

THE DISCOVERY OF TWO LYMAN α EMITTERS BEYOND REDSHIFT 6 IN THE SUBARU DEEP FIELD^{*,†}

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Abstract

We have performed a deep optical imaging survey using a narrowband filter (*NB921*) centered at $\lambda = 9196 \text{ \AA}$ together with i' and z' broadband filters covering an 814 arcmin^2 area of the Subaru Deep Field. We obtained a sample of 73 strong *NB921*-excess objects based on the following two color criteria; $z' - \text{NB921} > 1$ and $i' - z' > 1.3$. We then obtained optical spectroscopy of nine objects in our *NB921*-excess sample, and identified at least two $\text{Ly}\alpha$ emitters at $z = 6.541 \pm 0.002$ and $z = 6.578 \pm 0.002$, each of which shows the characteristic sharp cutoff together with the continuum depression at wavelengths shortward of the line peak. The latter object is more distant than HCM-6A at $z = 6.56$ and thus this is the most distant known object found so far. These new data allow us to estimate the first meaningful lower limit of the star formation rate density beyond redshift 6; $\rho_{\text{SFR}} \sim 5.2 \times 10^{-4} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. Since it is expected that the actual density is higher by a factor of several than this value, our new observation reveals that a moderately high level of star formation activity already occurred at $z \sim 6.6$.

Key words: cosmology: observations — early universe — galaxies: starburst — galaxies: formation — galaxies: evolution

1. INTRODUCTION

Probing the star formation activity in galactic or subgalactic systems in early universe is important for understanding both the history of galaxies and the origin of cosmic reionization (e.g., Loeb, Barkana 2001). Recent advance in deep optical imaging capability with 8-10 m class telescopes enabled new searches for star-forming galaxies beyond redshift 5. In particular, imaging surveys using narrow-passband filters have proved to be an efficient way to find such galaxies (Ajiki et al. 2002; Cowie, Hu 1998, Hu et al. 1996, 1999, 2002; Kudritzki et al. 2000; Rhoads et al. 2001; Steidel et al. 2000; Taniguchi et al. 2003). Indeed, the most distant $\text{Ly}\alpha$ emitter (LAE) known to date, HCM 6A at $z = 6.56$ was discovered by using this technique (Hu et al. 2002). However, surveys for emission-line galaxies with narrow-band filters have an intrinsic limitation in redshift coverage and hence the survey volumes are not often large enough to ensure robust for success. In order to increase survey volumes and to reach faint limiting magnitude, we need wide-field CCD cameras on 8-10 m class telescopes. Suprime-Cam

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(Miyazaki et al. 2002) mounted at the prime focus of the 8.2 m Subaru Telescope (Kaifu 1998) on Mauna Kea, Hawaii, provides a unique opportunity for wide-field (a $34' \times 27'$ field of view), narrowband imaging surveys for emission-line objects at high redshift.

The most distant LAE, HCM 6A at $z = 6.56$ (Hu et al. 2002), is gravitationally amplified by a factor of 4.5 by the foreground cluster of galaxies Abell 370 at $z = 0.37$. Although the help of any gravitational lensing is highly useful in investigating faint high- z objects (Ellis et al. 2001; Hu et al. 2002), it is also important to search for high- z LAEs in a so-called blank field for an unbiased study. In an attempt to find star-forming objects at $z \approx 6.6$ in such a blank field, we have carried out a very deep optical imaging survey in the Subaru Deep Field (SDF) centered at $\alpha(\text{J2000}) = 13^{\text{h}} 24^{\text{m}} 21.4^{\text{s}}$ and $\delta(\text{J2000}) = +27^{\circ} 29' 23''$ (e.g., Maihara et al. 2001; Ouchi et al. 2003; Kashikawa et al. 2003). In this Letter, we report on our discovery of two Ly α emitters at $z \approx 6.5 - 6.6$.

2. OBSERVATIONS

2.1. Optical Imaging

In this survey, we used the narrow-passband filter, NB921, centered on $\lambda_c = 9196 \text{ \AA}$ with a passband of $\Delta\lambda(\text{FWHM}) = 132 \text{ \AA}$, corresponding to a redshift range between 6.508 and 6.617 for the Ly α emission. Optical imaging was made in the i' , z' , and NB921 bands on a central $34' \times 27'$ area of the SDF with Suprime-Cam. Our direct imaging was obtained during several observing runs between 2001 April and 2002 May. The total integrations time was 4.7 hr, 5.8 hr, and 5.0 hr for i' , z' , and NB921, respectively. The data reduction procedures are the same as those given in Yagi et al. (2002). The PSF FWHM of the final images is $0.''90$. Source detection and photometry are performed using SExtractor version 2.1.6 (Bertin, Arnouts 1996). The limiting magnitude (AB) for a 5σ detection on a $1.''8$ diameter aperture is 26.9, 26.1, and 25.7 for i' , z' , and NB921, respectively.

For each object detected in the NB921 image, i' , z' , and NB921 magnitudes are measured on a common aperture of $1.''8$ diameter. In total, 50,449 objects are detected down to NB921 = 25.7 (the 5σ limiting magnitude). The effective area used to search for NB921-excess objects is 814.3 arcmin^2 . The FWHM half-power points of the filter correspond to a co-moving depth along the line of sight of $40.9 h_{0.7}^{-1} \text{ Mpc}$. Thus a total volume of $202,000 h_{0.7}^{-3} \text{ Mpc}^3$ is probed in our NB921 image.

We select candidates of $z \simeq 6.6$ LAEs imposing two criteria, $z' - \text{NB921} > 1$ and $i' - z' > 1.3$, on the above objects. There are 404 objects satisfying the first criterion alone. The latter criterion is used to reduce contamination from foreground objects. Objects at $z \approx 6.6$ have sharp breaks because of the strong Ly α absorption at this redshift (Songaila, Cowie 2002) and are expected to exceed the adopted $i-z$ criterion while low redshift galaxies invariably do not. This latter criterion is applied only to objects brighter than $i' = 28.0$ ($\simeq 2\sigma$ limiting magnitude),

and we retain all the objects (satisfying $z' - NB921 > 1$) with $i' \geq 28.0$ in order not to miss possible faint LAEs. These selection procedures yield eventually a photometric sample of 73 LAE candidates. Note that among the objects with $i' \geq 28$, those brighter than $z' = 26.7$ (3σ limiting magnitude) satisfy automatically $i' - z' > 1.3$, but we cannot obtain a meaningful constraint on $i' - z'$ for those with $z' \geq 26.7$.

2.2. Optical Spectroscopy

In order to investigate the nature of LAE candidates found in our optical imaging survey, we obtained optical spectroscopy of nine objects in our LAE candidate sample using the Subaru Faint Object Camera And Spectrograph (FOCAS: Kashikawa et al. 2002) on 2002 June 7-9 under a $0.''55 - 1.''10$ seeing condition. This spectroscopic sample contains the brightest three objects with $NB921 < 24$. However, the remaining six objects are randomly selected from the photometric sample and they have $NB921 \approx 25 - 25.5$.

Our optical spectroscopy was made with the 300 lines mm^{-1} grating and an O58 order cut filter. The wavelength coverage was between 6000 Å to 10000 Å with a pixel resolution of 1.34 Å. The use of an 0.8 arcsec-wide slit gave a spectroscopic resolution of 9.0 Å at 9200 Å (or $R \simeq 1020$). The spatial resolution was $0.''3 \text{ pixel}^{-1}$ by 3-pixel, on-chip binning. Spectroscopy of the brightest object in our LAE sample ($NB921 = 23.01$) was obtained in the long-slit spectroscopy mode. The exposure time was 1800 seconds. This source was quickly identified as an [O III] $\lambda 5007$ emitter at $z \approx 0.84$. Other eight objects were observed in the multi-object spectroscopy (MOS) mode. We chose two fields that contained as many LAE candidates as possible; hereafter field 1 and field 2. We succeeded in obtaining spectra of three targets in Field 1 and five in Field 2. The same grating, filter, and slit as those in the long-slit mode were used in this MOS mode. We obtained twelve and six 1800s exposures for Field 1 and Field 2, respectively. We also obtained the spectrum of a standard star Hz 44 for flux calibration.

3. RESULTS

Our optical spectroscopy (see Figure 1) indicates that at least two objects are well-defined LAEs between $z = 6.5$ and $z = 6.6$ because their emission-line shapes show the sharp cutoff on the UV side together with the continuum depression at wavelengths shortward of the line peak. Two more objects also show the sharp cutoff at wavelengths shortward of the line peak. However, their continuum magnitudes are so faint that we cannot see firm evidence for the continuum break. Although they are probable candidates of LAEs at $z \approx 6.5 - 6.6$, we do not include them in the later discussion¹. In the spectra of the well-defined two

¹ Spectroscopic properties of other five objects are as follows. Three objects show a single emission line around $\lambda 9200$ Å in our optical spectra. Since they show an almost symmetrical emission-line profile, we cannot identify them as LAEs solely basing upon our optical spectroscopy; they may be either an [O II] $\lambda 3727$ source at $z \approx 1.46$ or a LAE at $z \approx 6.6$ (e.g., Stern et al. 2000). It seems also worthwhile noting that a symmetric

LAEs, SDF J132415.7+273058 in Field 2 and SDF J132418.3+271455 in Field 1 [panels (a) and (b), respectively], continuum emission appears to be present at wavelengths longer than the Ly α peak. Combining these two spectra and applying a 3-pixel smoothing, we obtain the average spectrum in panel (c). The average continuum flux density between 1200 Å and 1210 Å is $(1.7 \pm 4.1) \times 10^{-19}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$ while that between 1219 Å and 1226 Å is $(6.4 \pm 3.7) \times 10^{-19}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$. This difference is regarded as evidence for the continuum break in the spectra of these two LAEs.

The redshifts of the two LAEs are estimated from the peak of the Ly α emission line and the results are given in Table 1 together with line widths. It is noted that SDF J132418.3+271455 ($z = 6.578$) is more distant than HCM 6A at $z = 6.56$ (Hu et al. 2002) because error of our redshift measurement is ± 0.002 . Therefore, SDF J132418.3+271455 is the most distant LAE known to date. Thumbnail images of the two objects are shown in Figure 2. The *NB921* images reveal that only SDF J132415.7+273058 is spatially extended; its angular diameter (FWHM) is estimated as 1.2 arcsec. Correcting for the seeing spread (0.9 arcsec), we obtain an angular diameter of 0.8 arcsec, corresponding to $4.4 h_{0.7}^{-1}$ kpc at $z = 6.541$.

4. DISCUSSION

The SDF is a so-called blank field and there is no apparent cluster of galaxies known to date at low and intermediate redshifts in our field. Since, further, the lensing effect is expected to be small in this field, our survey results allow us to perform a simple statistical analysis of star formation activity in the investigated volume even though our sample is not large.

First, we estimate the star formation rate of the LAEs at $z \approx 6.6$ by using the relation $SFR(\text{Ly}\alpha) = 9.1 \times 10^{-43} L(\text{Ly}\alpha) M_{\odot} \text{yr}^{-1}$ (Kennicutt 1998; Brocklehurst 1971). The observed Ly α flux, the Ly α luminosity, and the star formation rate, $SFR(\text{Ly}\alpha)$, of each LAE are summarized in Table 1 where a flat universe with $\Omega_{\text{matter}} = 0.3$, $\Omega_{\Lambda} = 0.7$, and $h = 0.7$ with $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ is adopted. The average SFR obtained for the two LAEs is $7.1 \pm 2.0 h_{0.7}^{-2} M_{\odot} \text{yr}^{-1}$, being comparable to those of LAEs at $z \simeq 5.1 - 5.8$ (e.g., Ajiki et al. 2002). It should be mentioned that the SFRs estimated above are lower limits because it is quite likely that a blue half or more of the Ly α emission may be absorbed by H I gas and dust grains in the galaxy itself and by the intergalactic H I gas (Miralda-Escudé 1998; Miralda-Escudé, Rees 1998; Cen, McDonald 2002). The SFR based on the Ly α luminosity tends to be underestimated by a few times or more than that based on the UV luminosity (see also Hu et al. 2002). Indeed, using the average UV continuum flux density between 1219 Å and 1226 Å for the combined spectrum shown in panel (c) of Figure 1 together with the relation (Kennicutt 1998), $SFR(\text{UV}) = 1.4 \times 10^{-28} L_{\nu} M_{\odot} \text{yr}^{-1}$, where L_{ν} is in units of ergs s $^{-1}$ Hz $^{-1}$, we obtain an average

emission-line profile does not necessarily rule out the case of Ly α emission (e.g., ESO 350-IG038 in Kunth et al. 1998). The remaining two sources are confirmed to be [O III] $\lambda 5007$ emitters at $z \approx 0.84$.

value of $SFR(UV) \simeq 22h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$ for the two LAEs. As for SDF J132415.7+273058, we obtained J -band imaging using the InfraRed Camera and Spectrograph (IRCS: Kobayashi et al. 2000) on the Subaru Telescope on 2002 July 15. The integration time was 6480 seconds (the detail will be given elsewhere). The J magnitude (AB) is estimated as $\simeq 24.9$. This photometry allows us to estimate the star formation rate at $\lambda_{\text{rest}} = 1650 \text{ \AA}$ for SDF J132415.7+273058; $SFR(UV) \simeq 36h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$, which is even higher by a factor of four than $SFR(\text{Ly}\alpha)$. This is suggestive of dust obscuration at the bluest wavelengths.

Now we can estimate the total star formation rate of 73 LAEs in our photometric sample using the equivalent width of NB921 flux. We have identified one LAE (SDF J132415.7+273058) in the three brightest candidates and the other (SDF J132418.3+271455) in the faint sample. Because of small number statistics, it seems modest to assume that approximately 22% ($=2/9$) of 73 LAE candidates are real LAEs at $z \approx 6.5 - 6.6$ in any magnitude range; note that 95 % confidence level based on the random sampling hypothesis ranges 8 % - 49 %. If we assume that all the 73 LAE candidates are true LAEs at $z \approx 6.5 - 6.6$, we obtain nominally a total star formation rate of $SFR_{\text{total}}^{\text{nominal}} = 475h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$. Provided that approximately 22% of 73 LAE candidates are real LAEs at $z \approx 6.5 - 6.6$, we can estimate the total star formation rate, $SFR_{\text{total}} \simeq 0.22 \times SFR_{\text{total}}^{\text{nominal}} \simeq 105h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$. Given the survey volume, $202,000 h_{0.7}^{-3} \text{ Mpc}^3$, we thus obtain a star formation rate density of $\rho_{\text{SFR}} \simeq 5.2 \times 10^{-4} h_{0.7} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. It should be reminded here again that we apply neither any reddening correction nor integration by assuming a certain luminosity function for LAEs. Further, we note that there are two more probable LAE candidates in our spectroscopic sample. Therefore, our estimate should be regarded as a robust and first meaningful lower limit for the star formation rate density beyond $z = 6$. Let us compare this value with previous estimates in Figure 3; note that we convert all the previous estimates to those in the cosmology adopted in this Letter. In conclusion, the present study shows unambiguously that the moderate star formation activity already occurred in the early universe beyond $z = 6$.

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AJ, 123, 66

Table 1. Properties of the two LAEs

No.	Name ^a	Optical AB Magnitude			z	FWHM ^b		EW ^c	$F(\text{Ly}\alpha)$ $10^{-17} \text{ ergs/s/cm}^2$	$L(\text{Ly}\alpha)$ 10^{42} ergs/s	$SFR(\text{Ly}\alpha)$ $M_{\odot} \text{ yr}^{-1}$
		i'	z'	$NB921$		\AA	km/s				
1	SDF J132415.7+273058	27.48	25.82	23.99	6.541	10.9	357	160^{+520}_{-70}	2.06 ± 0.18	10.02 ± 0.09	9.1 ± 0.8
2	SDF J132418.3+271455	28.52	26.66	24.98	6.578	< 9.0	< 290	$330^{+\infty}_{-200}$	1.13 ± 0.05	5.58 ± 0.25	5.1 ± 0.2

^a The sky position, $\alpha(\text{J2000})$ and $\delta(\text{J2000})$, is given in the name.

^b Full width at half maximum of the $\text{Ly}\alpha$ emission line.

^c Equivalent width of the $\text{Ly}\alpha$ emission line at observed frame.

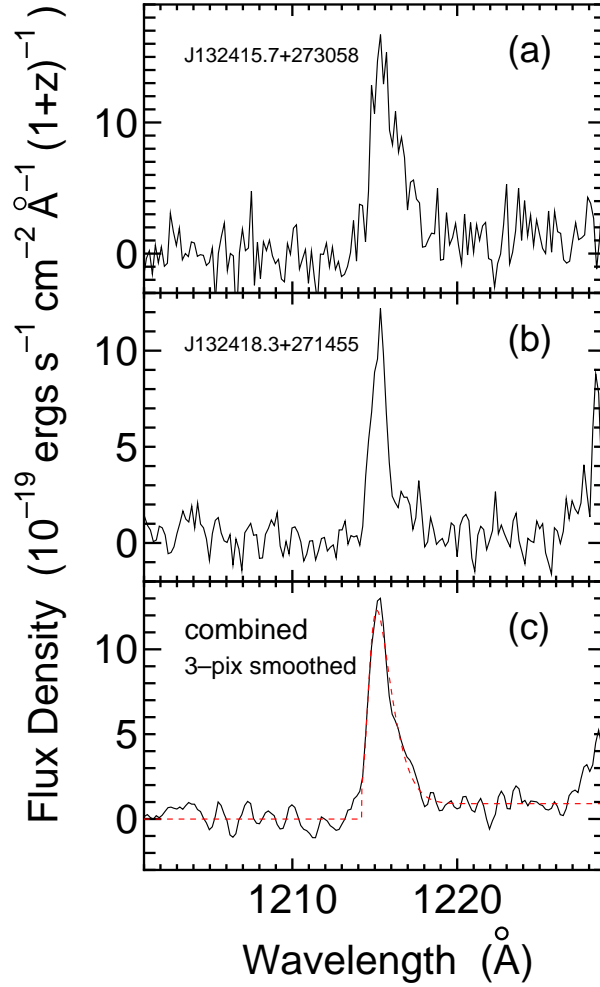


Fig. 1. The rest-frame UV spectra of two LAE candidates between 1200 \AA and 1230 \AA . The spectra of SDF J132415.7+273058 and SDF J132418.3+271455 are shown in panel (a) and (b), respectively. The combined spectrum of these two LAEs is shown in panel (c). A trial of the profile fitting with a combination between emission and absorption is shown by red line.

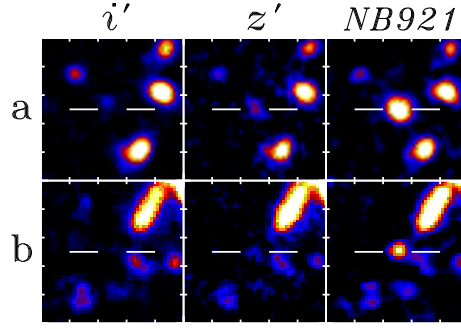


Fig. 2. Thumbnail images of the two well-defined LAEs, (a) SDF J132415.7+273058 and (b) SDF J132418.3+271455. The size of each image is $10'' \times 10''$, and north is up and east is left.

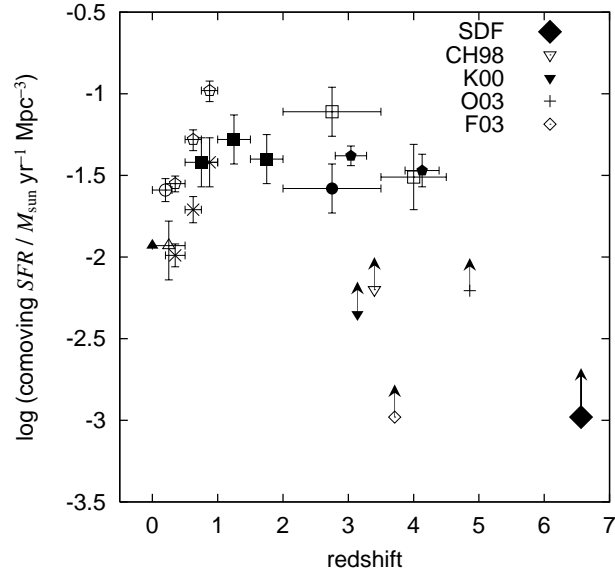


Fig. 3. The star formation rate density (ρ_{SFR}) as a function of redshift z . Our estimate at $z \approx 6.6$ (large filled diamond) is shown together with the results of previous Ly α searches at $z \sim 3 - 5$ (CH98 = Cowie & Hu 1998, K00 = Kudritzki et al. 2000, F03 = Fujita et al. 2003, and O03 = Ouchi et al. 2003). The previous investigations are shown by filled triangle (Gallego et al. 1996), open triangle (Treyer et al. 1998), open circle (Tresse & Maddox 1998), stars (Lilly et al. 1996), open pentagons (Hammer et al. 1999), filled squares (Connolly et al. 1997), filled circles (Madau 1998), and open squares (Pettini et al. 1999). Other results for Lyman break galaxies between $z = 3 - 4$ are also shown by filled pentagons (Steidel et al. 1999).