A PHOTOMETRIC SURVEY FOR Lyα−He ii DUAL EMITTERS: SEARCHING FOR POPULATION III STARS IN HIGH-REDSHIFT GALAXIES

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ABSTRACT

We present a new photometric search for high-z galaxies hosting Population III (Pop III) stars based on deep intermediate-band imaging observations obtained in the Subaru Deep Field (SDF), using Suprime-Cam on the Subaru Telescope. By combining our new data with the existing broadband and narrowband data, we searched for galaxies that emit strongly in both Lyα and He ii λ1640 (dual emitters) and are promising candidates for Pop III–hosting galaxies at 3.93 ≤ z ≤ 4.01 and 4.57 ≤ z ≤ 4.65. Although we found 10 dual emitters, most of them turn out to be [O iii]−[O ii] dual emitters or Hβ+(Hα+[N ii]) dual emitters at z < 1, as inferred from their broadband colors and from the ratio of the equivalent widths. No convincing candidate Lyα−He ii dual emitter of SFR$_{PopIII}$ ≥ 2 $M_{\odot}$ yr$^{-1}$ was found by our photometric search in 4.03 × 10$^3$ Mpc$^3$ in the SDF. This result disfavors low-feedback models for Pop III star clusters and implies an upper limit on the Pop III SFR density of SFR$_{PopIII} < 5 \times 10^{-6} M_{\odot}$ yr$^{-1}$ Mpc$^{-3}$. This new selection method to search for Pop III–hosting galaxies should be useful in future narrowband surveys to achieve the first observational detection of Pop III–hosting galaxies at high redshifts.

Subject headings: early universe — galaxies: evolution — galaxies: formation — galaxies: starburst — stars: early-type

Online material: color figures

1. INTRODUCTION

Population III (Pop III) stars are those formed out of primordial gas, enriched only through big bang nucleosynthesis. Since massive Pop III stars are promising candidates as sources for cosmic reionization (e.g., Ciardi et al. 2000; Loeb & Barkana 2001; Wyithe & Loeb 2003; Sokasian et al. 2004) and an important population for early phases of the cosmic chemical evolution (e.g., Wasserburg & Qian 2000; Abia et al. 2001; Qian & Wasserburg 2001; Bromm et al. 2003), their properties have been extensively investigated from the theoretical point of view. Pop III stars have not been discovered yet; obviously, their direct detection and observational studies of their properties would provide a completely new and important step toward understanding the evolution of galaxies. The expected observables of high-z galaxies hosting Pop III stars have been theoretically investigated in recent years. Such galaxies are expected to show strong Lyα emission, with an extremely large equivalent width (EW) and moderately strong He ii λ1640 emission (e.g., Tumlinson & Shull 2000; Tumlinson et al. 2001, 2003; Oh et al. 2001; Schaerer 2002, 2003), due to the high effective temperature, up to ~10$^5$ K for Pop III stars (e.g., Bromm et al. 2001; Tumlinson et al. 2003). Most models predict that Pop III stars dominated the reionization of the universe at 7 ≤ z ≤ 15. However, they also predict that Pop III stars may still exist at redshifts currently accessible with 8–10 m class telescopes, i.e., z < 7, although it may depend both on some model parameters of Pop III (e.g., initial mass function [IMF]) and on some environmental parameters, such as the mixing efficiency (e.g., Scannapieco et al. 2003, 2006; Jimenez & Haiman 2006; Schneider et al. 2006; Brook et al. 2007; Tornatore et al. 2007). Some observations have found Lyα emitters (LAEs) at z > 4 with a very large EW, which is hard to explain through star formation without Pop III (e.g., Malhotra & Rhoads 2002; Nagao et al. 2004, 2005a, 2007; Shimasaki et al. 2006; Dijkstra & Wyithe 2007). However, the search for He ii λ1640 emission as direct evidence for the presence of Pop III in such galaxies is far more controversial. Jimenez & Haiman (2006) pointed out the possible He ii λ1640 signature in the composite spectrum of ~1000 Lyman break galaxies (LBGs) at z ~ 3 made by Shapley et al. (2003), although the He ii λ1640 feature in the LBG composite spectrum may be attributed to a stellar wind feature associated with massive stars, as mentioned by Shapley et al. (2003). On the other hand, other searches for He ii λ1640 in higher z galaxies have failed, through stacking analysis of LAEs (Dawson et al. 2004; Ouchi et al. 2008) or through ultradeep near-infrared spectroscopy of an individual LAE (Nagao et al. 2005b). Nevertheless, the He ii λ1640 emission from Pop III–hosting galaxies may already be detected in current deep narrowband (NB) surveys (mostly aiming for LAE searches) as NB-excess objects, but not identified as He ii emitters (Tumlinson et al. 2001), since NB surveys are more sensitive to faint emission lines than spectroscopic observations. Galaxies in a young Pop III–hosting phase are expected to show He ii λ1640 emission with EW$_{rest} > 20$ Å.
hosting galaxies. Note that the central wavelengths and the half-widths of the transmittance of NB 816 and NB 921 are $(\lambda_c, \Delta\lambda_{FWHM}) = (8150 \, \AA, 120 \, \AA)$ and $(9196 \, \AA, 132 \, \AA)$, respectively. We did not consider the NB 973 data, which are too shallow to search for He $ii\lambda 1640$ emission from Pop III–hosting galaxies. We also did not use the NB 704 and NB 711 data, because their wavelengths are too blue, resulting in redshifts that are too low ($z < 3.3$ for He $ii\lambda 1640$ emitters). The NB 816 and NB 921 filters can be used to search for He $ii\lambda 1640$ emitters at $3.93 \leq z \leq 4.01$ or $4.57 \leq z \leq 4.65$, respectively. If there are He $ii\lambda 1640$ emitters in these redshift ranges, they should show very strong Ly$\alpha$ emission at $5992 \, \AA \leq \lambda_{obs} \leq 6089 \, \AA$ or $6769 \, \AA \leq \lambda_{obs} \leq 6867 \, \AA$. We then used two intermediate-passband filters (IA filter system; see, e.g., Yamada et al. 2005; Taniguchi et al. 2005b), whose wavelengths correspond to the expected Ly$\alpha$ wavelengths with broader transmission FWHM than NB filters. Specifically, we used IA 598 and IA 679, whose central wavelengths and half-widths of transmittance are $(\lambda_c, \Delta\lambda_{FWHM}) = (6008 \, \AA, 298 \, \AA)$ and $(6782 \, \AA, 339 \, \AA)$, respectively. Note that the wide IA filters select LAEs with a very large EW (e.g., Fujita et al. 2003a; Ajiki et al. 2004; Yamada et al. 2005). This is not a problem for this project, since Pop III–hosting galaxies are expected to show Ly$\alpha$ emission with a very large EW ($EW_{rest} > 100 \, \AA$; e.g., Schaerer 2002, 2003; Scannapieco et al. 2003).

In summary, we can select Ly$\alpha$–He $ii$ dual emitters at $3.93 \leq z \leq 4.01$ by combining the IA 598 and NB 816 data and at $4.57 \leq z \leq 4.65$ by combining the IA 679 and NB 921 data. In Figure 1, a schematic view of this selection method is shown. The target redshift ranges are shown more clearly in Figure 2, where the IA and NB filter transmission curves are shown as functions of the targeted redshift.

2.2. Observations and the Data Reduction

The SDF was observed on 2007 April 22 (UT) with Suprime-Cam (which has a field of view [FOV] of $34 \times 27 \, \text{arcmin}^2$; Miyazaki et al. 2002) on the Subaru Telescope (Iye et al. 2004). We used two intermediate-passband filters, IA 598 and IA 679, as described above. The individual exposure time was 120 or 900 s. A small dithering was performed between individual exposures to cover the gaps between the detectors and the bad pixels. The typical seeing during the observation was $0.6^\prime\prime–0.9^\prime\prime$.

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**TABLE 1**

| Filter | $t_{exp}$ (minutes) | $m_{lim}^a$ (mag) | $A_V^b$ (mag) | References |
|--------|---------------------|------------------|--------------|------------|
| $B$..  | 595                 | 28.45            | 0.07         | 1          |
| $V$..  | 340                 | 27.74            | 0.05         | 1          |
| $R_C$..| 600                 | 27.80            | 0.04         | 1          |
| $i'$.. | 801                 | 27.43            | 0.03         | 1          |
| $z'$.. | 504                 | 26.62            | 0.02         | 1          |
| IA 598 | 111                 | 26.52            | 0.05         | 2          |
| IA 679 | 231                 | 27.07            | 0.04         | 2          |
| NB 704 | 198                 | 26.67            | 0.04         | 3, 4       |
| NB 711 | 162                 | 25.99            | 0.04         | 4, 5, 6    |
| NB 816 | 606                 | 26.63            | 0.03         | 1, 4, 7    |
| NB 921 | 899                 | 26.54            | 0.02         | 1, 4, 8, 9, 10 |
| NB 973 | 900                 | 25.5             | 0.02         | 11, 12     |

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* The 3 $\sigma$ limiting magnitude for $2'' \phi$ apertures, without the Galactic reddening correction.

* Galactic extinction for each band (Schlegel et al. 1998), calculated by adopting the Galactic extinction curve (Cardelli et al. 1989).

References.—(1) Kashikawa et al. 2004; (2) this work; (3) Shimasaku et al. 2004; (4) Ly et al. 2007; (5) Ouchi et al. 2003; (6) Shimasaku et al. 2003; (7) Shimasaku et al. 2006; (8) Kodaira et al. 2003; (9) Taniguchi et al. 2005a; (10) Kashikawa et al. 2006; (11) Iye et al. 2006; (12) Ota et al. 2008.

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2. DATA

2.1. Method and Filter Selection

The field investigated in this project is the SDF, centered at $\alpha = 13^h 24^m 38.9^s$ and $\delta = +27^\circ 29' 25.9''$ (J2000.0; Kashikawa et al. 2004), where the Galactic dust extinction is low ($E_{B-V} = 0.017$ mag; Schlegel et al. 1998). The optical photometric data obtained in the SDF so far are summarized in Table 1. Among the five existing NB images, we focus on the NB 816 and NB 921 data to search for the putative He $ii\lambda 1640$ emission from Pop III–

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The reduced data and the catalog are available at http://soaps.naoj.org.

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in FWHM. We discarded frames with bad seeing (two 900 s frames for each filter); as a consequence, the total integration times used to construct the final combined images of the IA 598 and IA 679 data are 111 and 231 minutes, respectively (Table 1). We also observed spectrophotometric standard stars, G93-48, GD 108, HZ 21, and HZ 44, for the flux calibration.

The individual CCD data were reduced and combined by using the data reduction package SDFRED (Yagi et al. 2002; Ouchi et al. 2004). Since the point-spread function (PSF) sizes of the reduced and combined IA 598 and IA 679 data (0.91″ and 0.93″ in FWHM, respectively) are smaller than that of the existing SDF imaging data (0.99″), we matched the PSF of the IA 598 and IA 679 data to the existing SDF data by smoothing with proper Gaussian kernels. After masking the low-quality regions, such as the edge of the FOV and the regions affected by bright stars, the effective surveyed area is 875 arcmin². Consequently, the co-moving survey volume at 3.93 \leq z \leq 4.01 is 2.08 \times 10^{5} \text{ Mpc}^3 and that at 4.57 \leq z \leq 4.65 is 1.95 \times 10^{5} \text{ Mpc}^3; the total volume surveyed by this study is thus 4.03 \times 10^{5} \text{ Mpc}^3.

2.3. Source Detection and Photometry

By using the final images, we extracted the IA 598—selected and IA 679—selected object catalogs. Source detection and photometry

![Fig. 2.—Transmission curves of IA 598 and NB 816 (left, dashed and solid lines), and those of IA 679 and NB 921 (right, dashed and solid lines), normalized by their peak transmittances and shown as a function of redshift.](image1)

![Fig. 3.—IA 598—detected objects (which are also detected at 2 \sigma in both R_c and i' images), plotted on a diagram of C598 vs. IA 598 (black dots; 63,660 objects). The dashed horizontal line denotes the excess criterion limit, C598 – IA 598 = 0.3. The solid curve denotes 3 \sigma uncertainty in the C598 – IA 598 color. Objects with a lower limit on the color of C598 – IA 598 are shown with arrows. Filled circles denote the selected IA 598– excess galaxies (133 objects). [See the electronic edition of the Journal for a color version of this figure.]](image2)

![Fig. 4.—IA 679–detected objects (which are also detected at 2 \sigma in both R_c and i' images), plotted on a diagram of C679 – IA 679 vs. IA 679 (black dots; 97,234 objects). The dashed horizontal line denotes the excess criterion limit, C679 – IA 679 = 0.3. The solid curve denotes 3 \sigma uncertainty in the C679 – IA 679 color. Objects with a lower limit on the color of C679 – IA 679 are shown with arrows. Filled circles denote the selected IA 679– excess galaxies (234 objects). [See the electronic edition of the Journal for a color version of this figure.]](image3)
were performed by using SExtractor version 2.3.2 (Bertin & Arnouts 1996). We adopted the criteria of five adjacent pixels and $2\sigma$ above the noise level for source detection. Photometry was performed with a 200$''$ diameter aperture for each band image. The 3$\sigma$ limiting magnitudes of IA 598 and IA 679 for 200$''$ apertures are 26.52 and 27.07 mag, respectively (Table 1). In the following sections we used the inferred photometric catalogs with a correction for the Galactic reddening of $E_{B-V}=0.017$ mag (Schlegel et al. 1998), adopting the extinction curve by Cardelli et al. (1989).

3. RESULTS

3.1. Selection of IA-Excess Objects

To select objects with excess emission in the IA filters (IA-excess objects), we determined the matched continuum magnitudes for IA 598 and IA 679, which will be identified as C598 and C679 hereafter. They are obtained by $f_{C598} = 0.45f_V + 0.55f_{Rc}$ and $f_{C679} = 0.75f_{Rc} + 0.25f_i$, respectively, where $f_X$ is the flux density at band $X$. The weighting factors used here are calculated by taking the effective wavelengths of the related filters into account. The 3$\sigma$ limiting magnitudes of C598 and C679 are estimated to be 27.77 and 27.70 mag, respectively, without correction for Galactic extinction. We then selected IA 598–excess objects as those matching all of the following criteria:

$$21.0 < IA 598 < 26.52 \ (=3\ \sigma),$$  
$$R_c > 28.24 \ (=2\ \sigma),$$  
$$i' > 27.87 \ (=2\ \sigma),$$  
$$C598 - IA 598 > 0.3,$$  
$$C598 - IA 598 > 3\ \sigma \ (C598 - IA 598),$$

and similarly, IA 679–excess objects were selected as those matching all of the following criteria:

$$21.0 < IA 679 < 27.07 \ (=3\ \sigma),$$  
$$R_c > 28.24 \ (=2\ \sigma),$$  
$$i' > 27.87 \ (=2\ \sigma),$$  
$$C679 - IA 679 > 0.3,$$  
$$C679 - IA 679 > 3\ \sigma \ (C679 - IA 679).$$
The bright-end limit on the IA magnitudes for the selection was introduced to avoid saturation and/or nonlinearity effects. The IA-excess magnitude adopted here (0.3 mag) corresponds to a selection limit in terms of EW of EW$_{\text{obs}}$ $\gtrsim$ 114 Å for IA 598 and EW$_{\text{obs}}$ $\gtrsim$ 145 Å for IA 679.

Note that the adopted limiting EWs are much lower than intrinsic EWs theoretically expected for Pop III–hosting galaxies [EW$_{\text{rest}}$(Ly$\alpha$) $\gtrsim$ 100 Å, which corresponds to EW$_{\text{obs}}$(Ly$\alpha$) $\gtrsim$ 500 Å]. However, even in low dust abundance environments, Ly$\alpha$ photons from H ii regions could suffer from resonance scattering through the neutral hydrogen, and accordingly the surface brightness of the Ly$\alpha$ emission could be diminished, resulting in lower observed EWs. Taking this possibility into account, we set the limiting IA-excess magnitude (i.e., the limiting EWs) as described above.

In Figures 3 and 4, we show the selected IA 598–excess and IA 679–excess objects on the diagram of C598 − IA598 versus IA 598 and that of C679 − IA679 versus IA 679. The numbers of selected IA 598–excess objects and of IA 679–excess objects are 133 and 234, respectively.

### 3.2. Selection of IA-NB Dual Emitters

The IA-excess–selected samples also include low-z objects, not only the LAEs we are focusing on. More specifically, the IA 598–excess objects may contain [O iii] emitters at z $\sim$ 0.20, H$\beta$ emitters at z $\sim$ 0.24, and [O ii] emitters at z $\sim$ 0.61. IA 679–excess objects may contain H$\alpha$ (+[N ii]) emitters at z $\sim$ 0.03, [O iii] emitters at z $\sim$ 0.35, H$\beta$ emitters at z $\sim$ 0.40, and [O ii] emitters at z $\sim$ 0.82. Note that fainter emission lines, such as [Ne ii] and higher order Balmer lines, are expected to be excluded from the IA-excess object samples, since we are sensitive only to relatively high EW objects (EW$_{\text{obs}}$ $\gtrsim$ 100 Å).

Generally, such low-z interlopers should be removed before analyzing any statistical properties of high-z LAEs (see, e.g., Ajiki et al. 2003). However, we are now focusing on IA-NB dual emitters as candidates for Ly$\alpha$–He ii dual emitters (i.e., Pop III–hosting galaxies). Since low-z H$\alpha$ and [O iii] emitters do not show any emission-line features around corresponding NB wavelengths (∼8150 ± 60 Å for IA 598 emitters and ∼9196 ± 66 Å for IA 679 emitters), IA 598–NB 816 dual emitters and IA 679–NB 921 dual emitters do not contain them. The possible low-z contamination in IA-NB dual emitter samples is from [O ii]–[O iii] dual emitters and H$\beta$+(H$\alpha$+[N ii]) dual emitters, because the wavelength ratios of Ly$\alpha$/He ii, [O ii]/[O iii], and H$\beta$/H$\alpha$ are so similar (∼0.741, ∼0.744, and ∼0.741, respectively). More specifically, [O ii] emitters observed as NB 816 and NB 921 emitters are at 0.62 $\lesssim$ z $\lesssim$ 0.64 and 0.82 $\lesssim$ z $\lesssim$ 0.85, which show [O ii] emission at 6020 Å $\lesssim$ z $\lesssim$ 6110 Å and 6800 Å $\lesssim$ z $\lesssim$ 6890 Å that is covered by the IA 598 and IA 679 filters, respectively, as shown in Figure 5. Similarly, H$\alpha$ (+[N ii]) emitters observed as NB 816 and NB 921 emitters are at 0.23 $\lesssim$ z $\lesssim$ 0.25 and 0.39 $\lesssim$ z $\lesssim$ 0.41, which show H$\beta$ emission at 5990 Å $\lesssim$ z $\lesssim$ 6080 Å and 6760 Å $\lesssim$ z $\lesssim$ 6860 Å that is covered by the IA 598 and IA 679 filters, respectively, as shown in Figure 5. Therefore, we select IA-NB dual emitters at first and then classify them into Ly$\alpha$–He ii, [O ii]–[O iii], and H$\beta$–(H$\alpha$+[N ii]) dual emitters.

In Figures 6 and 7, we investigate possible NB 816 excesses of IA 598–excess objects in the diagram of C816 − NB 816 versus NB 816, and possible NB 921 excesses of IA 679–excess objects in the diagram of z$^\prime$ − NB 921 versus NB 921, respectively. Here the matched continuum for NB 816, C816, is defined as f$_{C816} = 0.62f_{z} + 0.38f_{C816}$. The 3 σ limiting magnitude of C816 is 27.05 mag, before Galactic reddening correction. We use the z$^\prime$-band magnitude as the continuum for NB 921. Note that there
are +0.10 and −0.05 mag offsets in the color (C816 – NB 816 and $z’$ – NB 921, respectively) distribution of the detected objects, as mentioned also by Ly et al. (2007). By requiring a minimum NB 816 excess of 0.3 mag (i.e., C816/NB 816 > 0.3, which corresponds to EW$_{\text{obs}} \geq 45$ Å), there are three IA 598–NB 816 dual-excess objects with an NB 816 excess significant at higher than 3 $\sigma$ and one other IA 598–NB 816 dual-excess object with an NB 816 excess significance higher than 2 $\sigma$ (Fig. 6). Adopting a minimum NB 921 excess of 0.15 mag (i.e., $z’$–NB 921 > 0.15, which corresponds to EW$_{\text{obs}} \geq 20$ Å), there are six IA 679–NB 921 dual-excess objects with a significance of the NB 921 excess larger than 3 $\sigma$. There are no IA 679–NB 921 dual-excess objects with a significance of the NB 921 excess between 2 and 3 $\sigma$ (Fig. 7).

### TABLE 2

| ID       | B   (mag) | V   (mag) | R   (mag) | $i’$ (mag) | $z’$ (mag) | IA 598 (mag) | IA 679 (mag) | NB 704 (mag) | NB 711 (mag) | NB 816 (mag) | NB 921 (mag) |
|----------|----------|----------|----------|------------|------------|--------------|--------------|--------------|--------------|--------------|--------------|
| IA 598..082646 | 25.13     | 24.72    | 24.26    | 24.25      | 24.32      | 24.54        | 24.55        | 23.78        | 24.43        |              |              |
| IA 598..117217 | 28.81     | 27.15    | 26.24    | 26.39      | 27.13      | 25.72        | 26.57        | 26.70        | 25.90        | 25.91        |              |
| IA 598..118588 | 22.92     | 22.46    | 21.93    | 22.09      | 22.21      | 21.64        | 22.37        | 22.37        | 21.38        | 22.30        |              |
| IA 598..124836 | 24.69     | 24.41    | 23.79    | 23.97      | 24.24      | 23.52        | 24.46        | 24.43        | 22.89        | 24.29        |              |
| IA 679..020953 | 26.82     | 26.06    | 25.28    | 25.42      | 25.58      | 26.18        | 24.94        | 24.81        | 25.78        | 25.77        | 25.03        |
| IA 679..034587 | 24.31     | 24.11    | 23.84    | 23.50      | 23.23      | 23.72        | 24.11        | 24.11        | 24.11        | 25.78        | 25.77        |
| IA 679..062442 | 23.81     | 23.43    | 22.62    | 23.05      | 22.92      | 23.48        | 22.14        | 22.49        | 23.66        | 23.33        | 22.20        |
| IA 679..074091 | 24.77     | 24.19    | 23.74    | 23.89      | 23.76      | 24.11        | 24.46        | 24.11        | 24.11        | 25.78        | 25.77        |
| IA 679..090877 | 24.38     | 24.24    | 23.93    | 23.79      | 23.11      | 24.23        | 23.59        | 23.99        | 23.99        | 23.67        | 22.81        |
| IA 679..167041 | 26.08     | 26.20    | 25.12    | 25.74      | 26.06      | 25.93        | 24.73        | 24.47        | 24.47        | 25.93        | 24.45        |

Note.—Corrected for the Galactic extinction.

Fig. 8.—SEDs of the IA 598–NB 816 dual emitters. Error bars in the y-axis direction denote the 1 $\sigma$ photometric errors. The ID of each object is shown at the top left corner of each panel.
3.3. Selection of Lyα–He II Dual Emitters

In Table 2 we give the photometric properties of the four IA 598–NB 816 dual-excess objects and of the six IA 679–NB 921 dual-excess objects. Their spectral energy distributions (SEDs) are shown in Figures 8 and 9, respectively. Except for a faint IA 598–NB 816 dual-excess object, IA 598_117217 (the only object with an NB-excess significance below 3σ), the photometric properties of all of the IA-NB dual-excess objects are apparently inconsistent with the interpretation that they are Lyα–He II dual emitters at 4.0 ≤ z ≤ 4.6. This is because the IA-NB dual-excess objects show relatively blue B − V colors, unlike star-forming galaxies at z ≥ 4, which are expected to have B fluxes reduced by Lyman absorption. In Figure 10, the predicted B − V colors of galaxy spectral models in the observed frame are plotted as functions of redshift. We have used the galaxy SED models by Bruzual & Charlot (2003), combined with the cosmic transmission by Madau et al. (1996). The galaxy models are selected to
have solar \((Z = 1 Z_\odot)\) or subsolar \((Z = 0.005 Z_\odot)\) metallicity, a Salpeter IMF, and an exponentially declining star formation history with \(t = 1\) Gyr. It is clear that galaxies at \(z \sim 4.0\) are expected to have \(B - V \sim 1.8\), or even redder if dust reddening effects and the contribution of \(\text{Ly}_\alpha\) photons to the \(V\)-band flux are taken into account. Galaxies at \(z \sim 4.6\) are expected to have \(B - V > 3\), due to the dropout of \(B\)-band flux caused by redshifted Lyman limit absorption at \(912(1 + z) \; \text{Å} \sim 5100 \; \text{Å}\).

The three IA 598–NB 816 dual-excess objects (again except for IA 598–117217) show \(B - V \sim 0.4\), which is consistent with the interpretation that they are star-forming galaxies at \(z < 1\). All of the six IA 679–NB 921 dual-excess objects show \(-0.1 \leq B - V \leq 0.8\), again consistent with the interpretation that those are star-forming galaxies at \(z < 1\). Note that, based on the broad-band classification method for emission-line galaxies by Ly et al. (2007), we confirmed that the NB excess of the IA-NB dual-excess objects is consistent with \(H_\alpha\) emission or \([\text{O} \; iii]\) emission. We also confirmed that all of the 10 IA-NB dual-excess objects are detected in the newly obtained \(U\)-band data,\(^{10}\) which strongly supports our conclusion that these IA-NB dual emitters are at \(z < 1\).

Several IA-NB dual emitters have a large ratio of the NB-excess flux to the IA-excess flux, as shown in Table 3. The ratios of the inferred EWs, EW(IA) to EW(NB) estimated following the manner of Fujita et al. (2003b), can be used to obtain rough estimates of the flux ratios of the two emission lines. \(\text{Ly} \alpha – \text{He} \; ii\) dual emitters (i.e., Pop III–hosting galaxies) cannot have such large flux ratios of \(\text{He} \; ii / \text{Ly} \alpha\) (which should instead be \(\lesssim 0.1\), depending on the adopted Pop III models; e.g., Schaerer 2003). In contrast, star-forming galaxies have a flux ratio of \([\text{O} \; iii] / [\text{O} \; ii] \sim 0.1–10\) (depending on the gas metallicity and/or the ionization parameter; e.g., Kewley & Dopita 2002; Nagao et al. 2006), and those of \((\text{H}_\alpha + \lbrack \text{N} \; ii \rbrack) / \text{H} \beta \gtrsim 3\) (because the case B flux ratio of \(\text{H}_\alpha / \text{H} \beta \sim 3\); e.g., Osterbrock 1989). Therefore, the ratios of the IA excess to the NB excess observed in all IA-NB dual-excess objects are more consistent with the \([\text{O} \; ii] / [\text{O} \; ii]\) or \((\text{H}_\alpha + [\text{N} \; ii]) / \text{H} \beta\) flux ratio of star-forming galaxies at \(z < 1\), rather than the \(\text{He} \; ii / \text{Ly} \alpha\) of the Pop III–hosting galaxies.

One interesting object is IA 598–117217, which shows only a marginal NB excess with a \(\sim 2\) \(\sigma\) significance. Its \(B - V\) color is \(\sim 1.7\) mag, which is consistent with the color of galaxies at \(z \sim 4.0\). However, this object has a significant NB 921 excess, in addition to IA 598 and NB 816 excess (Fig. 8). The corresponding rest-frame wavelength is \(\lambda_{\text{rest}} \sim 1840\; \text{Å}\) for \(z \sim 4.0\) and \(\lambda_{\text{rest}} \sim 5641\; \text{Å}\) for \(z \sim 0.63\), where no strong emission line is expected in either case. One possibility is that this object harbors an active galactic nucleus (AGN). Since the data of different bands were obtained in different observing runs that span 6 years, the time variation of the AGN may cause a spurious IA and/or NB excess that is not related to emission lines. See, e.g., Morokuma et al. (2008) for the time variation of photometric properties of faint AGNs in deep survey data. Although the nature of this object is not clear, we do not regard it as a strong candidate of \(\text{Ly} \alpha – \text{He} \; ii\) dual emission at \(z \sim 4.0\).

We thus conclude that most of the 10 IA-NB dual emitters found in this survey are \([\text{O} \; ii] / [\text{O} \; ii]\) or \(\text{H} \beta – \text{He} \; ii + [\text{N} \; ii]\) dual emitters and that photometric candidates of \(\text{Ly} \alpha – \text{He} \; ii\) dual emitters are located in the galaxy models have a Salpeter IMF and an exponentially declining star formation history with \(t = 1\) Gyr. Blue, green, yellow, and red solid lines correspond to the model predictions for an age of \(2, 3, 4, \) and \(8\) Gyr, respectively. Vertical dashed lines denote the redshifts, where the IA-NB dual-excess objects are expected to be located. Models with a metallicity of \(Z = Z_\odot\) and \(Z = 0.005 Z_\odot\) are shown in the top and bottom panels, respectively. [See the electronic edition of the Journal for a color version of this figure.]

### Table 3

| ID             | EW_{obs}(IA) (Å) | EW_{obs}(NB) (Å) |
|----------------|------------------|------------------|
| IA 598–082646  | 181 ± 20         | 83 ± 8           |
| IA 598–117217  | 483 ± 157        | 137 ± 67         |
| IA 598–118588  | 218 ± 2          | 147 ± 1          |
| IA 598–124836  | 224 ± 14         | 299 ± 6          |
| IA 679–020953  | 191 ± 37         | 96 ± 28          |
| IA 679–034857  | 167 ± 9          | 72 ± 3           |
| IA 679–062442  | 349 ± 4          | 141 ± 2          |
| IA 679–074091  | 154 ± 9          | 43 ± 5           |
| IA 679–090877  | 147 ± 10         | 542 ± 4          |
| IA 679–167041  | 297 ± 36         | 709 ± 62         |

\(^{10}\) The \(U\)-band data, obtained recently at the Kitt Peak National Observatory Mayall 4 m telescope, are now in the final analysis stages and will be published in a forthcoming paper (C. Ly et al. 2008, in preparation).
emitters have not been found. Note that their inferred EW_{rest} are extremely large (Table 3). Some objects have EW_{rest} > 100 Å. Although such large-EW objects at z < 1 are very rare, some other NB and IA surveys also found such interesting objects (Ajiki et al. 2006; Kakazu et al. 2007). Kakazu et al. (2007) investigated spectra of NB-selected emission-line galaxies with EW_{rest} ≥ 100 Å and found that some of the targets are extremely metal-poor galaxies [XMPGs, whose oxygen abundance is 12 + log (O/H) < 7.65; e.g., Kniazev et al. 2003]. Since some of our low-z IA-NB dual emitters have observational properties similar to XMPGs, follow-up spectroscopy is of interest.

4. DISCUSSION

In § 3.3 we showed that there are neither Lyα–He II dual emitters with EW_{obs}(He II) ≥ 45 Å at 3.93 ≤ z ≤ 4.01 or those with EW_{obs}(He II) ≥ 20 Å at 4.57 ≤ z ≤ 4.65 detected in the SDF area at our limiting magnitudes. Here we discuss the implication of these results for the abundance of the Pop III–hosting galaxies at these redshift ranges.

Schaerer (2003) investigated the temporal evolution of EW(He II) for Pop III stellar clusters by assuming IMF's with a Salpeter slope and considering the following three cases: (M_{low}, M_{up}) = (1 M☉, 100 M☉), (1 M☉, 500 M☉), and (50 M☉, 500 M☉), where M_{low} and M_{up} are the lower and upper mass cutoff values. Here we focus on the predictions of EW(He II) in the case of (M_{low}, M_{up}) = (50 M☉, 500 M☉), because numerical simulations suggest IMFs are biased toward very high masses (e.g., Bromm et al. 1999, 2002; Nakamura & Umemura 2001; Abel et al. 2002). Although the predicted EW(He II) reaches ~10 Å at the zero age of the Pop III star formation, it rapidly decreases and becomes undetectable at an age of ~2 Myr, if an instantaneous burst is assumed. In the case of constant star formation, at the equilibrium stage the predicted EW(He II) is ~20 Å. This corresponds to EW_{obs}(He II) ~ 100 Å at z = 4.0 and EW_{obs}(He II) ~ 110 Å at z = 4.6 (or equivalently, a NB excess of ~0.6 mag for both redshift ranges), which are much larger than the detection limit of our observation. This suggests that Pop III–hosting galaxies younger than ~2 Myr or having ongoing Pop III formation with a high enough star formation rate (SFR_{PopIII}) should be detected in our surveys.

In the following, we quantify the minimum SFR_{PopIII} to which our survey is sensitive. By assuming constant star formation, the He II luminosity can be written as follows:

\[ L(\text{He II}) = (1 - f_{esc}) f_{1640} \left( \frac{\text{SFR}_{\text{PopIII}}}{M_\odot \text{yr}^{-1}} \right), \]

where f_{esc} is the escape fraction of the He^{+}-ionizing photon and f_{1640} is a proportionality constant. In the following, we assume that f_{esc} is negligibly small. Schaerer (2003) predicted f_{1640} = 6.01 × 10^{-4} for Pop III stellar clusters with (M_{low}, M_{up}) = (50 M☉, 500 M☉). This corresponds to F(He II) = 3.91 × 10^{-18} (SFR_{PopIII}/M_\odot \text{yr}^{-1}) for z = 4.0 and F(He II) = 2.81 × 10^{-18} (SFR_{PopIII}/M_\odot \text{yr}^{-1}) for z = 4.6, in units of ergs s^{-1} cm^{-2}. Since the 3 σ limiting flux of objects with EW_{obs} = 100 Å in our NB 816 observation is 7.4 × 10^{-18} ergs s^{-1} cm^{-2} and that of objects with EW_{obs} = 110 Å in our NB 921 observation is 5.9 × 10^{-18} ergs s^{-1} cm^{-2}, our survey can detect Pop III–hosting galaxies if their SFR is higher than ~2 M_\odot yr^{-1}. Therefore, the nondetection of Lyα–He II dual emitters suggests that there are no Pop III–hosting galaxies with SFR_{PopIII} ≥ 2 M_\odot yr^{-1} at 4.0 ≤ z ≤ 4.6 toward the SDF in a volume of 4.03 × 10^5 Mpc^{3}. This result implies an upper limit on the Pop III SFR density of SFR_{PopIII} < 5 × 10^{-6} M_\odot yr^{-1} Mpc^{-3}, if only galaxies with SFR_{PopIII} > 2 M_\odot yr^{-1} are taken into account. Note that the inferred upper limit on SFR_{PopIII} is uncertain, since the predicted flux of He II for a given SFR_{PopIII} strongly depends on the assumed IMF (e.g., Schaerer 2003). It also depends on the evolutionary processes of Pop III stars, especially the mass loss during their evolution (e.g., El Eid et al. 1983; Tumlinson et al. 2001; Schaerer 2002).

Some theoretical studies suggest that the volume-averaged intergalactic medium (IGM) metallicity quickly reached Z_{crit} = 10^{-4} Z_☉ at z > 10 (e.g., Mackey et al. 2003; Yoshida et al. 2004; Tornatore et al. 2007), where Z_{crit} is the critical metallicity, below which very massive stars could be formed. However, this does not necessarily suggest that the formation of Pop III stars was terminated at such a high redshift, because of the inhomogeneous metal distribution in the early universe (e.g., Scannapieco et al. 2003, 2006; Brook et al. 2007; Tornatore et al. 2007). As demonstrated by Scannapieco et al. (2003), the redshift evolution of the SFR_{PopIII} density in the universe depends sensitively on some Pop III model parameters, especially the feedback efficiency that is closely related to the Pop III IMF (see also Scannapieco et al. 2006). Low-feedback models of Scannapieco et al. (2003) predict a large fraction (~30%) of Pop III–hosting galaxies among LAEs at 4.0 ≤ z ≤ 4.6 with log L(\text{Ly}α) ~ 10^{41} ergs s^{-1} (again M_{low} = 50 M☉ is assumed here). A similarly large fraction of Pop III–hosting galaxies among high-z LAEs is also inferred by Dijkstra & Wuythe (2007). Since the number density of LAEs with this luminosity at similar redshifts is ~10^{-5}–10^{-4} Mpc^{-3} (Ouchi et al. 2003, 2008; Yamada et al. 2005), the number of Pop III–hosting galaxies in our survey, expected by such low-feedback models, is roughly 1–10. Therefore, the nondetection in our Lyα–He II dual emitters survey may suggest that low-feedback models are not appropriate and that Pop III stars may instead be characterized by a relatively large feedback efficiency.

This photometric survey for Lyα–He II dual emitters demonstrated that wide and deep imaging observations, combining narrowband and/or intermediate-band filters, are potentially a powerful tool to search for or constrain the properties of Pop III–hosting galaxies at high redshifts. The data recently obtained by sensitive narrowband near-infrared surveys at 1.19 μm (Willis & Courbin 2005; Cuby et al. 2007; Willis et al. 2008) and similar wide and deep surveys planned in future may be useful to search for Lyα–He II dual emitters at z ~ 6.3, by adding data of narrow- or intermediate-band observations at λ ~ 8820 Å to check strong Lyα emission. Such a survey is promising, since SFR_{PopIII} increases at higher redshifts (see, e.g., Dijkstra & Wuythe 2007). In future observational searches for Lyα–He II dual emitters, serious sources of contamination would be [O iii]–[O ii] and Hβ–(He iii+[N ii]) dual emitters, as demonstrated in this paper. In addition to broadband color criteria, the flux (or EW) ratio of the dual excesses is also a powerful diagnostic to discriminate the populations and to identify Lyα–He II dual emitters among the photometric candidates.

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