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High-redshift Lyα 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 Lyα 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 Lyα emitters at $z = 6.11$ and 6.00. Their rest-frame equivalent widths are 153Å and 114Å, 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 100Å 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 Lyα emitters with a large Lyα equivalent width, in a wider redshift range than 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 100Å is significantly higher at $z \sim 6$ (the cosmic age of $\sim$1 Gyr) than that at $z \sim 3$ ($\sim$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. early universe – galaxies: evolution – galaxies: formation – galaxies: individual (SDF J132345.6+271701, SDF J132519.4+271829) – galaxies: starburst

1. Introduction

Observational searches for high-z galaxies have achieved important progress in this decade. Thanks to large tele-

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

No.	Name	Redshift	i'^{a}	z'^{a}	$NB921^{a}$	$z' - NB921$	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).

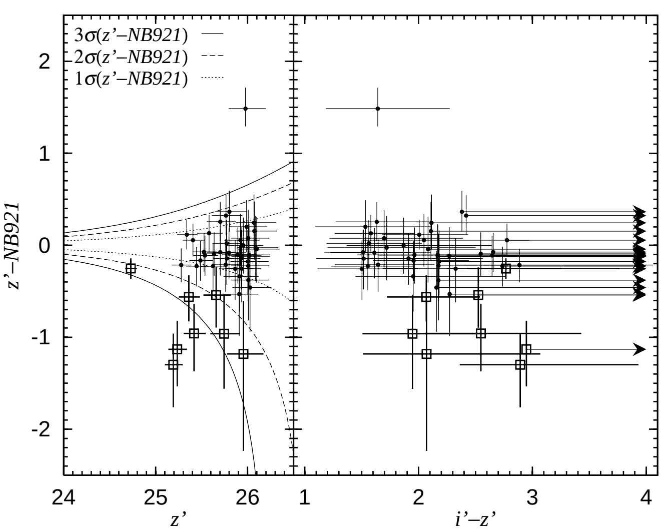

Fig. 1. Color-magnitude diagram of $z' - NB921$ vs. z' (*left*) and $z' - NB921$ vs. $i' - z'$ color-color diagram (*right*). The 48 i'-dropout objects detected in the SDF are plotted. The NB921-depressed i'-dropout objects are shown by open squares, and the other i'-dropout objects are shown by filled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

scopes such as Subaru, VLTs and Keck, a few dozens of 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 Lyα 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) presented their theoretical estimates that large Lyα equivalent widths [$EW_0 \gtrsim 150$Å for a Salpeter initial-mass function (IMF) and $EW_0 \gtrsim 240$Å 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 Lyα equivalent widths which could reach up to $EW_0 \sim 1000$Å (e.g., Schaerer 2002, 2003; Tumlinson et al. 2003; Scannapieco et al. 2003). Therefore, the frequency distribution of the Lyα equivalent width in high-z galaxies and its evolution with redshift are important in understanding the early stages of galaxy evolution (e.g., Shimasaku et al. 2006; Ando et al. 2006).

However, the observational study of the Lyα equivalent width in galaxies at high redshift is not straightforward. Although Malhotra & Rhoads (2002) reported that more than half of their sample of 150 Lyα emitters (LAEs) have Lyα equivalent width larger than 240Å, their analysis is based only 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 Lyα emission, and thus 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 to identify LAEs with a large Lyα equivalent width, that is, i' dropout with a "depression" in the narrow-band filter NB921 (see §2) (Nagao et al. 2004, 2005a). If galaxies are at $6.0 < z < 6.5$, their redshifted Lyα emission is expected at $8500\text{Å} \lesssim \lambda_{\rm obs} \lesssim 9100$Å. In this case, the narrow-band magnitude at $\lambda \sim 9200$Å has no contamination from Lyα emission and thus traces only the continuum, while the z'-band magnitude is enhanced by the contribution of the strong Lyα 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 Lyα 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 usual i'-dropout selection (see Nagao et al. 2005a for more details).

In this paper, we report new spectroscopy of a sample of NB921-depressed i'-dropout galaxies. Throughout this paper, we adopt a cosmology with ($\Omega_{\rm tot}$, $\Omega_{\rm M}$, Ω_Λ) = (1.0, 0.3, 0.7) and $H_0 = 70$ km s^{-1} 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, $R_{\rm C}$, i', and z') and narrow-band photometric data [NB816 and NB921; the central wavelengths and the half-widths of the transmittance are (8150Å, 120Å) and (9196Å, 132Å), 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
– $R_{\rm C} > 27.8$ (below 3σ background error).

Among the 48 selected i'-dropout galaxies in SDF, we identified as a "NB921-depressed i'-dropout galaxy" an object whose $z' - NB921$ is less than -2σ of the sky noise. Here "sky noise" refers to the error on the $z' - NB921$ color due to sky noise in the z' and $NB921$ filters. The $z' - NB921$ versus z' color-magnitude diagram and the $z' - NB921$ versus $i' - z'$ color-color diagram are shown in Figure 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 Figure 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 J132426.5.0+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 accomodationg 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 – 10000Å, with a dispersion of $\sim$ 0.95Å pixel^{-1}. The adopted slit width was 0.83 arcsec, giving a spectral resolution of $R \sim 1500$ or $\Delta\lambda \sim 6$Å at $\sim$ 9000Å 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

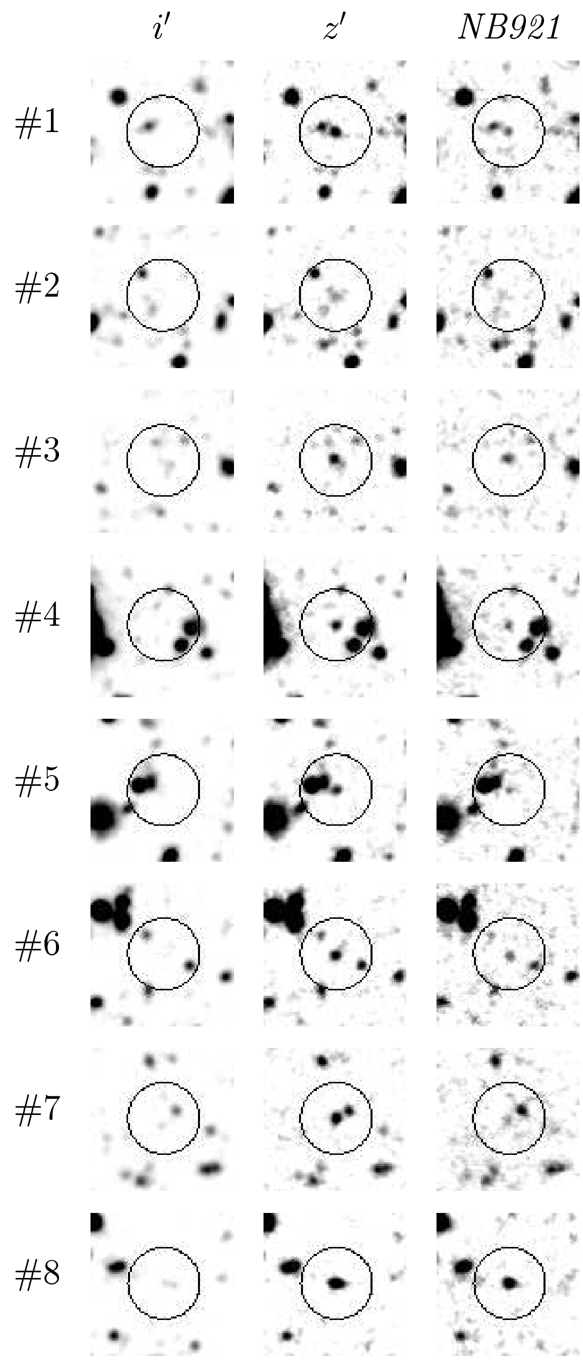

Fig. 2. Thumbnail images of NB921-depressed i'-dropout galaxies. The square regions around each object in the i', z', and NB921 images are shown from left to right. The IDs given at the left side of the panels correspond to those in Table 1. The size of panels and the radius of circles are 16 arcsec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

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

No.	Redshift	F(Lyα)[a] (10^{-17} ergs/s/cm^2)	FWHM[b] (km s^{-1})	EW_0(Lyα)[c] (Å)	$EW_0^{\rm min}$(Lyα)[d] (Å)	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 = 6.2Å).
[c] Not corrected for the absorption effects due to the Lyα-forest, and thus lower limits on the intrinsic equivalent width.
[d] Minimum EW_0(Lyα) 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 §§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.

the observation (0.5 − 1.0 arcsec). The total integration times were 7200 sec for SDF J132345.6+271701 (#1) and SDF J132422.0+271742 (#2), and 9000 sec 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 (Figure 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 8634Å and 8512Å, respectively. In Figures 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 (∼1.6 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 Lyα. Note that if the detected emission line were Hβ, [O III]λ5007 or Hα, other rest-frame optical emission line(s) should be seen in the observed wavelength range. If the detected emission line was [O II]λ3727, it should be resolved as a doublet emission, since the expected wavelength separation of the redshifted [O II]$\lambda\lambda$3726,3729 is ∼ 6Å (or ∼6 pixels), which corresponds to ∼ 210 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 Lyα at $z \sim 6$.

To quantify the asymmetry of the detected emission lines, we calculated two independent parameters; $f_{\rm red}/f_{\rm blue}$ and S_w. The former is the ratio between $f_{\rm red}$ and $f_{\rm blue}$, where $f_{\rm red}$ is the flux at wavelengths longer than the emission-line peak, while $f_{\rm blue}$ is that at shorter wavelengths (Taniguchi et al. 2005; Nagao et al. 2005a; see also Haiman 2002 for a theoretical discussion on the parameter $f_{\rm red}/f_{\rm blue}$). 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 at the blue side of the Lyα emission may be over-subtracted (Fig.4). The $f_{\rm red}/f_{\rm blue}$ ratio of both line-detected objects is significantly larger than unity, and also larger than that of most LAEs reported by Taniguchi et al. (2005). This result is consistent with the interpretation that the detected emission lines are Lyα. 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 Lyα. Taking the derived values of $f_{\rm red}/f_{\rm blue}$ and S_w for the two line-detected objects into account, we conclude that the detected emission lines are Lyα and accordingly that the redshifts of the two objects are 6.11 and 6.00, respectively. The observed Lyα fluxes are (4.5±0.1)×10^{-17} ergs s^{-1}

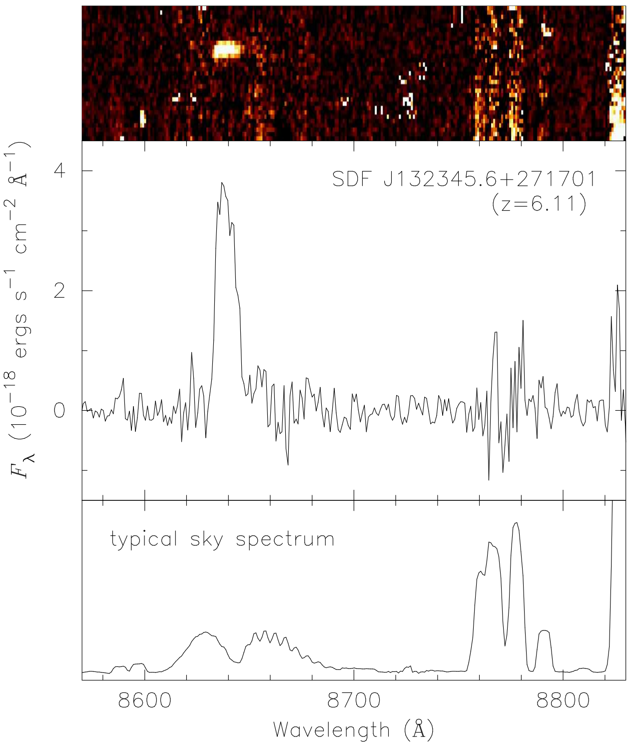

Fig. 3. Sky-subtracted optical position-velocity spectrogram (*top*) and one-dimensional spectrum (*middle*) of SDF J132345.6+271701 (#1) obtained with FOCAS on Subaru. The typical spectrum of the sky emission is also shown in the bottom panel.

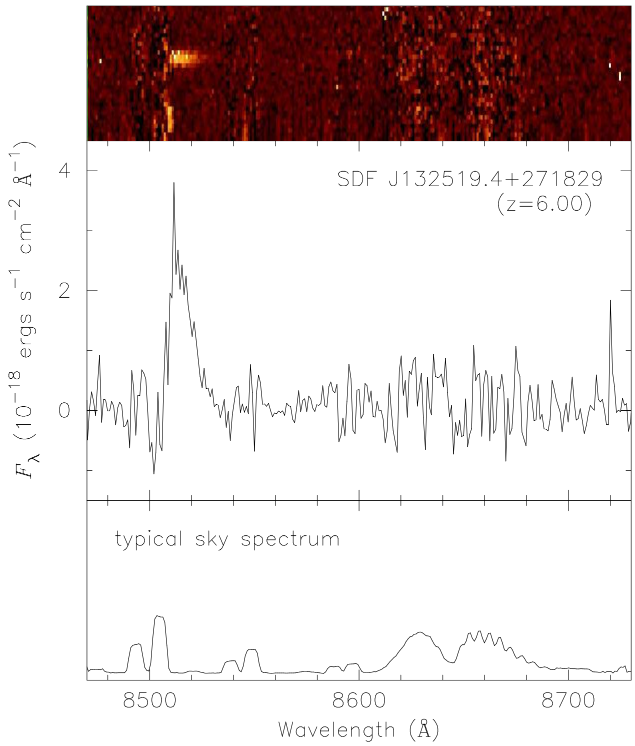

Fig. 4. Same as Figure 3 but for SDF J132519.4+271829 (#6).

cm^{-2} and $(3.4{\pm}0.2){\times}10^{-17}$ ergs s^{-1} cm^{-2}, without any correction for slit loss. The Lyα luminosities are thus calculated to be $1.9{\times}10^{43}$ ergs s^{-1} and $1.3{\times}10^{43}$ ergs s^{-1}, respectively. The measured emission-line widths in FWHM are $11.3^{+1.1}_{-1.6}$Å and $8.6^{+1.9}_{-5.7}$Å. These values correspond to $9.6^{+1.3}_{-2.0}$Å and $6.2^{+2.4}_{-6.2}$Å, or velocity widths of 330^{+50}_{-70} km s^{-1} and 220^{+80}_{-220} km s^{-1}, respectively, after corrected for the instrumental broadening effect. Here the absorption effects are not taken into account.

Adopting these redshifts, the N Vλ1240 emission line would be expected at 8816Å and 8680Å 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 Figures 3 and 4). The 3σ upper limits for the N V emission are 5.7×10^{-18} ergs s^{-1} cm^{-2} and 6.9×10^{-18} ergs s^{-1} cm^{-2} for these two objects respectively, assuming the same velocity widths as Lyα. 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 Lyα (e.g., De Breuck et al. 2000; Nagao et al. 2006; see also Malkan et al. 1996).

As mentioned in §1, it is sometimes very difficult to estimate the Lyα 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 Lyα 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 $f_\lambda = (4.1 \pm 1.1) \times 10^{-20}$ ergs s^{-1} cm^{-2} Å^{-1} and $(4.2{\pm}1.2){\times}10^{-20}$ ergs s^{-1} cm^{-2} Å^{-1} at the wavelengths of the Lyα peak, respectively. Then the rest-frame equivalent widths of the Lyα emission are calculated to be 153 ± 42Å and 114 ± 32Å for SDF J132345.6+271701 (#1) and SDF J132519.4+271829 (#6) respectively, assuming a flat UV continuum. Note that if the detected emission lines were [O II], the rest-frame equivalent widths would be 470Å and 349Å, respectively. These large 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 Lyα.

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(Lyα) 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 §§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 Lyα emission shows a clear asymmetric profile and especially a prominent tail toward the red side of the emission-line peak, the Lyα emission of LAEs is expected to be resolved with the current wavelength resolution $R \sim 1500$. This means that the Lyα emission should be found even when the redshifted Lyα line falls on an isolated (i.e., unresolved) OH airglow emission line. However, the Lyα detection would be difficult when the Lyα emission line falls on blended OH lines, such as the lines at 8760Å $\lesssim \lambda \lesssim$ 8780Å seen at the bottom panel of Figure 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, $z' - NB921 = -0.25$. Therefore the expected Lyα equivalent width of this object is so small (which is estimated to be $\sim$ 50Å in the rest frame by assuming $z = 6.0$ and a flat UV slope) that the detection of Lyα 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 Lyα 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 Lyα equivalent width of all of the five Lyα-detected objects is quite large, at least $\sim$ 100Å, 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 on the limiting EW(Lyα) of the NB921-depressed i'-dropout selection method. This selection technique does not select only LAEs with a large EW_0(Lyα) in principle, because the selection criterion on the NB921 depression is based on the sky error as described in §2. This is different from usual LAE surveys

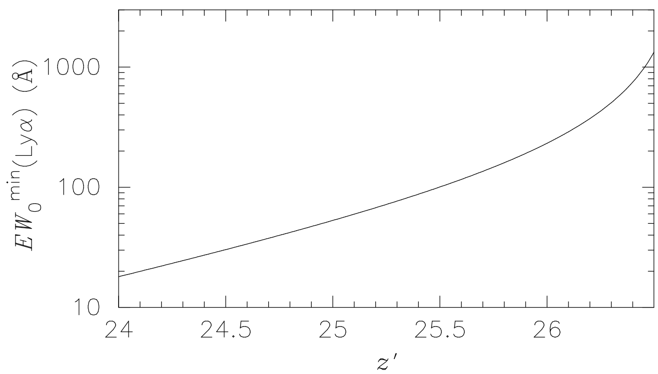

Fig. 5. Minimum EW_0(Lyα) that can be selected by the NB921-depressed i'-dropout method [$EW_0^{\rm min}$(Lyα)] as a function of the z'-band magnitude, estimated by assuming $z = 6.0$ and a flat UV slope.

based on the narrow-band excession, for which a certain excess magnitude is generally used instead of the sky noise. Therefore the NB921-depressed i'-dropout method would select LAEs with a relatively small EW_0(Lyα) if the imaging data were enough deep and accordingly the sky noise was very small. In other words, the minimum EW_0(Lyα) that can be selected by the NB921-depressed i'-dropout method [hereafter $EW_0^{\rm min}$(Lyα)] depends on the magnitude of target galaxies, since the $z' - NB921$ 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 $EW_0^{\rm min}$(Lyα) on the z' magnitude for the case of the SDF dataset in Figure 5, where $z = 6.0$ and a flat UV slope are assumed. It is demonstrated that only LAEs with EW_0(Lyα) $\gtrsim$ 100Å are selected among faint galaxies with $z' \gtrsim 25.5$, while LAEs with EW_0(Lyα) $\sim$ a tens of 10Å 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 $EW_0^{\rm min}$(Lyα) and the detected EW_0(Lyα) for each NB921-depressed i'-dropout galaxy, we also give $EW_0^{\rm min}$(Lyα) 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 $z' - NB921$ 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 of 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 Lyα equivalent width of the NB921-depressed i'-dropout galaxies with a Lyα detection (given in Table 2) ranges from 94Å to 236Å. Although these values are less than the "critical value" $EW_0(\mathrm{Ly}\alpha) = 240$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 Lyα 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). It has been extensively argued whether Lyα photons from galaxies at an earlier epoch than the completion of the cosmic re-ionization are observable or not. Some calculations suggest that the Lyα 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 Lyα 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 Lyα 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 Lyα flux to the total (intrinsic) Lyα flux $[F_0(\mathrm{Ly}\alpha)/F_{\mathrm{tot}}(\mathrm{Ly}\alpha)]$ is estimated to be ∼10% for typical LAEs with a star-formation rate (SFR) $\sim 10\ M_\odot\ \mathrm{yr}^{-1}$ and ∼50% for LAEs with $SFR \sim 100 M_\odot\ \mathrm{yr}^{-1}$. Following this result, we assume $F_0(\mathrm{Ly}\alpha)/F_{\mathrm{tot}}(\mathrm{Ly}\alpha)$ ∼0.5 to correct the absorption effect on the observed Lyα flux rather conservatively, in the sense that the actual $F_0(\mathrm{Ly}\alpha)/F_{\mathrm{tot}}(\mathrm{Ly}\alpha)$ of our spectroscopic sample would be smaller than 0.5 since the SFR is less than 100 $M_\odot\ \mathrm{yr}^{-1}$ (Nagao et al. 2004, 2005a). See also, e.g., Santos (2002) and Dijkstra et al. (2006) for the justification of our adopted value of $F_0(\mathrm{Ly}\alpha)/F_{\mathrm{tot}}(\mathrm{Ly}\alpha)$. Interestingly, by adopting this assumption, the intrinsic $EW_0(\mathrm{Ly}\alpha)$ for three out of the five spectroscopically identified NB921-depressed i'-dropout galaxies is then expected to exceed the critical value $EW_0(\mathrm{Ly}\alpha) = 240$Å. This result is consistent with the idea that galaxies at $z \gtrsim 6$ contains 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 Lyα 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 IIλ1640 emission (see, e.g., Tumlinson & Shull 2000; Oh et al. 2001; Schaerer 2002, 2003). Although the He IIλ1640 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 alpha equivalent width distribution

It has been known that narrow-band selected galaxies (e.g., emission-line galaxies) at high redshift tend to have high Lyα equivalent widths, which sometimes exceeds the critical value of $EW_0(\mathrm{Ly}\alpha) = 240$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 high Lyα equivalent widths. For instance, at $z \sim 3$ the fraction of LBGs showing $EW_0(\mathrm{Ly}\alpha) > 100$Å is ≈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 $EW_0(\mathrm{Ly}\alpha) \gtrsim 100$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 Lyα 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 ($i' - NB921 = 0.98$). Therefore we estimate the fraction of i'-dropout galaxies having $EW_0(\mathrm{Ly}\alpha) \gtrsim 100$Å is $4/48 \approx 8\%$. Note that this estimated fraction is a conservative lower limit, because (1) some Lyα non-detected NB921-depressed i'-dropout galaxies may also have such a high 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 $EW_0(\mathrm{Ly}\alpha) \gtrsim 100$Å is significantly higher than the value at $z \sim 3$. However, it should be noted that the limiting magnitude of these two samples are different; that is, while the spectroscopic survey of LBGs at $z \sim 3$ by Shapley et al. (2003) reaches down to $R_{\mathrm{AB}} \sim 25.5$, 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) reported that the LBGs with a high Lyα equivalent width are rarer in brighter samples than in fainter samples, at $z \gtrsim 5$. Shapley et al. (2003) also reported based on their huge number of a LBG spectroscopic sample that the broad-band magnitude of LBGs with a stronger Lyα emission tends to be fainter than that of LBGs with a weaker Lyα emission (or with a Lyα 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 $EW_0(\text{Ly}\alpha) \gtrsim 100\text{Å}$ between at $z \sim 6$ and at $z \sim 3$ should be even more significant. Note that the significance may be intrinsically much more if the IGM effect against the Lyα 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 $EW_0(\text{Ly}\alpha) \gtrsim 100\text{Å}$ 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 other two NB921-depressed i'-dropout galaxies are also LAEs with $EW_0(\text{Ly}\alpha) > 100\text{Å}$ 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 $EW_0(\text{Ly}\alpha) \gtrsim 100\text{Å}$ at $6.0 \lesssim z \lesssim 6.5$; these results suggest that the NB921-depressed i'-dropout selection method is an efficient technique to identify strong LAEs in a wide redshift range, $6.0 \lesssim z \lesssim 6.5$.

The obtained results also suggest that more than 8% of the i'-dropout galaxies in the SDF have a large Lyα equivalent width of $EW_0(\text{Ly}\alpha) \gtrsim 100\text{Å}$. This is in contrast with LBGs at $z \sim 3$, where such strong LAEs are much rarer (∼1%). This also implies a strong redshift evolution in the Lyα equivalent width distribution from $z \sim 6$ to $z \sim 3$, consistently 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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