A Lyα GALAXY AT REDSHIFT z = 6.944 IN THE COSMOS FIELD

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ABSTRACT

Lyα emitting galaxies can be used to study cosmological reionization, because a neutral intergalactic medium (IGM) scatters Lyα photons into diffuse halos whose surface brightness falls below typical survey detection limits. Here, we present the Lyα emitting galaxy LAE J095950.99+021219.1, identified at redshift z = 6.944 in the COSMOS field using narrowband imaging and follow-up spectroscopy with the IMACS instrument on the Magellan I Baade telescope. With a single object spectroscopically confirmed so far, our survey remains consistent with a wide range of IGM neutral fraction at z ≈ 6, but further observations are planned and will help clarify the situation. Meantime, the object we present here is only the third Lyα-selected galaxy to be spectroscopically confirmed at z ≥ 7, and is ~2–3 times fainter than the previously confirmed z ≈ 7 Lyα galaxies.

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

Online-only material: color figure

1. INTRODUCTION

Lyα emitting galaxies provide a valuable probe of reionization, because resonant scattering of Lyα photons in the intergalactic medium (IGM) can suppress the observed Lyα line by a factor of >2 for any neutral fraction >50% (Malhotra & Rhoads 2004; Santos 2004). Such strong flux suppression will cause a change in the Lyα luminosity function that should be obvious — especially since Lyα galaxies show little evolution at 3 ≲ z ≲ 6, either in luminosity function (Dawson et al. 2007; Zheng et al. 2012) or physical properties (Malhotra et al. 2012). Early studies concluded that the IGM neutral fraction was already small at z ≈ 6.5 (Malhotra & Rhoads 2004; Stern et al. 2005). More recent work has established the Lyα luminosity function at both z ≈ 5.7 and 6.5 to considerable accuracy (Ouchi et al. 2010; Hu et al. 2010; Kashikawa et al. 2011), showing a modest but statistically significant difference between these observed Lyα luminosity functions. The z = 6.5 luminosity function is below that at z = 5.7, and the difference can be adequately characterized by a pure luminosity evolution by a factor of ~1.3 (Ouchi et al. 2010).

Yet, other Lyα based tests for reionization — including the apparent spatial clustering of Lyα galaxies (McQuinn et al. 2007), the minimum ionized volume around observed Lyα sources (Malhotra & Rhoads 2006), and Lyα line profiles (Hu et al. 2010; Ouchi et al. 2010) — show little evidence for neutral gas at z ≈ 6.5. This leaves an open question — is the lower Lyα luminosity function at z = 6.5 due to neutral gas or is it an intrinsic evolution in the galaxy populations?

To distinguish between these possibilities, we can look to still higher redshifts, where the IGM neutral fraction should be higher and its effects on Lyα stronger. The highest redshift readily accessible to Lyα searches using CCDs is z ≈ 7.0, in the 9650 Å window in the night sky OH emission spectrum. We are pursuing a 9650 Å narrowband survey using the Inamori Magellan Areal Camera and Spectrograph (IMACS) imaging spectrograph on the 6.5 m Magellan I Baade Telescope at Las Campanas Observatory (Hibon et al. 2011). We surveyed 465 arcmin$^2$, corresponding to ~72,000 Mpc$^3$. After a careful selection, we found six z ≈ 6.96 LAE candidates (Hibon et al. 2011). To confirm whether these are real Lyα emitters (LAEs), we obtained multi-object spectra with IMACS. In this Letter, we present the spectrum of LAE J095950.99+021219.1, which was identified as a candidate redshift z ≈ 7 Lyα emitting galaxy (candidate LAE 3) in Hibon et al. (2011). Our spectroscopy reveals a single, isolated Lyα line at redshift z = 6.944.

Throughout the Letter, we adopt a ΛCDM “concordance cosmology” with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$.

2. SPECTROSCOPIC OBSERVATIONS AND ANALYSIS

2.1. Observations

We observed our candidate z ≈ 7 Lyα galaxies using IMACS on the 6.5 m Magellan I Baade Telescope on the nights of 2010 December 29–30 and 2011 February 8. The February data were of lower quality and are not used here. We used custom multi-slit masks, shared between two primary observing programs. We selected the f/2 camera and the 300-line red-blazed grism with 1″ slitlets as the best compromise between areal coverage, spectral coverage, and spectral resolution.

Observations were split among five slit masks (two per night in December and one in February). The time per mask and observing conditions are summarized in Table 1. While the position angle of the masks were not all identical, the data were taken without dithering the telescope. Moreover, the targets were centered on their slitlets, and LAE J095950.99+021219.1 is compact compared to the seeing. This allows us to combine all of the spectroscopic data into a single one-dimensional spectrum (see below).
Figure 1. Two-dimensional spectra of LAE J095950.99+021219.1. Upper panel: full December data set (14 exposures, 7.05 hr integration) stacked together. Wavelength increases from 9550 Å at left to 9800 Å at right. The spatial extent is 12″ from bottom to top. Lower panels: first night (left) and second night (right) of data separately. The lower panels have been lightly smoothed for clarity, with a Gaussian kernel having $\sigma = 0.6$ pixel. Cyan bars at top and bottom mark the wavelengths of night sky emission lines, with longer bars denoting brighter lines. (A color version of this figure is available in the online journal.)

| Mask ID     | Observation Date (UT) | Number of Exposures | Time per Exposure | Seeing (approx.) |
|-------------|-----------------------|---------------------|-------------------|-----------------|
| COSMOS1     | 2010 Dec 30           | 4                   | 1800              | 0′5–0′9         |
| COSMOS2     | 2010 Dec 30           | 3                   | 1800              | 0′5–0′9         |
| COSMOS3     | 2010 Dec 31           | 4                   | 1800              | 1″−4′5          |
| COSMOS4     | 2010 Dec 31           | 3                   | 1800              | 1″−1′5          |
| COSMOS-Feb  | 2011 Feb 8            | 5                   | 1800              | 1′2−2′          |

2.2. Data Reduction

We performed initial data reduction steps using the COSMOS software package. COSMOS steps include bias frame subtraction, spectroscopic flat fielding using continuum (quartz) lamp exposures, and wavelength calibration using arc lamp exposures. COSMOS also sky-subtracts the spectra, using the Kelson (2003) algorithm to remove night sky lines. Finally, COSMOS extracts a two-dimensional, rectified spectrum for each slitlet.

We performed subsequent steps in two ways, either (1) combining exposures from each mask separately, and then combining results from different masks; or (2) directly combining all exposures from multiple masks.

Treating masks separately gives four two-dimensional spectra of LAE J095950.99+021219.1 from December and one more from February. Most of these two-dimensional stacks show a weak but visible emission line in the spectrum of LAE J095950.99+021219.1. We next combined the four December spectra into a stacked two-dimensional spectrum comprising our best 7.05 hr of data. To do this, we first averaged the four two-dimensional spectra. Next, we made a median-combined stack. We then subtracted the two, and computed the (sigma-clipped) noise level in the difference. Finally, we constructed a hybrid stack, using the value from the average stack almost everywhere, but the value from the median stack wherever the difference between these two stacks exceeded 10σ. This yields a lower noise estimate than the median, yet remains more robust to outliers than the mean. The emission line becomes readily evident in this combined stack.

To test the robustness of our results, we also combined all December exposures in single 14-frame stacks, using various outlier rejection schemes (median stacking with $3\sigma$ and $5\sigma$ rejection, and average stacking with $2.5\sigma$ rejection). The emission line remains comparably significant in all of these stacks. The stacked two-dimensional spectrum around the emission line, using average stacking and $2.5\sigma$ rejection, is shown in Figure 1.

Note the double meaning of the acronym COSMOS. We deny any responsibility for the ensuing confusion.
 dependent noise estimate, and the line is significant at the variance among these five parallel traces provides a wavelength-slit. Each should be essentially a pure noise spectrum. The stacked spectrum, each at a different spatial position along the get another estimate of the noise level in the data, we extracted unweighted extraction of 1 stage stacking (method “1”), using the IRAF task “apall” with an exposures.

We also made stacks by bootstrap resampling, stacking 14 exposures selected randomly with repetitions permitted. We remeasured the flux at the location of the detected line, using aperture photometry in the two-dimensional stacks. The bootstrap fluxes were 104% ± 10% of the “normal” stack flux for a 10 pixel diameter (2′′ × 20 Å) aperture, and 116% ± 21% for a 14 pixel diameter (2′8 × 28 Å) aperture. Among 1000 bootstrap simulations, the lowest measured fluxes were 77% and 66% of “normal” for the 10 and 14 pixel apertures. The plotted noise is based on the sigma image from the 14-frame stack, scaled for the number of spatial pixels combined in the one-dimensional extraction.

We next extracted a one-dimensional spectrum from the two-stage stacking (method “1”), using the IRAF task “apall” with an unweighted extraction of 1′4 (7 pixel) window width, centered on the emission line and parallel to the dispersion axis. (COSMOS two-dimensional output has the dispersion axis parallel to the x-axis, so we need not fit a trace to the continuum, which is undetected in the present data anyway.) We performed no further sky subtraction, since that too is done by the COSMOS package. To get another estimate of the noise level in the data, we extracted five further one-dimensional spectra from the two-dimensional stacked spectrum, each at a different spatial position along the slit. Each should be essentially a pure noise spectrum. The variance among these five parallel traces provides a wavelength-dependent noise estimate, and the line is significant at the 4.5σ level against this estimate. The extracted one-dimensional spectrum is shown in Figure 2.

**Significance.** To explore the significance of the line detection, we measured aperture fluxes at a grid of clean locations in the two-dimensional spectrum of LAE J095950.99+021219.1 (after rescaling the two-dimensional spectrum by the noise ratio $\frac{\sigma(9658 \text{ Å})}{\sigma(\lambda)}$). The rms counts among these apertures correspond to a 1σ noise of $1.34 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$, against which our line is a 6.3σ event. Among $\geq 400$ non-overlapping 5 pixel apertures, the brightest two were 4.1σ and 3.2σ events (65% and 51% as bright as the LAE J095950.99+021219.1 line), suggesting only mildly non-Gaussian noise.

The search that found this line was based on six candidates, each with a position known to 1′″ and an expected line wavelength known to $\Delta \lambda = 90$ Å. Given our spatial and spectral resolution, this corresponds to $\sim 5 \times 5 = 250$ independent resolution elements. Our significance level estimates range from $4.5\sigma$ to 6.3σ, and for Gaussian noise, the corresponding chance probabilities in 240 trials range from $< 10^{-3}$ to $< 10^{-2}$.

**Spectroscopic flux calibration.** Each mask included two blue stars with well-measured photometry from the COSMOS project (Capak et al. 2007). We flux calibrate the observed emission line of LAE J095950.99+021219.1 by direct comparison with the observed counts in one of these stars, which was observed under identical conditions as our science targets. Both the emission line count rate and the comparison star’s count rate per unit wavelength were measured directly in the two-dimensional spectra and at the same wavelength. For the emission line, we used the 10 pixel diameter (2′′ × 20 Å) aperture. This yields a flux of $8.5 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ for LAE J095950.99+021219.1, corresponding to line luminosity $4.9 \times 10^{38}$ erg s$^{-1}$ at $z = 0.944$.

The fractional uncertainties in this flux are $\sim 20\%$ from photon counting statistics (with a statistical signal-to-noise ratio of $S/N = 4.5–6.3$ from the one-dimensional or two-dimensional spectra), 12% from the choice of aperture used to measure the line flux in the two-dimensional spectrum, and $\lesssim 10\%$ from the assumption that the comparison star’s flux density at 9680 Å equals its z-band flux density. The final spectroscopic flux measurement is $(8.5 \pm 2) \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$.

**2.3. Comparison to Narrowband Imaging Results**

The observed spectroscopic line flux is smaller than the narrowband flux (Hibon et al. 2011). Part of the discrepancy can be attributed to continuum in the narrowband filter. The emission line is near the blue edge of the filter bandpass, so continuum emission redward of the line will contribute relatively strongly to the narrowband flux.

We also re-examined the narrowband flux measurements for LAE J095950.99+021219.1. Following Hibon et al. (2011), we used moderately bright stars that are well detected but unsaturated in both the public COSMOS z-band image and our NB9680 image. The narrowband magnitudes in Hibon et al. (2011) were based on 1′ diameter aperture fluxes, with an aperture correction based on the difference between SEExtractor “magiso” and aperture fluxes (see Hibon et al. 2011 for more details). In the present work, we omitted the aperture correction step, using instead identical 1′2 diameter flux measurements for both the science objects and the reference stars in the NB9680 image. (The precise aperture diameter is unimportant, since LAE J095950.99+021219.1 is compact compared to the point-spread function.) We obtained a narrowband magnitude $NB9680_{AB} = 24.86 \pm 0.18$. The corresponding narrowband flux is $12 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$.

This is almost 50% more than the spectroscopically determined emission line flux (a 1.7σ difference). If we attribute the difference to continuum emission in the narrowband filter, the corresponding flux density is $f_{\nu} \sim (f_{NB} - f_{spec})/\lambda \approx 3.5 \times 10^{-18}/60 \approx 5.8 \times 10^{-20}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ or AB $= 25.75$. The implied observer-frame equivalent width is $\sim 120$ Å (though
consistent with an arbitrarily large equivalent width at 1.5σ). While the object is undetected in the z' filter down to AB > 26.4, a continuum magnitude of 25.75 redward of the line at 9657 Å remains allowed, since most of the z' filter's transmission lies blueward of that wavelength. The object is also undetected in the WIRDS J-band image (Bielby et al. 2012), with a 1.2 aperture flux ~$(1.8 \pm 2.1) \times 10^{-30}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$, corresponding to $J_{\text{AB}} \gtrsim 24.1$ (3σ).

3. INTERPRETATION

We interpret the line at 9657 Å in LAE J095950.99+021219.1 as Lyα at redshift $z = 6.944$, based on non-detections in all filters blueward of this line, and on the absence of other optical lines.

Were the primary line Hα (at $z \approx 0.472$) or [O iii] λ5007 (at $z \approx 0.928$), we would expect other prominent emission lines in our IMACS spectrum. Figure 3 shows non-detections in the one-dimensional spectrum at the expected line wavelengths. Corresponding upper limits are summarized in Table 2. The “Hα” case ($z \approx 0.472$) is disfavored by the non-detections of [O iii] λ5007 and [O iii] λ3727, with 3σ line ratio limits $f(\text{O iii})/f(\text{Hα}) < 1/2$ and $f(\text{O iii})/f(\text{Hα}) < 2/3$. If the primary line is [O iii] λ5007, unfortunately placed night sky line residuals overlap the expected locations of [O iii] λ4959 and Hβ, precluding interesting limits. Fortunately, the expected [O iii] λ3727 line location is clean and gives a tight upper limit $f(\text{O iii})/f(\text{O iii}) < 0.2$ (3σ). This provides some evidence against the [O iii] λ5007 interpretation. Ratios of $f(\text{O iii})/f(\text{O iii})$ this small are seen in a significant minority of star-forming galaxies (Xu et al. 2007; McLinden et al. 2011; Richardson et al. 2011; L. Xia et al. 2012, in preparation), but more can be ruled out by this line ratio.

To address the [O iii] λ3727 possibility and further improve our constraints on [O iii] λ5007, we examine equivalent widths.
Following Hibon et al. (2011), we combine our spectroscopic line flux with optical magnitude limits of 27.9, 27.6, and 27.3 mag (5σ, AB) in the g', r', and i' filters, respectively. Since star-forming galaxies have $f_s \sim$ constant, we have $f_s(9657 \ Å) \approx 3.6 \times 10^{-20} \times 10^{-0.4 \times 28} \times c/(9657 \ Å)^2 = 7.3 \times 10^{-21} \ erg \ cm^{-2} \ s^{-1} \ Å^{-1}$. The nondetection in these optical images then implies a 5σ limit $EW \equiv f_{\text{lin}}/f_s \approx (8 \times 10^{-18} / 7.3 \times 10^{-21}) \ Å = 1100 \ Å$ (observer frame).

While [OIII] $\lambda5007$ and Hα emission line sources with equivalent widths large exist (Rhoads et al. 2000; Kakazu et al. 2007; Straughn et al. 2008, 2009; van der Wel et al. 2011; Atek et al. 2011), they are exceptional, rare objects. In Hibon et al. (2011), we estimated the numbers expected in our survey based on published line luminosity functions (Kakazu et al. 2007; Geach et al. 2010) and equivalent width distributions (Straughn et al. 2009). We found that $^{\leq}0.3$ [OIII] $\lambda5007$ emitters and $^{\leq}0.6$ Hα emitters are expected.

[OII] $\lambda3727$ emitters have generally smaller equivalent widths. We found no [OII] $\lambda3727$-selected objects with EW $\gtrsim 1100 \ Å/(1 + z_{\text{obj}}) \approx 425 \ Å$ in the samples from Straughn et al. (2009) (30 objects), Kakazu et al. (2007) (24 objects), Xia et al. (2012) (11 objects), or Drozdovskiy et al. (2005) (400 objects). Thus, $^{\leq}1/465 = 0.0022$ of [OII] $\lambda3727$ emitters might enter our sample as LAE candidates. The luminosity function from Rigopoulou et al. (2005) suggests that our survey volume should contain $\sim45$ [OII] $\lambda3727$ galaxies. Among these, $^{\leq}0.1$ objects should pass our Lyα selection criteria.

Thus, the aggregate sample of foreground emitters expected in our survey is $<1$ galaxy. In contrast, our survey volume at $z \approx 6.95$ should contain between $\sim2.5$ and $\sim11$ Lyα galaxies with line fluxes $\gtrsim 8 \times 10^{-18} \ erg \ cm^{-2} \ s^{-1}$, based on the $z \approx 6.5$ luminosity functions of Hu et al. (2010) and Ouchi et al. (2010). We thus regard Lyα as the best interpretation of the observed emission line.

### 4. DISCUSSION

Redshift $z \approx 7$ is the current frontier in reionization studies, an area of active exploration where our observational knowledge is growing rapidly.

The recently discovered quasar at $z \approx 7.1$ (Mortlock et al. 2011), combined with spectroscopic follow-up (and occasional confirmation) of $z \approx 7$ galaxy candidates from HST WFC3 surveys, provides an unprecedented look at this epoch. Observations of these objects seem to favor the continued existence of significant neutral intergalactic gas as late as $z \sim 7$. This is surprising, given that microwave background polarization data from WMAP favor a characteristic reionization redshift $z_r \sim 11$, and that the IGM at $z \sim 6.2$ is highly ionized, with a neutral fraction of only 1%–4% based on quasar spectra (Fan et al. 2006). Nonetheless, the ionized bubble around the $z \approx 7.1$ quasar appears too small to be comfortably explained in a fully ionized medium, unless the quasar is itself remarkably young ($\sim10^6$ years) (Bolton et al. 2011). Similarly, three independent research groups have argued that the fraction of $z \sim 7$ Lyman break candidates showing Lyα emission appears smaller than would be expected in an ionized medium (Vanzella et al. 2011; Stark et al. 2010; Ono et al. 2012; Pentericci et al. 2011). Still, these results depend on the reliability of photometric selection criteria, and a contamination of order 50% could explain the observations without recourse to neutral gas (e.g., Schenker et al. 2012).

Lya galaxy surveys offer a complementary approach to studying reionization. The underlying physics is the same as for spectroscopic follow-up of Lyman break samples, but the survey selection proceeds differently, leading to different potential selection biases. The uncertainties in the method are likewise very different from those associated with the quasar near-zone measurement (Mortlock et al. 2011; Bolton et al. 2011) or the Gunn–Peterson trough (Fan et al. 2006). Because of this, conclusions about cosmological reionization will be strongest when they are based on multiple independent methods.

The work we present here is only the second large-area narrowband survey for Lyα galaxies at redshift $z \approx 7.0$, following on the work of Iye et al. (2006) and Ota et al. (2010). The spectroscopic confirmation of LAE J095950.99+021219.1 demonstrates that such objects can be identified at flux levels considerably fainter than the $2 \times 10^{-17} \ erg \ cm^{-2} \ s^{-1}$ line of IOK-1 (Iye et al. 2006) or the recently reported $z \approx 7.2$ narrowband-selected Lyα galaxy SXDF-NB1006-2 (Shibuya et al. 2012). Our observed line flux, $8.5 \times 10^{-18} \ erg \ cm^{-2} \ s^{-1}$, corresponds to a rest-frame line luminosity of only $L_{\text{Lyα}} = (4.9 \pm 1) \times 10^{42} \ erg \ s^{-1}$. This is at or below the characteristic line luminosity $L_{\text{Lyα}}^*$ of Schechter function fits to $z \approx 6.5$ Lyα samples (e.g., $L_{\text{Lyα}}^* = (4.4 \pm 0.6) \times 10^{42} \ erg \ s^{-1}$ and $\Phi^* = 8.5 \times 10^{-4} \ cm^{-3} \ erg^{-1}$; Ouchi et al. 2010; $L_{\text{Lyα}}^* = 1.0 \times 10^{43} \ erg^{-1}$; Hu et al. 2010).

Thus, our survey has achieved sensitivity to typical Lyα emitters. Were the $z \approx 7$ luminosity function unchanged that at $z = 6.5$, we would expect our survey volume to contain 11 or 2.6 Lyα emitters brighter than LAE J095950.99+021219.1, based on the LF of Ouchi et al. (2010) or Hu et al. (2010), respectively. This reflects large differences in expectations from different published $z = 6.5$ luminosity functions. We will present a detailed analysis of our survey’s constraints on the Lyα luminosity function in a future paper, after we have more sensitive spectra for our remaining candidates. For now, the galaxy LAE J095950.99+021219.1 is among the few most distant spectroscopically confirmed galaxies known, and the faintest to be discovered through a direct search for Lyα line emission.
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