

High-redshift Ly α emitters with a large equivalent width

Properties of i' -dropout galaxies with an NB921-band depression in the Subaru deep field

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ABSTRACT

We report new follow-up spectroscopy of i' -dropout galaxies with an NB921-band depression found in the Subaru Deep Field. The NB921-depressed i' -dropout selection method is expected to select galaxies with large equivalent-width Ly α emission over a wide redshift range, $6.0 \lesssim z \lesssim 6.5$. Two of four observed targets show a strong emission line with a clear asymmetric profile, identified as Ly α emitters at $z = 6.11$ and 6.00 . Their rest-frame equivalent widths are 153 \AA and 114 \AA , which are lower limits on the intrinsic equivalent widths. Through our spectroscopic observations (including previous ones) of NB921-depressed i' -dropout galaxies, we identified 5 galaxies in total with a rest-frame equivalent width larger than 100 \AA at $6.0 \lesssim z \lesssim 6.5$ out of 8 photometric candidates, which suggests that the NB921-depressed i' -dropout selection method is possibly an efficient way to search for Ly α emitters with a large Ly α equivalent width, in a wider redshift range than with usual narrow-band excess techniques. By combining these findings with our previous observational results, we infer that the fraction of broad-band selected galaxies having a rest-frame equivalent width larger than 100 \AA is significantly higher at $z \sim 6$ (the cosmic age of ~ 1 Gyr) than that at $z \sim 3$ (~ 2 Gyr), being consistent with the idea that the typical stellar population of galaxies is significantly younger at $z \sim 6$ than that at $z \sim 3$. The NB921-depressed i' -dropout galaxies may be interesting candidates for hosts of massive, zero-metallicity Population III stars.

Key words. cosmology: early universe – galaxies: evolution – galaxies: formation – galaxies: individual: J132345.6+271701 – galaxies: individual: J132519.4+271829 – galaxies: starburst

1. Introduction

Observational searches for high- z galaxies have progressed a lot in this decade. Thanks to large telescopes such as Subaru, VLTs, and Keck, a few dozen galaxies at $6 < z < 7$ have been spectroscopically confirmed so far (Hu et al. 2002; Kodaira et al. 2003; Cuby et al. 2003; Rhoads et al. 2004; Kurk et al. 2004; Nagao et al. 2004, 2005a; Taniguchi et al. 2005; Stern et al. 2005; Kashikawa et al. 2006). Statistical properties of these high- z galaxies, such as their luminosity function and their correlation function provide information on galaxy evolution, the cosmic star-formation rate, and the re-ionization history of the universe.

In addition to statistical properties, properties of individual galaxies at high redshift also shed light on galaxy evolution. In particular, the equivalent width (EW) of the Ly α emission provides clues on the stellar population of high- z galaxies, for which it is generally difficult to investigate stellar spectral features due to the limited observational sensitivity of currently

available instruments. Malhotra & Rhoads (2002) present their theoretical estimates that large Ly α equivalent widths ($EW_0 \gtrsim 150 \text{ \AA}$ for a Salpeter initial-mass function (IMF) and $EW_0 \gtrsim 240 \text{ \AA}$ for a flatter IMF) suggest a very young ($< 10^7$ years) stellar population (e.g., Tumlinson et al. 2003). More interestingly, it has been theoretically predicted that galaxies hosting zero-metallicity stars (or Population III stars, hereafter PopIII) should show huge Ly α equivalent widths that could reach up to $EW_0 \sim 1000 \text{ \AA}$ (e.g., Schaerer 2002, 2003; Tumlinson et al. 2003; Scannapieco et al. 2003). Therefore, the frequency distribution of the Ly α equivalent width in high- z galaxies and its evolution with redshift are important for understanding the early stages of galaxy evolution (e.g., Shimasaku et al. 2006; Ando et al. 2006).

However, observational study of the Ly α equivalent width in galaxies at high redshift is not straightforward. Although Malhotra & Rhoads (2002) report that more than half of their

Table 1. Photometric properties of NB921-depressed i' -dropout galaxies in the Subaru Deep Field.

No.	Name	Redshift	i'^a	z'^a	NB921 ^a	$z' - \text{NB921}$	Ref. ^b
1	SDF J132345.6+271701	6.11	>27.9	25.24	26.37	-1.13	1
2	SDF J132422.0+271742	–	>27.9	25.96	>27.0	<-1.0	1
3	SDF J132426.5+271600	6.03	27.43	25.36	25.92	-0.56	2
4	SDF J132440.6+273607	6.33	>27.9	25.66	26.20	-0.54	3
5	SDF J132442.5+272423	6.04	27.69	25.74	26.71	-0.97	2
6	SDF J132519.4+271829	6.00	>27.9	25.42	26.38	-0.96	1
7	SDF J132521.6+274229	–	>27.9	25.19	26.49	-1.30	–
8	SDF J132526.1+271902	–	27.50	24.73	24.98	-0.25	1

^a AB magnitude with a 2'' aperture photometry. Lower limits are 2σ limiting magnitudes.

^b References. 1: This work, 2: Nagao et al. (2005a), 3: Nagao et al. (2004).

sample of 150 Ly α emitters (LAEs) have Ly α equivalent width larger than 240 Å, their analysis is only based on photometric data. Especially for LAEs at $z \sim 6.5$ (which corresponds to the window between airglow emission at $\lambda \sim 9200$ Å), the z' -band magnitude is contaminated by the Ly α emission, so is an unreliable measure of continuum flux density. Even for the sample with spectroscopic data, the continuum emission of LAEs selected by using narrow-band magnitude is generally too faint to be detected in their spectra.

We are exploiting a new selection method for identifying LAEs with a large Ly α equivalent width, that is, i' dropout with a “depression” in the narrow-band filter NB921 (see Sect. 2) (Nagao et al. 2004, 2005a). If galaxies are at $6.0 < z < 6.5$, their redshifted Ly α emission is expected at $8500 \text{ \AA} \lesssim \lambda_{\text{obs}} \lesssim 9100 \text{ \AA}$. In this case, the narrow-band magnitude at $\lambda \sim 9200 \text{ \AA}$ has no contamination from Ly α emission and thus only traces the continuum, while the z' -band magnitude is enhanced by the contribution of the strong Ly α emission and thus the narrow-band magnitude is depressed with respect to the z' -band magnitude. Therefore this selection method finds galaxies with a large Ly α equivalent width in a wide redshift range, $6.0 < z < 6.5$. Note that this selection method does not select Galactic late-type stars, unlike the usual i' -dropout selection (see Nagao et al. 2005a, for more details).

In this paper, we report new spectroscopy for a sample of NB921-depressed i' -dropout galaxies. Throughout this paper, we adopt a cosmology with $(\Omega_{\text{tot}}, \Omega_{\text{M}}, \Omega_{\Lambda}) = (1.0, 0.3, 0.7)$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Target selection and observation

We selected our i' -dropout galaxy sample from the public catalog of the Subaru Deep Field (SDF) imaging survey (Kashikawa et al. 2004), which contains broad-band (B , V , R_C , i' , and z') and narrow-band photometric data (NB816 and NB921; the central wavelengths and the half-widths of the transmittance are (8150 Å, 120 Å) and (9196 Å, 132 Å), respectively). The adopted criteria to select the i' -dropout galaxy sample are:

- $z' < 26.1$ (i.e., above 5σ background error);
- $i' - z' > 1.5$;
- $B > 28.5$ (below 3σ background error); and
- $R_C > 27.8$ (below 3σ background error).

Among the 48 selected i' -dropout galaxies in SDF, we identified an object whose $z' - \text{NB921}$ is less than -2σ of the sky noise as an “NB921-depressed i' -dropout galaxy”. Here “sky noise” refers to the error on the $z' - \text{NB921}$ color due to sky noise in the z' and NB921 filters. The $z' - \text{NB921}$ versus z' color–magnitude

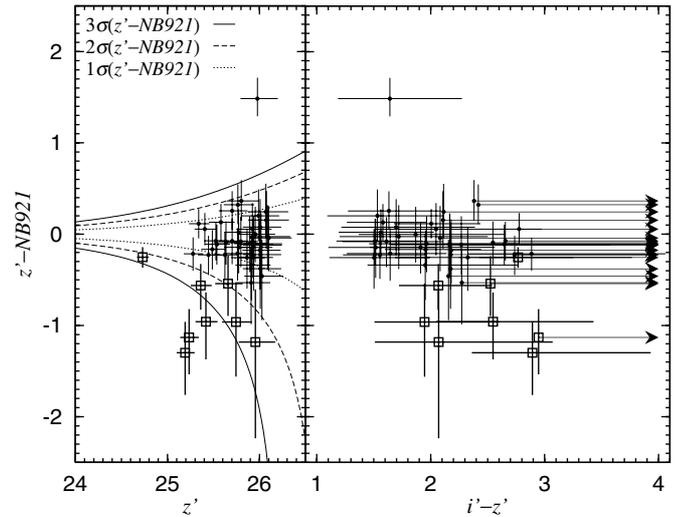


Fig. 1. Color–magnitude diagram of $z' - \text{NB921}$ vs. z' (left) and $z' - \text{NB921}$ vs. $i' - z'$ color–color diagram (right). The 48 i' -dropout objects detected in the SDF are plotted. The NB921-depressed i' -dropout objects are shown by open squares, and the other i' -dropout objects are shown by filled circles. Error bars denote 1σ uncertainty in the observed color or magnitude. In the left panel, 1, 2, and 3σ uncertainties of the $z' - \text{NB921}$ color are shown by the dotted, dashed, and solid lines, respectively.

diagram and the $z' - \text{NB921}$ versus $i' - z'$ color–color diagram are shown in Fig. 1. Eight i' -dropout galaxies satisfy this criterion and thus are classified as NB921-depressed i' -dropout galaxies. Note that the significance level of the NB921 depression of one of the eight NB921-depressed i' -dropout galaxies (SDF J132440.6+273607; Nagao et al. 2004) is slightly less than 2σ . However we included this object in our NB921-depressed i' -dropout galaxy sample. The object names and the photometric properties of this sample are summarized in Table 1, and the thumbnails of these objects are shown in Fig. 2.

We have already obtained optical spectra of 3 NB921-depressed i' -dropout galaxies; SDF J132440.6+273607 (#4; $z = 6.33$; Nagao et al. 2004), SDF J132426.5+271600, and SDF J132442.5+272423 (#3 and #5; $z = 6.03$ and 6.04 ; Nagao et al. 2005a). Among the remaining 5 NB921-depressed i' -dropout galaxies, we observed 4 objects on 26 April 2006 (UT). This spectroscopy was carried out with the Faint Object Camera And Spectrograph (FOCAS; Kashikawa et al. 2002) on the Subaru telescope (Iye et al. 2004) in its multi-object slit mode. The four objects were chosen to optimize the slit mask design (by also accomodating several other objects observed within the broader context of the SDF project). The 175 lines mm^{-1}

echelle grating and the SDSS z' filter were used. The resulting wavelength coverage was $\sim 8300\text{--}10\,000\text{ \AA}$, with a dispersion of $\sim 0.95\text{ \AA pixel}^{-1}$. The adopted slit width was 0.83 arcsec , giving a spectral resolution of $R \sim 1500$ or $\Delta\lambda \sim 6\text{ \AA}$ at $\sim 9000\text{ \AA}$ as measured from the widths of atmospheric OH emission lines. The spatial sampling was 0.31 arcsec per resolution element, as we adopted 3 pixel on-chip binning. The seeing was variable during the observation ($0.5\text{--}1.0\text{ arcsec}$). The total integration times were 7200 s for SDF J132345.6+271701 (#1) and SDF J132422.0+271742 (#2), and 9000 s for SDF J132519.4+271829 (#6) and SDF J132526.1+271902 (#8). Note that the position angle of the slits was set to the North-South direction for all the target objects. Since no neighboring objects are around the target objects (Fig. 2), the detected signal is believed to be from the targets. We also obtained spectra of the spectrophotometric standard star Feige 34 (Oke 1990) for flux calibration. The obtained data were reduced in the standard manner by using IRAF.

3. Results

Among the four observed objects, SDF J132345.6+271701 (#1) and SDF J132519.4+271829 (#6) show a strong emission line in their spectra, whose peak wavelengths are at 8634 \AA and 8512 \AA , respectively. In Figs. 3 and 4, the sky-subtracted position-velocity spectrogram, the extracted one-dimensional spectrum, and the typical sky spectrum are shown for these two objects, respectively. The aperture size used for the extraction of the one-dimensional spectrum is 5 binned pixels ($\sim 1.6\text{ arcsec}$). No continuum emission is detected for either object. Both emission lines show a clear asymmetric profile, i.e., a sharp decline on the blue side and a prominent tail on the red side, which suggests that the observed emission lines are Ly α . Note that if the detected emission line were H β , [O III] $\lambda 5007$ or H α , other rest-frame optical emission line(s) should be seen in the observed wavelength range. If the detected emission line was [O II] $\lambda 3727$, it should be resolved as a doublet emission, since the expected wavelength separation of the redshifted [O II] $\lambda\lambda 3726, 3729$ is $\sim 6\text{ \AA}$ (or ~ 6 pixels), which corresponds to $\sim 210\text{ km s}^{-1}$. Here we assume that the velocity width of the [O II] lines is not very broad; otherwise we could not resolve the [O II] doublet. However our assumption seems valid for normal star-forming galaxies, because the [O II] doublet of some star-forming galaxies in the SDF is indeed resolved in our previous spectroscopic follow-up observations (Shimasaku et al. 2006; Ly et al. 2007). The fact that we see only one strong emission line with an asymmetric profile in each spectrum strongly suggests that we have detected Ly α at $z \sim 6$.

To quantify the asymmetry of the detected emission lines, we calculated two independent parameters; $f_{\text{red}}/f_{\text{blue}}$ and S_w . The former is the ratio between f_{red} and f_{blue} , where f_{red} is the flux at wavelengths longer than the emission-line peak, while f_{blue} is that at shorter wavelengths (Taniguchi et al. 2005; Nagao et al. 2005a; see also Haiman 2002 for a theoretical discussion on the parameter $f_{\text{red}}/f_{\text{blue}}$). The measured ratios are 2.08 ± 0.12 and 2.47 ± 0.30 for SDF J132345.6+271701 (#1) and SDF J132519.4+271829 (#6), respectively. Note that the latter value may be overestimated, since the OH airglow emission on the blue side of the Ly α emission may be over-subtracted (Fig. 4). The $f_{\text{red}}/f_{\text{blue}}$ ratio of both line-detected objects is significantly higher than unity, and also higher than that of most LAEs reported by Taniguchi et al. (2005). This result is consistent with the interpretation that the detected emission lines

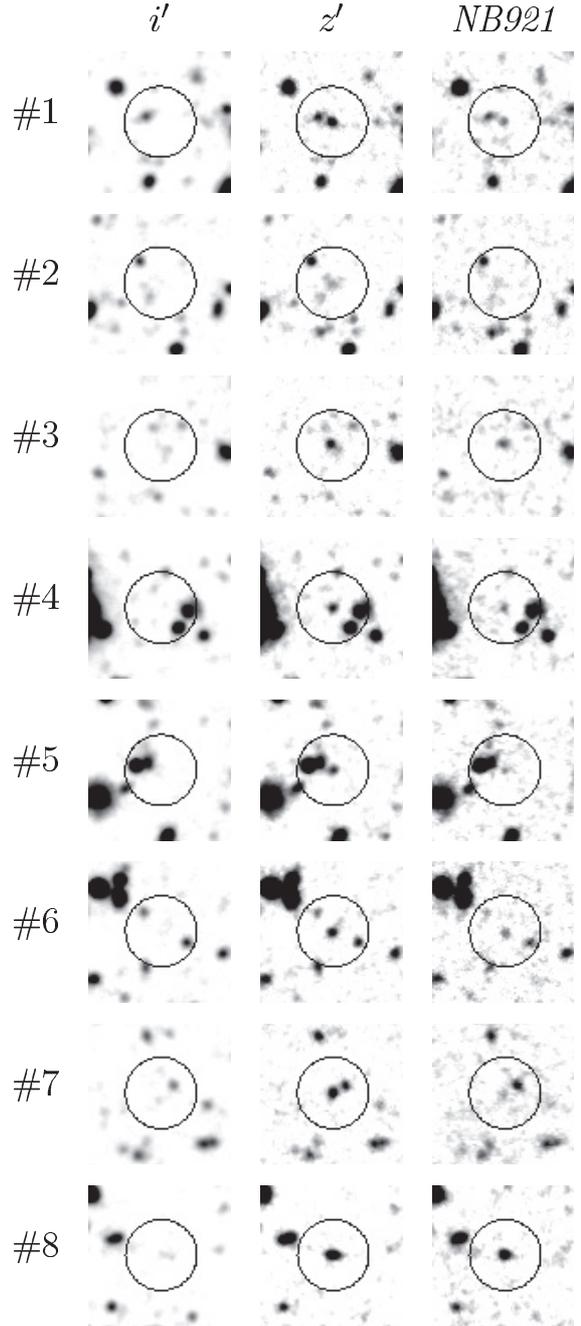


Fig. 2. Thumbnail images of NB921-depressed i' -dropout galaxies. The square regions around each object in the i' , z' , and NB921 images are shown from left to right. The IDs given on the left side of the panels correspond to those in Table 1. The size of panels and the radius of circles are 16 arcsec and 8 arcsec , respectively.

are Ly α . The latter parameter (S_w) is the weighted skewness (Shimasaku et al. 2006; Kashikawa et al. 2006), which is larger for objects with higher asymmetries and/or larger emission-line widths. The calculated values are 4.00 ± 0.22 and 8.72 ± 0.28 for SDF J132345.6+271701 (#1) and SDF J132519.4+271829 (#6), respectively. Since the weighted skewness of emission lines arising from possible low-redshift interlopers generally do not exceed 3 (Kashikawa et al. 2006; see also Shimasaku et al. 2006), the derived values of the weighted skewness are also consistent with the interpretation that the detected emission lines are Ly α . Taking the derived values of $f_{\text{red}}/f_{\text{blue}}$ and S_w for

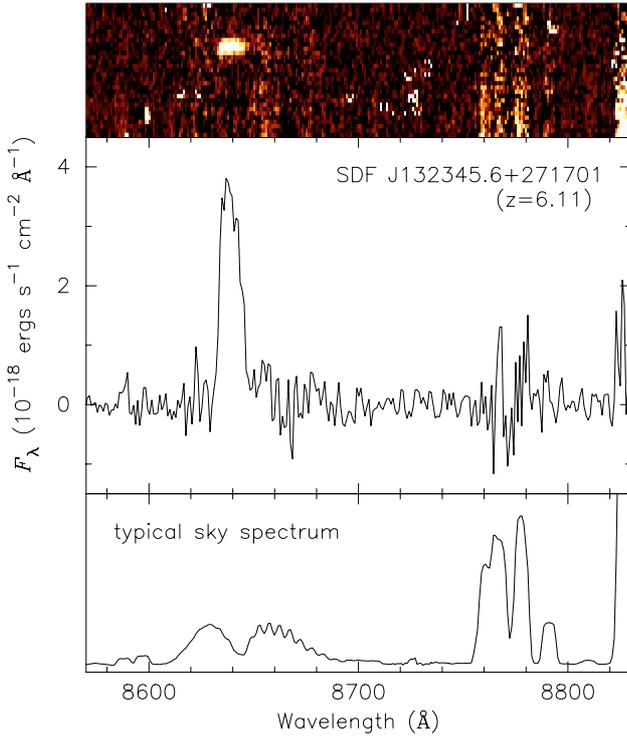


Fig. 3. Sky-subtracted optical position-velocity spectrogram (*top*) and one-dimensional spectrum (*middle*) of SDF J132345.6+271701 (#1) obtained with FOCAS on Subaru. The typical spectrum of the sky emission is also shown in the bottom panel.

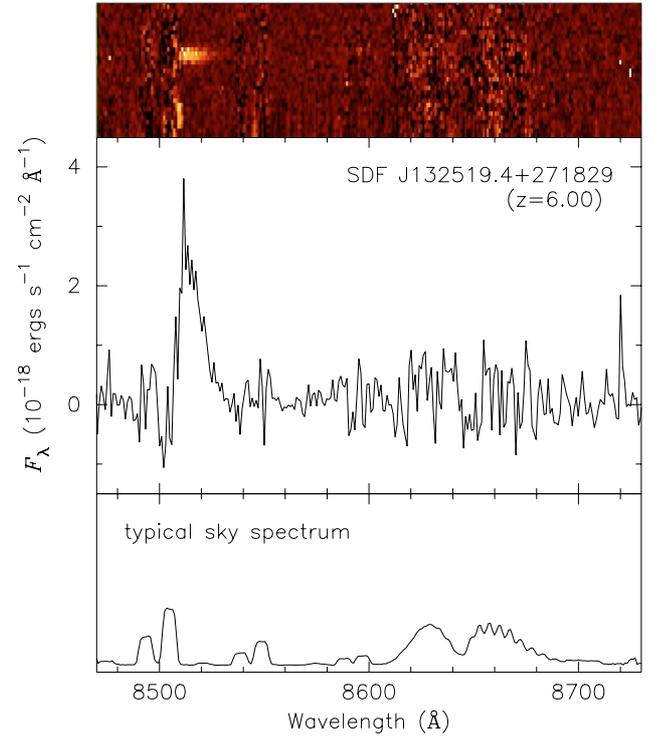


Fig. 4. Same as Fig. 3 but for SDF J132519.4+271829 (#6).

the two line-detected objects into account, we conclude that the detected emission lines are Ly α and, accordingly, that the redshifts of the two objects are 6.11 and 6.00. The observed Ly α fluxes are $(4.5 \pm 0.1) \times 10^{-17}$ erg s^{-1} cm^{-2} and $(3.4 \pm 0.2) \times 10^{-17}$ erg s^{-1} cm^{-2} , without any correction for slit loss. The Ly α luminosities are thus calculated to be 1.9×10^{43} erg s^{-1} and 1.3×10^{43} erg s^{-1} . The measured emission-line widths in *FWHM* are $11.3^{+1.1}_{-1.6}$ \AA and $8.6^{+1.9}_{-5.7}$ \AA . These values correspond to $9.6^{+1.3}_{-2.0}$ \AA and $6.2^{+2.4}_{-6.2}$ \AA , or velocity widths of 330^{+50}_{-70} km s^{-1} and 220^{+80}_{-220} km s^{-1} , respectively, after correction for the instrumental broadening effect. Here the absorption effects are not taken into account.

Adopting these redshifts, the Nv λ 1240 emission line would be expected at 8816 \AA and 8680 \AA for SDF J132345.6+271701 (#1) and SDF J132519.4+271829 (#6), respectively, if these two objects were active galactic nuclei (AGNs). However, no emission-line features are seen at the corresponding wavelengths (see Figs. 3 and 4). The 3σ upper limits for the N v emission are 5.7×10^{-18} erg s^{-1} cm^{-2} and 6.9×10^{-18} erg s^{-1} cm^{-2} for these two objects, assuming the same velocity widths as Ly α . However, we cannot completely rule out the possibility that one or both of these two objects are AGNs, since some high- z narrow-line radio galaxies show very weak N v compared with Ly α (e.g., De Breuck et al. 2000; Nagao et al. 2006; see also Malkan et al. 1996).

As mentioned in Sect. 1, it is sometimes very difficult to estimate the Ly α equivalent width because measuring the continuum in the low-S/N spectra is very difficult. However, we can determine the flux density of the continuum emission for those two galaxies from the NB921-band magnitude, since the NB921-band flux does not contain Ly α flux, unlike the case of LAEs selected by the NB921 excess (e.g., Kodaira et al. 2003;

Taniguchi et al. 2005). The NB921-band magnitudes of the two galaxies are 26.37 mag and 26.38 mag, which correspond to the flux densities of $f_\lambda = (4.1 \pm 1.1) \times 10^{-20}$ erg s^{-1} cm^{-2} \AA^{-1} and $(4.2 \pm 1.2) \times 10^{-20}$ erg s^{-1} cm^{-2} \AA^{-1} at the wavelengths of the Ly α peak, respectively. Then the rest-frame equivalent widths of the Ly α emission are calculated to be 153 ± 42 \AA and 114 ± 32 \AA for SDF J132345.6+271701 (#1) and SDF J132519.4+271829 (#6), assuming a flat UV continuum. Note that if the detected emission lines were [O II], the rest-frame equivalent widths would be 470 \AA and 349 \AA . These high values are quite rare for [O II] emitters (e.g., Ajiki et al. 2006), which also supports our interpretation that the detected emission lines are Ly α .

The obtained spectroscopic properties are summarized in Table 2. In the same table, properties of our previous spectra (Nagao et al. 2004, 2005a) are also given for the reader's convenience. Note that there are no spectral features in the obtained spectra of SDF J132422.0+271742 (#2) and SDF J132526.1+271902 (#8). We will discuss these non-detections briefly in the next section. In this table, we also give the minimum $EW_0(\text{Ly}\alpha)$ that can be detected by the NB921-depressed i' -dropout method for galaxies with the redshift and the z' -band magnitude of each NB921-depressed i' -dropout galaxy. We will discuss this quantity in Sect. 4.1.

4. Discussion

4.1. The success rate of the NB921-depressed i' -dropout selection method

In this observing run we observed four NB921-depressed i' -dropout galaxies, and found strong emission lines in two of them. Could the two remaining emission-line undetected objects also be strong LAEs at $6.0 < z < 6.5$, as expected by the NB921-depressed i' -dropout selection? Since high- z Ly α emission shows a clear asymmetric profile and especially a

Table 2. Spectroscopic properties of NB921-depressed i' -dropout galaxies in the Subaru Deep Field.

No.	Redshift	$F(\text{Ly}\alpha)^a$ (10^{-17} ergs/s/cm 2)	$FWHM^b$ (km s $^{-1}$)	$EW_0(\text{Ly}\alpha)^c$ (\AA)	$EW_0^{\min}(\text{Ly}\alpha)^d$ (\AA)	Ref. ^e
1	6.11	4.5 ± 0.1	330	153	72	1
3	6.03	3.6 ± 0.3	410	94	83	2
4	6.33	4.0 ± 0.1	— ^f	130	133	3
5	6.04	4.5 ± 0.3	220	236	146	2
6	6.00	3.4 ± 0.2	220	114	90	1

^a No correction for the slit loss.

^b Corrected for the instrumental broadening ($FWHM = 6.2 \text{ \AA}$).

^c Not corrected for the absorption effects due to the Ly α -forest, and thus lower limits on the intrinsic equivalent width.

^d Minimum $EW_0(\text{Ly}\alpha)$ that can be selected by the NB921-depressed i' -dropout method for galaxies with the redshift and the z' -band magnitude of each NB921-depressed i' -dropout galaxy, estimated by assuming a flat UV slope (see Sect. 4.1).

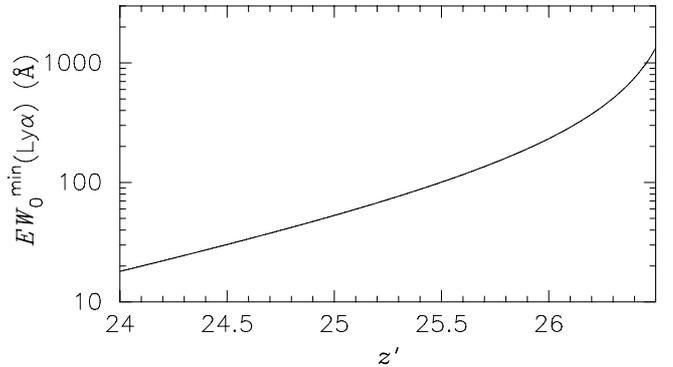
^e References. 1: This work, 2: Nagao et al. (2005a), 3: Nagao et al. (2004).

^f Observed line width is comparable to the instrumental broadening width.

prominent tail toward the red side of the emission-line peak, the Ly α emission of LAEs is expected to be resolved with the current wavelength resolution $R \sim 1500$. This means that the Ly α emission should be found, even when the redshifted Ly α line falls on an isolated (i.e., unresolved) OH airglow emission line. However, the Ly α detection would be difficult when the Ly α emission line falls on blended OH lines, such as the lines at $8760 \text{ \AA} \lesssim \lambda \lesssim 8780 \text{ \AA}$ seen in the bottom panel of Fig. 3 (which corresponds to a redshift range $6.21 \lesssim z \lesssim 6.22$). SDF J132422.0+271742 (#2) has z' and NB921 magnitudes, which are the faintest among the NB921-depressed i' -dropout galaxy sample. Thus the non-detection of the emission line might be simply due to an insufficient integration time. On the contrary, the z' and NB921 magnitudes of SDF J132526.1+271902 (#8) are the brightest among the NB921-depressed i' -dropouts. Since this object is so bright, it is selected as an NB921-depressed object in spite of its small amount of the NB921 depression, $z' - \text{NB921} = -0.25$. Therefore the expected Ly α equivalent width of this object is so small (which is estimated to be $\sim 50 \text{ \AA}$ in the rest frame by assuming $z = 6.0$ and a flat UV slope) that the detection of Ly α could be more difficult than the other NB921-depressed i' -dropout galaxies. Taking all of these considerations into account, we cannot reject the possibility that the two Ly α non-detected objects are also LAEs at $6.0 < z < 6.5$. Deeper spectroscopic observations are necessary to investigate these objects further.

Therefore, the “success rate” of the NB921-depressed i' -dropout selection method (i.e., the probability that this selection identify LAEs at $6.0 < z < 6.5$ correctly) is between 5/8 (63%) and 8/8 (100%). The rest-frame Ly α equivalent width of all of the five Ly α -detected objects is quite large, at least $\sim 100 \text{ \AA}$, as also expected by the selection method (see Table 2). It should be mentioned here that, as discussed in Nagao et al. (2005a), the NB921 depression is not expected in Galactic late-type stars and thus this selection method is not contaminated by stars, unlike a simple i' -dropout sample (see, e.g., Stanway et al. 2004).

Here we discuss the limiting $EW(\text{Ly}\alpha)$ of the NB921-depressed i' -dropout selection method. This selection technique does not select only LAEs with a large $EW_0(\text{Ly}\alpha)$ in principle, because the selection criterion on the NB921 depression is based on the sky error as described in Sect. 2. This is different from the usual LAE surveys based on the narrow-band excession, for which a certain excess magnitude is generally used instead of the sky noise. Therefore

**Fig. 5.** Minimum $EW_0(\text{Ly}\alpha)$ that can be selected by the NB921-depressed i' -dropout method [$EW_0^{\min}(\text{Ly}\alpha)$] as a function of the z' -band magnitude, estimated by assuming $z = 6.0$ and a flat UV slope.

the NB921-depressed i' -dropout method would select LAEs with a relatively small $EW_0(\text{Ly}\alpha)$ if the imaging data were deep enough and accordingly the sky noise was very small. In other words, the minimum $EW_0(\text{Ly}\alpha)$ that can be selected by the NB921-depressed i' -dropout method [hereafter $EW_0^{\min}(\text{Ly}\alpha)$] depends on the magnitude of target galaxies, since the $z' - \text{NB921}$ color of brighter objects is less affected by the sky error with respect to that of fainter objects. To see this effect quantitatively, we show the dependence of $EW_0^{\min}(\text{Ly}\alpha)$ on the z' magnitude for the case of the SDF dataset in Fig. 5, where $z = 6.0$ and a flat UV slope are assumed. It is demonstrated that only LAEs with $EW_0(\text{Ly}\alpha) \geq 100 \text{ \AA}$ are selected among faint galaxies with $z' \geq 25.5$, while LAEs with $EW_0(\text{Ly}\alpha) \sim$ a tens of 10 \AA could be also selected among relatively bright galaxies with $z' \lesssim 25.0$. Note that the latter case corresponds to the case of SDF J132526.1+271902 (#8). To compare $EW_0^{\min}(\text{Ly}\alpha)$ and the detected $EW_0(\text{Ly}\alpha)$ for each NB921-depressed i' -dropout galaxy, we also give $EW_0^{\min}(\text{Ly}\alpha)$ for each set of the redshift and the z' -band magnitude of 5 spectroscopically identified NB921-depressed i' -dropout galaxies in Table 2.

In order to carry out systematic surveys for strong LAEs utilizing the NB921-depressed i' -dropout method, it would be more appropriate to adopt a certain $z' - \text{NB921}$ depression magnitude as a selection criterion rather than using the sky error. The reason for adopting the selection criterion based on the sky noise is that one of our motivations in the photometric selection is to construct a sample of the target objects for our spectroscopic

observations to find candidates for PopIII-hosting galaxies (see Nagao et al. 2005b). Due to the limited observing time, we had to focus on convincing candidates, i.e., objects with a significant NB921 depression with respect to the sky error.

4.2. Implication for the stellar population

The rest-frame Ly α equivalent width of the NB921-depressed i' -dropout galaxies with a Ly α detection (given in Table 2) ranges from 94 Å to 236 Å. Although these values are lower than the “critical value” $EW_0(\text{Ly}\alpha) = 240$ Å above which it cannot be explained by normal stellar populations (e.g., Malhotra & Rhoads 2002), it should be noted that the values we obtained are not corrected for absorption effects. The amount of the Ly α absorption depends on various parameters, including the neutral fraction of the inter-galactic matter (IGM) and the kinematic status of neutral hydrogen within LAEs themselves (e.g., Neufeld 1990; Haiman 2002; Mas-Hesse et al. 2003; Ahn 2004). Here it should be kept in mind that the IGM is not perfectly re-ionized at $z \sim 6$, which is suggested by recent observations of high- z quasars (Fan et al. 2006) and LAEs (Kashikawa et al. 2006). There have been extensive arguments about whether Ly α photons from galaxies at an earlier epoch than the completion of the cosmic re-ionization are observable or not. Some calculations suggest that the Ly α photons from such galaxies are strongly suppressed (e.g., Miralda-Escude 1998; Miralda-Escude & Rees 1998; Loeb & Rybicki 1999) and other theoretical works infer that a large fraction of the Ly α photons can transmit due to cosmological H II regions (e.g., Madau & Rees 2000; Cen & Haiman 2000). Haiman (2002) investigated various parameter dependences of the Ly α transmission fraction for high- z LAEs by taking both the neutral hydrogen within LAEs themselves and the neutral IGM into account. They showed that the ratio of the transmitted Ly α flux to the total (intrinsic) Ly α flux [$F_0(\text{Ly}\alpha)/F_{\text{tot}}(\text{Ly}\alpha)$] is estimated to be $\sim 10\%$ for typical LAEs with a star-formation rate (SFR) $\sim 10 M_\odot \text{ yr}^{-1}$ and $\sim 50\%$ for LAEs with $SFR \sim 100 M_\odot \text{ yr}^{-1}$.

Following this result, we assume $F_0(\text{Ly}\alpha)/F_{\text{tot}}(\text{Ly}\alpha) \sim 0.5$ to correct the absorption effect on the observed Ly α flux rather conservatively, in the sense that the actual $F_0(\text{Ly}\alpha)/F_{\text{tot}}(\text{Ly}\alpha)$ of our spectroscopic sample would be smaller than 0.5 since the SFR is less than $100 M_\odot \text{ yr}^{-1}$ (Nagao et al. 2004, 2005a). See also, e.g., Santos (2002) and Dijkstra et al. (2006) for the justification of our adopted value of $F_0(\text{Ly}\alpha)/F_{\text{tot}}(\text{Ly}\alpha)$. Interestingly, by adopting this assumption, the intrinsic $EW_0(\text{Ly}\alpha)$ for three out of the five spectroscopically identified NB921-depressed i' -dropout galaxies is then expected to exceed the critical value $EW_0(\text{Ly}\alpha) = 240$ Å. This result is consistent with the idea that galaxies at $z \gtrsim 6$ contain young stellar populations, whose age may be younger than $\sim 10^7$ years as discussed by Malhotra & Rhoads (2002); see also Shimasaku et al. (2006).

The huge intrinsic Ly α equivalent width would indicate that the NB921-depressed i' -dropout galaxies may contain a significant number of PopIII stars. Therefore our NB921-depressed i' -dropout galaxy sample offers fascinating targets for observational searches for PopIII stars, which will be an important topic in the forthcoming decade (see, e.g., Jimenez & Haiman 2006). We have already searched for an observational signature in one of the NB921-depressed i' -dropout galaxies, SDF J132440.6+273607 (#4; Nagao et al. 2005b), through He II λ 1640 emission (see, e.g., Tumlinson & Shull 2000; Oh et al. 2001; Schaerer 2002, 2003). Although

the He II λ 1640 emission was not detected in this object, similar observations will provide important constraints on theoretical PopIII models (e.g., Scannapieco et al. 2003; Nagao et al. 2005b).

4.3. Evolution of the Ly α equivalent width distribution

It has been known that narrow-band selected galaxies (e.g., emission-line galaxies) at high redshift tend to have large Ly α equivalent widths, which sometimes exceed the critical value of $EW_0(\text{Ly}\alpha) = 240$ Å (e.g., Malhotra & Rhoads 2002; Shimasaku et al. 2006). However, some broad-band selected high- z galaxies such as Lyman-break galaxies (LBGs) rarely have large Ly α equivalent widths. For instance, at $z \sim 3$ the fraction of LBGs showing $EW_0(\text{Ly}\alpha) > 100$ Å is $\approx 1\%$ of ~ 1000 galaxies (Shapley et al. 2003). Since our sample is also broad-band selected, it is interesting to compare the fraction of galaxies with a large equivalent width to investigate whether the stellar population of galaxies evolves as a function of redshift. At $z \sim 6$, our i' -dropout galaxy sample (48 objects) contains at least 5 galaxies with $EW_0(\text{Ly}\alpha) \gtrsim 100$ Å (here we retain SDF J132426.5+271600 (#3) as a large EW object although its EW is slightly below the criterion). However, z' -band flux of the NB921-depressed i' -dropout galaxies is strongly boosted by the Ly α contamination. After correction for this effect, they may fail to satisfy the i' -dropout criterion, $i' - z' > 1.5$. Indeed if adopting the NB921 magnitude instead of z' as a continuum magnitude at the long side of the Lyman break, SDF J132442.5+272423 (#5) should be removed from the SDF i' -dropout galaxy sample ($i' - \text{NB921} = 0.98$). Therefore we estimate the fraction of i' -dropout galaxies having $EW_0(\text{Ly}\alpha) \gtrsim 100$ Å is $4/48 \approx 8\%$. Note that this estimated fraction is a conservative lower limit, because (1) some Ly α non-detected NB921-depressed i' -dropout galaxies may also have as large an equivalent width as discussed above, and (2) some of the 48 i' -dropout objects may be emission-line galaxies at lower redshift or Galactic late-type stars, since most of the SDF i' -dropout objects have not been confirmed by spectroscopic follow-up observations (see, e.g., Stanway et al. 2004).

The derived lower limit of the fraction of i' -dropout objects having $EW_0(\text{Ly}\alpha) \gtrsim 100$ Å is significantly higher than the value at $z \sim 3$. However, it should be noted that the limiting magnitude of these two samples is different; that is, while the spectroscopic survey of LBGs at $z \sim 3$ by Shapley et al. (2003) reaches down to $R_{\text{AB}} \sim 25.5$, our SDF i' -dropout sample consists of galaxies with $z' < 26.1$. These limiting magnitudes correspond to the absolute UV magnitudes of $M_{1500} = -20.0$ and -20.6 , respectively, and thus the galaxies in the $z \sim 6$ sample are intrinsically brighter with respect to those in the $z \sim 3$ sample, systematically. Recently, Ando et al. (2006) report that the LBGs with a high Ly α equivalent width are rarer in brighter samples than in fainter samples, at $z \gtrsim 5$. Based on their huge number of a LBG spectroscopic sample, Shapley et al. (2003) also reported that the broad-band magnitude of LBGs with a stronger Ly α emission tends to be fainter than that of LBGs with a weaker Ly α emission (or with a Ly α absorption instead of emission; see Table 3 of Shapley et al. 2003).

Therefore, taking the difference in the limiting magnitude between the samples at $z \sim 6$ and at $z \sim 3$ and the dependence of the equivalent width on the luminosity into account, the difference in the fraction of galaxies with $EW_0(\text{Ly}\alpha) \gtrsim 100$ Å between $z \sim 6$ and $z \sim 3$ should be even more significant. Note that the significance may be intrinsically much more if the

IGM effect against the Ly α transmission is stronger at $z \sim 6$ than at $z \sim 3$. This result is consistent with a recent study by Shimasaku et al. (2006) that the fraction of LBGs having $EW_0(\text{Ly}\alpha) \geq 100 \text{ \AA}$ significantly evolves from $z \sim 3$ to $z \sim 6$. All of these results are consistent with the idea that the typical stellar population of galaxies is significantly younger at $z \sim 6$ than that at $z \sim 3$. This may also be consistent with recent findings that the slope of the rest-frame UV continuum of some galaxies is bluer at $z \sim 6$ than the typical UV slope at $z \sim 3$ (e.g., Stanway et al. 2004, 2005; Bouwens et al. 2005; Yan et al. 2005).

5. Summary

In earlier papers we identified 8 NB921-depressed i' -dropout galaxies, which are expected to be strong LAEs at $6.0 \lesssim z \lesssim 6.5$, through the narrow-band and broad-band photometric data of the SDF (Nagao et al. 2004, 2005a). In addition to 3 previously spectroscopically confirmed ones, we found that two other NB921-depressed i' -dropout galaxies are also LAEs with $EW_0(\text{Ly}\alpha) > 100 \text{ \AA}$ at $z = 6.11$ and 6.00 , by new optical spectroscopy. This result, combined with our previous spectroscopic runs, means that at least 5 objects among 8 NB921-depressed i' -dropout galaxies are indeed LAEs having $EW_0(\text{Ly}\alpha) \geq 100 \text{ \AA}$ at $6.0 \lesssim z \lesssim 6.5$; these results suggest that the NB921-depressed i' -dropout selection method is an efficient technique for identifying strong LAEs in a wide redshift range, $6.0 \lesssim z \lesssim 6.5$.

These results also suggest that more than 8% of the i' -dropout galaxies in the SDF have a large Ly α equivalent width of $EW_0(\text{Ly}\alpha) \geq 100 \text{ \AA}$. This contrasts with LBGs at $z \sim 3$, where such strong LAEs are much rarer ($\sim 1\%$). This also implies a strong redshift evolution in the Ly α equivalent-width distribution from $z \sim 6$ to $z \sim 3$, consistent with a stellar population of broad-band selected galaxies, which is significantly younger at $z \sim 6$ than at $z \sim 3$.

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