THE DISCOVERY OF A VERY NARROW-LINE STAR FORMING OBJECT AT A REDSHIFT OF 5.66$^{1,2}$

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ABSTRACT

We report on the discovery of a very narrow-line star forming object beyond redshift of 5. Using the prime-focus camera, Suprime-Cam, on the 8.2 m Subaru telescope together with a narrow-passband filter centered at $\lambda_c = 8150$ Å with passband of $\Delta \lambda = 120$ Å, we have obtained a very deep image of the field surrounding the quasar SDSSp J104433.04−012502.2 at a redshift of 5.74. Comparing this image with optical broad-band images, we have found an object with a very strong emission line. Our follow-up optical spectroscopy has revealed that this source is at a redshift of $z = 5.655 \pm 0.002$, forming stars at a rate $\sim 13 h_{0.7}^{-2} M_\odot$ yr$^{-1}$. Remarkably, the velocity dispersion of Ly$\alpha$-emitting gas is only 22 km s$^{-1}$. Since a blue half of the Ly$\alpha$ emission could be absorbed by neutral hydrogen gas, perhaps in the system, a modest estimate of the velocity dispersion may be $\gtrsim 44$ km s$^{-1}$. Together with a linear size of 7.7 $h_{0.7}^{-1}$ kpc, we estimate a lower limit of the dynamical mass of this object to be $\sim 2 \times 10^9 M_\odot$. It is thus suggested that LAE J1044−0123 is a star-forming dwarf galaxy (i.e., a subgalactic object or a building block) beyond redshift 5 although we cannot exclude a possibility that most Ly$\alpha$ emission is absorbed by the red damping wing of neutral intergalactic matter.

Subject headings: galaxies: individual (LAE J1044−0123) — galaxies: starburst — galaxies: formation

1. INTRODUCTION

Searches for Ly$\alpha$ emitters (hereafter LAEs) at high redshift are very useful in investigating the early star formation history of galaxies (Partridge & Peebles 1967). Recent progress in the observational capability of 10-m class optical telescopes has enabled us to discover more than a dozen of Ly$\alpha$ emitting galaxies beyond redshift 5 (Dey et al. 1998; Weymann et al. 1998; Hu et al. 1999, 2001, 2002; Dawson et al. 2001, 2002; Ellis et al. 2001; Ajiki et al. 2002; see also Spinrad et al. 1998; Rhoads & Malhotra 2001). The most distant object known to date is HCM-6A at $z = 6.56$ (Hu et al. 2002). These high-$z$ Ly$\alpha$ emitters can be also utilized to investigate physical properties of the intergalactic medium (IGM) because the epoch of cosmic reionization ($z_r$) is considered to be close to the redshifts of high-$z$ Ly$\alpha$ emitters; i.e., $z_r \sim 6 - 7$ (Djorgovski et al. 2001; Becker et al. 2001; Fan et al. 2002). In other words, emission-line fluxes of the Ly$\alpha$ emission from such high-$z$ galaxies could be absorbed by neutral hydrogen in the IGM if neutral gas clouds are located between the source and us (Gunn & Peterson 1965; Miralda-Escudé 1998; Miralda-Escudé & Rees 1998; Haiman 2002 and references therein). Therefore, careful investigations of Ly$\alpha$ emission-line properties of galaxies with $z > 5$ provides very important clues simultaneously both on the early star formation history of galaxies and on the physical status of IGM at high redshift.

The first step is to look for a large number of Ly$\alpha$ emitter candidates at high redshift through direct imaging surveys. The detectability of high-redshift objects is significantly increased if they are hosts to recent bursts of star formation which ionize the surrounding gas and result in strong emission lines like the hydrogen recombination line Ly$\alpha$. These emission-line objects can be found in principle through deep optical imaging with narrow-passband filters customized to the appropriate redshift. Indeed, recent attempts with the Keck 10 m telescope have revealed the presence of Ly$\alpha$ emitters in blank fields at high redshift (e.g., Cowie & Hu 1998; Hu et al. 2002). These recent successes have shown the great potential of narrow-band imaging surveys with 8-10 m telescopes in the search for high-$z$ Ly$\alpha$ emitters. It is also worthwhile noting that subgalactic populations at high redshift have been recently found thanks to the gravitational lensing (Ellis et al. 2001; 2002; see also Spinrad et al. 1998; Rhoads & Malhotra 2001).
In an attempt to find star-forming objects at $z \approx 5.7$, we have carried out a very deep optical imaging survey in the field surrounding the quasar SDSSp J104433.04−012502.2 at redshift of $5.74^{11}$ (Fan et al. 2000; Djorgovski et al. 2001; Goodrich et al. 2001), using Suprime-Cam (Miyazaki et al. 1998), the wide-field ($34′ \times 27′$ with a 0.2 arcsec/pixel resolution) prime-focus camera on the 8.2 m Subaru telescope (Kaiˇfu 1998). In this Letter, we report on our discovery of a very narrow-line star-forming system at $z \approx 5.7$.

2. OBSERVATIONS

2.1. Optical Imaging

In this survey, we used the narrow-passband filter, NB816, centered on 8150 Å with a passband of $\Delta \lambda$ (FWHM) = 120 Å; the central wavelength corresponds to a redshift of 5.70 for Ly$\alpha$ emission. We also used broad-passband filters, $B$, $R_C$, $I_C$, and $z'$. A summary of the imaging observations is given in Table 1. All of the observations were done under photometric condition and the seeing size was between 0.7 arcsec and 1.3 arcsec during the run. Note that we analyzed only two CCD chips, in which quasar SDSSp J104433.04−012502.2 is present to avoid delays for follow-up spectroscopy. The CCD data were reduced and combined using IRAF and the mosaic-CCD data reduction software developed by Yagi et al. (2002). Photometric and spectrophotometric standard stars used in the flux calibration are SA101 for the $B$, $R_C$, and $I_C$ data, and GD 108, GD 58 (Oke 1990, and PG 1034+001 (Massey et al. 1988) for the NB816 data. The $z'$ data were calibrated by using the magnitude of SDSSp J104433.04−012502.2 (Fan et al. 2000).

The total size of the field is $11.67′$ by $11.67′$, corresponding to a solid angle of $\approx 136$ arcmin$^2$. The volume probed by the NB816 imaging has (co-moving) transverse dimensions of $27.56~h_0^{0.4} \times 27.56~h_0^{0.4}~$Mpc$^2$, and the half-power points of the filter correspond to a co-moving depth along the line of sight of $44.34~h_0^{−0.4}~$Mpc ($z_{\text{min}} \approx 5.653$ and $z_{\text{max}} \approx 5.752$; note that the transmission curve of our NB816 filter has a Gaussian-like shape). Therefore, a total volume of $3.4 \times 10^3~h_0^{−2}~$Mpc$^3$ is probed in our NB816 image. Here, we adopt a flat universe with $\Omega_{\text{matter}} = 0.3$, $\Omega_{\Lambda} = 0.7$, and $h = 0.7$ where $h = H_0/(100~$km$~s^{-1}~$Mpc$^{-1})$.

Source detection and photometry were performed using SExtractor version 2.2.1 (Bertin, & Arnouts 1996). Our detection limit (a 3σ detection within a 2″.8 diameter aperture) for each band is listed in Table 1. As for the source detection in the NB816 image, we used a criterion that a source must be a 13-pixel connection above 5σ noise level. Adopting the criterion for the NB816 excess, $I_C - NB816 > 1.0$ mag, we have found two strong emission-line sources. Our follow-up optical spectroscopy of these sources reveals that one source found at $\alpha$(J2000)=10h 44m 27s and $\delta$(J2000)=−01° 23′ 45″ (hereafter LAE J1044−0123) is a good candidate to be a sub-galactic object at high redshift$^{12}$. Its AB magnitude in the NB816 band is 24.73. The optical thumb-nail images of LAE J1044−0123 are given in Fig. 1. As shown in this figure, LAE J1044−0123 is seen clearly only in the NB816 image. Although it is seen in the $I_C$ image, its flux is below the 3σ noise level. The observed equivalent width is $E_{\text{W,obs}} > 238$ Å. The NB816 image reveals that LAE J1044−0123 is spatially extended; its angular diameter is 1.6 arcsec (above the 2σ noise level). The size of the point spread function in the NB816 image is 0.90 arcsec. Correcting for this spread, we obtain an angular diameter of 1.3 arcsec.

2.2. Optical Spectroscopy

Our optical spectroscopy was made by using the Keck II Echelle Spectrograph and Imager (ESI: Sheinis et al. 2000) on 2002 March 15 (UT). We used the Echelle mode with the slit width of 1 arcsec, resulting in a spectral resolution $R \approx 3400$ at 8000 Å. The integration time was 1800 seconds. The spectrum of LAE J1044−0123, shown in Fig. 2, presents a narrow emission line at $\lambda = 8900$ Å. This is the only emission line that was detected within the ESI wavelength range (from 4000 Å to 9500 Å). This line may be either Ly$\alpha$ or [O ii]λ3727. The emission-line profile appears to show a sharper cutoff at wavelengths shortward of the line peak, providing some evidence that this line is Ly$\alpha$. A stronger argument in favor of this line identification comes from the lack of structure in the profile. If this line were [O ii] emission, the redshift would be $z \approx 1.17$. Since the [O ii] feature is a doublet line of [O ii]λ3726.0 and [O ii]λ3728.8, the line separation would be larger than 6.1 Å and the lines would be resolved in the ESI observations. Further, if the line were H$\beta$, [O iii]λ4959, [O iii]λ5007, or H$\alpha$ line, we would detect some other emission lines in our spectrum. Therefore, we conclude that the emission line at 8090 Å is Ly$\alpha$, giving a redshift of $5.655 \pm 0.002$.

3. RESULTS AND DISCUSSION

3.1. Star Formation Activity in LAE J1044−0123

The rest-frame equivalent width of Ly$\alpha$ emission becomes $E_{\text{W,0}} > 36$ Å. Our Keck/ESI spectrum gives the observed Ly$\alpha$ flux of $f(\text{Ly}\alpha) = (1.3 \pm 0.1) \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ and the rest-frame equivalent width of Ly$\alpha$ emission $E_{\text{W,0}} > 36$ Å. On the other hand, our NB816 magnitude of LAE J1044−0123 gives $f(\text{Ly}\alpha) \simeq 4.1 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$, being higher than by a factor of 3 than the Keck/ESI flux. Since the Keck/ESI spectrum was calibrated by a single measurement of a spectroscopic standard star, HZ 44, the photometric accuracy may not be good. Further, our slit width may not cover the entire Ly$\alpha$ nebula of LAE J1044−0123. Therefore, we use the NB816-based flux to estimate the star formation rate. The NB816 flux gives the Ly$\alpha$ luminosity $L(\text{Ly}\alpha) \simeq 1.4 \times 10^{43}$ h$_0^{−2}$ ergs s$^{-1}$. Using the relation $SFR = 9.1 \times 10^{-43} L(\text{Ly}\alpha) M_0\text{yr}^{-1}$ (Kennicutt 1998; Brocklehurst 1971), we obtain $\sim 13 h_0^{−2} M_0\text{yr}^{-1}$. This is a lower limit because no correction was made for possible internal extinction by dust grains in the system. The lack of UV continuum from this object prevents us from determining the importance of this effect.

The most intriguing property of LAE J1044−0123 is that the observed emission-line width (full width at half

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$^{11}$The discovery redshift was $z = 5.8$ (Fan et al. 2000). Since, however, the subsequent optical spectroscopic observations suggested a bit lower redshift; $z = 5.73$ (Djorgovski et al. 2001) and $z = 5.745$ (Goodrich et al. 2001), we adopt $z = 5.74$ in this Letter.

$^{12}$Another source has been identified as a Ly$\alpha$ emitter at $z = 5.687$ (Ajiki et al. 2002)
maximum; FWHM) of redshifted Lyα is only 2.2 ± 0.3 Å. Since the instrumental spectral resolution is 1.7 ± 0.1 Å, the intrinsic width is only 1.4 ± 0.5 Å; note that this gives a upper limit because the line is barely resolved. It corresponds to $FWHM_{\text{obs}} \approx 52 \pm 19 \text{ km s}^{-1}$ or a velocity dispersion $\sigma_{\text{obs}} = FWHM_{\text{obs}}/(2\sqrt{2\ln2}) \approx 22 \text{ km s}^{-1}$. This value is comparable to those of luminous globular clusters (Djorgovski 1995).

It is interesting to compare the observational properties of LAE J1044−0123 with similar LAEs at $z \geq 5$. For this comparison, we choose Abell 2218 a (Ellis et al. 2001), LAE J1044−0130 (Ajiki et al. 2002), and J123649.2+621539 (Dawson et al. 2002) because these objects were also observed using Keck/ESI. A summary is given in Table 2. This comparison shows that LAE J1044−0123 has the narrowest line width that may be roughly comparable to that of Abell 2218 a although the mass of Abell 2218, $\sim 10^9 M_\odot$, is much smaller than that of LAE J1044−0123 (see next subsection). Another important point appears that the line profile of LAE J1044−0123 does not show dense red wing emission which is evidently seen in those of the other three LAEs. The diversity of the observational properties of these LAEs suggest that the H i absorptions affect significantly the visibility of the Lyα emission line. Further, the contribution of superwinds may be different from LAE to LAE.

3.2. What is LAE J1044−0123 ?

Now a question arises: “What is LAE J1044−0123 ?”. There are two alternative ideas: (1) LAE J1044−0123 is a part of a giant system and we observe only the bright star-forming clump, or (2) LAE J1044−0123 is a single star-forming system. Solely from our observations, we cannot judge which is the case. If this is the first case, LAE J1044−0123 may be similar to Abell 2218 a found by Ellis et al. (2001). One problem in this interpretation seems that the spatial extension, $\sim 7.7$ kpc, of LAE J1044−0123 is fairly large for such a less-massive system. Therefore, adopting the second case, it seems important to investigate possible dynamical status of LAE J1044−0123 for future consideration.

If a source is surrounded by neutral hydrogen, Lyα photons emitted from the source are heavily scattered. Furthermore, the red damping wing of the Gunn-Peterson trough could also suppress the Lyα emission line (Gunn & Peterson 1965; Miralda-Escudé 1998; Miralda-Escudé & Rees 1998; Haiman 2002 and references therein). If this is the case for LAE J1044−0123, we may see only a part of the Lyα emission. Haiman (2002) estimated that only 8% of the Lyα emission is detected in the case of HCM-6A at $z = 6.56$ found by Hu et al. (2002). However, the observed Lyα emission-line profile of LAE J1044−0123 shows the sharp cutoff at wavelengths shortward of the line peak. This property suggests that the H i absorption is dominated by H i gas in the system rather than that in the IGM. Therefore, it seems reasonable to adopt that blue half of the Lyα emission could be absorbed in the case of LAE J1044−0123. Then we estimate a modest estimate of the velocity dispersion, $\sigma_0 \sim 2\sigma_{\text{obs}} \sim 44 \text{ km s}^{-1}$. Given the diameter of this object probed by the Lyα emission, $D \approx 7.7h_9^{-1/2}\text{kpc}$, we obtain the dynamical timescale of $\tau_{\text{dyn}} \sim D/\sigma_0 \sim 1.7 \times 10^8 \text{ yr}$. This would give a upper limit of the star formation timescale in the system; i.e., $\tau_{\text{SF}} \lesssim \tau_{\text{dyn}}$. However, if the observed diameter is determined by the so-called Strömgren sphere photoionized by a central star cluster, it is not necessary to adopt $\tau_{\text{SF}} \sim \tau_{\text{dyn}}$. It seems more appropriate to adopt a shorter timescale for such a high-z star-forming galaxies, e.g., $\tau_{\text{SF}} \sim 7 \text{ yr}$, as adopted for HCM-6A at $z \approx 6.56$ (Hu et al. 2002) by Haiman (2002). One may also derive a dynamical mass $M_{\text{dyn}} = (D/2)\sigma_0^2 G^{-1} \sim 2 \times 10^9 M_\odot$ (neglecting possible inclination effects).

At the source redshift, $z = 5.655$, the mass of a dark matter halo which could collapse is estimated as $M_{\text{vir}} \sim 9 \times 10^9 r_{\text{vir},1}^2 h_{0.7}^{-1} M_\odot$ where $r_{\text{vir},1}$ is the Virial radius in units of 1 kpc [see equation (24) in Barkana & Loeb (2001)]. If we adopt $r_{\text{vir}} = D/2 = 3.85$ kpc, we would obtain $M_{\text{vir}} \sim 5 \times 10^9 M_\odot$. However, the radius of dark matter halo could be ten times as long as $D/2$. If this is the case, we obtain $M_{\text{vir}} \sim 5 \times 10^9 M_\odot$ and $\sigma_0 \sim 75 \text{ km s}^{-1}$. Comparing this velocity dispersion with the observed one, we estimate that the majority of Lyα emission would be absorbed by neutral hydrogen.

The most important issue related to LAE J1044−0123 seems how massive this source is; i.e., $\sim 10^9 M_\odot$ or more massive than $10^{10} M_\odot$. If the star formation timescale is as long as the dynamical one, the stellar mass assembled in LAE J1044−0123 at $z = 5.655$ exceeds $10^9 M_\odot$, being comparable to the nominal dynamical mass, $M_{\text{dyn}} \sim 2 \times 10^9 M_\odot$. Since it is quite unlikely that most mass is assembled to form stars in the system, the dark matter halo around LAE J1044−0123 would be more massive by one order of magnitude at least than the above stellar mass. If this is the case, we could miss the majority of the Lyα emission and the absorption could be attributed to the red damping wing of neutral hydrogen in the IGM. Since the redshift of LAE J1044−0123 ($z = 5.655$) is close to that of SDSSp J104433.04−012502.2 ($z = 5.74$), it is possible that these two objects are located at nearly the same cosmological distance. The angular separation between LAE J1044−0123 and SDSSp J104433.04−012502.2, 113 arcsec, corresponds to the linear separation of 4.45 $h_9^{-1}$ Mpc. The Strömgren radius of SDSSp J104433.04−012502.2 can be estimated as $r_S \sim 6.3(t_\odot/2 \times 10^7 \text{ yr})^{1/3}$ Mpc using equation (1) in Haiman & Cen (2002) where $t_\odot$ is the lifetime of the quasar (see also Cen & Haiman 2000). Even if this quasar is amplified by a factor of 2 by the gravitational lensing (Shioya et al. 2002), we obtain $r_S \sim 4.9$ Mpc. Therefore, it seems likely that the IGM around LAE J1044−0123 may be ionized completely. If this is the case, we cannot expect that the Lyα emission of LAE J1044−0123 is severely absorbed by the red damping wing emission. In order to examine which is the case, L-band spectroscopy is strongly recommended because the redshifted [O ii]λ5007 emission will be detected at 3.33 μm. However, we need the James Webb Space Telescope to complete it.

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### Table 1

**A JOURNAL OF IMAGING OBSERVATIONS**

| Band | Obs. Date (UT)       | Total Integ. Time (s) | $m_{\text{lim}}(\text{AB})$<sup>a</sup> | FWHM$_{\text{star}}$<sup>b</sup> (arcsec) |
|------|----------------------|-----------------------|----------------------------------------|------------------------------------------|
| B    | 2002 February 17     | 1680                  | 26.6                                   | 1.2                                      |
| $R_C$| 2002 February 15, 16 | 4800                  | 26.2                                   | 1.4                                      |
| $I_C$| 2002 February 15, 16 | 3360                  | 25.9                                   | 1.2                                      |
| $NB816$| 2002 February 15 - 17 | 36000                 | 26.0                                   | 0.9                                      |
| $z'$ | 2002 February 15, 16 | 5160                  | 25.3                                   | 1.2                                      |

<sup>a</sup>The limiting magnitude (3σ) with a 2.8″φ aperture.

<sup>b</sup>The full width at half maximum of stellar objects in the final image.

### Table 2

**COMPARISON WITH SIMILAR LAES BEYOND REDSHIFT 5**

| Name              | Redshift | $f(\text{Ly} \alpha)$<sup>a</sup> | $FWHM(\text{Ly} \alpha)$<sup>b</sup> | Ref.<sup>c</sup> |
|-------------------|----------|----------------------------------|--------------------------------------|------------------|
| LAE J1044−0123    | 5.655    | 4.1                              | 52                                   | This paper       |
| Abell 2218 a       | 5.576    | 6.2<sup>d</sup>                  | ~70<sup>e</sup>                      | 1                |
| LAE J1044−0130     | 5.687    | 1.5                              | 340                                  | 2                |
| J123649.2+621539   | 5.190    | 3.0                              | 280                                  | 3                |

<sup>a</sup>Observed Lyα flux in units of $10^{-17}$ ergs s$^{-1}$ cm$^{-2}$.

<sup>b</sup>Corrected FWHM of Lyα flux in units of km s$^{-1}$.

<sup>c</sup>1. Ellis et al. (2001), 2. Ajiki et al. (2002), and 3. Dawson et al. (2002).

<sup>d</sup>In Ellis et al. (2001), the Lyα fluxes obtained with both Keck LRIS and ESI are given. The Lyα flux given in this table is their average.

<sup>e</sup>Observed line width, 2.24 Å, is roughly estimated from Fig. 3 in Ellis et al. (2002). After correcting the instrumental line width, 1.25 Å, we obtain the corrected FWHM $\sim$ 70 km s$^{-1}$. 
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Fig. 1.— Thumb-nail images of LAE J1044−0123 (upper panel). The angular size of the circle in each panel corresponds to 8 arcsec. Their contours are shown in the middle panel. The lower panel shows the spectral energy distribution on a magnitude scale.
Fig. 2.— The optical spectrum of LAE J1044-0123 obtained with the Keck II Echelle Spectrograph and Imager (ESI). We show the spectrogram in the upper panel and the one-dimensional spectrum extracted with an aperture of 1.2 arcsec.