Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
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Observational Search for Population III Stars in High-Redshift Galaxies

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Abstract. In this contribution we present our new photometric search for high-z galaxies hosting Population III (PopIII) stars based on deep intermediate-band imaging observations, by using Supreme-Cam on the Subaru Telescope. By combining our new data with the existing broad-band and narrow-band data in the target field, we searched for galaxies which emit strongly both in Lyα and in HeIIλ1640 ("dual emitters") that are promising candidates for PopIII-hosting galaxies, at $4 \lesssim z \lesssim 5$. Although we found 10 "dual emitters", most of them turn out to be [OII]-[OIII] dual emitters or Hβ-Hα dual emitters at $z < 1$, as inferred from their broad-band colors and from the ratio of the equivalent widths. No convincing candidate of Lyα-HeII dual emitter with $SFR_{\rm PopIII} \gtrsim 2 M_\odot$ yr^{-1} was found. This result disfavors low feedback models for PopIII star clusters, and implies an upper limit of the PopIII SFR density of $SFRD_{\rm PopIII} < 5 \times 10^{-6} M_\odot$ yr^{-1} Mpc^{-3}. This new selection method to search for PopIII-hosting galaxies should be useful in future surveys for the first observational detection of PopIII-hosting galaxies at high redshift.

Keywords. early universe, galaxies: evolution, galaxies: formation, stars: early-type

1. Introduction

Population III (PopIII) stars are those formed out of primordial gas, enriched only through Big-Bang nucleosynthesis. Since massive PopIII stars are promising candidates as sources for cosmic reionization and an important population for early phases of the cosmic chemical evolution, their properties have been extensively investigated from the theoretical point of view. PopIII stars have not been discovered yet; obviously, their direct detection and the 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 PopIII 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 HeIIλ1640 emission (e.g., Tumlinson & Shull 2000; Tumlinson *et al.* 2001; Oh *et al.* 2001; Schaerer 2002, 2003; Tumlinson *et al.* 2003), due to the high effective temperature up to $\sim 10^5$ K of PopIII stars.

Most models predict that PopIII stars dominated the re-ionization of the universe at $7 \lesssim z \lesssim 15$. However, they also predict that PopIII stars may still exist at redshifts currently accessible with 8–10m-class telescopes, i.e., $z < 7$ (e.g., Scannapieco *et al.* 2003, 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 PopIII (e.g., Malhotra & Rhoads 2002; Nagao *et al.* 2004, 2005a, 2007; Shimasaku *et al.* 2006; Dijkstra & Wyithe 2006). However, the search for HeIIλ1640 emission as direct evidence for PopIII in such galaxies is far more controversial. Jimenez & Haiman (2006) pointed out the possible HeIIλ1640 signature in the composite spectrum of LBGs at $z \sim 3$ made by Shapley *et al.* (2003), although it 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 HeIIλ1640 in higher-z galaxies have failed, through stacking analysis of LAEs (Dawson *et al.* 2004; Ouchi *et al.* 2008) or through ultra-deep near-infrared spectroscopy of an individual LAE (Nagao *et al.* 2005b).

Nevertheless, the HeIIλ1640 emission from PopIII-hosting galaxies may already be detected in current deep narrow-band (NB) surveys (mostly aiming for LAE searches) as NB-excess objects, but not identified as HeII emitters (Tumlinson *et al.* 2001) since NB surveys are more sensitive to faint emission lines than spectroscopic observations. If a NB-excess object is due to HeIIλ1640 emission, then the same object should show stronger Lyα emission at a shorter wavelength, since the PopIII-hosting galaxies should emit Lyα with $EW_{\rm rest} > 500$Å (e.g., Schaerer 2003). Therefore, by performing additional NB (or intermediate-band) imaging observations whose wavelength is matched to the redshifted Lyα, we may be able to find "Lyα-HeII dual emitters" that are promising candidates for PopIII-hosting galaxies. Motivated by these considerations, we performed new intermediate-band imaging observations (see Nagao *et al.* 2008 for details).

2. Observations

The field investigated in this project is the Subaru Deep Field (SDF: Kashikawa *et al.* 2004; Taniguchi *et al.* 2005). Among some existing NB images in the SDF, we focus on NB816 and NB921 that can be used to search for HeII emitters at $3.93 \lesssim z \lesssim 4.01$ or $4.57 \lesssim z \lesssim 4.65$, respectively. If there are HeII emitters in these redshift ranges, they should show very strong Lyα emission at 5992Å $\lesssim \lambda_{\rm obs} \lesssim$ 6089Å or 6769Å $\lesssim \lambda_{\rm obs} \lesssim$ 6867Å. To detect possible Lyα emission in these wavelengths, we observed the SDF on 22 April 2007 (UT) with Suprime-Cam on the Subaru Telescope, using two intermediate-passband filters, IA598 and IA679. By combining these new data with the existing imaging data, we can search for "Lyα-HeII dual emitters" in photometric way, as schematically shown in Fig 1.

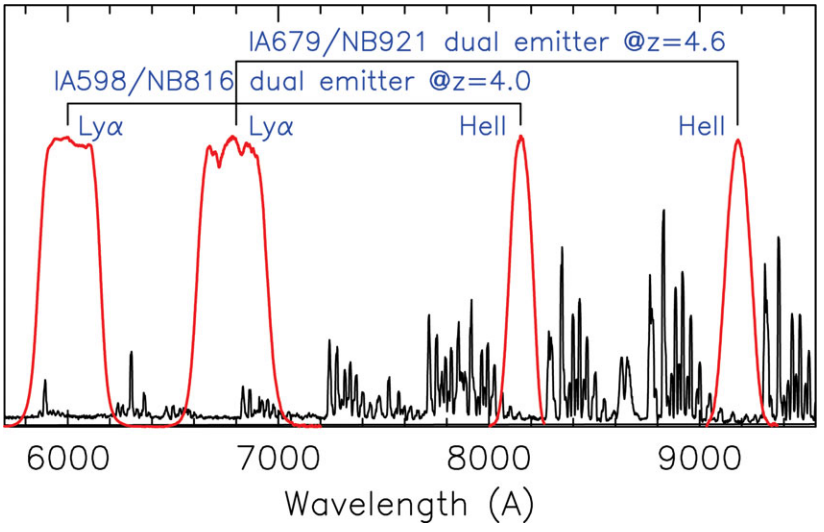

Figure 1. Schematic view of our selection method for Lyα-HeII dual emitters. The black solid spectrum denotes a typical sky spectrum. Red solid curves denote the filter transmission curves of IA598, IA679, NB816, and NB921. The dual excess of the combination of IA598 and NB816, and that of IA679 and NB921 corresponds to $z \sim 4.0$ and $z \sim 4.6$, respectively.

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3. Results

To search for Lyα-HeII dual emitters, we first identified the IA-excess objects (i.e., emission-line galaxies) by adopting an IA-excess criterion of 0.3 mag, that corresponds to the emission-line EW of $EW_{\rm obs} \sim 100$Å. Note that this limiting EWs are lower than intrinsic EWs of Lyα theoretically expected for PopIII-hosting galaxies. The numbers of the identified IA-excess objects are 133 and 234 for IA598 and IA679, respectively. We then investigated possible NB816 excesses for IA598-excess objects, and also possible NB921 excesses for IA679-excess objects. By adopting the NB816-excess criterion of 0.3 mag (i.e., $EW_{\rm obs} \gtrsim 45$Å) for IA598-excess objects, we found 4 IA598-NB816 dual excess objects. In addition, by adopting the NB921-excess criterion of 0.15 mag (i.e., $EW_{\rm obs} \gtrsim 20$Å) for IA679-excess objects, we also found 6 IA679-NB921 dual excess objects.

Fig 2 shows the SEDs of 6 IA679-NB921 dual-excess objects. These SEDs are apparently inconsistent with the interpretation that they are galaxies at $z > 4$. This is because the objects shown in Fig 2 show relatively blue $B - V$ colors ($B - V < 1$), unlike star-forming galaxies at $z > 4$ that should show B-band dropout due to the Lyman-limit absorption (i.e., $B - V \gtrsim 2$). Instead they are more consistent to star-forming galaxies at $z < 1$. This is also true for IA598-NB816 dual-excess objects. The possible low-z contamination in IA-NB dual emitter sample is from [OII]-[OIII] dual emitters and Hβ-Hα dual emitters, because the wavelength ratios of Lyα/HeII, [OII]/[OIII], and Hβ/Hα are so similar (~ 0.741, ~ 0.744, and ~ 0.741, respectively). Note that several IA-NB dual

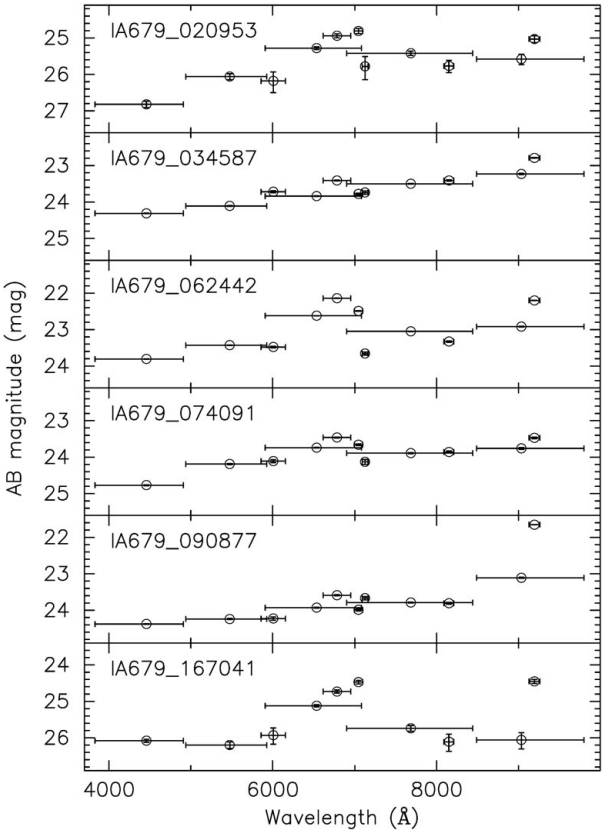

Figure 2. SEDs of the IA679-NB921 dual emitters. Error bars in the y-axis direction denote the 1σ photometric errors. The ID of each objects is shown at the upper-left corner of each panel.

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emitters have a large ratio of the NB-excess flux to the IA-excess flux. Lyα-HeII dual emitters cannot have such a large flux ratios of HeII/Lyα (which should instead be $\lesssim$0.1, depending on the adopted PopIII models; e.g., Schaerer 2003). In contrast, star-forming galaxies have the flux ratio of [OIII]/[OII] $\sim$ 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 Hα/Hβ $\gtrsim$ 3. Therefore, the ratios of the IA excess to the NB excess observed in IA-NB dual-excess objects are again consistent with star-forming galaxies at $z < 1$, rather than PopIII-hosting galaxies.

4. Discussion

Schaerer (2003) investigated the temporal evolution of EW(HeII) for PopIII stellar clusters by assuming IMFs with a Salpeter slope and some combinations of lower and upper mass cut-offs ($M_{\rm low}$, $M_{\rm up}$). Here we focus on the predictions of EW(HeII) in the case of ($M_{\rm low}$, $M_{\rm up}$) = ($50M_{\odot}$, $500M_{\odot}$). Then the HeII luminosity can be written as L(HeII) = 6.01×10^{41} ($SFR_{\rm PopIII}/M_{\odot}{\rm yr}^{-1}$). Taking the 3σ limiting fluxes for the NB excesses into account, our survey can detect PopIII-hosting galaxies if their SFR is higher than $\sim 2M_{\odot}$ yr^{-1}. Therefore, the non-detection of Lyα-HeII dual emitters suggests that there are no PopIII-hosting galaxies with $SFR_{\rm PopIII} \gtrsim 2M_{\odot}$ yr^{-1} at $4.0 \lesssim z \lesssim 4.6$ toward the SDF, in a volume of 4.03×10^5 Mpc^3. This result implies an upper-limit of the PopIII SFR density of $SFRD_{\rm PopIII} < 5 \times 10^{-6} M_{\odot}$ yr^{-1} Mpc^{-3}, if taking only galaxies with $SFR_{\rm PopIII} > 2M_{\odot}$ yr^{-1} into account. Note that the inferred upper limit on $SFR_{\rm PopIII}$ is uncertain, since the predicted flux of HeII for a given $SFR_{\rm PopIII}$ strongly depends on the assumed IMF (e.g., Schaerer 2003). It also depends on the evolutionary processes of PopIII stars, especially the mass loss during their evolution (e.g., Tumlinson *et al.* 2001; Schaerer 2002).

Some theoretical studies suggest that the volume-averaged IGM metallicity quickly reached $Z_{\rm crit} = 10^{-4} Z_{\odot}$ at $z > 10$ (e.g., Tornatore *et al.* 2007), where $Z_{\rm crit}$ is the critical metallicity, below which very massive stars could be formed. However, this does not necessarily suggest that the formation of PopIII stars was terminated at such a high redshift, because of the inhomogeneous metal distribution in the early universe (e.g., Scannapieco *et al.* 2003; Tornatore *et al.* 2007). As demonstrated by Scannapieco *et al.* (2003), the redshift evolution of the $SFR_{\rm PopIII}$ density in the universe depends sensitively on some PopIII model parameters, especially the feedback efficiency that is closely related to the PopIII IMF. Low-feedback models of Scannapieco *et al.* (2003) predict a large fraction ($\sim$30%) of PopIII-hosting galaxies among LAEs at $4.0 \lesssim z \lesssim 4.6$ with log L(Lyα) $\sim 10^{43}$ ergs s^{-1}. A similarly large fraction of PopIII-hosting galaxies among high-z LAEs is also inferred by Dijkstra & Wyithe (2007). Since the number density of LAEs with this luminosity at similar redshifts is $\sim 10^{-5} - 10^{-4}$ Mpc^{-3} (e.g., Ouchi *et al.* 2008), the number of PopIII-hosting galaxies in our survey, expected by such low-feedback models, is roughly 1 to 10. Therefore, the non-detection in our Lyα-HeII dual emitters survey may suggest that low-feedback models are not appropriate, and that PopIII stars may instead by characterized by a relatively large feedback efficiency.

This photometric survey for Lyα-HeII dual emitters demonstrated that wide and deep imaging observations, combining narrow-band and/or intermediate-band filters, are potentially a powerful tool to search or constrain the properties of PopIII-hosting galaxies at high redshifts. The data recently obtained by sensitive narrow-band near-infrared surveys and similar wide and deep surveys planned in future may be useful to search for Lyα-HeII dual emitters at $z > 6$, by adding data of narrow- or intermediate-band observations at corresponding wavelengths to check strong Lyα emission. Such a survey is

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promising, since $SFRD_{\rm PopIII}$ increases at higher redshifts (see, e.g., Dijkstra & Wyithe 2007). In future observational searches for Lyα-HeII dual emitters, serious sources of contamination would be [OII]-[OIII] and Hβ-Hα dual emitters, as demonstrated in this paper. In addition to broad-band color criteria, the flux (or EW) ratio of the dual excesses is also a powerful diagnostic to discriminate the populations and to identify Lyα-HeII dual emitters among the photometric candidates.

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