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A STRONG Lyα EMITTER AT $z = 6.33$ IN THE SUBARU DEEP FIELD SELECTED AS AN i'-DROPOUT[1]

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ABSTRACT

We report on the discovery of a star-forming galaxy at $z = 6.33$ in the Subaru Deep Field. This object is selected as a candidate of an i'-dropout high-redshift galaxy around $z = 6$ because of its red $i' - z'$ color in our deep optical imaging survey in the Subaru Deep Field. Our follow-up optical spectroscopy reveals that this object is a strong Lyα emitter with only very faint ultraviolet continuum. The rest-frame equivalent width of the detected Lyα emission is as much as 130 Å. Thus the light detected in our z' image is largely attributed to the Lyα emission, i.e., ~40% of the z'-band flux is the strong Lyα emission, giving a very red $i' - z'$ color. This is consistent with the photometric property of this object because the narrowband data obtained with the NB921 filter show a significant depression, $z' - \mathrm{NB921} = -0.54$ mag. By using the photometric data, we show that some other objects among the 48 i'-dropout high-redshift galaxy candidates found in the Subaru Deep Field also show a significant NB921 depression. We briefly discuss the nature of these NB921-depressed objects.

Subject headings: early universe — galaxies: evolution — galaxies: formation — galaxies: individual (SDF J132440.6+273607) — galaxies: starburst

1. INTRODUCTION

The star formation in the early universe provides important clues about the understanding of both galaxy formation and the ionization state of intergalactic matter (e.g., Loeb & Barkana 2001). Currently, two alternative methods are frequently used to find very high-z objects; one is to search for strong emission-line objects by using narrow-passband filters (e.g., Hu et al. 2002; Ouchi et al. 2003; Ajiki et al. 2003; Kodaira et al. 2003; see, for a review, Taniguchi et al. 2003), which selectively pick up high-z objects with a strong emission line such as Lyα (Lyα emitters, hereafter LAEs). The other method is to search for redshifted Lyman break objects based on broad-band color selections (e.g., Steidel et al. 1996a, 1996b, 1999; Iwata et al. 2003; Stanway et al. 2003; Ouchi et al. 2004; Giavalisco et al. 2004). Since this method relies on the stellar Lyman break spectral feature, this method tends to select high-z galaxies with strong UV continuum emission, i.e., Lyman break galaxies (LBGs). Since some LBGs also show a strong Lyα emission, LAEs may be regarded as a subclass of LBGs (see, e.g., Shapley et al. 2003).

And very recently, based on imaging surveys with broad passband filters, objects with a very red $i' - z'$ color (i.e., i'-dropout objects) are intensively explored as candidates of galaxies at $z \gtrsim 6$, where the cosmic reionization ended (e.g., Stanway et al. 2003; Bouwens et al. 2003, 2004; Dickinson et al. 2004; Bunker et al. 2004). In this Letter, we report on the discovery of a luminous star-forming galaxy at $z = 6.33$ in the Subaru Deep Field (SDF). This object is originally selected as a candidate of an i'-dropout high-redshift galaxy because of its red $i' - z'$ color by the imaging survey for SDF. This object is interesting because our follow-up spectroscopy shows that it presents only very faint UV continuum emission. We adopt a cosmology with $(\Omega_{\mathrm{tot}}, \Omega_M, \Omega_\Lambda) = (1.0, 0.3, 0.7)$ and $H_0 = 70$ km s^{-1} Mpc^{-1} throughout this Letter. We use the AB photometric system for optical magnitudes.

2. OBSERVATIONS

2.1. *Optical Deep Imaging*

We have carried out a very deep optical imaging survey in the SDF centered at $\alpha = 13^{\mathrm{h}}24^{\mathrm{m}}38\overset{\mathrm{s}}{.}9$ and $\delta = +27°29'25\overset{''}{.}9$ (J2000.0) by using Suprime-Cam (Miyazaki et al. 2002), which consists of 5 × 2 CCDs of 2k × 4k pixels with a pixel scale of $0\overset{''}{.}202$ pixel^{-1}, on the 8.2 m Subaru Telescope (Kaifu et al. 2000; Iye et al. 2004). The observations were made with five broad passband filters, B, V, R_{C}, i', and z', and two narrow passband filters, NB816 and NB921. The central wavelengths and the half-widths of the transmittance of the two narrow passband filters are $(\lambda_c, \Delta\lambda_{\mathrm{FWHM}}) = (8150$ Å, 120 Å) and

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TABLE 1
A Summary of Optical Imaging Observations

Band	Exposure Time (s)	m_{AB}(lim)[a]
B	35,700	28.45
V	20,400	27.74
R_C	36,000	27.80
i'	48,060	27.43
z'	30,240	26.62
NB816	36,000	26.63
NB921	53,940	26.54

[a] Limiting magnitude (AB) for a 3 σ detection on a 2.″0 diameter aperture.

(9196 Å, 132 Å); see Ajiki et al. (2003) and Kodaira et al. (2003) for more details. The data were collected in several observing runs during a period between 2001 and 2003. A summary of the imaging observations is given in Table 1.

The individual CCD data were reduced and combined using IRAF and the mosaic CCD data reduction software developed by Yagi et al. (2002). The combined images for individual bands were aligned and smoothed with Gaussian kernels to match their seeing sizes. The point-spread function (PSF) FWHM of the final images is 0.″98. Exposure times and limiting magnitudes are listed in Table 1. Photometric calibrations are made using usual standard stars. Source detection and photometry are performed using SExtractor version 2.1.6 (Bertin & Arnouts 1996). Here the z' image is used for the source detection. The effective area of this imaging survey is 761 arcmin^2.

We select candidates of i'-dropout galaxies at $z \sim 6$ imposing the following four criteria on the z'-selected sample: $i' - z' > 1.5$, $z' < 26.1$ (above 5 σ), $B > 28.5$ (below 3 σ), and $R_C > 27.8$ (below 3 σ), where the magnitudes are measured by adopting the aperture size of a 2.″0 diameter. We finally obtain a photometric sample of 48 i'-dropout galaxy candidates at $z \sim 6$.

2.2. *Optical Spectroscopy*

In order to investigate the nature of i'-dropout high-z galaxy candidates found in our optical imaging survey, we have completed optical spectroscopy of nine objects in our 48 i'-dropout sample up to now. We used the Subaru Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) in 2003 May and June. Among the nine objects, we concentrate our discussion on an interesting object, SDF J132440.6+273607, in this Letter. The observational properties of the other i'-dropout sample will be described elsewhere. For the spectroscopy of SDF J132440.6+273607, the 300 lines mm^{-1} grating was used with an order cut filter O58. The wavelength coverage was ~5800–10,000 Å with a pixel resolution of 1.35 Å. The use of a 0.″8 slit gave a spectroscopic resolution of 9.0 Å at 9000 Å that is measured by atmospheric OH airglow lines. This corresponds to the spectral resolution of $R \simeq 1000$. The spatial sampling was 0.″31 per resolution element as we adopted 3 pixel on-chip binning. We obtained seven 1800 s exposure frames for SDF J132440.6+273607. Typical seeing size was 0.″4–0.″6 during the observation. We also obtained the spectra of spectroscopic standard stars Hz 44 and Feige 34 for flux calibration.

3. RESULTS

As mentioned above, SDF J132440.6+273607 was selected by its red $i' - z'$ color, i.e., so-called i'-dropout selection. Indeed this object is not detected above the 3 σ level on the B, V, R_C, i', and NB816 images. SDF J132440.6+273607 is clearly detected in the z' and NB921 images; the 2.″0 aperture magnitudes are $z' = 25.66$ mag and NB921 = 26.20 mag. Since the 3 σ limiting magnitude of i' is $i'_{\rm lim} = 27.43$ mag, SDF J132440.6+273607 has a color of $i' - z' > 1.77$, satisfying our criterion for the i'-dropout selection, $i' - z' > 1.5$. The optical thumbnail images are shown in Figure 1. The image size of SDF J132440.6+273607 in FWHM is 5.8 pixels or 1.″1 in the z'-band image and 6.0 pixels or 1.″2 in the NB921-band image, respectively. Both of these two images may be only marginally larger than the PSF size.

In Figure 2, we show the sky-subtracted optical position-velocity spectrogram and sky-subtracted one-dimensional spectrum of SDF J132440.6+273607, obtained by FOCAS on Subaru. The aperture size to extract the one-dimensional spectrum is 5 binned pixels (1.″6). We can see a prominent single emission line whose peak is at 8909 Å and no significant continuum emission in the whole of the covered wavelength range. The spectral feature seen at ~8885 Å is a residual of the sky subtraction. The observed velocity width of the emission line is ~8 Å in FWHM, roughly comparable to the instrumental width. However, we can see a clear asymmetric feature below the half-maximum of the emission line, i.e., a very prominent redward tail that extends up to ~8930 Å. This asymmetry and the photometric property strongly suggest that the detected emission line is the Lyα emission and that SDF J132440.6+273607 is at $z = 6.33$. Note that this object is thought not to be an emission-line object at lower redshift, i.e., an Hα emitter at $z \sim 0.36$, an [O III] λ5007 emitter at $z \sim 0.78$, or an Hβ emitter at $z \sim 0.83$. This is because there is no emission line in the covered wavelength range other than the prominent emission at 8909 Å. We cannot completely deny the possibility that SDF J132440.6+273607 is a [O II] λ3727 emitter at $z \sim 1.39$, because the [O II] λ3727 doublet cannot be resolved by our observation (the expected wavelength separation of the [O II] doublet is 6.7 Å). However, this does not seem plausible because the observed red tail or shoulder of the detected emission line is hard to be understood if the emission line is [O II] λ3727. Therefore, taking both the photometric and the spectroscopic properties into account, we conclude that SDF J132440.6+273607 is a strong Lyα emitter without strong UV stellar continuum emission at $z = 6.33$. The observed Lyα flux is $(4.0 \pm 0.1) \times 10^{-17}$ ergs s^{-1} cm^{-2}, where the slit loss is not

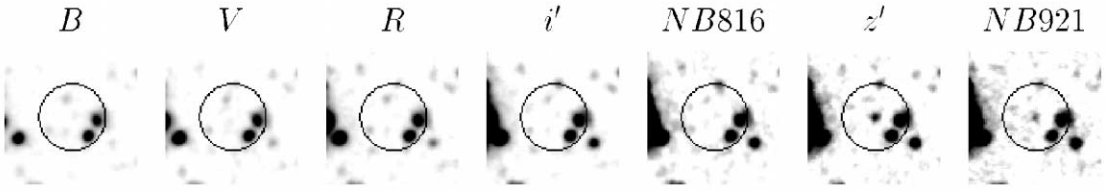

Fig. 1.—Thumbnail images of SDF J132440.6+273607. The square regions around SDF J132440.6+273607 in the B, V, R_C, i', NB816, z', and NB921 images are shown from left to right. Panel and circle sizes are 16″ and 8″, respectively.

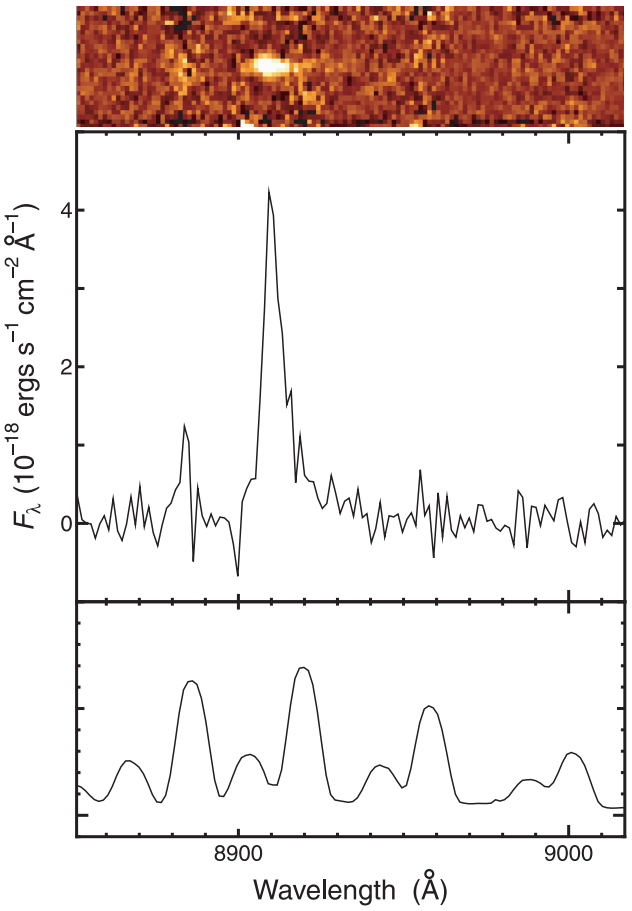

FIG. 2.—Sky-subtracted optical position-velocity spectrogram (*top*) and one-dimensional spectrum (*middle*) of SDF J132440.6+273607 obtained with FOCAS on Subaru. Spectrum of the sky emission is also shown in the bottom panel. The spatial size of the displayed area in the top panel is 8″.1.

taken into account. The Lyα luminosity is thus calculated to be 1.8×10^{43} ergs s^{-1}.

On the basis of the Lyα flux obtained by the spectroscopy, we can derive a Lyα-corrected z' magnitude, $z'_{\rm cor} = 26.16$ mag, which is very close to the NB921 magnitude. Since our i'-dropout search is complete only down to $z' = 25.93$ mag, we could not pick up SDF J132440.6+273607 as an i'-dropout object if there were no strong Lyα emission; i.e., $i' - z'_{\rm cor} > 1.27$, which does not satisfy our i'-dropout criterion ($i' - z' > 1.5$). Then we focus on the depressed NB921 magnitude compared to the z' magnitude; i.e., $z' - {\rm NB921} = -0.54$ mag. If we assume that the depression of the NB921 magnitude is caused only by the contribution of the Lyα emission in the z' band, the required flux of the Lyα emission is $(4.2 \pm 2.2) \times 10^{-17}$ ergs s^{-1} cm^{-2}. This is consistent with the spectroscopically measured Lyα flux, where we assume that all of the NB921 flux is attributed to the stellar UV continuum emission. This assumption leads to the UV continuum flux density of $(4.3 \pm 1.0) \times 10^{-20}$ ergs s^{-1} cm^{-2} Å^{-1}, which is consistent with the nondetection of the continuum emission in our optical spectroscopy of SDF J132440.6+273607 (Fig. 2).

4. DISCUSSION

As presented in the last section, our spectroscopic observation discloses that SDF J132440.6+273607 is a strong LAE with only faint UV stellar emission, despite the fact that it has been originally selected as an i'-dropout galaxy candidate by its red $i' - z'$ color. This LAE is thought to be an actively star-forming galaxy, although we cannot completely reject the possibility that it is a narrow-line QSO. Although the stellar continuum emission is not detected in our spectroscopy, we can estimate the equivalent width of the Lyα emission based on the NB921 data. The photometrically determined Lyα equivalent width of SDF J132440.6+273607 is ${\rm EW_{obs}(Ly\alpha)} = 980$ Å. We then obtain the equivalent width at the rest frame: ${\rm EW_0(Ly\alpha)} = 130$ Å. The derived equivalent width is very large as a broadband-selected galaxy, since a very small fraction of LBGs at $z \sim 3$ show ${\rm EW_0(Ly\alpha)} > 100$ Å (e.g., Steidel et al. 1999; Shapley et al. 2003). Rather, this extremely large equivalent width seems more similar to the narrowband-selected galaxies (e.g., Malhotra & Rhoads 2002; Ajiki et al. 2003; Hu et al. 2004). Hu et al. (2004) recently found a number of LAEs with ${\rm EW_0(Ly\alpha)} > 100$ Å at $z \sim 5.7$ by using a narrow-passband filter. Note that LBGs and LAEs do not necessarily have completely distinct properties such as ${\rm EW_0(Ly\alpha)}$ because they are defined just by their selection method. However, it is not clear how these two populations overlap or how different statistically, especially at the very high-z universe where the number of galaxies that have been investigated by spectroscopic observations is very small. Spectroscopic observations on a large number of high-z galaxies are also necessary to investigate whether or not the ${\rm EW_0(Ly\alpha)}$ frequency distribution depends on redshift, which is also a very interesting issue. Forthcoming intensive spectroscopic observations for high-z galaxies will hopefully solve these problems.

Our finding of SDF J132440.6+273607 naturally leads to the following question: Is this object a very peculiar object, or does any photometrically constructed i'-dropout sample generally contain a lot of galaxies with only faint UV stellar continuum? In order to investigate this issue, we focus on the photometrically selected 48 i'-dropout LBG candidates in SDF. In Figure 3, we show the $z' - {\rm NB921}$ colors of the i' dropout LBG candidates as functions of the z' magnitude and the $i' - z'_{\rm cor}$ color. The NB921 depression of SDF J132440.6+273607 is $z' - {\rm NB921} = -0.54$ as mentioned above, whose statistical significance is roughly $\sim 2\ \sigma$. Interestingly, there are three other i'-dropout galaxy candidates that show significant NB921 depression above the $3\ \sigma$ level (objects b, c, and e in Fig. 3).

There are three possibilities for such NB921-depressed, i'-dropout high-z galaxy candidates. The first possibility is the LAE at $6.0 \lesssim z \lesssim 6.5$ that corresponds to 8510 Å $\lesssim \lambda_{\rm Ly\alpha} \lesssim$ 9110 Å, just similar to the case of SDF J132440.6+273607. In this redshift range, the Lyα emission falls only in the z' band and not in the NB921 one, which results in the NB921 depression. The second possibility is the "NB921-dropout LBG"; i.e., the LBGs at $z \gtrsim 6.6$. In this case, the original categorization as i'-dropout LBGs is not wrong because the objects show the UV stellar continuum with a significant Lyman break. The third possibility is the i'-dropout galaxy with a significant absorption feature at the NB921 range, although it is not clear whether or not such an object really exists in such a high-redshift universe. In order to investigate these ideas further, we plot the expected colors of high-z galaxies with a strong Lyα emission on the $z' - {\rm NB921}$ versus $i' - z'$ two-color diagram (Fig. 3). Here we use the galaxy evolution model of Bruzual & Charlot (2003) by assuming that the star formation rate (SFR) of model galaxies is proportional to $\exp(-t/\tau)$, where $\tau = 1$ Gyr and $t = 1$ Gyr are adopted. Here we examine only three cases, i.e., ${\rm EW_0(Ly\alpha)} = 65$, 130, and 260 Å. The NB921 depression of -0.2, -0.6, and -1.0 mag can be realized for the cases of

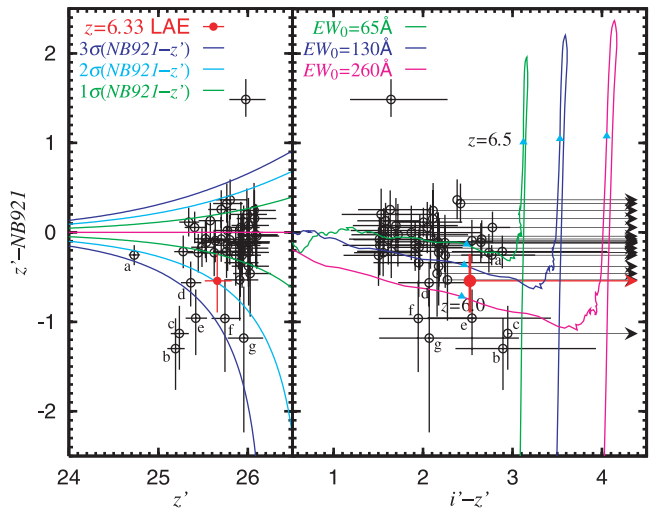

FIG. 3.—*Left*: Color of z' − NB921 of our 48 i'-dropout high-z galaxy candidates as a function of the z' magnitude. The error bars denote 1 σ uncertainties. The data of SDF J132440.6+273607 are marked by a red circle. The NB921-depressed objects with a greater than 2 σ significance are labeled from a to g, sorted in order of the z' magnitude. The magenta, green, light blue, and deep blue lines denote 0 σ, 1 σ, 2 σ, and 3 σ uncertainties of the color of z' − NB921, respectively. The lower direction in this diagram means a depression of the NB921 flux compared to the z' flux. *Right*: Same as the left panel, but shown as a function of $i' - z'$ color. For the data with only upper limited $i' - z'$ colors, an arrow is given. The NB921-depressed objects with a greater than 2 σ significance are also labeled in this panel. The green, blue, and magenta lines denote the expected color of model galaxies with EW(Lyα)$_0$ = 65, 130, and 260 Å, respectively.

EW$_0$(Lyα) = 65, 130, and 260 Å for the first possibility. On the other hand, more significant NB921 depression appears for the second possibility. As for the second possibility, a very red color of $i' - z' > 3$ is also expected. However, an extremely deep i' image is required to discriminate these possibilities clearly. Since the two NB921-depressed i'-dropout objects with $i' - z' \sim 3$ may be NB921-dropout galaxies, a follow-up spectroscopic observation will be very interesting to access galaxies at $z \gtrsim 6.6$.

Here we discuss the star-forming activity in SDF J132440.6+273607. The Lyα flux of this object measured by our spectroscopy is 4.0×10^{-17} ergs s^{-1} cm^{-2}, which corresponds to the Lyα luminosity of 1.8×10^{43} ergs s^{-1}. We can estimate the SFR by using the following relation: SFR(Lyα) = $9.1 \times 10^{-43} L$(Lyα) $M_\odot$ yr^{-1} (Kennicutt 1998; Brocklehurst 1971). We then obtain SFR(Lyα) $\simeq 16\ M_\odot$ yr^{-1}. This is a lower limit because no correction was made for possible absorption effects on the Lyα emission. We can also estimate the SFR by the luminosity of the UV stellar continuum by adopting the following relation: SFR(UV) = $1.4 \times 10^{-28} L_\nu\ M_\odot$ yr^{-1} (Kennicutt 1998). By using the UV continuum flux density measured from the NB921 magnitude, f_ν(NB921) = 1.2×10^{-30} ergs s^{-1} cm^{-2} Hz^{-1}, we obtain SFR(UV$_{1255}$) $\simeq 10.4\ M_\odot$ yr^{-1}. One of the reasons that SFR(UV$_{1255}$) is smaller than SFR(Lyα) may be that SFR(UV) would be underpredicted for objects with a very large EW$_0$(Lyα). This is because it is difficult for such a huge EW$_0$(Lyα) to be created by a continuous star formation with a normal initial-mass function, which is assumed in the above relation between the SFR and the luminosity of the UV stellar continuum. Schaerer (2000) presented that SFR(UV) is underestimated for star-forming galaxies with an age of less than 10^8 yr. Taking all of the above considerations into account, we conclude that the SFR of SDF J132440.6+273607 is greater than 16 $M_\odot$ yr^{-1}. Since there may be a large number of objects with large EW$_0$(Lyα) as suggested by Figure 3, systematic spectroscopic studies on i'-dropout galaxies are crucial to understand the star-forming activities of galaxies at $z \gtrsim 6$, which is a very important epoch in relation to the cosmic reionization.

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