Lyα Galaxies in the Epoch of Reionization (LAGER): Spectroscopic Confirmation of Two Redshift ∼7.0 Galaxies

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Abstract

We spectroscopically confirmed two narrowband-selected redshift 7.0 Lyα galaxies and studied their rest-frame UV spectra. The Lyα and other UV nebular lines are very useful to confirm the galactic redshifts and diagnose the different mechanisms driving the ionizing emission. We observed two narrowband-selected z = 7.0 Lyα candidates in the LAGER Chandra Deep Field South (CDFS) field with IMACS at the Magellan telescope and confirmed they are Lyα emitters at z ≈ 6.924 and 6.931. In one galaxy, we also obtained deep near-infrared (NIR) spectroscopy, which yields non-detections of the high-ionization UV nebular lines. We measured the upper limits of the ratios of C IV1548/Lyα, H eII1660/Lyα, O III]1666/Lyα, and C III]1909/Lyα from the NIR spectra. These upper limits imply that the ionizing emission in this galaxy is dominated by normal star formation instead of an active galactic nucleus.

Key words: dark ages, reionization, first stars – galaxies: high-redshift

1. Introduction

Reionization of hydrogen in the intergalactic medium (IGM) was a landmark in the structure formation of the early universe. Resonant scattering of Lyα photons is sensitive to neutral hydrogen in the IGM, making Lyα emitters a sensitive, practical, and powerful probe of the central phase of reionization (Dijkstra 2014). Previous studies have found thousands of Lyα-emitting galaxies (LAEs) at z > 5.7 and 6.6. The Lyα luminosity function observed at z ≈ 6.6 shows modest evolution from those at z > 5.7 (e.g., Malhotra & Rhoads 2004; Hu et al. 2010; Ouchi et al. 2010; Kashikawa et al. 2011; Konno et al. 2018). The current estimate of the neutral hydrogen fraction of the IGM is XHI = 0.3 ± 0.2 at z ≈ 6.6 based on the Lyα luminosity function (Konno et al. 2018). At z > 7.0, Lyα searches (Tilvi et al. 2010; Konno et al. 2014; Ota et al. 2017; Zheng et al. 2017; Itoh et al. 2018) have found a few tens of LAEs and shown a significant drop of the Lyα luminosity function relative to that at z ≈ 6.6.

In the “LAGER” project (Lyα Galaxies in the Epoch of Reionization) we search z ≈ 7 LAEs by taking deep narrowband images with CTIO/DECam. In the first result, we found 23 z ≈ 7 Lyα emitters and showed that the z ≈ 7 Lyα luminosity function in the COSMOS deep field has an excess of the brightest source (Zheng et al. 2017). We have confirmed these bright LAEs using spectroscopy from Magellan/IMACS (Hu et al. 2017).

With many z ≈ 7 LAEs being found, we can start to understand their roles in reionization. Do these LAEs have strong Lyman continuum emission? What mechanisms drive their galactic properties? In a few z ≈ 6–9 galaxies, observations have found high-ionization UV emission lines, such as C IV1548,1551, H eII1640, N vλ1240, and O III]1661,1666 (Stark et al. 2015a; Mainali et al. 2017; Laporte et al. 2017; Sobral et al. 2019), and suggested the presence of very hot metal-poor stars, active galactic nuclei (AGNs), metal-free Population III stars, or a directly collapsing black hole. However, observations of a few other bright LAEs at z ≈ 6–7 have found non-detections of strong UV nebular lines with deep near-infrared (NIR) spectroscopy (Shibuya et al. 2018; Mainali et al. 2018).

To confirm our photometric-selected z ≈ 7 LAEs and study their properties, we started a program to take their spectra using the Magellan telescopes. In this article, we report the optical and NIR observations of z ≈ 7 LAEs found in the LAGER Chandra Deep Field South (CDFS) field.

2. Observations and Data Reduction

In the “LAGER” project we take deep narrowband images with CTIO/DECam (a field of view of 3 deg²). We use an optimally designed narrowband NB964 filter (FWHM ∼ 90 Å) to identify Lyα lines at z ≈ 7.0, where they fall in a dark wavelength region between strong night-sky OH lines. We have gathered 44 hr narrowband exposure in the COSMOS field and 34 hr narrowband exposure in the CDFS field. The selection of LAE candidates is shown in Hu et al. (2019). In our first two observation runs, we obtained optical and NIR spectra of two LAE candidates in the CDFS field with IMACS (Dressler et al. 2011) and FIRE (Simcoe et al. 2013), respectively, at the Magellan telescope. Below we describe the details of the observations and data reduction.

2.1. Narrowband and Broadband Imaging

In the CDFS field, our narrowband and broadband images reach 5σ limiting AB magnitudes of 25.03, 23.3, 27.5, 27.5, 27.3, 27.0 (2′′ diameter aperture) in the NB964, u, g, r, i, z bands. We selected LAE candidates with narrowband color excess NB964 − z < −1.5 and non-detections in the u, g, r, i bands.
candidate selection is presented in Hu et al. 2019). A sample of 30 $z \sim 7$ LAE candidates was selected in the CDFS field. Figure 1 shows the imaging cutouts of the two observed LAEs — CDFS-LAE1 ($R.A. = 03:33:05.95$ decl. $= -28:24:59.10$ J2000) and CDFS-LAE51 ($R.A. = 03:32:51.68$ decl. $= -28:32:42.51$ J2000).

2.2. Magellan/IMACS Spectroscopy

We observed two LAEs using IMACS on the 6.5 m Magellan I Baade Telescope on 2017 October 20–21. We used the IMACS f/2 camera with 300-line red-blazed grism and a multi-slit mask. The mask has 1″ slit width and covers the two bright $z \approx 7.0$ LAEs, dropout-selected galaxies, other emission-line galaxies at intermediate redshifts, flux-calibration stars, and alignment stars. On October 20, the sky was clear and seeing $\sim 0''6$–$0''8$ and we observed the mask in the second-half night for 220 minutes ($12 \times 20$ minutes per exposure). On October 21, the weather was partly cloudy with passing clouds and we obtained 60 minutes of observations under clear sky conditions.

The spectra coverage is 6000–11000 Å. The spectra resolution is about 194 km s$^{-1}$ at 9640 Å.

We reduced the IMACS data with the pipeline COSMOS2 (Oemler et al. 2017). Following the standard pipeline procedures, we find the stacked wavelength-calibrated 2D spectra. We stacked 280 minutes of exposure into one final 2D spectrum. The $1\sigma$ flux limit at 9640 Å is $1.8 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$. Then we extract the spectra within an aperture of 1″2 (box extraction). We fit a blackbody model to the spectra of one flux-calibration star on the mask to get the sensitivity function and applied it to the 1D spectra of the LAEs.

2.3. Magellan/FIRE Spectroscopy

We observed these two LAEs using Magellan/FIRE in Echelle mode on 2017 December 26–27. On December 26, the seeing was $0''6$–$0''7$ and we observed CDFS-LAE-1 for 200 minutes with the 0″75 slit. On December 27, the seeing was $1''0$–$1''2$ and we observed CDFS-LAE-51 for 220 minutes with the 0″75 slit for the first hour and with the 1″ slit for the remaining time. A telluric star was observed every 1–2 hr throughout the night.

We reduced the FIRE data with the FIREHOSE pipeline. After the 2D sky subtraction, the 1D LAE spectra were...
extracted in each frame using the trace and spatial profile of the telluric star as a reference. Then, the 1D spectra were stacked together. The 1D spectra covers the wavelength range 8500–21000 Å. The 1D spectra have a 1σ flux limit of $1.4 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ at 9640 Å.

### 3. Results

#### 3.1. LAE Confirmations

In the optical and NIR spectra, one line at wavelength $\sim 9640$ Å is clearly detected for both LAEs. Figure 2 shows the IMACS 2D and 1D spectra of these two emission lines. These two lines are detected signal-to-noise ratios ($S/Ns$) = 12 and 9, respectively. These two lines could be Lyα lines at $z \sim 7.0$ or lower-redshift emission lines. We ruled out the possibility of low-redshift lines for the following reasons. (1) They are not detected in the deep g–r–i band images reaching $5\sigma$ limiting magnitudes of 27.5 mag. (2) Strong optical lines, such as [O III] $\lambda 4959,5007$, [O II] $\lambda 3727$, Hα, and Hβ have companion lines that were covered in the observed spectra but not detected. For example, if the line is [O III] $\lambda 5007$ (or [O III] $\lambda 4959$), we expect to see the [O III] $\lambda 4959$ (or [O II] $\lambda 5007$) in the IMACS spectra and the Hα line in the near-infrared spectra; if the line is [O II] $\lambda 3727$, we expect to see the [O III] $\lambda 4959,5007$, Hα and Hβ lines in the near-infrared spectra. Yet those companion lines are not detected. (3) The line profiles are asymmetric with red wings, which are typical of high-redshift Lyα emission lines.

![Figure 3. FIRE 2D and 1D spectra of CDFS-LAE1 at the wavelength of Lyα, N V $\lambda 1240$, C IV $\lambda 1548,1551$, He II $\lambda 1640$, O III $\lambda 4959,1661,1666$, C III][]{fig3.png}

**Table 1**

| Object | Redshift | Line          | Flux ($10^{-18}$ erg s$^{-1}$ cm$^{-2}$) |
|--------|----------|---------------|-----------------------------------------|
| LAE1   | 6.9245   | Lyα (IMACS)   | 21.8 ± 1.8                              |
|        |          | Lyα (FIRE)    | 20.6 ± 1.4                              |
|        |          | N V1240       | <6.4                                    |
|        |          | C IV1548.2    | <1.4                                    |
|        |          | C IV1550.8    | <5.0                                    |
|        |          | He II1640.4   | <1.7                                    |
|        |          | O III1660.8   | <2.8                                    |
|        |          | O III1666.2   | <1.9                                    |
|        |          | C III1907.0   | <1.7                                    |
|        |          | C III1909.0   | <1.2                                    |
| LAE51  | 6.931    | Lyα (IMACS)   | 15.6 ± 1.8                              |

Note. The non-detections of UV nebular Lines are 2σ upper limits. The errors of Lyα line fluxes are 1σ errors.

Therefore, we conclude these two lines are Lyα lines. The Lyα redshifts for LAE1 and LAE51 are 6.9245 and 6.931.

We measure the Lyα line fluxes by integrating the spectra range of $-200$ to $450$ km s$^{-1}$ around the Lyα line in the IMACS spectra. The Lyα line fluxes are $(21.8 \pm 1.8) \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ for LAE1 and $(15.6 \pm 1.8) \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ for LAE51 (Table 1). The FWHMs (corrected for instrumental resolution) of the Lyα line for LAE1 and LAE51 are 229 and 318 km s$^{-1}$. The Lyα line luminosities are $1.21 \times 10^{43}$ erg s$^{-1}$ for LAE1 and
0.87 × 10^{43} \text{erg s}^{-1} \text{ for LAE51. Assuming a 10\% Ly} \alpha \text{ escape fraction and Ly} \alpha / \text{H} \alpha = 8.7 \text{ in Case-B recombination, and the prescriptions for calculating star formation rates in Kennicutt & Evans (2012), the corresponding star formation rates are 75 \, M_\odot \text{yr}^{-1} \text{ for LAE1 and 54 \, M_\odot \text{yr}^{-1} for LAE51.}

Note that in the spectra of LAE1 there is another very narrow spike at 9562 Å that overlaps with the sky line. Its wavelength is covered in the FIRE spectra but no signal is detected at 9562 Å. Therefore, we discard it as an artifact from imperfect sky subtraction.

***3.2. UV Nebular Lines***

Although Ly\alpha is the only detected line in the spectra, we can put limits on the other UV nebular lines from the FIRE spectra. In the FIRE spectra of CDFS-LAE1, the Ly\alpha line is clearly detected, with a line flux of $(20.6 \pm 1.4) \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2}$ and intrinsic FWHM of 218 km s$^{-1}$. We focus on this object in the following analysis. In the FIRE spectra of CDFS-LAE51, the Ly\alpha line is not detected, with a $3\sigma$ flux upper limit of $9.0 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$, which is slightly lower than the line flux in

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**Figure 4.** Comparisons of Ly\alpha and C IV\lambda1551, He II\lambda1640, O III\lambda1666, and C III\lambda1909 for LAE1 and other $z = 5.6 \sim 8.6$ galaxies in the literature. Points without downward arrows are detections (at the $\sim 3\sigma$–$5\sigma$ level). Points with downward arrows are $2\sigma$ upper limits. We assume the two single lines have equal fluxes for the doublets of C IV\lambda1548,1551, O III\lambda1661,1666, and C III\lambda1907,1909. When the upper limits of the two single lines of doublets were reported in the literature, we used the smaller upper limits. The dashed lines show Ly\alpha to UV nebular line ratios of 10:1 and 100:1. The numbers in the legend represent the following references: (1) Shibuya et al. (2018), (2) Mainali et al. (2017), (3) Stark et al. (2015a, 2015b), (4) Mainali et al. (2018), Stark et al. (2017), (5) Laporte et al. (2017), (6) Kashikawa et al. (2012), (7) Zabl et al. (2015), (8) Nagao et al. (2005), (9) Sobral et al. (2019). Note that a few galaxies in references (2), (3), (4) are gravitationally lensed, and the plots show their uncorrected observed line luminosities.
IMACS spectra. This could be caused by larger slit loss at poor seeing (∼1"0−1"2) and possibly larger blind-offset errors during the FIRE observation.

In Figure 3, we show the spectra of CDFS-LAE1 at the wavelength of Lyα, ννλ1240, C IVλ1548,1551, He IIλ1640, O IIIλ1661,1666, and C IIIλ1907,1909 lines. The expected line positions are calculated assuming a redshift of 6.9245. For the non-detected UV nebular lines, we assume a line width of 200 km s⁻¹ and calculate the 2σ upper limits (Table 1).

In CDFS-LAE1, the 2σ upper limits of the flux ratios of C IVλ1548/Lyα, He IIλ1640/Lyα, O IIIλ1660/Lyα, and C IIIλ1909/Lyα are about 0.06−0.1. There are two spikes near the position of N Vλ1240 line. Both spikes are very narrow with FWHM ∼20 km s⁻¹, and they are not shown in the rectified 2D spectra. Therefore, they were discarded as noise spikes. There are also marginal signal, in the position of He IIλ1640 line, but the current data are inconclusive.

We considered the contributions of active galactic nuclei in these galaxies. Because the Lyα line is very narrow with FWHM ∼220 km s⁻¹, we compared it to the narrow lines of AGNs. The narrow C IVλ1548 line-to-Lyα ratios of narrow-line AGNs at intermediate redshifts are about 0.1−0.2 (Alexandroff et al. 2013). The C IVλ1548 to Lyα ratio in CDFS-LAE1 is smaller than 0.07. Therefore, the contribution from an AGN is small and the H ionizing emission is dominated by normal star formation instead of AGNs.

We also compared the ratios in LAE1 with similar measurements for Lyα galaxies at z = 5.6−8.6 in the literature (a compilation in Matthee et al. 2017) in Figure 4. LAE1 has a Lyα luminosity of 1.21 × 10⁴³ erg s⁻¹, which is relatively lower than that of other galaxies. The line ratios of LAE1 are consistent with the other measurements as shown in Figure 4. Among these high-redshift galaxies, except for a few detections at 3σ−5σ levels, most flux measurements of UV nebular lines are upper limits at ~1%−10% of Lyα line flux. To diagnose the ionizing properties of LAEs, the UV spectra should ideally reach a depth of 1%−5% Lyα line flux. Because the C IV, C III, and He II lines are very weak relative to Lyα lines in these LAEs, unless Lyα overlaps with strong sky lines, it is easier to use Lyα emission lines to measure the galactic redshift.

### 4. Conclusions

We spectroscopically confirmed two redshift ~7 Lyα galaxies (LAE1 and LAE51) found in the LAGER survey. In LAE1, our deep NIR spectroscopy yields non-detections of the high-ionization UV nebular lines. We derived strong upper limits of the ratios of C IVλ1548/Lyα, He IIλ1640/Lyα, O IIIλ1660/Lyα, and C IIIλ1909/Lyα. Because its C IVλ1548 line-to-Lyα ratio is smaller than the typical ratio in AGNs, the ionizing emission in LAE1 is dominated by normal star formation instead of AGNs.

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