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PROBING THE FIRST STARS WITH HYDROGEN AND HELIUM RECOMBINATION EMISSION

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ABSTRACT

Unusual patterns of recombination emission from gas ionized by metal-free stars may distinguish early star-forming galaxies from their present-day counterparts. This pattern arises from the harder ionizing spectrum expected from metal-free stars, which strongly enhances the strength of He II recombination lines. Our calculations indicate that line fluxes of He II λ1640 and λ4686 are sufficiently large to be detected by narrowband and spectroscopic searches for high-redshift emission-line sources at $z \sim 5$ using current instruments. An unknown fraction of Lyα emitters may harbor low-metallicity or metal-free stars. As the predicted He II λ1640 flux is comparable to and may exceed hydrogen Lyα, searches for high-redshift galaxies should consider He II recombination lines as possible identifications for single emission lines in observed spectra. Spectra of metal-free stars may show both H I and He II emission lines, improving the constraints on their redshift and identification. We assess the considerable uncertainties that affect our expectations for the detection and identification of true first-generation stars with present search techniques, including the role of stellar mass loss in spectral evolution and the confusion of ionization by primordial stellar sources and AGN in the early universe.

Subject headings: stars: early type — intergalactic medium — cosmology: theory

1. INTRODUCTION

The first stars have long attracted interest from a cosmological point of view, and recent detailed studies of their properties have renewed interest in their cosmological importance. Within the constraints of big-bang nucleosynthesis, these stars must have been metal free, which modifies their structure in fundamental ways: metal free stars have smaller radii, hotter cores, and higher effective temperatures than their counterparts of equal mass but finite metallicity (Tumlinson & Shull 2000). These stars are leading candidates for the sources that reionized the intergalactic medium (Gnedin 2000; Haiman & Loeb 1997), and they produced the first heavy elements that enriched subsequent stellar generations. Tumlinson & Shull (2000) found that these stars, here called Population III or simply metal-free, have harder spectra and emit more ionizing photons in the He II ionizing continuum than do stars of typical solar or sub-solar metallicity. Thus, they may dominate He II reionization in the high-redshift universe.

Distinctive spectral features of their surrounding nebulae may provide a means of detecting the first stars, during and after the epoch of reionization. Tumlinson & Shull (2000) noted that the hard spectra of Pop III stars produce large He III regions, which may emit detectable He II recombination emission. Recombination lines of He II at λ1640 ($n = 3 \rightarrow 2$), λ3203 ($n = 5 \rightarrow 3$), and λ4686 ($n = 4 \rightarrow 3$) are particularly attractive for this purpose, because they suffer minimal effects of scattering by gas and decreasing attenuation by intervening dust. Thus, an assessment of the near-term prospects for discovering metal-free stellar sources is timely. However, uncertainties about the primeval initial mass function (IMF), the importance of stellar mass loss at zero metallicity, and the features of stellar evolution must be addressed.

In this *Letter*, we consider the possibility of detecting metal-free stars using He II recombination emission, and the uncertainties inherent in this technique. Main-sequence mass loss, not well understood from an evolutionary standpoint, can affect the detectability of the first stars via nebular emission lines. Emission line ratios and line profiles may discriminate between stars and active galactic nuclei (AGN) as sources of ionization. We address these issues in the context of existing tracks and assess their importance to the detectability of metal-free stars.

In § 2 we derive an expression for the observed He II emission-line flux of a metal-free stellar population in terms of the star formation rate and evolutionary properties. In § 3 we use evolutionary tracks and model atmospheres to assess the effects of stellar evolution on the detectability of metal-free stellar populations. In § 4 we compare our predictions to current observational searches for high-redshift stellar populations, including present-day emission-line techniques, and we discuss the ambiguity between emission lines produced by metal-free stars and AGN. In § 5 we summarize our results and comment on directions for future work.

2. EMISSION LINES FROM METAL-FREE STARS

We begin by estimating a relationship for the observed He II emission-line flux from metal-free stars as a function of star formation rate (SFR) and stellar evolutionary parameters. Using the zero-age structure and atmosphere models presented by Tumlinson & Shull (2000), we use recombination theory to estimate the total luminosity in the He II emission lines. We assume that few He II ionizing photons escape the galaxies where they are produced ($f_{esc} \simeq 0$) and that the sources themselves contain no dust. We use the Kennicutt (1983) law to relate the luminosity of the Hα line to the star formation rate, L(Hα) = (1.12×10^{41} erg s^{-1}) (SFR/M$_\odot$ yr^{-1}). For case B recombination at T = 20,000 K (corresponding to a higher nebular temperature in low-metallicity gas) and $n_{\rm HeIII}/n_{\rm HII}$ = 0.0789, we

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find $j_{4686}/j_{\mathrm{H}\alpha} = 0.33$, $j_{1640}/j_{\mathrm{H}\alpha} = 2.3$, and $j_{3203}/j_{\mathrm{H}\alpha} = 0.14$ (Seaton 1978). Kennicutt (1983) assumed a Salpeter-like IMF and used stellar evolution tracks for Population I massive stars. We assume a similar IMF and include a factor, $f_{\rm evol}$ (of order unity), designed to account for the time evolution of the stellar ionizing continuum radiation, and defined to be unity if the evolution in He II ionizing photon rate for metal-free stars is identical to the evolution of H I ionizing photons used by Kennicutt (1983). The factor $f_{\rm evol}$ can be evaluated using Pop III evolutionary tracks coupled with model atmospheres (see § 3). Using the results of Tumlinson & Shull (2000), we scale the He II ionizing photon production of zero-metallicity stars to the H I ionizing photon production implicit in the Kennicutt (1983) relation. We find that Pop III stars produce $10^{-1.1}$ as many He II ionizing photons as the Pop I stars produce H I ionizing photons. Scaling the luminosity of He II λ1640 to Hα, we find:

$$L_{1640} = (4.2 \times 10^{40}\ \mathrm{erg\ s^{-1}})\ f_{\rm evol} \left(\frac{\rm SFR}{M_\odot \mathrm{yr}^{-1}} \right). \quad (1)$$

For deceleration parameter $q_0 = 0.5$, the flux of this source is:

$$F_{1640}(z) = \frac{(4.1 \times 10^{-18}\ \mathrm{erg\ cm^{-2}\ s^{-1}}) h_{65}^2 f_{\rm evol} \mathrm{SFR}}{[(1+z)-(1+z)^{\frac{1}{2}}]^2}, \quad (2)$$

where h_{65} is the Hubble constant in units 65 km s^{-1} Mpc^{-1}. The flux of He II λ4686 is 7.1 times lower than F_{1640}, and the flux of λ3203 is 16.2 times lower. (Hereafter we concentrate on the two stronger lines.) This relation is plotted in Figure 1 for SFR = 5 and 20 $M_\odot$ yr^{-1} and $f_{\rm evol} = 0.4$ and 2.0; these choices of $f_{\rm evol}$ are justified in § 3. We also plot detection limits of three recent emission-line searches for high-redshift galaxies. Figure 1 shows that, even for conservative estimates of $f_{\rm evol}$, metal-free stellar populations may be detectable to $z = 2-5$ for a reasonable range of SFR. If a detection can be made and its redshift accurately measured, the star formation rate can be constrained if $f_{\rm evol}$ is carefully calibrated by stellar evolution models.

3. STELLAR EVOLUTION EFFECTS

Stellar evolution at zero metallicity is uncertain and may enhance or diminish the detectability of metal-free stars. Tumlinson & Shull (2000) estimated the ionizing photon production from zero-age main sequence (ZAMS) metal-free stars of mass $2-90\,M_\odot$ using static stellar structure models and NLTE model atmospheres. The He II ionization produced by these stars is a direct result of their high effective temperatures. However, published evolutionary tracks of metal-free stars (Castellani et al. 1983; Chieffi & Tornambe 1984) show that these stars may evolve to cooler temperatures and larger radii over their lifetimes if they do not experience mass loss. Because mass loss may play a significant role in the spectral evolution of the star, it produces uncertainty in the interpretation of emission-line diagnostics.

With model atmospheres similar to those presented by Tumlinson & Shull (2000), Hubeny, Lanz, & Heap (2000) argue that line-blanketed, radiation pressure-driven winds are not initiated for stars with $Z \lesssim 0.001$, owing to the relative lack of metal line-blanketing in their atmospheres. Kudritzki (2000) draws similar conclusions. However, these groups have not, as yet, extended their models to the range $T_{\rm eff} \geq 60000$ K occupied by metal-free massive stars.

Because these stars radiate near the Eddington limit, they may drive winds with electron-scattering opacity. El Eid et al. (1983) used an empirical mass-loss prescription from Chiosi (1981) that scaled $\dot{M}$ to the Eddington luminosity with no explicit dependence on metallicity. They found typical mass loss rates of $\dot{M} \sim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ for stars of 80 - 500 $M_\odot$, with little dependence on luminosity. At these rates, a star with initial mass 80 $M_\odot$ will fall to 40 $M_\odot$ by the end of hydrogen burning, when it begins an excursion to hotter $T_{\rm eff}$ in the HR diagram. As its outer layers are lost, hotter regions below are exposed, and the interior structure adjusts to the changing mass and photospheric conditions. At late times, $T_{\rm eff}$ increases by 0.2 dex over their ZAMS, increasing the production of He II ionizing photons by an order of magnitude.

To evaluate the importance of stellar evolution and mass loss on the production of He II ionizing photons, we make two limiting assumptions: (1) mass loss from Population III stars is negligible, with no effect on their evolution; (2) mass loss is important and affects the structural and spectral evolution of the star. We use the 25 $M_\odot$ track calculated by Castellani et al. (1983) to represent the first case, and the 80 $M_\odot$ mass-loss track by El Eid et al. (1983) for the second. These tracks are not intended to replace the stellar models on which our flux estimates are based. Rather, they represent extremes of mass loss used to constrain the parameter space of $f_{\rm evol}$. If mass loss is unimportant to the evolution of metal-free stars, then the general trend to lower $T_{\rm eff}$ seen in the 25 $M_\odot$ track should hold for stars at all mass and will favor low values of $f_{\rm evol}$. Conversely, if mass loss substantially affects the later evolutionary phases of metal-free stars, then the trends toward higher $T_{\rm eff}$ at late time will favor larger $f_{\rm evol}$.

Model atmospheres were calculated with the TLUSTY code (Hubeny & Lanz 1995) for a set of points along the evolutionary tracks, placed to capture the time evolution of $T_{\rm eff}$ and surface gravity g. We define a time-averaged flux parameter,

$$f_{Q_i} = \frac{\int_{t_{\rm PSN}} Q_i(t)dt}{Q_i(0)t_{\rm PSN}}, \quad (3)$$

where $Q_{i=0,1,2}$ are the ionizing photon production rates for H I, He I, and He II, respectively, and $t_{\rm PSN}$ is the pre-supernova lifetime of the star. The 25 $M_\odot$ star evolves to lower $T_{\rm eff}$ during H burning and experiences a burst of He II ionizing photons near the onset of He burning. The 80 $M_\odot$ star loses over half of its mass during its lifetime and makes two brief excursions to high $T_{\rm eff}$ and high Q_2. For the constant-mass (25 $M_\odot$) track, we derive $f_{Q_0} = 1.3$, $f_{Q_1} = 1.1$, and $f_{Q_2} = 0.32$. For the 80 $M_\odot$ track with mass loss, we find $f_{Q_0} = 1.2$, $f_{Q_1} = 1.1$, and $f_{Q_2} = 1.80$. For comparison, we estimate that $f_{Q_0} = 0.7$, $f_{Q_1} = 0.4$, and $f_{Q_2} = 0.3$ are characteristic of the Chiosi, Nasi, & Sreenivasan (1978) Population I tracks used by Kennicutt (1983). Because $f_{\rm evol}$ compares the evolutionary trends in the He II ionizing flux from metal-free stars with the time average in H I ionizing flux from Pop I, our estimate is given by $f_{\rm evol} = f_{Q_2}$ (Pop III)/f_{Q_0} (Pop I). Thus, on timescales long compared to the evolution of massive stars, $f_{\rm evol}$ may range from 0.4 to 2.6. The two limiting cases imply different behavior on short timescales. For $\dot{M} = 0$, the He II emission fades and H I emission brightens over time as the stars evolve to cooler temperatures. For $\dot{M} \neq 0$ the He II emission from a Pop III cluster increases over time, as stars of successively lower mass exhaust their central hydrogen and make excursions to hotter $T_{\rm eff}$.

Our calculation illustrates a key feature of the ionizing photon production by the first stars: emission-line diagnostics evolve with their stellar populations, and this must be con-

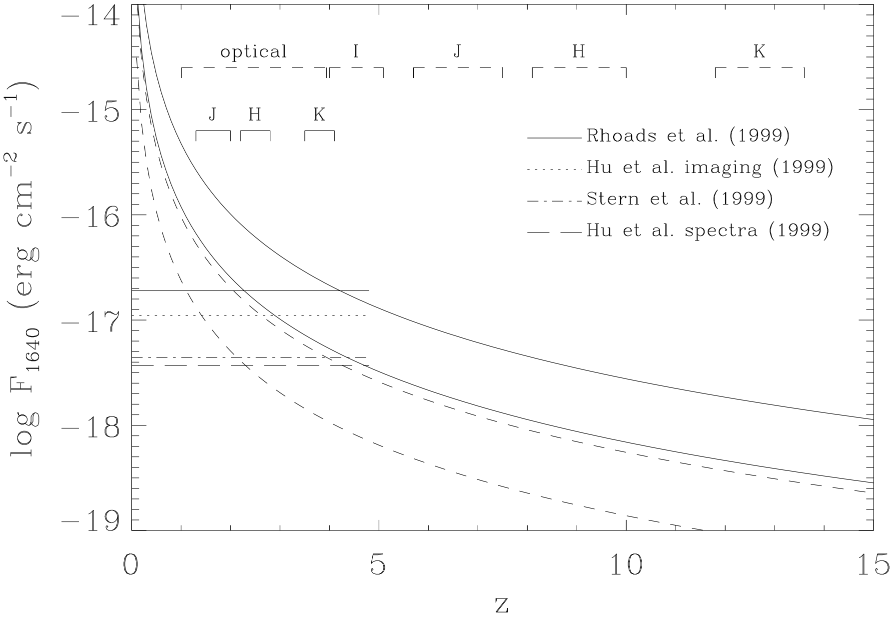

FIG. 1.— Flux of He II λ1640 line as a function of source redshift (eq. 2). The dashed and solid curves correspond to $f_{\rm evol}$ = 0.4 and 2.0, respectively. The upper and lower curves in each pair correspond to star formation rates 20 and 5 $M_\odot$ yr^{-1}. The flux for λ4686 is 7.1 times lower than F_{1640}. The horizontal solid, dotted, dash-dot, and dashed lines show the limits of current Lyα emission-line surveys, as described in the text. The flux limits have been corrected for the energy difference between 1216 Å and 1640 Å. At the top, we mark the ranges of redshift probed by the He II λ1640 (above) and λ4686 (below) lines for optical and infrared searches. Optical searches for $z = 1-5$ are feasible now, and infrared searches may be possible in the near future.

sidered in the planning and interpretation of observational searches. A single snapshot of a metal-free stellar population in its He II recombination lines would not distinguish between the $\dot{M} = 0$ and $\dot{M} \neq 0$ cases, because of the degeneracy in the parameters $f_{\rm evol}$ and SFR (eq. 2). Measuring the star formation rate of metal-free stars with He II emission requires that f_{Q_2} be carefully calibrated by stellar evolution calculations.

The evolution of the ionizing photon production may provide a means of distinguishing between the two cases presented above. The time evolution of Q_i for the limiting cases of $\dot{M} = 0$ and $\dot{M} \neq 0$ illustrates a key difference between the two possibilities. The 25 $M_\odot$ star at constant mass exhibits most efficient He II ionization at the beginning of its H-burning main-sequence, giving $Q_2/Q_0 = 10^{-4}$. The 80 $M_\odot$ star with $\dot{M} \neq 0$, by contrast, achieves the maximum value $Q_2/Q_0 = 0.40$ at the end of its life. This ratio is larger than the range of $Q_2/Q_0 = 0.05-0.12$ for the most massive stars studied by Tumlinson & Shull (2000) and Bromm, Kudritzki, & Loeb (2000). Thus, the two extreme cases can be distinguished by observed He II to H I ionization ratios that exceed those achieved by constant-mass stars.

4. COMPARISON WITH OTHER EMISSION-LINE DIAGNOSTICS

The relatively bright He II emission-line fluxes predicted for metal-free stars raise the possibility of detection with present-day broadband and spectroscopic searches. In particular, we examine the possibility that He II λ1640 emitters have already been observed and mistaken for Lyα emitters. Recent searches for high-redshift galaxies use narrow-band imaging and spectroscopic techniques. These emission lines are believed to be Lyα because deep spectra reveal no other galactic emission lines ([O III] λ5007, [O II] λ3727, Hα), and these identifications for the single line can be eliminated by the absence of corresponding emission.

In Figure 1 we plot the detection limits of three current Lyα searches for high-redshift galaxies. Hu, Cowie, and McMahon (1999) quote a 5σ detection limit 1.5×10^{-17} erg cm^{-2} s^{-1} for narrowband imaging and 5.0×10^{-18} erg cm^{-2} s^{-1} (5σ) for spectroscopic searches. In a 1.5 hour Keck exposure, Stern et al. (2000) achieved a limiting flux 6.0×10^{-18} erg cm^{-2} s^{-1} in a 1″ slit for an unresolved line. Rhoads et al. (2000) achieved detections ranging between $1.8-2.6 \times 10^{-17}$ erg cm^{-2} s^{-1} using combinations of imaging and spectroscopy. As shown in eq. 2, such a detection of He II lines would measure the product of SFR and $f_{\rm evol}$. Therefore, careful calibration of $f_{\rm evol}$ with stellar evolution models could break the degeneracy and independently constrain the star formation rate.

Hu, McMahon, & Cowie (1999) reported the detection of a single line in the spectrum of a luminous galaxy, using a combination of narrowband imaging and spectroscopic observations. Identifying this line as Lyα, they infer $z = 5.74$, a total line flux 1.7×10^{-17} erg cm^{-2} s^{-1} at 8195 Å, and a star formation rate of 19 $M_\odot$ yr^{-1}. If this line is He II λ1640 at $z = 4.0$, the implied SFR would be 80, 32, and 16 $M_\odot$ yr^{-1} for $f_{\rm evol}(Q_2)$ = 0.4, 1.0, and 2.0, respectively. Typical Lyman-break galaxies have inferred SFR $\simeq 10-100\,M_\odot$ yr^{-1} (Steidel et al. 1999). Thus, the SFR by itself does not rule out identification as He II λ1640 for implied values of $f_{\rm evol}$ consistent with the $\dot{M} \neq 0$ case. The implied total flux in λ4686 is 2.3×10^{-18} erg cm^{-2} s^{-1} at 2.34 μm, below the K-band sensitivity limits of the Hu et al. (1999) survey. The flux predictions in § 2 suggest that this line might be He II λ1640 at $z = 4.0$, were it not for the presence of a spectral break across the line produced by intergalactic Lyα absorption. The absence of the break may provide key spectroscopic evidence for identifications of He II recombination lines. Without a break, the U, B, and V dropout techniques commonly used to discover high-redshift galaxies (Steidel et al. 1999) may not select these objects for spectroscopic followup. Because Q_0 for Pop III is similar to that of Pop I (Tumlinson & Shull 2000), the observed fluxes of He II λ1640 and H I Lyα should be comparable. The predicted line fluxes and the separation of Lyα and He II λ1640 by 424(1+z) Å suggests that some detections may show two emission lines, confirming identification and redshift in the range $z = 2-5$. Future spaceborne missions such as *NGST* may also be used to detect high-redshift AGN and metal-free stars via associated He II λ1640 and λ4686 nebular emission (Oh, Haiman, & Rees 2001).

It remains an issue, however, how the detection of a single nebular line would permit one to discriminate between stellar and AGN sources of ionizing radiation. Intrinsic line widths may not be sufficient to resolve the confusion. Recent surveys of Wolf-Rayet galaxies (Schaerer et al. 1999 and references therein) show broad He II λ4686 emission from stellar winds and narrow nebular emission. These lines are usually detected at fluxes of 1 – 4% of the observed Hβ fluxes from these galaxies, and the broad wind features are generally brighter than the nebular emission. Spectroscopic Lyα surveys (Hu et al. 1999) typically use low resolution, R $\sim$ 1000, to achieve their required sensitivity. Identifying stellar and AGN ionization may require resolution of $\sim$100 km s^{-1} to distinguish broad, cuspy line profiles of AGN lines from narrow nebular emission due to massive stars. The He II to H I line ratios for metal-free stars may provide a further discriminant. The $\dot{M} \neq 0$ case (§ 3) gives a maximum value of $Q_2/Q_0 = 0.40$. For a power-law AGN spectrum, $f \sim \nu^{-\alpha}$, this ratio is $Q_2/Q_0 = 4^{-\alpha}$. For the composite radio-quiet AGN spectrum ($\alpha = 1.8$) from Zheng et al. (1997), this ratio is $Q_2/Q_0 = 0.08$. However, distinguishing metal-free stars from AGN with harder spectra than the power-law composite may be more difficult. If mass loss is important to the evolution of metal-free stars, this maximum ratio technique may provide a convenient means of distinguishing them from AGN in the early universe. The prospects for distinguishing stellar and AGN ionization improve for cases where lines of both H I and He II are observed.

As a potential discriminant between AGN and metal-free stars, IGM ionization ratios of He II to H I may show different signatures of AGN or stellar ionization. However, the hard AGN-like ionizing continuum of metal-free stars may confuse the issue. Fardal, Giroux, & Shull (1998) define the column density ratio $\eta = \mathrm{N}_{\mathrm{HeII}}/\mathrm{N}_{\mathrm{HI}}$. Ultraviolet studies of the He II Gunn-Peterson absorption toward quasars at $z = 2.7-3.3$ (Davidsen, Kriss, & Zheng 1996; Reimers et al. 1997; Hogan, Anderson, & Rugers 1997) suggest that the IGM reionizes in He II at $z \approx 3$. The ionizing spectrum required to match the optical depths, τ_{HI} and τ_{HeII}, at $z \leq 3$ is relatively soft, with $\eta = 100-200$, in contrast to the harder spectra from unfiltered AGN and metal-free stars, which yield $\eta \approx 30$. If metal-free stars are implicated in the He II reionization, then observational searches for the characteristic He II emission lines (λ1640 and λ4686) from starburst galaxies at $z = 3-5$ would be extremely helpful. These lines should be measured together with high-ionization metal absorption lines (C IV, S IV), to assess any shift in the quality of the ionizing spectrum at $z \approx 3$ (Songaila & Cowie 1996). Discriminating stellar from AGN sources may depend on detailed line ratio predictions from accretion models (Hubeny et al. 2000) and stellar population synthesis. The maximum line ratio technique sketched above must be extended to account for IMF and evolution effects, but it holds promise if complete H I and He II recombination spectra are observed.

5. SUMMARY

In summary, our main conclusions are the following:

1. Predicted fluxes for He II emission lines from nebulae ionized by metal-free stars are comparable to the detection limits of present-day narrowband and spectroscopic searches for high-redshift galaxies. Observational searches for these stars at $z \sim 3-5$ are feasible now at optical wavelengths. Higher redshift surveys may need to await space-based infrared instruments.

2. Mass loss by metal-free stars may restrict or enhance their detectability with emission-line techniques. Careful calibration with detailed evolutionary tracks and theoretical work on mass loss from metal-free stars are necessary to refine this program.

3. If multiple line detections are made for a single object, He II and H I emission lines may provide important diagnostics of the stellar parameters. These line ratios may provide a means of distinguishing stellar and AGN sources even if the line profiles are unresolved.

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