

The Discovery of Two Lyman α Emitters beyond Redshift 6 in the Subaru Deep Field ^{*,†}

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(Received 2003 January 6; accepted 2003 February 21)

Abstract

We performed a deep optical imaging survey using a narrow-band filter (*NB* 921) 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 *NB* 921-excess objects based on the following two color criteria: $z' - \text{NB} 921 > 1$ and $i' - z' > 1.3$. We then obtained optical spectroscopy of nine objects in our *NB* 921-excess sample, and identified at least two Ly α 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 continuum depression at wavelengths shortward of the line peak. The latter object is more distant than HCM-6A at $z = 6.56$, which is the most distant known object that has been 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 several times higher 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: evolution — galaxies: formation — galaxies: starburst

1. Introduction

Probing the star-formation activity in galactic or subgalactic systems in the early universe is important for understanding both the history of galaxies and the origin of cosmic reionization (e.g., Loeb, Barkana 2001). Recent advances 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, McMahon 1996; Hu et al. 1999, 2002; Kudritzki et al. 2000; Rhoads, Malhotra 2001; Steidel et al. 2000; Taniguchi et al. 2003). Indeed, the most distant Ly α 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 often not large enough to ensure sufficient robustness for success. In order to increase the survey volumes and to reach the faint limiting magnitude, we need wide-field CCD cameras on 8–10 m class telescopes. Suprime-Cam (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

* Based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

† This work has been conducted with collaboration between the Subaru Deep Field Project led by the association of builders of the Subaru Telescope and the common-use Intensive Program (S02A-IP-2) led by Y. Taniguchi.

view), narrow-band 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 for 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 carried out a very deep optical imaging survey in the Subaru Deep Field (SDF) centered at $\alpha(\text{J2000}) = 13^{\text{h}}24^{\text{m}}21^{\text{s}}.4$ 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 a 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 of 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 integration times were 4.7 hr, 5.8 hr, and 5.0 hr for i' , z' , and *NB921*, respectively. The data-reduction procedures were the same as those given in Yagi et al. (2002). The PSF FWHM of the final images was $0''.90$. 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, the i' , z' , and *NB921* magnitudes were measured on a common aperture of $1''.8$ diameter. In total, 50449 objects are detected down to *NB921* = 25.7 (the 5σ limiting magnitude). The effective area used to search for *NB921*-excess objects was 814.3 arcmin^2 . The FWHM half-power points of the filter corresponded to a co-moving depth along the line of sight of $40.9 h_{0.7}^{-1} \text{ Mpc}$. Thus a total volume of $202000 h_{0.7}^{-3} \text{ Mpc}^3$ was probed on our *NB921* image.

We selected candidates of $z \approx 6.6$ LAEs while imposing two criteria, $z' - \text{NB921} > 1$ and $i' - z' > 1.3$, on the above objects. There were 404 objects satisfying the first criterion alone. The latter criterion was used to reduce the 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 $i' = 28.0$ ($\approx 2\sigma$ limiting magnitude), and we retained all the objects (satisfying $z' - \text{NB921} > 1$) with $i' \geq 28.0$ in order not to miss possible faint LAEs. These selection procedures eventually yielded 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) automatically satisfied $i' - z' > 1.3$, but we could not

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 the 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 contained the brightest three objects with *NB921* < 24. However, the remaining six objects were randomly selected from the photometric sample and have *NB921* ≈ 25 – 25.5 .

Our optical spectroscopy was made with 300 lines mm^{-1} grating and an O58 order-cut filter. The wavelength coverage was between 6000 \AA to 10000 \AA with a pixel resolution of 1.34 \AA . The use of an $0''.8$ wide slit gave a spectroscopic resolution of 9.0 \AA at 9200 \AA (or $R \approx 1020$). 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 s. This source was quickly identified as an [O III] $\lambda 5007$ emitter at $z \approx 0.84$. Eight other objects were observed in the multi-object spectroscopy (MOS) mode. We chose two fields that contained as many LAE candidates as possible; hereafter called Field 1 and Field 2. We succeeded to obtain 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 1800 s exposures for Field 1 and Field 2, respectively. We also obtained the spectrum of a standard star Hz 44 for a 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 a sharp cutoff on the UV side together with 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 any 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 discussion.¹ In the spectra of the two well-defined 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 obtained the average spectrum, as shown in panel (c). The average

¹ Spectroscopic properties of five other objects are as follows. Three objects show a single emission line around 9200 \AA in our optical spectra. Since they show an almost symmetrical emission-line profile, we cannot identify them as LAEs solely based 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 also seems worthwhile to note that a symmetric 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 $z \approx 0.84$.

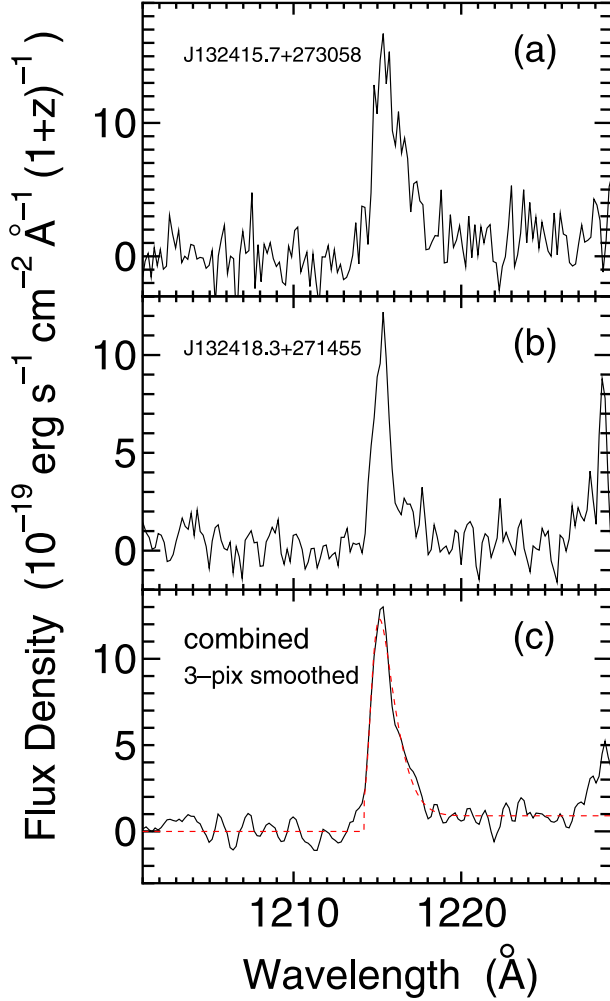


Fig. 1. Rest-frame UV spectra of two LAE candidates between 1200 Å and 1230 Å. The spectra of SDF J132415.7+273058 and SDF J132418.3+271455 are shown in panels (a) and (b), respectively. The combined spectrum of these two LAEs is shown in panel (c). A trial of the profile fitting with a combination between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

continuum flux density between 1200 Å and 1210 Å is $(1.7 \pm 4.1) \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$, while that between 1219 Å and 1226 Å is $(6.4 \pm 3.7) \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$. This difference is regarded as being evidence for the continuum break in the spectra of these two LAEs.

The redshifts of the two LAEs were estimated from the peak of the Ly α emission line; 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 the 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 to be $1''.2$. Correcting for the seeing spread ($0''.9$), we obtained an angular diameter of $0''.8$, corresponding to $4.4 h_{0.7}^{-1} \text{ kpc}$ at $z = 6.541$.

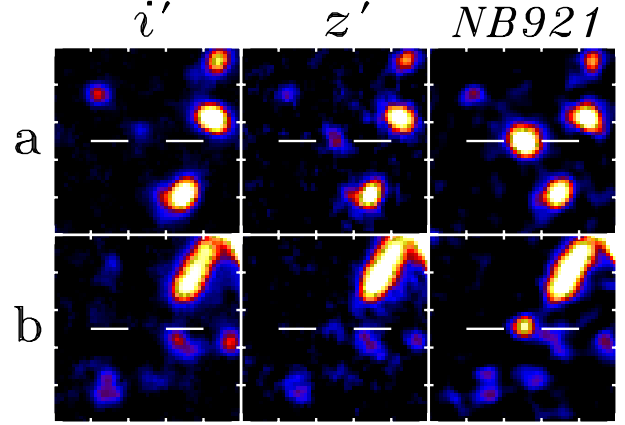


Fig. 2. Thumbnail images of the two well-defined LAEs, (a) SDF J132415.7+273058 and (b) SDF J132418.3+271455. The size of each image is $10'' \times 10''$, and north is up and east is left.

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 the star-formation activity in the investigated volume even though our sample was not large.

First, we estimated 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 $h = H_0 / (100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ was 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 $z \approx 5.1$ – 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 $\text{erg s}^{-1} \text{ Hz}^{-1}$, we obtain an average value of $SFR(\text{UV}) \approx 22 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$ 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 s (the details will be given elsewhere). The J magnitude (AB) is estimated to be ≈ 24.9 . This photometry allows us to estimate the star-formation rate at $\lambda_{\text{rest}} = 1650 \text{ Å}$ for SDF J132415.7+273058; $SFR(\text{UV}) \approx 36 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$, which is even higher by a factor of four than $SFR(\text{Ly } \alpha)$. This is suggestive of dust obscuration at the bluest wavelengths.

Table 1. Properties of the two LAEs.

No.	Name*	Optical AB Magnitude			z	FWHM [†]		EW [‡]	$F(\text{Ly}\alpha)$ $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$	$L(\text{Ly}\alpha)$ $10^{42} \text{ erg s}^{-1}$	$SFR(\text{Ly}\alpha)$ $M_{\odot} \text{ yr}^{-1}$
		i'	z'	NB 921		Å	km s ⁻¹				
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

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

† Full width at half maximum of the Ly α emission line.

‡ Equivalent width of the Ly α emission line at the observed frame.

We can now estimate the total star-formation rate of 73 LAEs in our photometric sample using the equivalent width of the NB 921 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 the small number statistics, it seems to be 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 the 95% confidence level based on the random sampling hypothesis ranges from 8% to 49%. If we assume that all of the 73 LAE candidates are true LAEs at $z \approx 6.5$ – 6.6 , we nominally obtain a total star-formation rate of $SFR_{\text{total}}^{\text{nominal}} = 475 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$. 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, $SFR_{\text{total}} \approx 0.22 \times SFR_{\text{total}}^{\text{nominal}} \approx 105 h_{0.7}^{-2} M_{\odot} \text{ yr}^{-1}$. Given the survey volume, $202000 h_{0.7}^{-3} \text{ Mpc}^3$, we thus obtained a star-formation rate density of $\rho_{\text{SFR}} \approx 5.2 \times 10^{-4} h_{0.7} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. It should be reminded here again that we applied neither any reddening correction nor integration by assuming a certain luminosity function for the LAEs. Further, we note that there were 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 $z = 6$. We compare this value with previous estimates in figure 3; note that we converted all of the previous estimates to those in the cosmology adopted in this Letter. In conclusion, the present study shows unambiguously that moderate star-formation activity already occurred in the early universe beyond $z = 6$.

We would like to thank the Subaru Telescope staff for their invaluable assistance. We would also like to thank Prof. Hy Spinrad for both useful comments concerning an earlier version of this paper and for encouragement. We also thank a

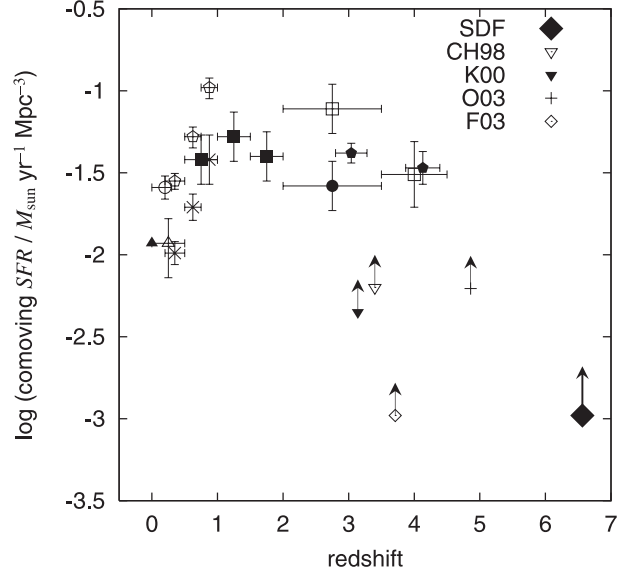


Fig. 3. Star-formation rate density (ρ_{SFR}) as a function of the redshift z . Our estimate at $z \approx 6.6$ (large filled diamond) is shown together with the results of previous Ly α searches at $z \sim 3$ – 5 (CH98=Cowie, Hu 1998, K00=Kudritzki et al. 2000, F03 = Fujita et al. 2003, and O03=Ouchi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

referee, Daniel Stern, and another anonymous referee for their useful comments and suggestions.

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