First Results from the Lyman Alpha Galaxies in the Epoch of Reionization (LAGER) Survey: Cosmological Reionization at $z \sim 7$

Zhen-Ya Zheng\textsuperscript{1,2,3}, Junxian Wang\textsuperscript{4}, James Rhoads\textsuperscript{5,6}, Leopoldo Infante\textsuperscript{2}, Sangeeta Malhotra\textsuperscript{5,6}, Weida Hu\textsuperscript{4}, Alistair R. Walker\textsuperscript{7}, Linhua Jiang\textsuperscript{8}, Chunyan Jiang\textsuperscript{1,3,9}, Pascale Hibon\textsuperscript{10}, Alicia Gonzalez\textsuperscript{5}, Xu Kong\textsuperscript{4}, XianZhong Zheng\textsuperscript{11}, Gaspar Galaz\textsuperscript{2}, and L. Felipe Barrientos\textsuperscript{2}

\textsuperscript{1}CAS Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Shanghai 200030, China; zhengzy@shao.ac.cn
\textsuperscript{2}Institute of Astrophysics and Center for Astroengineering, Pontificia Universidad Catolica de Chile, Santiago 7820436, Chile; infante@astro.puc.cl
\textsuperscript{3}Chinese Academy of Sciences South America Center for Astronomy, Santiago 7591245, Chile
\textsuperscript{4}CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei, Anhui 230026, China; jxw@ustc.edu.cn
\textsuperscript{5}School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA; Sangeeta.Malhotra@asu.edu, James.Rhoads@asu.edu
\textsuperscript{6}Astrophysics Science Division, Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
\textsuperscript{7}The Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China
\textsuperscript{8}Núcleo de Astronomía, Facultad de Ingeniería y Ciencias, Universidad Diego Portales, Av. Ejército 441, Santiago, Chile
\textsuperscript{9}Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile
\textsuperscript{10}European Southern Observatory, Alonso de Cordova 3107, Casilla 19010, Santiago, Chile
\textsuperscript{11}Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China

Received 2017 March 8; revised 2017 June 9; accepted 2017 June 13; published 2017 June 21

Abstract

We present the first results from the ongoing Lyman Alpha Galaxies in the Epoch of Reionization (LAGER) project, which is the largest narrowband survey for $z \sim 7$ galaxies to date. Using a specially built narrowband filter NB964 for the superb large-area Dark Energy Camera (DECam) on the NOAO/CTIO 4m Blanco telescope, LAGER has collected 34 hr NB964 narrowband imaging data in the 3 deg\(^2\) COSMOS field. We have identified 23 Ly\textsubscript{$\alpha$} Emitter candidates at $z = 6.9$ in the central 2-deg\(^2\) region, where DECam and public COSMOS multi-band images exist. The resulting luminosity function (LF) can be described as a Schechter function modified by a significant excess at the bright end (four galaxies with $L_{\text{Ly}\alpha} \approx 10^{43.6} \pm 0.2$ erg s\(^{-1}\)). The number density at $L_{\text{Ly}\alpha} \sim 10^{43.4} \pm 0.2$ erg s\(^{-1}\) is little changed from $z = 6.6$, while at fainter $L_{\text{Ly}\alpha}$ it is substantially reduced. Overall, we see a fourfold reduction in Ly\textsubscript{$\alpha$} luminosity density from $z = 5.7$ to $z = 6.9$. Combined with a more modest evolution of the continuum UV luminosity density, this suggests a factor of $\sim$3 suppression of Ly\textsubscript{$\alpha$} by radiative transfer through the $z \sim 7$ intergalactic medium (IGM). It indicates an IGM neutral fraction of $x_{\text{HI}} \approx 0.4$--0.6 (assuming Ly\textsubscript{$\alpha$} velocity offsets of 100--200 km s\(^{-1}\)). The changing shape of the Ly\textsubscript{$\alpha$} LF between $z \approx 6.6$ and $z = 6.9$ supports the hypothesis of ionized bubbles in a patchy reionization at $z \sim 7$.

Key words: cosmology; observations – dark ages, reionization, first stars – galaxies: high-redshift – galaxies: luminosity function, mass function

1. Introduction

In the past decade, much progress has been made in narrowing down the epoch of cosmological reionization to be between $z \sim 6$ (Ly\textsubscript{$\alpha$} saturation in $z \sim 6$ quasar; Fan et al. 2006) and $z \sim 9$ (Polarization of CMB photons; Planck Collaboration et al. 2016). In between, quasars, gamma-ray bursts (GRBs), and galaxies at $z \gtrsim 6$ are important to constrain the nature of reionization. However, the rarity of high-$z$ quasars (with only one known at $z \gtrsim 7$; Bolton et al. 2011), and of high-$z$ GRBs with rapid follow-up, limit their application as reionization probes. In contrast, hundreds of galaxies at $z \gtrsim 6$ have been reported from ground-based narrowband Ly\textsubscript{$\alpha$} line searches (e.g., Ouchi et al. 2010) from space-based broadband Lyman break searches (e.g., Bouwens et al. 2015; Finkelstein et al. 2015) and from newly taken space-based grism spectroscopic surveys (Tilvi et al. 2016; Bagley et al. 2017). Their luminosities, number densities, clustering, and ionizing powers are essential to probe the epoch of reionization (EoR).

Because Ly\textsubscript{$\alpha$} photons are resonantly scattered by neutral hydrogen, Ly\textsubscript{$\alpha$} emitters (LAEs) provide a sensitive, practical, and powerful tool to determine the epoch, duration, and inhomogeneities of reionization. With a sample of LAEs in EoR, the easiest Ly\textsubscript{$\alpha$} reionization test is the luminosity function (LF) test. Rhoads & Malhotra (2001) first applied this test at $z = 5.7$, then at 6.5 (Malhotra & Rhoads 2004; Stern et al. 2005). Subsequent surveys have confirmed and refined the $z = 6.5$--6.6 neutral fraction measurement to $x_{\text{HI}} \lesssim 0.3$ (Ouchi et al. 2010; Kashikawa et al. 2011), and have found a significant neutral fraction increase from $z = 6.6$ to $z = 7.3$ (Konno et al. 2014). Other implementations of Ly\textsubscript{$\alpha$} reionization tests include the Ly\textsubscript{$\alpha$} visibility test (Jensen et al. 2013; Faisst et al. 2014; Schenker et al. 2014), i.e., the Ly\textsubscript{$\alpha$} fraction in LBGs in EoR, the volume test (Malhotra & Rhoads 2006; J. Rhoads & S. Malhotra 2017, in preparation), i.e., each Ly\textsubscript{$\alpha$} galaxy is taken as evidence for a certain volume of ionized gas, and the clustering test, e.g., the signature of a patchy partially ionized intergalactic medium (IGM) is sought by looking for excess spatial correlations in the Ly\textsubscript{$\alpha$} galaxy distribution (Furlanetto et al. 2006; McQuinn et al. 2007; Jensen et al. 2013).

Redshift $z \gtrsim 7$ is the frontier in Ly\textsubscript{$\alpha$} and reionization studies. Many searches for LAEs at $z = 6.9$--7.0 (Iye et al. 2006; Ota et al. 2008, 2010; Hibon et al. 2011, 2012), $z = 7.2$--7.3 (Shibuya et al. 2012; Konno et al. 2014), and $z = 7.7$ (Hibon et al. 2010; Tilvi et al. 2010; Krug et al. 2012) have yielded $\sim$two dozen narrowband-selected candidates, but only three of
these have been spectroscopically confirmed so far (Iye et al. 2006; Rhoads et al. 2012; Shibuya et al. 2012). In comparison, hundreds of LAEs have been found at lower redshift at $z=0.6$ (e.g., Hu et al. 2010; Ouchi et al. 2010; Kashikawa et al. 2011; Matthee et al. 2015), and a large fraction of them have been spectroscopically confirmed (i.e., Kashikawa et al. 2011). The comoving volumes of the searches for $z \gtrsim 7$ LAEs are all less than $6 \times 10^{5}$ cMpc$^3$, which are more likely to be affected by cosmic variance. In fact, cosmic variance is more important for the observability of LAEs in patchy reionization. Furthermore, some of the surveys with 200 Å wide filters in the far-red inevitably (e.g., Ota et al. 2008, 2010) include one or two weak OH emission lines, limiting their sensitivity. Thus, there is an urgent need for a systematic survey at $z \sim 7$ with sufficient volume and depth to determine if the Ly$\alpha$ line is attenuated due to neutral IGM in a statistically significant way.

In this Letter, we report the discovery of a population of candidate $z \sim 7$ Ly$\alpha$ emitters in the first field (COSMOS) of the Lyman Alpha Galaxies in the Epoch of Reionization (LAGER) survey. With LAGER-COSMOS, we have the largest sample to date of candidate $z \sim 7$ LAEs. In Section 2, we describe the observation and data reduction of LAGER, then introduce the candidates selection method. In Section 3, we present the candidates and their Ly$\alpha$ LF at $z \sim 7$. In Section 4, we discuss the implications of these discoveries for EoR at $z \sim 7$.

2. Survey Description and Data

2.1. LAGER Survey

The LAGER survey is the largest narrowband survey yet for LAEs at $z \gtrsim 7$. It is currently ongoing, using the Dark Energy Camera (DECam, with FOV $\sim 3$ deg$^2$) on the NOAO-CTIO 4 m Blanco telescope together with an optimally designed custom narrowband filter, NB964\(^{12}\) (central wavelength $\sim 9642$ Å, FWHM $\sim 90$ Å). LAGER is designed to select more than a hundred $z \sim 7$ LAEs over an area of 12 deg$^2$ in four fields ($8 \times 10^5$ cMpc$^3$). Currently, LAGER has collected 47 hr NB964 narrowband imaging in three fields (CDF-S, COSMOS, and DLS-I5) taken during nine nights in 2015 December, 2016 February, March, and November.

The deepest NB964 imaging is done in COSMOS, where we have obtained 34 hr NB964 exposure in a 3 deg$^2$ field. The exposure time per NB964 frame is 900 s. Consecutive exposures were dithered by $\sim 100''$ so that chip gaps and bad pixels do not lead to blank areas in the final stacks. We also took $\sim 0.5$-$1$ hr $z$ and $Y$ band exposure per field to exclude possible transients. There are deep archival DECam and Subaru broadband images in COSMOS.

2.2. Data Reduction and Analysis

We downloaded the reduced and calibrated DECam resampled images from the NOAO Science Archive, which were processed through the NOAO Community Pipeline (version 3.7.0; Valdes et al. 2014). The individual frames were stacked following the weighting method in Annis et al. (2014) with SWarp (version 2.38.0; Bertin 2010). The seeing of the final stacked LAGER-COSMOS narrowband image is $0''.93$.

The zero-magnitudes of the DECam images were calibrated to the Subaru Suprime-Cam broadband magnitudes of the stars in the public COSMOS/UltraVISTA $K_s$-selected catalog (Muzzin et al. 2013). We estimated the image depth by measuring the root mean square (rms) of the background in blank places where detected ($>3\sigma$) signals were masked out. In a $2'$ diameter aperture, the $3\sigma$ limiting AB magnitudes of the DECam images are $[u, g, r, i, z, Y, NB964]_{3\sigma} = [26.2, 27.4, 26.9, 26.6, 26.1, 24.3, 25.6]$. Deep Subaru Suprime-Cam broadband and narrowband images are available in the central 2 deg$^2$ area. We downloaded the raw images from the archival server SMOKA (Baba et al. 2002), and produced our own broadband and narrowband stacked images (follow-up work of Jiang et al. 2013). Their $3\sigma$ limiting magnitudes within a 2 deg$^2$ aperture are $[B, g', V, r', i', z', NB711, NB816, NB921]_{3\sigma} = [27.9, 27.6, 27.2, 27.4, 27.3, 25.9, 26.0, 26.1, 26.2]$. These Subaru Suprime-Cam images are deeper and have better seeing than the DECam images on average.

We calculated the narrowband completeness via Monte Carlo simulations with the BALROG software (Suchyta et al. 2016). The completeness fraction is defined as the SExtractor recovery percentage of the randomly distributed artificial sources in the NB964 image as a function of narrowband magnitude. For point sources, the narrowband NB964 aperture magnitudes corresponding to the 80%, 50%, and 30% completeness fractions are 24.2, 25.0, and 25.3, respectively. For pseudo LAEs, we choose fake sources similar to those used in Konno et al. (2017), which have a Sérsic profile with the Sérsic index of $n=1.5$ and the half-light radius of $r_e \sim 0.9$ kpc (0.17 arcsec at $z=6.9$). The narrowband NB964 aperture magnitudes corresponding to the 80%, 50%, and 30% completeness fractions are 24.3, 24.7, and 25.0 for pseudo LAEs, respectively.

2.3. Selection Criteria for $z \sim 7$ LAEs

Since Subaru broadband images are deeper and have better seeings than those of the DECam broadband images, we only apply selection criteria for $z \sim 7$ LAEs in the central 2 deg$^2$ area covered by both the Suprime-Cam and the DECam. The selection criteria for $z \sim 7$ LAEs include narrowband NB964 with $>5\sigma$ detection (NB964 $\leq$ NB964$_{3\sigma} = 25.07$), narrowband NB964 excess over broadband $z$ ($z - NB964 \geq 1.0$),\(^{13}\) and nondetections in both DECam $ugri$ and Suprime-Cam $Bg' Vr'i'$ $\sigma$ $N711$, $N816$, $N921$ bands. We specially exclude broadband detections in the 1.08″ (4 pixel) diameter aperture to exclude marginal signals in these bands. 156 sources passed the selection criteria, but a large fraction of them are fake sources (bleed trails, diffraction spikes, etc.) after our visual check on NB964 image. With our team’s tripartite visual check on both NB964 and broadband images, 27 candidate $z \sim 7$ galaxies are selected. No transient was identified among them using the available broadband images.

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\(^{12}\) Please see the filter information at NOAO website: http://www.ctio.noao.edu/noao/content/Properties-N0964-filter.

\(^{13}\) As NB964 lies to the edge of $z$ band transmission curve, very red continuum sources may mimic emission line galaxies. We examine the $z$-NB versus $z$-$Y$ plot for bright NB detected sources, and find that red sources with $z$-$Y \sim 1.0$ mag have $z$-NB $\sim 0.4$ mag, thus such effect is not important.
3. Results

3.1. Candidate LAEs at $z \sim 7$ in LAGER-COSMOS

We estimate the Ly$\alpha$ line fluxes and EWs of the candidates using narrowband and broadband photometry.\(^{14}\) We further exclude 4 out of the 27 candidates with estimated line EW of $<10\AA$.

In total, 23 candidate $z \sim 7$ LAEs, which have Ly$\alpha$ line fluxes in the range of $0.8-7.8 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ and rest-frame equivalent widths $E(W) \geq 10\AA$, are selected. The corresponding observed Ly$\alpha$ line luminosities are $5.4-43.4 \times 10^{42}$ erg s$^{-1}$ Hz$^{-1}$. Their positions and their multi-band thumbnail images are plotted in Figure 1.

The four brightest LAEs, with $L(\text{Ly}\alpha) = 19.3-43.4 \times 10^{42}$ erg s$^{-1}$, are the most luminous candidate LAEs known at $z \gtrsim 7$, thanks to the large survey volume of LAGER. We have confirmed three of the brightest LAEs at $z \sim 7$ (Hu et al. 2017) with our recent Magellan/IMACS spectroscopic follow-up observations.

One of the candidates, J09:59:50.99+02:12:19.1, was previously selected and spectroscopically confirmed as a $z = 6.944$ LAE with Magellan/IMACS narrowband imaging and spectroscopy over a much smaller field (Rhoads et al. 2012). It is well recovered with our selection using new DECam narrowband imaging.

3.2. Ly$\alpha$ LF at $z \sim 7$

We use the $V/V_{\text{max}}$ method to calculate the Ly$\alpha$ LF at $z = 6.9$. The formula below is adopted as

$$\Phi(L) dL = \sum_{L \in [L-\Delta L/2, L+\Delta L/2]} \frac{1}{V_{\text{max}} f_{\text{comp}}(NB)}.$$

\(^{14}\) UltraVISTA $Y$ band (McCracken et al. 2012; DR3) is used to directly estimate the UV continuum of LAGER LAEs. For those without UltraVISTA $Y$ band coverage, we use DECam $z$ band and follow the Appendix of Zheng et al. (2016) to estimate the Ly$\alpha$ line fluxes and EWs. For broadband nondetections, 2σ upper limits are chosen. We assume a flat UV continuum of $f_\nu \propto \nu^0$ and the IGM absorption from Madau (1995) in the above calculations. For candidates with $z$ or $Y$ band detection, such assumption holds within statistical uncertainty.

| Log$_{10} (L_f)$ | $N \pm \Delta N^*$ | $f_{\text{comp}}$ | Log$_{10} \Phi(L_f)$ ($[d\log_{10}(L_f)^{-1} \text{MPc}^{-3}]$) |
|------------------|---------------------|------------------|------------------|
| 42.71            | $6^{+4}_{-2}$       | 0.21             | $-3.74^{+0.22}_{-0.22}$ |
| 42.84            | $7^{+4}_{-2}$       | 0.44             | $-4.00^{+0.19}_{-0.19}$ |
| 42.96            | $4^{+2}_{-0}$       | 0.56             | $-4.34^{+0.25}_{-0.25}$ |
| 43.09            | $2^{+2}_{-0}$       | 0.80             | $-4.80^{+0.37}_{-0.37}$ |
| 43.21            | $<2.6$              | 0.82             | $<5.10$           |
| 43.33            | $<2.6$              | 0.85             | $<5.13^{+0.52}_{-0.52}$ |
| 43.46            | $<2^{+2}_{-1}$      | 0.88             | $<4.84^{+0.37}_{-0.37}$ |
| 43.59            | $<2_{-1}$           | 0.90             | $<5.15^{+0.52}_{-0.52}$ |

Note.

Note. $^*$1 for Poisson errors from Gehrels (1986).

Here $V_{\text{max}}$ is simply a constant, the maximum survey volume for LAEs ($V_{\text{max}} = 1.26 \times 10^8$ cMpc$^3$ calculated from sky coverage and NB964 central wavelength/FWHM), and $f_{\text{comp}}(NB)$ is the detection completeness for sources with narrowband magnitude $m(NB)$ interpolated in the narrowband detection completeness for fake LAEs (see Section 2.2).

The Ly$\alpha$ LF of LAEs at $z \sim 7$ in the LAGER-COSMOS field is listed in Table 1, and plotted in Figure 2 together with LAE LFs at $z \sim 5.7-7.3$ from the literature. The LF shows dramatic evolution not only in normalization, but also in the shape.

The relatively fainter end of our LF (42.65 $\leq \log_{10}(L_f) \leq$ 43.25) at $z \sim 7$ can be fitted with a single Schechter function in the form of

$$\Phi(L)dL = \Phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp(-\frac{L}{L^*})d\left(\frac{L}{L^*}\right).$$

Because our survey does not go far below $L^*$, we fix $\alpha = -2.5$ in our fitting, which is suggested from recent studies on Ly$\alpha$ LFs at $z = 5.7$ and $z = 6.6$ by Konno et al. (2017). Konno et al. (2017) report the largest narrowband surveys to date for LAEs at $z = 5.7$ and $z = 6.6$ taken with Subaru HSC on the
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4. Discussion

4.1. The Evolution of Ly\(\alpha\) LF in EoR

Cosmological reionization was well under way by \(z \sim 9\) (Planck Collaboration et al. 2016) and ended by \(z \sim 6\) (Fan et al. 2006). Ly\(\alpha\) galaxies at \(z \gtrsim 6\), e.g., from LAE surveys at \(z = 5.7\) (Ouchi et al. 2008; Santos et al. 2016; Konno et al. 2017), at \(z = 6.6\) (Ouchi et al. 2010; Matthee et al. 2015; Konno et al. 2017), at \(z = 6.9\) (our LAGER-COSMOS sample in this work and Ota et al. 2017), and at \(z = 7.3\) (Konno et al. 2014), are unique samples useful to probe both galaxy evolution and reionization.

In this work, we detect for the first time a significant bump at the bright end of Ly\(\alpha\) LF at \(z \gtrsim 7\). Previous surveys for LAEs at \(z \gtrsim 7\) failed to reveal a bump as they covered much smaller volumes.

The existence of such a bright-end bump is consistent with the scenario proposed by Haiman & Cen (2005), that bright LAEs are less attenuated by a neutral IGM than faint LAEs, as the larger Strömgren sphere surrounding luminous LAEs alleviates the neutral IGM absorption (also see Santos et al. 2016; Konno et al. 2017). Therefore, the evolution in the bright end of the LF better reflects the intrinsic evolution of LAEs, while the faint end is controlled by the evolution of both galaxies and the IGM.

The bottom panel of Figure 3 shows the evolution of luminosity densities both for Ly\(\alpha\) and UV photons. Compared to LGBs (yellow shaded region), an accelerated evolution of LAE Ly\(\alpha\) densities from \(z = 6.6\) (green diamonds) to \(z = 7.3\) (purple cross), as reported by Konno et al. (2014), is clearly seen in Figure 3. Seeing that UV photons detected in LGBs are insensitive to the neutral hydrogen in EoR, Konno et al. (2014) concluded that such rapid evolution in LAE LFs can be attributed to a large neutral IGM fraction at \(z \sim 7.3\). Our LAGER survey shows rapid evolution from \(z = 6.6\) to 6.9, and a smaller difference between \(z = 6.9\) and 7.3 (see Figure 3). It is possible that the evolution in the neutral fraction accelerated after \(z = 6.9\), though a smooth, monotonic neutral fraction evolution at \(6.6 \lesssim z \lesssim 7.3\) also fits the LAGER results and the measurements of Konno et al. (2014) within their uncertainties. Note that the cosmic time from \(z \sim 6.6\) to 6.9 and from \(z \sim 6.9\) to 7.3 are approximately equal, which is about 50 Myr.

Furthermore, compared to the evolution of Ly\(\alpha\) densities \(\rho_{\text{Ly}\alpha}\) between redshifts of 5.7 and 6.9, the evolution in the bright end only \(\rho_{\text{Ly}\alpha}^{\text{bright}}\) follows a much smoother trend, somehow similar to that of the UV densities of LGBs (bottom panel of Figure 3). This demonstrates that either the intrinsic LAE LF evolves moderately between \(z = 5.7\) and 6.9, or that IGM attenuation plays a role even at the highest luminosity bin. Consequently, the dramatic and rapid evolution between \(z = 6.6\) and 6.9 in the faint end can be mainly attributed to the change of neutral IGM fraction. This evolution trend is in agreement with the Ly\(\alpha\) fraction test which shows the fraction of LGBs with visible Ly\(\alpha\) lines drops significantly at \(z \gtrsim 7\) (e.g., Schenker et al. 2014).

15 Using \(f_{\text{Ly}\alpha} = f_{\text{Ly}\alpha}^{\text{UV}} / f_{\text{Ly}\alpha}^{\text{UV}}\) interpolated from Finkelstein et al. (2015).
Table 2

| $z$  | Area   | Volume | $L_{[Ol]}/[L_{\odot}]$ | $\log_{10}(\Phi^{0})$ | $\log_{10}(\Phi^{a})$ | $\log_{10}(\Phi^{b})$ | $\log_{10}(\Phi^{c})$ | Reference          |
|------|--------|--------|------------------------|------------------------|------------------------|------------------------|------------------------|-------------------|
| 5.7  | 13.8   | $1.16 \times 10^{3}$ | 42.4–44.0 | 63.42 ± 0.05 | $-4.09^{+5.13}_{-0.11}$ | 39.54 ± 0.01 | 38.24 | Ouchi et al. (2008) + Konno et al. (2017) |
| 6.6  | 21.2   | $1.91 \times 10^{3}$ | 42.4–44.0 | 43.25 $^{+0.06}_{-0.05}$ | $-4.32 \pm 0.13$ | 39.33 ± 0.02 | 38.05 | Ouchi et al. (2010) + Konno et al. (2017) |
| 6.9  | 2.0    | $1.26 \times 10^{6}$ | 42.6–43.25 | 42.77 $^{+0.32}_{-0.16}$ | $-3.77^{+0.54}_{-0.76}$ | $38.92^{+0.03}_{-0.04}$ | $37.90$ | This study |
| 7.3  | 0.45   | $2.5 \times 10^{8}$ | 42.4–43.0 | 42.77 $^{+1.23}_{-0.34}$ | $-4.09^{+1.09}_{-1.91}$ | 38.55 $^{+0.08}_{-0.07}$ | $4^{\ldots}$ | Konno et al. (2014) |

Notes. The best-fit parameters in column 5 and column 6 are derived by fitting the Schechter function with fixed $\alpha = -2.5$ on the Ly$\alpha$ LFs listed in column 9 with the $\chi^2$ statistics. The errors in columns 5–7 are estimated from their 1σ confidence contours (e.g., Coe 2009) shown in the top panel of Figure 3.

$^a$ Ly$\alpha$ luminosity densities integrated over the best-fit Schechter functions at $42.4 < \log_{10}(\Phi^{c}) < 44.0$ (column 7). Note the errors of Ly$\alpha$ luminosity densities are likely underestimated because we do not consider the uncertainties of the faint-end slope in that calculation.

$^b$ Ly$\alpha$ luminosity densities integrated at the bright end (43.3 < $\log_{10}(\Phi^{c}) < 43.7$; column 8).

The Ly$\alpha$ luminosity densities in this row are calculated by integrating the truncated Schechter function plotted as the red solid curve in Figure 2 and discussed in Section 3.2. We use the Ly$\alpha$ density in column 7 of this row to estimate the neutral IGM fraction at $z \sim 7$ in Section 4.2.

$d$ The survey for $z = 7.3$ LAEs does not have large enough volume to cover the bright end.

\[ \frac{\rho^{UV}_{z=6.9}}{\rho^{UV}_{z=5.7}} = 0.63 \pm 0.09 \] is obtained from Finkelstein et al. (2015). We obtain the ratio of observed Ly$\alpha$ luminosity densities (column 7 in Table 2) $\frac{\rho^{LY}_{z=6.9}}{\rho^{LY}_{z=5.7}} = 0.24 \pm 0.03$.

Thus, we estimate $T'_{z=6.9} = 0.38 \pm 0.07$ (cf., $T'_{z=7.3} = 0.29$ from Konno et al. 2014 and $T'_{z=6.6} = 0.70 \pm 0.15$ from Konno et al. 2017).

Converting the Ly$\alpha$ emission line transmission factor to neutral IGM fraction $x_{HI}$ is model dependent (e.g., Santos 2004; Dijkstra et al. 2007; McQuinn et al. 2007). An important factor is the shift of the Ly$\alpha$ line with respect to the systemic velocity, which is widely observed and may be explained by Ly$\alpha$ radiative transfer in a galactic wind or outflow. The Ly$\alpha$ velocity shift measurements of $z \sim 6$–7 galaxies are very limited and are mostly around 100–200 km s$^{-1}$ (Stark et al. 2015, 2017; Pentericci et al. 2016; but see the two UV luminous galaxies with 400–500 km s$^{-1}$ reported by Willett et al. 2015). With the analytic model of Santos (2004), assuming a Ly$\alpha$ velocity shift of 0 and 360 km s$^{-1}$, the value of $T'_{z=6.9}$ is 0.38 corresponds to $x_{HI} \sim 0.0$ and 0.6, respectively.

By comparing our observed Ly$\alpha$ LF at $z = 6.9$ to that predicted with the radiative transfer simulations by McQuinn et al. (2007; their Figure 4), we obtain $x_{HI} \sim 0.40$–0.60 at $z = 6.9$. Similar results are obtained in the analytic studies considering ionization bubbles (Furlanetto et al. 2006; Dijkstra et al. 2007). We should note that these studies predicted a suppression of the LF that is rather uniform across a wide range of luminosities (e.g., Section 4 of McQuinn et al. 2007). This suggests that the true distribution of ionized region sizes may differ appreciably from those used in the literature (Furlanetto et al. 2006; Dijkstra et al. 2007; McQuinn et al. 2007). We conclude that the neutral hydrogen fraction is $x_{HI} \sim 0.4$–0.6 at $z = 6.9$, where both the uncertainties in the IGM transmission factor calculation and the theoretical model predictions are considered. The LBG Ly$\alpha$ fraction test by Schenker et al. (2014) yields a similar neutral hydrogen fraction.

\[ T'_{z=6.9} = \frac{\rho^{LY}_{z=6.9}}{\rho^{LY}_{z=5.7}} = \frac{\rho^{UV}_{z=6.9}}{\rho^{UV}_{z=5.7}} \frac{\rho^{LY}_{z=5.7}}{\rho^{LY}_{z=5.7}} \] (3)

Here $\rho^{UV}$ and $\rho^{LY}$ are UV and Ly$\alpha$ luminosity densities, respectively. The ratio of UV luminosity densities $\rho^{UV}_{z=6.9}/\rho^{UV}_{z=5.7}$ is $0.63 \pm 0.09$ is obtained from Finkelstein et al. (2015). We obtain the ratio of observed Ly$\alpha$ luminosity densities (column 7 in Table 2) $\rho^{LY}_{z=6.9}/\rho^{LY}_{z=5.7} = 0.24 \pm 0.03$.

\[ T'_{z=6.9} \] Note that the error of $T'_{z=6.9}$ is likely underestimated, as we ignore the uncertainties from the faint-end slope of the Ly$\alpha$ LFs.
could be powered by either Pop. III stars \((x_{\text{HI}} = 0.39^{+0.08}_{-0.09})\) at \(z \sim 7\). Note that smaller \(x_{\text{HI}} = 0.3 \pm 0.2\) at \(z = 6.6\) is obtained by Konno et al. (2017) with Subaru HSC and Suprime-Cam surveys.

4.3. Ionized Bubbles at \(z \sim 7\)

The bump at the bright end of the Ly\(\alpha\) LF is an indicator of large enough (\(>1\) pMpc radius) ionized bubbles, where the Hubble flow can bring Ly\(\alpha\) photons out of resonance, thus leading to a different evolution of Ly\(\alpha\) LF at the bright end and the faint end. The uneven distribution of these LAEs may indicate ionized bubbles in a patchy reionization at \(z \sim 7\). Larger LAGER samples in future will more definitely establish whether the degree of clustering in Figure 1 requires patchy reionization.

The origin of the ionized bubbles could be extrinsic, intrinsic, or both. From Malhotra & Rhoads (2006), which gave the proper radius of a Strömgren sphere and the Gunn–Peterson effect optical depth of a LAE with outflow velocity \(\Delta V\) in EoR, we know that even the brightest LAE can not produce a large enough ionized bubble to effectively reduce the optical depth to \(\tau \sim 1\). We thus would expect extrinsic contribution from additional satellite galaxies associated with the luminous LAEs. From Figure 1, we see such fainter nearby sources (e.g., the projected separations between LAE-1, 3, and 11 are \(\lesssim 3.4\) arcmin, which corresponds to 1 pMpc at \(z = 6.93\)). Further, deeper narrowband imaging would enable us to probe the bubbles by detecting more fainter galaxies associated with the luminous LAEs.

The intrinsic explanation is that these luminous LAEs may be physically unusual objects, perhaps of a type not commonly found at lower redshift. For example, they could represent an AGN population that dominates over the ordinary star-forming galaxies at \(\log L_{\text{Ly}\alpha} > 43.3\) (e.g., Matsuoka et al. 2016). Alternatively, they could be star-forming galaxies where metallicities and/or dust abundances are low enough to enable considerably larger Ly\(\alpha\) production or escape than is commonly seen at \(z < 6\) (e.g., Stark et al. 2015, 2017; Mainali et al. 2017). At \(z \sim 7\), Bowler et al. (2014) find an excess of luminous LBGs where there should be an exponential cutoff at the bright end of their UV LFs, NIR and FIR spectroscopic follow-up of these luminous LBGs show very large Ly\(\alpha\) velocity offsets (>300 km s\(^{-1}\); Willott et al. 2015; Stark et al. 2017), which are significantly larger than the predicted velocity offsets for galaxies in EoR by Choudhury et al. (2015). Besides that, unusually strong carbon lines reported in two other LBGs at \(z \sim 7\) (CIV\(\lambda 1548\) A in A1703-zd6 at \(z = 7.045\) and C\(\text{iii}\)\(\lambda 1909\) Å in EGS-zs8-1 at \(z = 7.73\)) indicate unusual harder and more intense UV radiation than that of \(z \sim 3\) LBGs (Stark et al. 2015, 2017). In addition, a strong He\(\text{ii}\) line has been reported in the brightest Ly\(\alpha\) emitter at \(z = 6.6\) (CR7), suggesting that it could be powered by either Pop. III stars (Sobral et al. 2015) or perhaps powered by accretion onto a direct collapse black hole (Pallottini et al. 2015).

Future deeper NB964 imaging and IR (NIR and/or FIR) spectroscopic observation will help us to determine the nature of these luminous LAEs, and probe the ionized bubbles in a patchy reionization at \(z \sim 7\).

5. Conclusion

In this Letter, we report the first results of our LAGER project, the discovery of 23 (22 new) candidate LAEs at \(z \sim 7\). This is the largest sample to date of candidate LAEs at \(z \gtrsim 7\). Furthermore, thanks to the large survey volume of LAGER, we find four most luminous candidate LAEs at \(z \sim 7\) with \(L(\text{Ly}\alpha) = 19-43 \times 10^{42}\) erg s\(^{-1}\). Compared to previous Ly\(\alpha\) LFs at \(z \gtrsim 6\), the Ly\(\alpha\) LF of LAGER LAEs at \(z \sim 7\) shows different evolution at the faint end and at the bright end, which indicates a large neutral hydrogen fraction of \(x_{\text{HI}} \sim 0.4-0.6\) and the existence of ionized bubbles at \(z \sim 7\). Our findings support the patchy reionization scenario at \(z \sim 7\).

We thank the anonymous referee for careful and helpful comments which improved the manuscript. We acknowledge financial support from National Science Foundation of China (grants No. 11233002 and 11421303) and Chinese Top-notch Young Talents Program for covering the cost of the NB964 narrowband filter. J.X.W. thanks support from National Basic Research Program of China (973 program; grant No. 2015CB857005) and CAS Frontier Science Key Research Program QYCDJ-SSW-SLH006. Z.Y.Z. acknowledges supports by the China-Chile Joint Research Fund (CCJRF No. 1503) and the CAS Pioneer Hundred Talents Program (C). The work of S.M., J.E.R., and A.G. on this project is supported in part by US National Science Foundation grant AST-1518057. L.I. is supported in part by CONICYT-Chile grants Basal-CATA PFB-06/2007, 3140542, and Conicyt-PIA-Act 1417. C.J. acknowledges support by Shanghai Municipal Natural Science Foundation (15ZR1446600).

We thank the Materion company for the manufacture of the NB964 filter, which made the LAGER project possible. We greatly appreciate the kind support from the staff at NOAO/CTIO that make our observations successful.

Based on observations at Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory (NOAO PID: 016A-0386, PI: Malhotra, and CNTAC PIDs: 2015B-0603 and 2016A-0610, PI: Infante), which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation. Based in part on data collected at the Subaru Telescope and obtained from the Subaru-Mitaka-Okayama-Kiso Archive System (SMOKA), which is operated by the Astronomy Data Center, National Astronomical Observatory of Japan.

This project used data obtained with the Dark Energy Camera (DECam), which was constructed by the Dark Energy Survey (DES) collaboration. Funding for the DES Projects has been provided by the DOE and NSF (USA), MISE (Spain), STFC (UK), HEFCE (UK), NCSA (UIUC), KICP (University of Chicago), CCAPP (The Ohio State University), MIFPA (Texas A&M University), CNPQ, FAPERJ, FINEP (Brazil), MINECO (Spain), DFG (Germany), and the collaborating institutions in the Dark Energy Survey, which are Argonne Lab, UC Santa Cruz, University of Cambridge, CIEMAT-Madrid, University of Chicago, University College London, DES-Brazil Consortium, University of Edinburgh, ETH Zurich, Fermilab, University of Illinois, ICE (IEEC-CSIC), IFAE Barcelona, Lawrence Berkeley Lab, LMU Munchen and the associated Excellence Cluster Universe, University of Michigan, NOAO, University of Nottingham, The Ohio State University, University of Pennsylvania, University of Portsmouth, SLAC National Lab, Stanford University, University of Sussex, and Texas A&M University.

Facilities: Blanco (DECam), Subaru (Suprime-Cam).
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