1. INTRODUCTION

The first stars, i.e., Population III (Pop III) stars with zero metallicity, are likely to be very massive due to inefficient cooling and the large Jeans mass in the early universe (Abel et al. 2002; Yoshida et al. 2006). Massive Pop III stars are probably key contributors both of the ionization photons that caused cosmic reionization and to the early phases of cosmic chemical evolution (Whalen et al. 2008; Mackey et al. 2003; Bromm et al. 2003). Although recent observations have provided major breakthroughs in understanding the universe at \( z \gtrsim 7 \) (e.g., Bouwens et al. 2010a; Yan et al. 2011), detection of high-redshift galaxies that contain Pop III stars remains a major challenge observationally. Indirect constraints on Pop III stars come from mapping the reionization history (Fan et al. 2006) or from studying the chemical evolution and the enrichment history through the observation of extremely metal-poor stars and hyper metal-poor stars (Beers & Christlieb 2005; Bessell et al. 2004). There are still no direct detections of high-redshift galaxies hosting star formation in zero metallicity gas.

Models show that Pop III stars are considerably hotter than present-day stars, for a given stellar mass (e.g., Johnson 2010; Bromm et al. 2003). Emission of ionizing radiation, specifically photons with energies above \( 54.4 \text{ eV} \) that ionize \( \text{He}^+ \), is enhanced by the high surface temperature photospheres of Pop III stars. \( \text{He}^+ \lambda 1640 \) has long been suggested as a direct probe of Pop III stars (Tumlinson & Shull 2000; Oh 2001; Schaerer 2002). \( \text{He}^+ \lambda 1640 \) emission is also relatively easy to model compared to resonance lines such as \( \text{Ly} \alpha \) or \( \text{He}^+ \lambda 304 \). The optical depth to \( \text{He}^+ \lambda 1640 \) is small in almost all circumstances, so it does not suffer the radiative transfer effects that complicate the interpretation of \( \text{Ly} \alpha \) flux in high-redshift galaxies (Schaerer 2003). In addition, it does not suffer from intergalactic medium (IGM) Gunn–Peterson absorption as \( \text{Ly} \alpha \) does (Tumlinson & Shull 2000).

How can \( \text{He}^+ \lambda 1640 \) emission from star formation in zero metallicity gas be distinguished from other sources? Calculations show that the \( \text{He}^+ \lambda 1640 \) emission in a metal-poor stellar population with metallicity as low as \( Z \sim 10^{-3} \) is still \( <10^{-3} \) times lower than that in a population formed in zero metallicity gas (Tumlinson et al. 2003; Schaerer 2003). It is also known that nebular \( \text{He}^+ \lambda 4686 \) was detected in a fairly large fraction of metal-poor \( \text{H}^+ \) regions (e.g., Skillman & Kennicutt 1993). The follow-up observations and theoretical investigations suggest that Wolf–Rayet (W-R) stars are responsible for this nebular \( \text{He}^+ \) emission (de Mello et al. 1998), but the hardness of this emission is more than one order of magnitude weaker than that originated by massive Pop III stars (Schaerer 2003; Jimenez & Haiman 2006). Also, the \( \text{He}^+ \lambda 1640 \) equivalent width of massive Pop III stars could be a factor of two larger than that of the typical active galactic nucleus (AGN; Prescott et al. 2009; Elvis et al. 1994).

A number of studies have been carried out to search for \( \text{He}^+ \) emission in high-redshift galaxies at \( 4 < z < 6.6 \). Dawson et al. (2004), Ouchi et al. (2008), and Nagao et al. (2005) searched for \( \text{He}^+ \lambda 1640 \) in either stacked or individual spectra of Ly\( \alpha \)-emitting galaxies. Nagao et al. (2008) carried out a survey for \( \text{Ly} \alpha \)–\( \text{He}^+ \) emitters using a combination of intermediate and narrowband filters in the optical window. But these observations so far have yielded only nondetections, constraining the massive Pop III star formation rate (hereafter SFR\(_{\text{PopIII}}\)) to a few \( M_\odot \text{yr}^{-1} \), usually a few tenths of the overall SFR in these galaxies. Yet Jimenez & Haiman (2006) predict SFR\(_{\text{PopIII}}\) still to be significant at \( z \sim 3–5 \). Even stronger metal-free star formation is expected at higher redshifts, due to less chemical feedback from Pop III stars after...
most sensitive part of the F130N filter. IOK-1 was observed by HST/WFC3 in 2010 March. Eight orbits (~20,000 s integration) were devoted to the F130N filter to measure the Hα flux; we also observed this galaxy using the F125W filter for two orbits to determine the underlying continuum level and UV continuum-based SFR. A F160W band observation was also carried out (E. Egami et al. 2011, in preparation).

The F130N observations are divided into two visits, each consisting of a four-point dither sequence with one orbit per dither. During the first visit, the first two dither positions were affected by the presence of a bright ghost image very close to IOK-1. We exclude these two images from further analysis. The F125W continuum observation was a two-orbit single visit, which is divided into two identical four-point dither sequences, one per orbit. No ghost image affected the F125W observations. The individual images were reduced by WFC3-IR standard pipelines. Both the F130N and F125W images were combined using Multidrizzle (Koekemoer et al. 2002) with final_scale = 0.06, which is 0.48 of the original pixel size, and final_pixfrac = 0.7. High-resolution images from the F130N and F125W bands are shown in Figure 1.

3. RESULTS

3.1. Photometry

Photometry is performed with SExtractor (Bertin & Arnouts 1996) using the rms map converted from the inverse variance image generated by Multidrizzle (Casertano et al. 2000). We measure the fluxes in the broadband (F125W and F160W) and the narrowband (F130N) images using the same Kron-like elliptical aperture determined from the F130N image (black elliptical aperture in Figure 1). The results are listed in Table 1. We also measure the flux in the F160W image of IOK-1 (E. Egami et al. 2011, in preparation), using the same aperture as used in the F125W and F130N images, finding a flux density of

Table 1

| Filter | Flux Density $f^2$ (10^{-20} erg s^{-1} cm^{-2} Å^{-1}) | $m_{AB}$ |
|--------|---------------------------------|--------|
| F130N  | 4.39 ± 0.68                     | 25.42 ± 0.17 |
| F125W  | 4.07 ± 0.19                     | 25.59 ± 0.05 |

4 These error bars only reflect the photometric uncertainties. There are big systematic uncertainties due to Lyα radiative transfer effect, galaxy IMF, and metallicity assumptions. The SFR_{Lyα} could change by a factor of two given these systematic uncertainties (also see Section 4).
where $f_{1640} = 2.44 \pm 0.14 \times 10^{-20} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$, corresponding to a magnitude of $m_{1640} = 25.98 \pm 0.06$. We fit the photometry by assuming a model spectrum with a power-law continuum with a dimensionless flux density $f_{\text{cont}} = A\lambda^{-\beta}$, where $A$ is a constant and a narrow Gaussian for the He II emission line of flux $F_{\text{He II}}$. The best-fit spectral energy distribution and photometry are shown in Figure 2. We find

$$f_{\text{cont}}(\lambda) = (4.85 \pm 0.23) \times 10^{-10}(\lambda/1 \text{Å})^{-2.46 \pm 0.36},$$

(1)

$$F_{\text{He II}} = (1.2 \pm 1.0) \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2}.$$  

(2)

At $z = 6.96$, this corresponds to a total He II luminosity of $L_{\text{He II}} = F_{\text{He II}} \times 4 \pi D_L^2 = (6.6 \pm 5.5) \times 10^{41} \text{erg s}^{-1}$, or a 2σ upper limit of $1.11 \times 10^{42} \text{erg s}^{-1}$. This 2σ upper limit is a factor of $(4-5) \times$ deeper than previous measurements. The rest-frame equivalent width of He II is $4.2 \pm 3.5 \text{Å}$. Our results also show that IOK-1 has a blue continuum. Bouwens et al. (2010b) studied the value of the UV-continuum slope $\beta$ in the Hubble Ultra Deep Field (HUDF). For luminous $L_{\text{z}} = 3$ galaxies (Steidel et al. 1999), $\beta \sim -2.0 \pm 0.2$. For lower luminosity 0.1 $L_{\text{z}} = 3$ galaxies, $\beta \sim -3.0 \pm 0.2$. IOK-1 has an absolute magnitude $M_{\text{AB}}(1500 \text{Å}) = -21.3$, comparable to $L_{\text{z}} = 3$.

3.2. Morphology

The half-light radius $r_{1/2}$ of IOK-1, based on our SExtractor measurements (Bertin & Arnouts 1996) and corrected for WFC3 PSF broadening, is 0′.12 in F125W. This corresponds to 0.62 ± 0.04 kpc. IOK-1 is an extremely compact galaxy, consistent with the size of $L_{\text{z}} = 3$ galaxies at $z \sim 7$ detected in the HUDF (Oesch et al. 2010). The observed surface brightness of IOK-1 is $\mu_f \sim 24.5 \text{mag arcsec}^{-2}$, corresponding to a surface brightness of $\mu_{\text{rest}} \sim 15.5 \text{mag arcsec}^{-2}$, after (1+z)$^4$ correction for cosmological dimming. From Figure 1, it is obvious that IOK-1 consists of two components. We use GALFIT (Peng et al. 2002) to deblend the F125W continuum image, assuming an exponential profile for both components. The F125W image shows roughly equal brightness for the two components. The northwest component has an effective radius of 0.49 ± 0.04 kpc and the southeast component has an effective radius of 0.57 ± 0.03 kpc. The two components are projected about 0′.2 (∼1 kpc) away from each other. More detailed discussions on the morphology are presented in E. Egami et al. (2011, in preparation). We also deblend the F130N narrowband image, which contains He II $\lambda$1640 emission. The northwest component is somewhat brighter. However, given the low signal-to-noise ratio of the data, this difference, while intriguing, is not statistically significant.

4. DISCUSSION

What limit can our observations place on the SFRPopIII and its contribution to the overall star formation in IOK-1 at $z \sim 7$? Photoionization by AGNs or hot dense stellar winds from W-R stars (see, e.g., Shapley et al. 2003; Brinchmann et al. 2008) may contribute to He II $\lambda$1640 emission although at a lower level than metal-free stars. More importantly, massive stars with the lowest, but non-zero metallicity (<10$^{-8}$) could generate a comparable amount of He II $\lambda$1640 emission to Pop III stars (Schauer 2003). However, here we assume that the observed He II emission originates entirely from metal-free stars. Therefore, our derived SFRPopIII should be regarded as an upper limit. In the case of constant star formation, at equilibrium, recombination line luminosities $L_i$ are proportional to the SFRPopIII (Schauer 2002), so

$$L_{\text{He II}} = c_{1640}(1 - f_{\text{esc}}) Q(\text{He}^+) \left( \frac{\text{SFRPopIII}}{M_\odot \text{yr}^{-1}} \right),$$

(3)

where $L_{1640, \text{norm}} \equiv c_{1640}(1 - f_{\text{esc}}) Q(\text{He}^+)$ is the theoretical He II $\lambda$1640 line luminosity normalized to SFR = 1 $M_\odot$ yr$^{-1}$. $c_{1640}$ is the He II $\lambda$1640 emission coefficient given in Table 1 of Schauer (2003): $c_{1640} = 5.67 \times 10^{-12} \text{erg s}^{-1} K^{-1}$, where nebular emission is calculated assuming case B recombination. $Q(\text{He}^+)$ is the number of He II ionizing photons per second and $f_{\text{esc}}$ represents the fraction of total ionizing radiation released into the IGM without being coupled to the ISM in the galaxy. We assume $f_{\text{esc}} = 0$, as it is expected to be small among high-redshift galaxies (e.g., Gnedin et al. 2008). Schauer (2002) calculates the total He II ionizing photon flux for a Salpeter initial mass function (IMF) with a range of lower and upper mass cutoffs and different assumptions of mass loss.

The conversion from He II $\lambda$1640 luminosity ($L_{1640, \text{norm}}$) to SFRPopIII is affected by a number of uncertainties, including: (1) IMF, (2) mass loss, and (3) photoionization model for the IMF. Theoretical calculations show that the lack of efficient cooling mechanisms generally result in an extremely top-heavy IMF compared to a galactic IMF (Abel et al. 2002; Bromm & Larson 2004; Yoshida et al. 2006; O’Shea & Norman 2006). However, both the shape and mass range of such an IMF are poorly constrained. Scannapieco et al. (2006) suggest a lower mass cutoff of 0.8 $M_\odot$ based on metal abundances in Galactic halo stars. Numerical simulations suggest that stars as massive as 500 $M_\odot$ can be formed by accretion into a primordial protostar (Bromm & Larson 2004), which is generally taken as an upper
limit in different simulations (Schaerer 2002; Scannapieco et al. 2003; Tumlinson 2006; Raiter et al. 2011). Both a Salpeter IMF (Schaerer 2003; Scannapieco et al. 2003) and a log-normal IMF (Tumlinson 2006) have been used in model calculations. Table 2 shows a factor of six difference in inferred SFR arising from different lower mass cutoffs in the Salpeter IMF.

As shown in Table 2, models with strong mass loss have a larger conversion factor $L_{1640, \text{norm}}$, therefore, for the same HeⅡ luminosity, they yield a lower SFR$_{\text{PopIII}}$ (Schaerer 2003). Kudritzki (2002) shows that very low metallicity stars close to the Eddington limit are subject to non-zero mass loss. Smith & Owocki (2006) argue that massive shells around luminous blue variables and so-called supernova impostors indicate that continuum-driven winds or hydrodynamic explosions dominate the mass loss of very massive stars, a claim which is insensitive to metallicity and so could apply to Pop III stars. Ekström et al. (2008) explores the effects of rotation, anisotropic mass loss, and magnetic fields on the core size of a Pop III star, pointing out that, under certain conditions, very massive stars (140 $M_\odot < M < 260 M_\odot$) losing mass through rotation could avoid ending their lives as pair-instability supernovae (PISNe). Whether Pop III stars end their lives as PISN or not will affect the metal ejection efficiency and hence affect the SFR$_{\text{PopIII}}$. From Table 2, stronger mass loss will lower SFR$_{\text{PopIII}}$ by a factor of more than three.

The derived SFR also depends on the photoionization model. Schaerer (2002) calculates nebular emission line assuming standard case B recombination, in which the optical depth of the HⅠ region is large. Equation (3) is derived under this assumption. However, for low-metallicity nebulae ionized by very hot Pop III stars, the case B predictions for line and continuum emission may have non-negligible deviations from real nebular astrophysics (Raiter et al. 2011). Therefore, the SFR$_{\text{PopIII}}$ upper limits derived from Equation (3) then need to be qualitatively revised here. According to Raiter et al. (2011), for a given HeⅡ luminosity, SFR$_{\text{PopIII}}$ could be a few times higher, depending on the ionizing parameters, e.g., the hydrogen number density $n(H)$, inner radius of the nebula $r_{\text{in}}$, and hydrogen ionizing photon flux $Q(H)$.

Our upper limit on the HeⅡ emission combined with our detection of IOK-1 in the Spitzer IRAC 1 and 2 bands (E. Egami et al. 2011, in preparation) suggest that IOK-1 is dominated by stars of metallicity above the critical value ($Z_{\text{crit}} \sim 5 \times 10^{-4} Z_\odot$), leading to a normal IMF (e.g., Bromm & Larson 2004). Using the relation given in Madau et al. (1998), the rest-frame UV luminosity of the galaxy IOK-1 corresponds to an overall SFR $\sim 20^{+0.9}_{-0.9} M_\odot \text{ yr}^{-1}$. These error bars only reflect the uncertainties in the $J$-band magnitude. The true errors are larger as the conversion from UV luminosity to overall SFR is highly and systematically uncertain. In this conversion, Madau et al. (1998) assume solar metallicity; lower metallicities down to 0.0004 could lower the SFR by a factor of two (Schaerer 2003).

Furthermore, the conversion assumes a Salpeter IMF with mass ranging from 0.1 to 125 $M_\odot$, whereas assuming a Scalo IMF would double the derived overall SFR. The UV-based overall SFR should be less obscured is somewhat higher than that based on the Lyα emission line ($\sim 10 \pm 2 M_\odot \text{ yr}^{-1}$; Iye et al. 2006), but consistent given the uncertainties in both the stellar population models and the Lyα radiative transfer effects.

The conversion of UV luminosity to an overall SFR above assumes a conversion factor between UV luminosity and SFR for Pop I and Pop II stellar populations, without correcting for Pop III stars with a top-heavy IMF. Using the fiducial Pop III Salpeter IMF of 50–500 $M_\odot$ and no mass loss, we find that our derived upper limit of 2.0 $M_\odot \text{ yr}^{-1}$ for SFR$_{\text{PopIII}}$ corresponds to an upper limit of $1.2 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{Å}^{-1}$ in F125W flux density. Note that the observed flux density is $(4.07 \pm 0.19) \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{Å}^{-1}$. After correcting for the UV luminosity contributed by Pop III stars, the overall SFR is $\sim 16^{+2.6}_{-2.6} M_\odot \text{ yr}^{-1}$. (As stated previously, this result could change a factor of two given the systematic uncertainties associated with the IMF and metallicity assumptions.) Thus, IOK-1 is not dominated by very massive Pop III stars. It should be noted that low-mass metal-free stars do not produce an appreciable amount of HeⅡ emission. Therefore, our observations only constrain the amount of high-mass Pop III star formation in the galaxy and cannot be used to rule out the existence of low-mass, low-surface population Pop III stars (although, as discussed in Section 4, most theoretical calculations favor a top-heavy IMF for Pop III). Trenti & Stiavelli (2009) show that the fraction of Pop III stars $f_{\text{III}}(z)$ per dark matter halo at $z \sim 10$ is only a few thousandths. Davé et al. (2006) and Tumlinson (2006) also suggest that $f_{\text{III}}(z)$ in halos at $z \sim 7$ is small: $\lesssim 1\%$. Taking into account the systemic uncertainties in the UV-based overall SFR, our observations indicate that the galaxy IOK-1 cannot be dominated by Pop III stars with very top heavy IMFs. For example, for a Salpeter IMF with $50 < M/M_\odot < 500$ and no mass loss, the ratio of SFR$_{\text{PopIII}}$ to the overall SFR is $\lesssim 25\%$. For a Salpeter IMF with $50 < M/M_\odot < 1000$ and mass loss, the ratio is $\lesssim 6\%$.

Our deep HST narrowband imaging places the strongest constraint yet on the SFR$_{\text{PopIII}}$ in high-redshift galaxies. Although we have not detected the HeⅡ emission line in IOK-1 at more than 1.2σ, this limit suggests that detection of HeⅡ emission from Pop III stars may be already within the reach of current facilities. Future facilities, especially the James Webb Space Telescope and GSMT, will be likely to probe down to the $\gtrsim 3\sigma$ level and directly detect the signatures of the earliest star formation in the universe.

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Table 2

| IMF (Salpeter) | Mass Loss | $L_{1640, \text{norm}}$ | SFR$_{\text{PopIII}}$ |
|---------------|-----------|-----------------------|----------------------|
| $1 \leq M/M_\odot \leq 500$ | No | $9.66 \times 10^{41}$ | $6.8 \pm 4.7$ |
| $50 \leq M/M_\odot \leq 1000$ | Yes | $3.12 \times 10^{41}$ | $2.1 \pm 1.5$ |
