CONSTRAINING VERY HIGH MASS POPULATION III STARS THROUGH He ii EMISSION IN GALAXY BDF-521 AT z = 7.01

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ABSTRACT

Numerous theoretical models have long proposed that a strong He ii λ1640 emission line is the most prominent and unique feature of massive Population III (Pop III) stars in high-redshift galaxies. The He ii λ1640 line strength can constrain the mass and initial mass function (IMF) of Pop III stars. We use F132N narrowband filter on the Hubble Space Telescope’s (HST) Wide Field Camera 3 to look for strong He ii λ1640 emission in the galaxy BDF-521 at z = 7.01, one of the most distant spectroscopically confirmed galaxies to date. Using deep F132N narrowband imaging, together with our broadband imaging with F125W and F160W filters, we do not detect He ii emission from this galaxy, but place a 2σ upper limit on the flux of 5.3 × 10^{-19} erg cm^{-2} s^{-1} Å^{-1}. This measurement corresponds to a 2σ upper limit on the Pop III star formation rate (SFR_{PopIII}) of ~0.2 M_⊙ yr^{-1}, assuming a Salpeter IMF with 50 ≤ M/M_⊙ ≤ 1000. From the high signal-to-noise broadband measurements in F125W and F160W, we fit the UV continuum for BDF-521. The spectral flux density is ~3.6 × 10^{-18} × λ^{-2.32} erg cm^{-2} Å^{-1}, which corresponds to an overall unobscured SFR of ~5 M_⊙ yr^{-1}. Our upper limit on SFR_{PopIII} suggests that massive Pop III stars represent ≤4% of the total star formation. Further, the HST high-resolution imaging suggests that BDF-521 is an extremely compact galaxy, with a half-light radius of 0.6 kpc.

Key words: dark ages, reionization, first stars – galaxies: high-redshift – stars: Population III

1. INTRODUCTION

The first generation stars, i.e., Population III (Pop III) stars with zero metallicity, form out of primordial material left over from the big bang. They are believed to produce a significant amount of energy in the ultraviolet (UV) and to serve as the main sources to re-ionize the intergalactic medium (IGM). The confirmation and analysis of Pop III stars or Pop III hosting high-redshift galaxies are among the most crucial goals in studies of the origin and evolution of galaxies in the early universe.

In recent years, a number of galaxy candidates at z = 7–10 have been found, mainly due to ambitious near-infrared (NIR) imaging surveys with greater depths and larger fields of view (e.g., Yan et al. 2012; Robertson et al. 2013). With the largest ground-based telescopes, significant progress has also been made in spectroscopically confirming Lyα emission from galaxies at z ~ 7 (Iye et al. 2006; Vanzella et al. 2011; Ono et al. 2012; Schenker et al. 2012; Finkelstein et al. 2013). However, the fraction of galaxy candidates at z = 7 that have Lyα emission is still very small, mainly because of a rising IGM neutral fraction to suppress the Lyα emission (e.g., Caruana et al. 2014; Bolton & Haehnelt 2013; Fontana et al. 2010). On the other hand, sensitive millimeter/sub-millimeter facilities like the Atacama Large Millimeter Array have allowed CO and [C ii] to serve as possible tracers of metallicity and to address the optical bias in star formation rate (SFR) measurements for galaxies at z ~ 7 (e.g., Ouchi et al. 2013).

Direct detections of Pop III signatures in high-redshift galaxies, however, remain a major challenge (e.g., Cai et al. 2011). Theoretical investigations suggest that Pop III stars have a high characteristic mass and short life spans on the order of a few million years (e.g., Bromm & Yoshida 2011). Feedback from the first stars will metal-enrich the local primordial interstellar medium (ISM) and quench further Pop III star formation (Yoshida et al. 2004; Muratov et al. 2013). Therefore, Pop III stars should only be dominant in very young galaxies at high redshift. On average, younger galaxies tend to be less massive than more mature systems at a given redshift, and thus they are intrinsically fainter in the continuum bands, making direct detection very challenging with today’s telescopes. Salvaterra et al. (2011) suggest that, at z ≥ 6, Pop-III-dominated (>50% of total luminosity) galaxies are extremely faint (M_{UV} > -14), which is below current detection limits.

The He ii λ1640 line from high-redshift galaxies has been long suggested to depend strongly on both the initial mass function (IMF) and the stellar metallicity (e.g., Schaerer 2002). Hard ionizing radiation, particularly photons that ionize Helium, is greatly enhanced by the high surface temperature of Pop III stars. Therefore, the resulting strong recombined He ii λ1640 line is a direct footprint of Pop III stars. Moreover, the He ii λ1640 line is much less complicated to model and interpret compared to the Lyα recombination line (Schaerer 2003). Also, He ii λ1640 photons pass more easily through the partially neutral IGM at high redshift than Lyα photons (Tumlinson & Shull 2000). Using the model of Schaerer (2002), one expects to detect strong He ii λ1640 emission in z ~ 7 spectroscopically confirmed galaxies if 30% of the SFR is contributed by Pop III stars with a top-heavy IMF.

In the past few years, a few observations have probed Pop III signatures in high-redshift galaxies by looking for strong He ii emission (Dawson et al. 2004; Nagaoka et al. 2005, 2008; Cai et al. 2011). These studies have reported nondetections, constraining the Pop III star formation rate (hereafter SFR_{PopIII}) to less than a few M_⊙ yr^{-1}. Note the narrow He ii line
(FWHM $\sim$ a few hundred km s$^{-1}$) is one of the Pop III star signatures, which is distinguished from broad He ii emission from active galactic nuclei (AGNs; Eldridge & Stanway 2012). The line width measurement through spectroscopy is required to unambiguously confirm the He ii from Pop III stars. Cassata et al. (2013) find that $\sim 10\%$ of galaxies at $z\sim 3$ with $t_{AB} < 24.75$ show He ii emission, with rest-frame equivalent widths (EWs) $\sim 1$–7 Å, and argue that some of the galaxies with narrow He ii lines are compatible with the predictions of a Pop III scenario. However, the EWs of these He ii emission lines are not exceptionally high compared with those from some other astrophysical objects, so the He ii emission also might be interpreted as metal-poor nebular He ii emission.

More metal-poor galactic environments could be expected at higher redshifts. It is thus important to search for secure Pop III signatures in the highest redshift galaxies. At $z \gtrsim 7$, the He ii $\lambda 1640$ line is redshifted into the J-band. Strong near-infrared sky lines make it challenging to conduct ground-based deep observations. The Wide Field Camera 3 (WFC3) on Hubble Space Telescope (HST) has a high throughput and does not suffer from active galactic nuclei (AGNs; Eldridge & Stanway 2012). The line width measurement through spectroscopy is required to unambiguously confirm the He ii from Pop III stars. At $z \gtrsim 7$, He ii $\lambda 1640$ for this galaxy lies within the WFC3/F132N narrowband filter. In this Letter, we report a non-detection of the He ii $\lambda 1640$ emission in this galaxy, which enables us to put the most stringent upper limit to date on massive Pop III star formation in galaxies at the end of reionization epoch. In addition, with HST broadband imaging, we measure the UV continuum level, UV slope, and galaxy morphology. This Letter is organized as follows. In Section 2, we discuss our observing strategies and data reduction. In Section 3, we provide the upper limit of He ii $\lambda 1640$ line flux, the measurements of UV continuum level, slope, and galaxy morphology. In Section 4, we discuss the implications of our results on the formation of Pop III stars. Throughout this Letter, we adopt a conventional cosmology: $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$.

2. HST OBSERVATIONS OF GALAXY BDF-521 AND DATA REDUCTION

The galaxy BDF-521 is spectroscopically confirmed by Vanzella et al. (2011) to be at $z = 7.008 \pm 0.002$. This galaxy is selected from the imaging survey obtained with the Very Large Telescope/Hawk-I (Castellano et al. 2010). Spectroscopy shows a clear, asymmetric $\text{Ly}_\alpha$ emission line with a total luminosity of $7.1 \pm 0.7 \times 10^{42}\text{ erg s}^{-1}$, corresponding to an overall SFR$_{\text{Ly}\alpha}$ of $6.5 \pm 0.7\text{ M}_\odot\text{ yr}^{-1}$ (uncorrected for Gunn–Peterson (GP) absorption, which reduces $\text{Ly}_\alpha$ flux). At this redshift, He ii $\lambda 1640$ falls at 13133 Â, fully in the sensitive part of the WFC3/IR F132N narrowband filter ($\lambda_c = 13188$ Â and FWHM = 162 Â), allowing us to use HST narrowband imaging to search for He ii emission. Eleven orbits ($\sim$ a 30,800 s of integration) are allocated in F132N to probe the He ii emission. A four-orbit integration was allocated to measure the continuum through the F125W and F160W filters, with two orbits for each broadband filter. The broadband imaging is used to perform an accurate continuum subtraction in the narrowband, as well as to measure the unobscured SFR and galaxy morphology. Our observations are designed to detect He ii emission at the 3$\sigma$ level if $30\%$ of the star formation in the galaxy is contributed by Pop III stars with a Salpeter IMF with $M_{\text{bol}} = -19.8$, comparable to $0.4 \times L^*_{\text{bol}}$. The photometry results are listed in Table 1. A standard power-law continuum is assumed with $f_{\text{cont}} = (\lambda/\lambda_0)\lambda^{-\alpha}$, where $\alpha$ is a constant. The spectral energy distribution (SED) is then fitted by the power-law continuum based on broadband photometry in F125W and F160W bands (Figure 2).

Table 1

| Band   | Aperture   | Flux       | $m_{\text{AB}}$ | $M_{\text{AB}}$ |
|--------|------------|------------|-----------------|-----------------|
| F125W  | 0′.48      | 10.5 ± 0.47 $\times 10^{-21}$ | 27.06 ± 0.05 | $-19.93 \pm 0.05$ |
| F160W  | 0′.48      | 6.48 ± 0.38 $\times 10^{-21}$ | 27.13 ± 0.06 | $-19.86 \pm 0.06$ |
| F132N  | 0′.48      | 6.88 ± 1.48 $\times 10^{-21}$ | 27.43 ± 0.22 | $-19.56 \pm 0.22$ |

Note. The circle aperture for photometry is 0′.48 for all the three different bands.

3. GALAXY PROPERTIES AND UPPER LIMIT OF He ii $\lambda 1640$ FLUX

Following the method described in Cai et al. (2011), we perform the photometry using SExtractor (Bertin & Arnouts 1996) using the rms map generated by Multidrizzle (Cai et al. 2011). The photometry is measured for BDF-521 in all three filters (F125W, F160W, and F132N) using a circular aperture with a diameter of 0′.45. The aperture is determined by the F132N image (2.5$\times$ half-light radius). BDF-521 has an absolute magnitude $M_{\text{AB}}(1500\text{ Â}) = -19.8$, comparable to $0.4 \times L^*_{\text{bol}}$. The photometry results are listed in Table 1. A standard power-law continuum is assumed with $f_{\text{cont}} = (\lambda/\lambda_0)\lambda^{-\alpha}$, where $\alpha$ is a constant. The spectral energy distribution (SED) is then fitted by the power-law continuum based on broadband photometry in F125W and F160W (Figure 2). We find

$$f_{\text{cont}}(\lambda) = (3.60 \pm 0.22) \times 10^{-11}(\lambda/\lambda_0)^{-2.32\pm 0.43} \text{ erg s}^{-1}\text{ cm}^{-2}.$$ (1)

After subtracting the continuum contribution in the narrowband image, we obtain the line flux of He ii ($F_{\text{He ii}}$):

$$F_{\text{He ii}} = (-0.7 \pm 0.5) \times 10^{-18}\text{ erg s}^{-1}\text{ cm}^{-2},$$ (2)

i.e., a non-detection. The 2$\sigma$ upper limit of He ii flux is $F_{\text{He ii}} \leq 1.0 \times 10^{-18}\text{ erg s}^{-1}\text{ cm}^{-2}$, which is the most stringent constraint to date for $z \sim 7$ galaxies.

At $z = 7.01$, this corresponds to a total He ii luminosity of $L_{\text{He ii}} = F_{\text{He ii}} \times 4\pi D_L^2 \leq (4.1 \pm 2.9) \times 10^{41}\text{ erg s}^{-1}$, or a
Figure 1. High-resolution images of the galaxy BDF-521 in the F125W (left), F160W (middle) broadband filters, and the F132N (right) narrowband filter. BDF-521 has a luminosity of $0.4 \times L^*_{7-8}(\lambda = 1500 \text{ Å})$ at $z = 7.01$, and the half light radius is about $0.64 \pm 0.06$ kpc. The BDF-521 is a compact galaxy. The size of BDF-521 is consistent with the size of $L^*_{7-8}(\lambda = 1500 \text{ Å}) \pm 50$-dropout and $Y_{105}$-dropout galaxy candidates at $z \sim 7-8$ detected in the HUDF12 (Ono et al. 2013). Photometric analysis of the F132N image do not reveal a strong He II $\lambda 1640$ emission.

Figure 2. Best-fit spectrum (black line) of the galaxy BDF-521 with the total UV continuum, as well as the Ly$\alpha$ (Vanzella et al. 2011) and He II lines (this work). The UV continuum is fit using our high S/N photometry in F125W (blue point with error bar), F132N (red point with error bar), and F160W (dark blue point with error bar) bands using the Hubble Space Telescope (HST; see Table 2). The filter response curves of WFC3/F110W (yellow dashed line), WFC3/F125W (blue dashed line), WFC3/F160W (dark blue dashed line), and WFC3/F132N (brown dashed line) are plotted. In addition, photometry in four different bands is overplotted at the effective wavelength of each filter, where F-band photometry (yellow point with error bar) is from Vanzella et al. (2011); and the $J$-, $H$-, and narrowband photometry are from our HST observations. The red arrow presents the non-detection $2\sigma$ upper limit of the He II $\lambda 1640$ emission line.

We do not detect the He II emission line from BDF-521 at $z = 7.01$. However, we put the strongest upper limit on the SFR$_{PopIII}$ to date. Combined with our He II upper limit on galaxies IOK-1 (Cai et al. 2011), we could constrain the formation of Pop III stars in two highest redshift, spectroscopically confirmed galaxies at $z \sim 7$. Note that He II emission, although at lower levels than for Pop III stars, can be arisen from other sources, such as photoionization by AGNs, or metal-poor nebular emission around massive stars. Due to the non-detection results in this Letter, we assume Pop III stars are the only source of He II emission, and the upper limit of metal-free stars derived under this assumption is a secure limit. Under the “standard” assumptions (Schaerer 2002, 2003; Raiter et al. 2010)—ionization-bounded nebula, constant electron temperature and density, and Case B recombination—the He recombination lines are fully specified and their luminosity is proportional to the ionizing photon production rate Q in the appropriate energy range. Following Raiter et al. (2010), the relation between line luminosity and He II ionizing photon production rate $Q(\text{He}^+)$ can be expressed as

$$L_{\text{B}}(\text{He II} \lambda 1640) = Q(\text{He}^+) \times c,$$

where $c = 5.67 \times 10^{-12}$ erg for $Z < 1/50 Z_\odot$ and $6.04 \times 10^{-12}$ erg for $Z > 1/50 Z_\odot$ (Raiter et al. 2010). Equation (3) can also be expressed by the following equation:
demonstrates different upper limits of SFRPopIII due to different (Schaerer 2002):

\[ L_B(\text{He} \, \lambda 1640) = L_{1640, \text{norm}} \left( \frac{\text{SFR}_{\text{PopIII}}}{M_{\odot} \text{ yr}^{-1}} \right). \]

Under the Case B recombination model, the He ionizing photon production rate \( Q(\text{He}^+) \) for a given SFRPopIII mainly depends on two parameters according to theoretical investigations (e.g., Schaerer 2002; Raiter et al. 2010; Woods & Gilfanov 2013): (1) IMF and (2) mass loss. Therefore, given Equations (3) and (4), \( L_{1640, \text{norm}} \) also depends on these two parameters.

A top-heavy IMF will yield a higher photon production rate (higher \( Q(\text{He}^+) \) value) for a given SFRPopIII. When the metallicity is smaller than the critical metallicity, with \( Z_{\text{crit}} \sim 10^{-4} Z_\odot \), stars are formed predominantly massive (Bromm et al. 2001), and the IMF should be much more top-heavy than a normal IMF (Bromm et al. 2001). A few theoretical studies suggested that, at \( z \gtrsim 7 \), a significant fraction of galaxies with gas masses \( \lesssim 10^9 M_\odot \) contain near pristine material of \( Z < Z_{\text{crit}} \).

The classical picture of Pop III star formation holds that the Pop III IMF is extremely top-heavy compared with a normal galactic IMF, and the typical mass for Pop III stars could be very massive of \( \sim 100 M_\odot \) (e.g., Abel et al. 2002). However, recent simulations suggest that dynamical effects can cause the protodisk to fragment into multiple clumps, which may result in the formation of binary or multiple systems (Turk et al. 2009; Stacy et al. 2010; Clark et al. 2011; Greif et al. 2012; Dopcke et al. 2013). Using a grid code to study fragmentation with the highest resolution per Jeans length in minihalos, Latif et al. (2013) argue that a protostar of \( \gtrsim 10 M_\odot \) can form via turbulent accretion. Thus, Pop III stars could have a lower characteristic mass than the previously suggested \( \sim 100 M_\odot \).

Our non-detections of strong He I \( \lambda 1640 \) for two galaxies at \( z = 7 \) disfavors the models of very massive Pop III stars dominating bright galaxies with \( L \gtrsim 0.5 L^*_{\text{ مستر 3}} \) at \( z \sim 7 \). Table 2 demonstrates different upper limits of SFRPopIII due to different mass ranges. A less top-heavy IMF corresponds to a weaker He I \( \lambda 1640 \) line for a given SFRPopIII.

Table 2

| IMF (Salpeter) | Mass Loss | \( L_{\text{norm}, 1640} \) (erg s\(^{-1}\)) | 2\( \sigma \) Upper Limit of SFRPopIII (\( M_\odot \) yr\(^{-1}\)) | 2\( \sigma \) Upper Limit of \( f_{\text{III}} \) |
|---------------|-----------|---------------------------------|---------------------------------|----------------|
| \( 1 \lesssim M/M_\odot \lesssim 500 \) | No | \( 9.66 \times 10^{40} \) | 6.0 | 100% |
| \( 50 \lesssim M/M_\odot \lesssim 500 \) | No | \( 6.01 \times 10^{41} \) | 1.0 | 20% |
| \( 1 \lesssim M/M_\odot \lesssim 500 \) | Yes | \( 3.12 \times 10^{41} \) | 1.9 | 38% |
| \( 50 \lesssim M/M_\odot \lesssim 1000 \) | Yes | \( 2.33 \times 10^{42} \) | 0.2 | 4% |

Note. \( f_{\text{III}} \) represents the ratio of the Pop III star formation rate to the overall unobscured star formation rate.

For BDF-521, previous ground-based observations suggest a extreme blue slope of \( \beta = -4 \) (Vanzella et al. 2011). Our HST measurement of the rest-frame UV luminosity has high S/N in both the J and H bands. Based on that photometry, we get a normal slope of \( \beta = -2.3 \) (Equation (2)). We derive the UV-based unobscured SFR from the rest-frame UV continuum. The UV-based overall SFR of BDF-521 is \( \sim 5 \pm 0.2 M_\odot \) yr\(^{-1}\), assuming the conversion for a Salpeter IMF between 0.1 and 100 \( M_\odot \) (Mahtani et al. 1998). Note that the conversion of the UV-based overall SFR assumes a normal stellar population, without the correction for Pop III stars with a top-heavy IMF. This conversion is reasonable given the non-detection of strong He I emission. Normally, one expects that a broad red wing of the GP trough would suppress the Ly\( \alpha \) line. As such, the Ly\( \alpha \)-based SFR may also be an underestimate. However, for BDF-521, the Ly\( \alpha \)-based SFR (Section 2) is close to the UV-derived SFR. This measurement suggests little extinction of Ly\( \alpha \) relative to the continuum and supports that BDF-521 has ionized a significant volume around itself, and the broad GP trough does not reach Ly\( \alpha \) emission.

If we assume the Pop III stars have an IMF with \( 50 \lesssim M/M_\odot \lesssim 500 \) and no mass loss, the ratio of SFRPopIII to the overall SFR (\( f_{\text{III}} \)) in BDF-521 is \( \sim 20\% \). If we assume Pop III stars have a Salpeter IMF with \( 50 \lesssim M/M_\odot \lesssim 1000 \) and strong mass loss, the ratio is \( \lesssim 4\% \) (Table 2). Kulkarni et al. (2013) use a semi-analytic model of galaxy formation to argue that measurements of relative abundances in high-\( z \) damped Ly\( \alpha \) systems can place constraints on the Pop III IMF. They show that the fractional contribution of very high mass Pop III stars to the ionization rate must be \( z < 10\% \) at \( z = 10 \). Our observations are consistent that constraint. Combined with our previous upper limit from the galaxy IOK-1 (Cai et al. 2011), our observations targeting He I emission suggest that Pop III star formation with a top-heavy IMF could not significantly contribute to the overall star formation in a \( L \sim L^*(z = 3) \) galaxy at \( z \sim 7 \).

If Pop III stars are not from very top-heavy IMFs (see, e.g., Stacy et al. 2010), the He I emission of galaxies at \( z > 6 \) is too weak for current telescopes to detect with a reasonable exposure time. Also, the clear, solid signatures of a Pop-III-dominated galaxy might require reaching the continuum level for fainter high-\( z \) galaxies. Zackrisson et al. (2012) suggest that the Pop III galaxies can experience significant Lyman continuum leakage (also see Inoue et al. 2011), and that such objects would stand out in surveys by the James Webb Space Telescope (JWST) due to their extremely blue rest-frame FUV continuum slopes. Mitra et al. (2011) and Choudhury & Ferrara (2007) predict that if the observations reach a magnitude of \( J_{110, AB} \sim 31–32, \sim 15–30 \) arcmin\(^{-2}\), Pop-III-dominated sources residing halo mass of \( M < 10^9 M_\odot \) will be detected at \( z > 7 \). Future facilities, especially JWST are expected to probe both the continuum and recombination lines for faint galaxies with low halo masses.
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