bubbles can escape, being dimmed by a small amount of scattering, due to the Lyα velocity redshifted from the IGM velocity of the Hubble flow. In the diagram, wavelengths of Lyα emission are expressed with the spectral bands of the blue to red colors, and the widths of the spectral bands indicate Lyα emission intensities. Center: Model Lyα spectra (Dijkstra et al. 2007). The Lyα lines produced by galaxies are shown with the blue dashed curves. The observed Lyα lines are shown with the red curves. These galaxies reside at ionized bubbles whose radii are small (0 pMpc, i.e. fully neutral IGM; top), medium (2 pMpc; middle), and large (10 pMpc; bottom), where pMpc stands for physical Mpc. Right: 21cm brightness temperature map at $z = 6.6$ predicted by numerical simulations (top; Kubota et al. 2018). The blue regions of 0 mK correspond to the fully ionized regions. The middle panel shows positions of the model LAEs (red circles) in the cosmic volume same as the one of the top panel. The bottom panel presents LAE-21cm cross-power spectra calculated on the basis of the models of the top and the middle panels for three conditions of neutral hydrogen fractions, 1.7% (blue line), 31% (purple line), and 60% (red line). The solid and dotted lines indicate the positive and negative cross-power spectra, respectively. For display purposes, the signs of the negative cross-power spectra (dotted lines) are changed to the positive signs. The data of center and right panels are adapted from Dijkstra et al. (2007) and Kubota et al. (2018), respectively, with permission.
neutral hydrogen of the IGM via the Lyα damping wing (DW). Lyα DW is a Lyα profile of the long wavelength tail given by the natural broadening (originated by the quantum effect).

There is another important mechanism of Lyα scattering in the neutral IGM at the EoR that is illustrated in Figure 17. Theoretical models of reionization predict that UV radiation of a galaxy make an ionized bubble around the galaxy in the neutral IGM, and that the galaxy resides within the ionized bubble (left panel of Figure 17). In this theoretical picture, Lyα photons can escape from the partly neutral IGM via the ionized bubble. At the back of the bubble on the border between the ionized and neutral hydrogen IGM, the neutral hydrogen gas is redshifted from the galaxy by the Hubble flow, which help Lyα photons of the galaxy escape from the partly neutral IGM to the observer (center column panels of Figure 17).

Constraining the amount of the Lyα scattering in the IGM by observations, various studies have estimated the neutral hydrogen fraction \(x_{\text{HI}}\) or the ionized fraction \(Q_{\text{HII}}\). A volume-averaged \(x_{\text{HI}}\) (or \(Q_{\text{HI}}\)) is derived by Lyα studies.

Recent observational studies have identified signatures of Lyα photons scattered by Lyα DW of the neutral hydrogen gas at the EoR. Bright continuum objects, Gamma-ray bursts (GRBs) and QSOs, at the EoR are good probes of Lyα DW absorption with an intrinsic continuum spectrum modeled with a power law and an average spectrum of low-z QSOs, respectively (Totani et al. 2016; Bañados et al. 2018). However, the small numbers of GRBs and quasars can probe the neutral hydrogen of the IGM on the small number of sight lines. For example, a theoretical model suggests that a single-object estimate of GRB gives a systematic bias at the moderately high level of \(\Delta x_{\text{HI}} \sim 0.3\), due to the patchy distribution of the neutral hydrogen at the EoR (McQuinn et al. 2008). Moreover, there is a well-known systematics of the ionization state of the IGM around a QSO (i.e. proximity effect Bajtlik et al. 1988). Here, observations of LAEs can complement the one with the bright continuum objects, GRBs and QSOs. Although there are a variety of Lyα emission spectral shapes in LAEs, one can investigate a large number of LAEs distributed from high to low density regions. The large statistics of LAEs allows us to understand the evolution of the average neutral hydrogen fraction with negligible bias raised by the diversity of Lyα emission spectral shapes (Weinberger et al. 2019).

There are two popular techniques that study the average amount of Lyα damping wing absorption in the IGM with LAEs. One technique is the Lyα LF via the comparison with the UV-continuum LF (Maihota & Rhoads 2004; Kashikawa et al. 2011; Itoh et al. 2018). Lyα and UV-continuum LDs are derived with the LFs. Note that the redshift evolution of the Lyα LD is determined by galaxy evolution and Lyα opacity of the IGM. Because the UV-continuum LD is a tracer of SFR and the dust extinction in the ISM, the Lyα LD decrease faster than the UV-continuum LD evolution suggests an increase of Lyα opacity of the IGM, which is shown in the top panel of Figure 7 (see Figure 11 of Itoh et al. 2018 for statistically significant results). Lyα LD rapidly drops from \(z \sim 6.5\) to 7.5, while the evolution of the UV-continuum LD is milder than the one of the Lyα LD. This evolutional difference allows us to estimate the Lyα opacity via the comparisons with analytical and numerical models of
Figure 18
Left: Fraction of Lyα emitting galaxies with Lyα EW ≥ 25Å, X_{Lyα}, as a function of redshift. The red filled circles and the blue filled squares indicate the average X_{Lyα} values for galaxies with the faint (M_{UV} > −20.25) and bright (M_{UV} < −20.25) UV-continuum magnitudes, respectively. These average X_{Lyα} values are estimated with the compilation data of the red open circles (M_{UV} > −20.25) and the blue open squares (M_{UV} < −20.25) that are so far obtained by various observational studies (Arrabal Haro et al. 2018; Caruana et al. 2018; Cassata et al. 2015; Curtis-Lake et al. 2012; De Barros et al. 2017; Kusakabe et al. 2020; Mallery et al. 2012; Mason et al. 2019; Ono et al. 2012; Pentericci et al. 2018; Schenker et al. 2014; Stark et al. 2011; Tilvi et al. 2014; Treu et al. 2013). Right: Neutral hydrogen fraction as a function of redshift (Itoh et al. 2018). The red and magenta circles represent x_{HI} estimates given by the Lyα LD evolution obtained with LF measurements. The cyan circle, square, and triangle are the constraints of x_{HI} given by the Lyα emitting galaxy fraction measurements. The orange pentagon shows the x_{HI} estimate calculated with the Lyα EW distribution of dropout galaxies. The magenta square denotes the x_{HI} value estimated with the LAE clustering. The blue triangle, square, and circle indicate x_{HI} values given by GRB Lyα damping wing (DW) measurements. The green diamonds and triangle show x_{HI} constraints obtained by the QSO Lyα DW observations, while the green squares represent those of QSO Gunn-Peterson optical depths. See Figure 14 of Itoh et al. (2018) for the references for the measurements. The black triangle presents the 1σ lower limit obtained with the CMB Thomson scattering optical depth measurement. The black curve and the gray shade denote the best-estimate x_{HI} and the error given with eqs. (17) and (21) and galaxy ρ_{UV} measurements (Ishigaki et al. 2018). The panel b is adapted from Itoh et al. (2018) with permission.

Another technique is to investigate a fraction of Lyα emitting galaxies to all of the UV continuum-selected galaxies (Stark et al. 2011; Pentericci et al. 2011; Ono et al. 2012). The left panel of Figure 18 and Table 4 summarize the measurements of the Lyα emitting galaxy fractions for galaxies with the two different limits of the UV-continuum magnitudes. In Figure 18 and Table 4, we show the average Lyα emitting galaxy fractions with standard errors that are estimated from the compilation of the data so far obtained by various observational studies (Arrabal Haro et al. 2018; Caruana et al. 2018; Cassata et al. 2015; Curtis-Lake et al. 2012; De Barros et al. 2017; Kusakabe et al. 2020; Mallery et al. 2012; Mason et al. 2019; Ono et al. 2012; Pentericci et al. 2018; Schenker et al. 2014; Stark et al. 2011; Tilvi et al. 2014; Treu et al. 2013). The Lyα emitting galaxy fraction is increasing from z ~ 4 to 6, while this fraction clearly decreases from z ~ 6 to 8, indicating that the Lyα opacity is increasing from z ~ 6 to 8. The decrease of the Lyα emitting galaxy fraction is modeled, providing estimates of the cosmic average x_{HI}. The x_{HI} estimates, thus obtained, are summarized in the right panel.
of Figure 18 indicating the cosmic reionization history. The neutral hydrogen gas fraction increases from $z \sim 6$ towards high-$z$, and the mid-point of cosmic reionization, $x_{\text{HI}} = 50\%$, is estimated to be $z \sim 7.5$.

Table 4 Fraction of Lyα Emitting Galaxies with $E_{\text{W0}} \geq 25\AA$

| Sample  | Magnitude  | Redshift  | $X_{\text{Lyα}}$ |
|---------|------------|-----------|------------------|
| Bright  | $M_{\text{UV}} < -20.5$ | 4.0        | 0.12 ± 0.02      |
|         |            | 4.8        | 0.22 ± 0.02      |
|         |            | 6.0        | 0.15 ± 0.09      |
|         |            | 7.0        | 0.10 ± 0.03      |
|         |            | 8.0        | < 0.08           |
| Faint   | $M_{\text{UV}} > -20.5$ | 4.0        | 0.25 ± 0.04      |
|         |            | 4.9        | 0.35 ± 0.05      |
|         |            | 5.9        | 0.42 ± 0.10      |
|         |            | 7.0        | 0.20 ± 0.02      |
|         |            | 8.0        | < 0.16           |

Lyα emission is the strongest line found in the optical wavelength for majority of objects at $z \sim 2 - 7$. Although this characteristics of Lyα emission is very advantageous for studies of high-$z$ objects, this advantage may not be true for sources at the middle or early EoR. This is because a chance of a detection of Lyα emitting galaxy decreases towards high-$z$ (left panel of Figure 18), due to the fact that Lyα photons from galaxies are scattered by the neutral hydrogen of the IGM at the EoR $z > 6$. If LAEs and the IGM are static and uniformly distributed, no Lyα photons can escape from the neutral universe. However, in reality, Lyα photons come out of the highly neutral IGM with the help of the Lyα velocity shifts (from the neutral IGM) given by the peculiar motions of galaxies as well as the ionized bubbles around clustered galaxies. Theoretical models indicate that about 10% of Lyα fluxes can escape from the highly neutral IGM by the help of these physical effects (Gnedin & Prada 2004). There is an open question whether a redshift limit of a Lyα detection exists and what redshift is the limit, if it exists. A future accurate measurement of the Lyα observability at the early EoR ($z \sim 10$) will allow us to understand the physical properties of the LAE dynamics and the ionized bubbles.

Theoretical studies predict that LAEs are key sources for identifying signals of the HI 21cm emission originated from neutral hydrogen at the EoR (Lidz et al. 2009, Sobacchi & Mesinger 2015, Hutter et al. 2018). Although there are several high-sensitivity radio telescopes targeting the EoR 21cm emission (e.g. LOw Frequency ARray, LOFAR; Jelíč et al. 2014), no signals of the EoR 21cm emission have been detected so far, mainly due to the bright foreground emission of the Earth’s ionosphere. Here, LAEs can be used as signposts for the EoR 21cm emission detections. The large sample of LAEs with known positions and redshifts allows us to conduct cross-correlation analysis with EoR 21cm data (Lidz et al. 2009), and to identify a signal of the EoR 21cm emission, removing the problematic foreground emission. The bottom right panel of Figure 17 presents the LAE-21cm cross-power spectra predicted by numerical simulations (Kubota et al. 2018). These cross-power spectra are calculated with the simulation data of the 21cm brightness temperature (LAE distribution) map shown in the top (middle) right panel of Figure 17. The cross-power spectrum consists of two components at small and large scales. The large-scale component
is the negative signal (i.e. anti-correlation) representing ionizing sources (LAEs) that make ionized bubbles (i.e. no neutral hydrogen around LAEs), while the small-scale component is the positive signal indicating that LAEs form in an overdensity of neutral hydrogen. There exists a transition between the negative and positive signals, due to the ionized bubbles around LAEs. A detection of the negative and positive signals will confirm an existence of ionized bubbles at the EoR. In summary, the LAE-21cm cross correlation analysis will help the detection of the EoR 21cm signal, and characterize the cosmic reionization process via the ionized bubble topology.

LAEs are young SFGs that have abundant massive stars producing ionizing photons contributing to cosmic reionization. For faint SFGs with $M_{\text{UV}} > -20.25$, the number fraction of LAEs reaches $\sim 50\%$ of the faint SFGs at the redshift of the EoR $z \sim 6$\(^{18}\) (left panel of Figure 18), indicating that LAEs are dominant population of SFGs that supply ionizing photons for cosmic reionization. In fact, the UV-continuum luminosity function of LAEs is comparable to the one of LBGs at $z \sim 6$, while those of LAEs fall below those of LBGs by an order of magnitude at $z \sim 3 - 4$ (See Figure 22 of Ouchi et al. 2008).

With the ionizing photon production rate $\dot{n}_{\text{ion}}$ that is defined by the number of ionizing photons per volume and time, the budget of ionizing photons in cosmic reionization is modeled in the one zone model of the ionization equation (Madau et al. 1999; Robertson et al. 2015). Here the derivative of ionized fraction (eq. 16) with respect to time $\dot{Q}_{\text{HII}}$ is written as

$$
\dot{Q}_{\text{HII}} = \frac{\dot{n}_{\text{ion}}}{\langle n_H \rangle} \frac{Q_{\text{HII}}}{t_{\text{rec}}} \ (17)
$$

where $\langle n_H \rangle$ and $t_{\text{rec}}$ are the average hydrogen number density and the recombination time, respectively, defined by

$$
\langle n_H \rangle = \frac{X_p \Omega_b \rho_c}{m_H} \ (18)
$$

$$
t_{\text{rec}} = \frac{1}{C_{\text{HI}} \alpha_B(T)(1 + Y_p/4X_p) \langle n_H \rangle (1 + z)^3}. \ (19)
$$

The parameters, $m_H$, $\rho_c$, and $X_p$ ($Y_p$) are the mass of the hydrogen atom, the critical density, and the primordial mass fraction of hydrogen (helium), respectively. In eq. (19), the parameters of $C_{\text{HI}}$ and $\alpha_B(T)$ represent the clumping factor and the case B hydrogen recombination coefficient for the IGM temperature $T$ at a mean density, respectively. All of these parameters are determined by physics and cosmology, except for $C_{\text{HI}}$ and $\dot{n}_{\text{ion}}$. The parameter of $\dot{n}_{\text{ion}}$ is closely related to galaxy formation, and estimated by

$$
\dot{n}_{\text{ion}} = \int_0^{\infty} f_{\text{esc}}(L_{\text{UV}}) \xi_{\text{ion}}(L_{\text{UV}}) \phi(L_{\text{UV}}) L_{\text{UV}} dL_{\text{UV}} \ (20)
$$

$$
= f_{\text{esc}} \xi_{\text{ion}} \rho_{UV} \ [\text{for no LUV dependences}], \ (21)
$$

where $f_{\text{esc}}$ and $\xi_{\text{ion}}$ are the ionizing photon escape fraction\(^{19}\) and the ionizing photon production efficiency, respectively. The values of $L_{\text{UV}}$, $\phi(L_{\text{UV}})$, $\rho_{UV}$ are the UV-continuum

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\(^{18}\)Although the fraction of LAEs decreases from $z \sim 6$ towards high-$z$, this decrease is just made by a low observability given by the external effect of the neutral IGM that scatters Ly$\alpha$ photons.

\(^{19}\)Note that this parameter of $f_{\text{esc}}$ is different from the escape fraction of Ly$\alpha$ photons (eq. 9).
luminosity, the UV-continuum LF, and the UV-continuum LD, respectively (Section 3). The equation (21) assumes no luminosity dependence in the parameters of $f_{\text{ion}}$ and $\xi_{\text{ion}}$.

There are three major parameters for $\dot{n}_{\text{ion}}$: i) $\rho_{\text{UV}}$, ii) $\xi_{\text{ion}}$, and iii) $f_{\text{ion}}$. i) The LAEs’ contribution to $\rho_{\text{UV}}$ is large at high redshift. As discussed in Section 3, the fraction of LAEs to all galaxies in $\rho_{\text{UV}}$ increases from the local universe towards the EoR $z \sim 6$. This increase indicates that LAEs’ contribution to cosmic SFRDs increases (Ouchi et al. 2008; Ciardullo et al. 2012). The fraction of the Ly$\alpha$ emitting galaxies reaches nearly 50% at $z \sim 6$ (Stark et al. 2011). Because LAEs are abundant and major galaxies at the EoR, ionizing photon emission properties of LAEs are critical to understand sources of cosmic reionization. ii) For the photon production, it is recently claimed that the LAEs’ $\xi_{\text{ion}}$ is higher than other high-$z$ galaxy populations. The typical ionizing photon production efficiency of LAEs is $\log(\xi_{\text{ion}}/[\text{Hz} \text{ erg}^{-1}]) \sim 25.5$, significantly higher than those of LBGs at a given UV magnitude (Harikane et al. 2018). iii) It is suggested that the average ionizing photon escape fraction is also high for LAEs. Deep spectroscopy and NB imaging observations reveal that the average $f_{\text{ion}}$ value is $\sim 20\%$ for LAEs at $z \sim 3$ (Shapley et al. 2006) see also Vanzella et al. 2016 de Barros et al. 2016. In other words, a positive correlation between $f_{\text{ion}}$ and Ly$\alpha$ EW$_0$ is suggested (Iwata et al. 2009; Nestor et al. 2013). Deep NIR spectroscopy studies find that the line flux ratios of [Oiii]5007 to [Oii]3727, $O_{32}$, of LAEs at $z \sim 2$ are large, $O_{32} \sim 10$ (Nakajima et al. 2013). Because such galaxies with large $O_{32}$ values show a high ionizing photon escape fraction, $f_{\text{ion}} \sim 5-50\%$ (Izotov et al. 2016; Vanzella et al. 2016). LAEs are thought to be major emitters of ionizing photons at high redshift. For the physical origin of ionizing photon emission of LAEs, various scenarios including density-bounded nebula are suggested (Nakajima & Ouchi 2014). However, the physical reason of escaping ionizing photons is still under debate.

10. Open Questions and Future Prospects

In observational studies of Ly$\alpha$ emission, there are five major questions$^{20}$ that are listed below.

1. What are dominant sources of Ly$\alpha$ photons in LAEs including ELANe, LABs, and LAHs? Are the majority of Ly$\alpha$ photons produced in HII regions of star formation and/or AGN? Are there any major contributions of Ly$\alpha$ photons from gravitational cooling? (Section 2)

2. How faint LAEs exist? What is the dark-matter low-mass limit of SFGs that emit Ly$\alpha$? What is the faint-end slope $\alpha$ of the Ly$\alpha$ LF? (Section 3)

3. What is the major physical origin of the high Ly$\alpha$ emissivity of LAEs such characterized by the large Ly$\alpha$ EW$_0$ and the high $f_{\text{ion}}$? What makes LAEs different from other SFGs with weak/no Ly$\alpha$ emission? (Sections 3–8)

$^{20}$Because Ly$\alpha$ emission is produced by recombination in hydrogen gas of the ISM that absorbs ionizing photons, strong Ly$\alpha$ emission should not be found in galaxies emitting ionizing photons. However, even under this physical picture, model calculations suggest that there is a positive correlation between $f_{\text{ion}}$ and Ly$\alpha$ EW$_0$ in the regime of the moderately low Ly$\alpha$ EW$_0$ values (Nakajima & Ouchi 2014).

$^{21}$In addition to these five major questions, various observational measurements should be refined and revisited. One example is the determination of Ly$\alpha$ LF, where the flux contributions of extended Ly$\alpha$ halos are not included in many of previous studies (Herenz et al. 2019).
4. What are the ionization state of the ISM and CGM of LAEs? Is the density-bounded picture possible in the ISM? Do regular LAEs (that do not include ELANe with an active AGN) have the CGM gas mainly consisting of neutral hydrogen? What makes the observational trend of the high fraction of Lyman-continuum leaking for LAEs that is important for sources of reionization? (Sections 6-7 and 9)

5. Do pop III LAEs exist, as originally predicted by Partridge & Peebles (1967)? If pop III LAEs exist, are they observable at the post EoR (late epoch) and/or the EoR (early epoch) that may or may not have a mechanism allowing the Lyα escape from the partly neutral universe? Does the Lyα escape from the partly neutral universe depend on reionization topology? (Sections 6 and 9)

There are a number of on-going and next generation instrument projects that are critical for resolving these five questions. Such instruments include those for statistical studies, Subaru/HSC, Prime-Focus Spectrograph (PFS), and HETDEX, high sensitivity observations, VLT/MUSE, and Keck/KCWI (Morrissey et al. 2018), and submm/mm wavelength observations, ALMA. Lyα emission studies will be boosted with the next generation large telescopes, James Webb Space Telescope (JWST) and extremely large telescopes (ELTs) by the great sensitivities. Moreover, the H1 21cm observations with Hydrogen Epoch of Reionization Array (HERA) and Square Kilometre Array (SKA) will complement the Lyα emission studies at the EoR (Section 9). Because the future imaging and spectroscopic data such taken with HSC, PFS, and HETDEX are too large to be analyzed by visual inspections for quality assessments, one will need new analysis technique of artificial intelligence that includes machine learning.

In the past two decades, observations have targeted SFGs emitting Lyα that are easily detected. Recent studies change the observational targets to diffuse Lyα emission around galaxies and filaments of the large-scale structures that are new observational frontiers. Although Lyα emission traces both Hii and H1 gas with a great sensitivity, the origins of the Lyα emission cannot be clearly distinguished between, e.g. recombination and resonant scattering. The future observing programs should combine the Lyα emission results with the complementary non-resonant hydrogen emission (Hα and Hβ) and H1 absorption observations (Lee et al. 2014), exploiting the high sensitivity instruments and the next generation large telescopes. Including the 21cm observations at the EoR, future observations will reveal the H1 and Hii gas distribution in the universe in the scales from star-forming regions to the large-scale structures.

11. Summary and Final Thoughts

Since the first discoveries of strong Lyα emitting high-z galaxies in the late 1990s, Lyα emission has been one of the major probes for the high redshift universe. Defining LAEs as galaxies with Lyα $EW_0 \gtrsim 20\AA$, more than 1,000 (20,000) LAEs are spectroscopically (photometrically) identified to date. Observations suggest that LAEs emerge at high redshift, and the fraction of LAEs to the other galaxies increases (for a given UV-continuum luminosity) towards high redshift up to the EoR (Section 3). LAEs are galaxies of a major population at high redshift. This emergence of LAEs are understood by the increase of Lyα escape fraction for high-z SFGs.

At high redshift ($z \gtrsim 2$), a majority of LAEs with a $L^*$ Lyα luminosity are low-mass ($M_* \sim 10^8 - 10^9 M_\odot$ and $M_h \sim 10^{10} - 10^{11} M_\odot$) galaxies with a star-forming activity $(1 - 10 \ M_\odot \ yr^{-1};$ Figure 9). Such typical LAEs are high-z analogs of dwarf galaxies having...
a young dust-poor stellar population with a sub-solar metallicity in the ISM gas, showing
a compact disky morphology \((n_s \sim 1)\) with an effective radius of \(\sim 1 \, \text{pkpc} \) (Sections 4-6).
These physical properties of LAEs can be explained by the nature of the faint continuum
\((\text{sub} \, L^*_\text{UV})\); Section 5. In fact, LAEs follow the size-mass relation and the SFR-mass metal-
licity relation. LAEs are probably SFGs similar to those of dropout galaxies or LBGs with
weak or no Ly\(\alpha\) emission. In this case, the difference of LAEs from the other galaxies is
characterized by the Ly\(\alpha\) emission duty cycle of \(\sim 1\% \) (Section 8) caused by the combination
of intermittent star formation and time-dependent Ly\(\alpha\) escape.

Ly\(\alpha\) emission is not only observed at the ionized hydrogen clouds by recombination, but
also at the neutral hydrogen clouds by resonant scattering. The resonance nature of Ly\(\alpha\)
allows us to probe diffuse gas in the ISM/CGM of a galaxy as well as the IGM. For the
ISM, the skewed profiles of galaxy Ly\(\alpha\) emission suggest the existence of neutral hydrogen
gas outflowing from Ly\(\alpha\) sources (such as star-forming regions) that is explained by the ES
model (Sections 2 and 9). For the CGM (Section 7), diffuse Ly\(\alpha\) emission around an SFG,
i.e. LAH, is ubiquitas. Although it is not understood whether the LAH is made by the
recombination process of the ionized clouds or the resonant scattering of the neutral clouds,
the CGM includes metal at least up to \(\sim 10 \, \text{pkpc} \) such identified by the extended carbon
emission with a radial profile similar to those of LAHs, indicative that the CGM is metal-
enriched by outflow. The LAH extends beyond the virial radius of a galaxy dark-matter
halo up to 1 cMpc or more, perhaps originating from filaments in the large-scale structures.

Strong Ly\(\alpha\) emission is easily detected by observations, being used as a signpost of
high-\(z\) objects. Reports of Ly\(\alpha\)-emission detection have been made for galaxies up to \(z \sim 9\),
to date. The redshift frontier of galaxy observations has entered into the EoR, where Ly\(\alpha\)
is scattered by the partly neutral hydrogen IGM. Large statistics of galaxy Ly\(\alpha\) emission
provides the average amount of Ly\(\alpha\) scattered by the neutral IGM at the EoR, having
revealed the cosmic reionization history, so far, up to the middle point of reionization
\(x_{\text{HI}} \sim 50\% \) at \(z \sim 7-8 \) (Section 9). The Ly\(\alpha\) escape from the partly neutral hydrogen IGM
is not only a probe of cosmic reionization, but also a signal of the galaxies and ionized-
bubble relation (determined by galaxy clustering, star-formation duty cycle, and galaxy
peculiar motions). One critical question about Ly\(\alpha\) sources is how early epoch, e.g. \(z \sim 10\)
or \(z \sim 15\), Ly\(\alpha\) emission can escape (Section 10).

Throughout this review, we have devoted some pages to explain the observational dif-
erences of LAEs from the other SFGs emitting weak/no Ly\(\alpha\), discussing possible physical
origins of the high Ly\(\alpha\) emissivity of LAEs such characterized by the large Ly\(\alpha\) \(E_0\) and
the high \(f_{\text{Ly}\alpha}^{\text{esc}}\). Although the major physical origin of the Ly\(\alpha\) emissivity difference is an
open question as raised in the item 3 of Section 10, we have a physical picture that a column density of \(\text{HI}\) gas towards a Ly\(\alpha\) source (such as star-forming regions) is a key physical
quantity that controls the Ly\(\alpha\) emissivity. For LAEs, the Ly\(\alpha\) offset velocities are compa-
rable with outflow velocities \((\Delta v_{\text{Ly}\alpha} \sim V_{\text{exp}} \sim 200 \, \text{km} \, \text{s}^{-1})\), and this kinematic property
of LAEs can be explained by a small \(\text{HI}\) column density producing no significant backscat-
tered Ly\(\alpha\) photons (Section 6). The high \(O32\) ratios and the existence of the strong high
ionization lines suggest that the ISM of LAEs are highly ionized, and this photoionization
property of LAEs indicates a small fraction of \(\text{HI}\) gas in LAEs (Section 6). There is an
anti-correlation between Ly\(\alpha\) \(E_0\) and the Ly\(\alpha\) spatial offset \(\delta_{\text{Ly}\alpha}\) on the sky, and this
Ly\(\alpha\) morphological property can be explained by the long mean-free path (less resonant
scattering) of Ly\(\alpha\) photons for LAEs with a small \(\text{HI}\) column density towards the observer
(Section 4). This explanation for the Ly\(\alpha\) \(E_0-\delta_{\text{Ly}\alpha}\) anti-correlation is consistent with
the fact that the Lyα halos are small for LAEs whose central part \((r < 8\) pkpc) of Lyα luminosity is bright (Section 7). In this way, all of the independent observational properties of kinematics, photoionization, and morphology consistently support the physical picture that a column density of H\(_i\) gas is a key physical quantity for the Lyα emissivity, and that LAEs are different from the other SFGs emitting weak/no Lyα due to the small H\(_i\) column density of LAEs. In this physical picture, we would witness SFGs at the galaxy evolutionary phase of the highly-ionized H\(_i\) poor state as LAEs, when the SFGs are free from dusty and gaseous starbursts such triggered by gas rich mergers. Because the cosmic average of \(f_{\text{Ly}\alpha}^{15}\) (i.e., average Lyα emissivity) increases from \(z = 0\) to 6 by two orders of magnitudes (Section 8), in galaxy formation a number of early young galaxies should experience the highly-ionized H\(_i\) poor (LAE) phase.

As reviewed in this article, observations of Ly α emission have driven various studies of the high-redshift universe for more than two decades. Lyα observations have been pioneering the redshift frontier and investigating low-mass high-z galaxies. Moreover, recently, Lyα observations have attracted attention for studying cosmic structures traced by diffuse neutral and ionized hydrogen gas of the CGM and the IGM, serving as a new observational role. Because the studies of the CGM and the IGM have been (will be) conducted by hydrogen and metal absorption observations (radio low-frequency 21cm observations), forthcoming studies combining these absorption (radio) observations with Lyα emission from neutral and ionized hydrogen will open up a new territory of study, cosmic structures and its connection to galaxy formation that are uncovered to date.

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LITERATURE CITED

Adams JJ, Blanc GA, Hill GJ, Gebhardt K, Drory N, et al. 2011. ApJS 192:5
Ahn SH. 2004. ApJ 601:L25–L28
Ando M, Ohita K, Iwata I, Akiyama M, Aoki K, Tamura N. 2006. ApJ 645:L9–L12
Ao Y, Matsuda Y, Henkel C, Iono D, Alexander DM, et al. 2017. The Astrophysical Journal 850:178
Arrabal Haro P, Rodríguez Espinosa JM, Muñoz-Tuñón C, Pérez-González PG, Dannerbauer H, et al. 2018. MNRAS 478:3740–3755
Atek H, Kunth D, Schaerer D, Mas-Hesse JM, Hayes M, et al. 2014. Astronomy and Astrophysics 561:A89
Bañados E, Venemans BP, Mazzucchelli C, Farina EP, Walter F, et al. 2018. Nature 553:473–476
Bacon R, Conseil S, Mary D, Brinchmann J, Shepherd M, et al. 2017. A&A 608:A1
Bajtlik S, Duncan RC, Ostriker JP. 1988. ApJ 327:570
Bardeen JM, Bond JR, Kaiser N, Szalay AS. 1986. ApJ 304:15

Ouchi et al.
Konno A, Ouchi M, Shibuya T, Ono Y, Shimasaku K, et al. 2018. PASJ 70:S16
Kubota K, Yoshiura S, Takahashi K, Hasegawa K, Yajima H, et al. 2018. MNRAS 479:2754–2766
Kusakabe H, Blaizot J, Garel T, Verhamme A, Bacon R, et al. 2020. A&A 638:A12
Kusakabe H, Shimasaku K, Nakajima K, Ouchi M. 2015. ApJ 806:L29
Kusakabe H, Shimasaku K, Ouchi M, Nakajima K, Goto R, et al. 2018. PASJ 70:4
Lai K, Huang JS, Fazio G, Gawiser E, Ciardullo R, et al. 2008. ApJ 674:70–74
Lake E, Zheng Z, Cen R, Sadoun R, Momose R, Ouchi M. 2015. ApJ 806:46
Laporte N, Ellis RS, Boone F, Bauer FE, Quénard D, et al. 2017. ApJ 837:L21
Larson RL, Finkelstein SL, Pirzkal N, Ryan R, Tilvi V, et al. 2018. ApJ 858:94
Laursen P. 2010. Interpreting Lyman α radiation from young, dusty galaxies. Ph.D. thesis, Dark
Cosmology Centre, Niels Bohr Institute Faculty of Science, University of Copenhagen
Laursen P, Duval F, Östlin G. 2013. ApJ 766:124
Leclercq F, Bacon R, Wisotzki L, Mitchell P, Garel T, et al. 2014. ApJ 795:L12
Leibler CN, Cantalupo S, Holden BP, Madau P. 2018. MNRAS 480:2108
Lemaux BC, Cucciati O, Stark LAM, Le Fèvre O, Zamorani G, et al. 2014. Ypap 572:A41
Lidz A, Zahn O, Furlanetto SR, McQuinn M, Hernquist L, Zaldarriaga M. 2009. ApJ 690:252–266
Liu C, Mutch SJ, Angel PW, Duffy AR, Geil FM, et al. 2016. MNRAS 462:235–249
Madau P, Haardt F, Rees M. 1999. ApJ 514:648–659
Malhotra S, Rhoads JE. 2002. The Astrophysical Journal 565:L71–L74
Malkotra S, Rhoads JE. 2004. ApJ 617:L5–L8
Malkotra S, Rhoads JE, Finkelstein SL, Hathi N, Nilsson K, et al. 2012. ApJ 750:L36
Mallory RP, Mobasher B, Capak P, Kakazu Y, Masters D, et al. 2012. ApJ 760:128
Markowate AT, Heckman TM, Wyse RFG, Schommer R. 1995. ApJ 438:563
Mason CA, Fontana A, Treu T, Schmidt KB, Hoag A, et al. 2019. MNRAS 485:3947–3969
Matsuda Y, Yamada T, Hayashino T, Tamura H, Yamauchi R, et al. 2004. AJ 128:569–584
Matsuda Y, Yamada T, Hayashino T, Tamura H, Yamauchi R, et al. 2005. Ypapj 634:L125–L128
Matsuda Y, Yamada T, Hayashino T, Yamauchi R, Nakamura Y, et al. 2011. MNRAS 410:L13–L17
Matsuda Y, Yamada T, Hayashino T, Yamauchi R, Nakamura Y, et al. 2012. MNRAS 425:878–883
Matthee J, Sobral D, Santos S, Röttgering H, Darvish B, Mobasher B. 2015. MNRAS 451:400–417
McCarthy PJ, Spinrad H, Djorgovski S, Strauss MA, van Breugel W, Liebert J. 1987. ApJ 319:L39
McLinden EM, Finkelstein SL, Hayashi T, Hayashino T, Yamauchi R, et al. 2012. ApJ 745:12
McQuinn M, Spinrad H, Wisotzki L, Zaldarriaga M, Dutta S. 2007. MNRAS 381:75–96
McQuinn M, Lidz A, Zaldarriaga M, Hernquist L, Dutta S. 2008. MNRAS 388:1101–1110
Miley GK, Overzier RA, Tsvetanov ZI, Bouwens RJ, BenY Yitez N, et al. 2004. Ynat 427:47–50
Miller TB, Chapman SC, Aravena M, Ashby MLN, Hayward CC, et al. 2018. Ynat 556:469–472
Momose R, Ouchi M, Nakajima K, Ono Y, Shibuya T, et al. 2014. MNRAS 442:110–120
Momose R, Ouchi M, Nakajima K, Ono Y, Shibuya T, et al. 2016. MNRAS 457:2318–2330
Morrissey P, Matuszewski M, Martin DC, Neill JD, Epps H, et al. 2018. ApJ 864:93
Nagamine K, Ouchi M, Springel V, Hernquist L. 2010. PASJ 62:1455
Nakajima K, Ellis RS, Iwata I, Inoue AK, Kusakabe H, et al. 2016. ApJ 831:L9
Nakajima K, Fletcher T, Ellis RS, Robertson BE, Iwata I. 2018. MNRAS 477:2098–2111
Nakajima K, Ouchi M. 2014. MNRAS 442:900–916
Nakajima K, Ouchi M, Shimasaku K, Hashimoto T, Ono Y, Lee JC. 2013. ApJ 769:3
Nakajima K, Ouchi M, Shimasaku K, Ono Y, Lee JC, et al. 2012. ApJ 745:12
Nestor DB, Shapley AE, Kornei KA, Steidel CC, Siana B. 2013. ApJ 765:47
Neufeld DA. 1991. ApJ 370:L85
Oesch PA, Brammer G, van Dokkum PG, Illingworth GD, Bouwens RJ, et al. 2016. ApJ 819:129
Oesch PA, van Dokkum PG, Illingworth GD, Bouwens RJ, Momcheva I, et al. 2015. ApJ 804:L30
Ono Y, Ouchi M, Mobasher B, Dickinson M, Penner K, et al. 2012. ApJ 744:83
Ono Y, Ouchi M, Shimasaku K, Akiyama M, Dunlop J, et al. 2010a. MNRAS 402:1580–1598
Steidel CC, Adelberger KL, Shapley AE, Pettini M, Dickinson M, Giavalisco M. 2000. ApJ 532:170–182

Steidel CC, Bogosavljević M, Shapley AE, Kollmeier JA, Reddy NA, et al. 2011. ApJ 736:160

Steidel CC, Erb DK, Shapley AE, Pettini M, Reddy N, et al. 2010. ApJ 717:289–322

Steidel CC, Rudie GC, Strom AL, Pettini M, Reddy NA, et al. 2014. The Astrophysical Journal 795:165

Storey PJ, Zeippen CJ. 2000. MNRAS 312:813–816

Sugahara Y, Ouchi M, Harikane Y, Bouché N, Mitchell PD, Blaizot J. 2019. arXiv e-prints: arXiv:1904.03106

Tamura Y, Mawatari K, Hashimoto T, Inoue AK, Zackrisson E, et al. 2019. ApJ 874:27

Taniuchi Y, Murayama T, Scoville NZ, Sasaki SS, Nagao T, et al. 2009. ApJ 701:915–944

Tilvi V, Papovich C, Finkelstein SL, Long J, Song M, et al. 2014. ApJ 794:5

Toshikawa J, Kashikawa N, Overzier R, Malkan MA, Furusawa H, et al. 2016. ApJ 826:114

Toshikawa J, Kashikawa N, Overzier R, Shibuya T, Ishikawa S, et al. 2014. ApJ 792:15

Totani T, Aoki K, Hattori T, Kawai N. 2016. PASJ 68:15

Totuji H, Kihara T. 1969. PASJ 21:221

Trainor RF, Strom AL, Steidel CC, Rudie GC. 2016. ApJ 832:171

Trebitsch M, Verhamme A, Blaizot J, Rosdahl J. 2016. A&A 593:A122

Treu T, Schmidt KB, Trenti M, Bradley LD, Stiavelli M. 2013. ApJ 775:L29

Umehata H, Hatsukade B, Smail I, Alexander DM, Ivison RJ, et al. 2018. ApJS 70:65

van Ojik R, Roettgering HJA, Miley GK, Hunstead RW. 1997. A&A 317:358–384

Vanzella E, de Barros S, Vasei K, Alavi A, Giavalisco M, et al. 2016. ApJ 825:41

Vargas CJ, Bish H, Acquaviva V, Gawiser E, Finkelstein SL, et al. 2014. ApJ 783:26

Venemans BP, Röttgering HJA, Miley GK, van Breugel WJM, de Breuck C, et al. 2007. ApJ 661:823–845

Vernet JC, H Decin LB, Barden R, Kneib JP, et al. 2005. ApJ 622:21

Weinberger LH, Haehnelt MG, Kulkarni G. 2019. MNRAS 485:1350–1366

Wistricky I, Bacon R, Blaizot J, Brinchmann J, Herenz EC, et al. 2016. A&A 587:A98

Wisotzki L, Bacon R, Brinchmann J, Cantalupo S, Richter P, et al. 2018. Nature 562:229–232

Xue R, Lee KS, Dey A, Reddy N, Hong S, et al. 2017. ApJ 837:172

Yajima H, Li Y, Zhu Q, Abel T, Gronwall C, Ciardullo R. 2012. ApJ 754:118

Yamada T, Matsuda Y, Kousai K, Hayashino T, Morimoto N, Umemura M. 2012a. ApJ 751:29

Yamada T, Nakamura Y, Matsuda Y, Hayashino T, Yamauchi R, et al. 2012b. AJ 143:79

Yang Y, Zabludoff A, Eisenstein D, Davé R. 2010. ApJ 719:1654–1671

Yang Y, Zabludoff A, Jahnke K, Davé R. 2014. The Astrophysical Journal 793:114

Zackrisson E, Inoue AK, Jensen H. 2013. ApJ 777:39

Zhang H, Ouchi M, Itoh R, Shibuya T, Ono Y, et al. 2019. arXiv e-prints: arXiv:1905.09841

Zheng Z, Wallace J. 2014. ApJ 794:116

Zheng ZY, Wang J, Rhoads J, Infante L, Malhotra S, et al. 2017. ApJ 842:L22

Zirm AW, Overzier RA, Miley GK, Blakeslee JP, Clampin M, et al. 2005. ApJ 630:68–81

Zitrin A, Labbé I, Bell S, Bouwens R, Ellis RS, et al. 2015. ApJ 810:L12