HEII RECOMBINATION LINES FROM THE FIRST LUMINOUS OBJECTS

S. Peng Oh, Zoltán Haiman
Princeton University Observatory, Princeton, NJ 08544, USA
peng@astro.princeton.edu, zoltan@astro.princeton.edu

Martin J. Rees
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK
mjr@ast.cam.ac.uk

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ABSTRACT

The hardness of the ionizing continuum from the first sources of UV radiation plays a crucial role in the reionization of the intergalactic medium (IGM). While usual stellar populations have soft spectra, mini–quasars or metal–free stars with high effective temperatures may emit hard photons, capable of doubly ionizing helium and increasing the IGM temperature. Absorption within the source and in the intervening IGM will render the ionizing continuum of high–redshift sources inaccessible to direct observation. Here we show that HeII recombination lines from the first luminous objects are potentially detectable by the Next Generation Space Telescope. Together with measurements of the Hα emission line, this detection can be used to infer the ratio of HeII to HI ionizing photons, $Q = N_{\text{HeII}}^{\text{ion}}/N_{\text{HI}}^{\text{ion}}$. A measurement of this ratio would shed light on the nature and emission mechanism of the first luminous sources, with important astrophysical consequences for the reheating and reionization of the IGM.

Subject headings: cosmology: formation – galaxies: formation – quasars: emission lines

1. INTRODUCTION

The launch of the Next Generation Space Telescope (NGST) raises the exciting possibility of direct imaging and spectroscopy of the first luminous objects that reionized the universe at high redshifts $z \sim 5–30$. The first mini–galaxies are likely detectable in rest frame UV emission (Haiman & Loeb 1997), assuming a cold dark matter (CDM) cosmology, and an average star formation efficiency calibrated to the observed metallicity of the Lyα forest at redshift $z \sim 3$. Similarly, mini–galaxies with black hole (BH) masses comparable to those found in nearby galaxies (Gebhardt et al. 2000; Ferrarese & Merritt 2000) and shining at the Eddington limit would be observable (Haiman & Loeb 1998). Detection of these sources before the epoch of reionization in the Lyα emission line is difficult due to the high optical depth of the intervening neutral IGM. This causes the Lyα photons to be spread out over an extended low surface brightness halo (Loeb & Rybicki 1999), although if the first ionizing sources were very luminous quasars, they may ionize a sufficiently large surrounding region that Lyα detection becomes feasible (Cen & Haiman 2000, Madau & Rees 2000). By comparison, resonant scattering is unimportant for Balmer line emission, which is likely to be detectable by NGST (Oh 1999), even for sources which do not ionize their surroundings out to great distances.

The above observations do not strongly constrain the hardness of the ionizing spectrum. Hard sources of ionizing radiation are certainly plausible at high redshift, and can vary from mini–quasars (Haiman & Loeb 1998), to very massive objects ($\gtrsim 100 \, M_\odot$) VMOs, Bond, Carr, & Arnett 1984), metal–free stars (Castellani et al. 1983; El Eid et al. 1983; Tumlinson & Shull 2000), thermal and non-thermal emission from supernova remnants (Oh 2000a), X-ray binaries, and so forth. In particular, while low-metallicity (Z $\sim 10^{-2} Z_\odot$) stellar populations with a Salpeter or Scalo IMF (which are often used in reionization models) emit a negligible amount of HeII ionizing photons, this is not the case for these other sources of ionizing radiation.

The spectral hardness of the first sources of ionizing radiation has important consequences for cosmological reionization. If the first ionizing sources emit copious numbers of HeII ionizing photons, HeII might be substantially reionized at high redshifts. The fast recombination time of HeII allows efficient transfer of energy from the radiation field to the IGM, raising the IGM to significantly higher temperatures (Miralda-Escudé & Rees 1994). In addition, if the ionizing spectrum extends to X-ray energies ($\sim 1$ keV), the hard photons promote H$_2$ molecule formation and cooling inside minihalos, by increasing their free electron fraction (Haiman, Abel & Rees 2000). As a result, reionization could commence at higher redshifts. Finally, due to their large mean free path, hard X–ray photons also change the topology of reionization, making it gradual and homogeneous (Oh 2000b).

Despite its importance, the ionizing continuum of high–redshift sources will likely be inaccessible to direct observation, because of strong absorption by neutral H and He within the source, and also in the neutral IGM in which the sources are embedded. In particular, the very high optical depth to resonant scattering in the IGM by neutral hydrogen implies that flux shortward of rest–frame Lyα is sharply attenuated (Gunn & Peterson 1965). The production rate of ionizing photons may be indirectly inferred by Hα observations with NGST. As shown recently by Tumlinson & Shull (2000), the composite spectrum of a metal–free stellar population is significantly harder than...
that of its low–metallicity counterpart: as a consequence, HeII recombination lines from metal–free stars might also be observable with NGST. The IGM is optically thin to these recombination lines, since the de–excitation time for level transitions is very short and HeII always resides in the ground state. In this paper, we show that that observing HeII recombination lines from the first ionizing sources is feasible, and can serve as a general diagnostic of any hard source of ionizing radiation. A measurement of the strength of these emission lines can help distinguish between different reionization scenarios: e.g. whether mini–galaxies or mini–quasars were the dominant sources of ionizing radiation at high redshift.

We now consider two examples for the detectability of the HeII recombination lines: a metal–free stellar population with a Salpeter IMF, or a mini–quasar with a BH of mass $M_{\odot}$. For metal–free stars the ionizing photon production rates are given by $N_{\text{ion}}^{\text{HeII}} \approx 1.5 \times 10^{33}(\text{SFR}/M_{\odot} \text{yr}^{-1})$ photons s$^{-1}$, and $N_{\text{ion}}^{\text{HeII}} \approx 10^{31.8}(\text{SFR}/M_{\odot} \text{yr}^{-1})$ photons s$^{-1}$, implying $\eta \approx 0.05$ (Tumlinson & Shull, 2000). Thus, the flux from the He recombination line $i$ is

$$J_{\text{stars}} = \frac{L_i}{4\pi d_L^2} \frac{\alpha_i}{\nu_i} \approx 26 \left( \frac{q_i}{1.2} \right) \left( \frac{R}{1000} \right) \left( \frac{1+z}{10} \right)^{-1} \times$$

$$\left( \frac{Q}{0.05} \right) \left( \frac{\text{SFR}}{10^7 M_{\odot} \text{yr}^{-1}} \right) \left( 1 - f_{\text{HeII}}^{0.05} \right) \text{nJy},$$

where $q_i \equiv f_i n_{\text{HeII}} / n_{\text{HeII}}$ (so that $q_{\lambda 4686} = 0.53, q_{\lambda 1640} = 1.2, q_{\lambda 3203} = 0.15$), $R \equiv \lambda / \delta \lambda$ is the spectral resolution, and SFR is the star formation rate. We have assumed that the line is unresolved, so that the measured flux is linearly proportional to the spectral resolution. The intensity of the HeII lines is only a few percent of the flux from H$\alpha$ emission. For mini–quasars emitting ionizing radiation with a power law spectrum $L_\nu \propto \nu^{-\alpha}$, we have $Q = 4^{-\alpha}$. The median spectrum of Elvis et al. (1994) suggests $\alpha \approx 1$, while the observations of Zheng et al. (1997) suggest $\alpha \approx 1.8$ (note that the latter was observed only in the radio–quiet AGN subsample at energies up to 2.6 Ry, short of the 4.0 Ry HeII edge). We infer an implied range of $Q = 0.08 - 0.25$, so that a somewhat larger fraction of the ionizing radiation from quasars is able to ionize HeII. Assuming the BH emits radiation at the Eddington rate, we find the He recombination flux:

$$J_{\text{qasar}} \approx 56 \left( \frac{q_i}{1.2} \right) \left( \frac{R}{1000} \right) \left( \frac{1+z}{10} \right)^{-1} \left( \frac{M_{\odot}}{10^7 M_{\odot}} \right) \times$$

$$\left( \frac{4^{-\alpha}}{0.25} \right) \left( 1 - f_{\text{HeII}}^{0.05} \right) \text{nJy}.$$  

Note that $f_{\text{HeII}}^{0.05}$ for QSOs can be somewhat larger than that for stars. Since the central black hole is a point source, it can create an ionized chimney of gas perpendicular to the disk through which ionizing photons can escape. This is also the case if gas is clumpy and the covering factor of neutral clouds is low. However, unless the escape fractions are very high ($f_{\text{HeII}}^{0.05} > 50\%$), this does not significantly affect our estimates.

Despite the fact that HeII line flux is a small fraction of the H$\alpha$ line, the HeII line can still be detected. To estimate the signal–to–noise ratio of the emission lines, we use the the expression for the noise expected for NGST given by Gillett & Mountain (1998, page 44, see also Oh 1999). In the relevant range of fluxes and wavelengths (a few nJy at 1 $\mu$m $\leq \lambda \leq 10\mu$m), the noise is expected to be dominated by the detector dark current and the sky background. In the 1–5.5 $\mu$m range we adopt a dark current of 0.02 e$^{-}$ s$^{-1}$, based on the current design goal of NGST. The detector noise at $\lambda > 5.5\mu$m is expected to increase substantially; we assume a dark current of 0.3 e$^{-}$ s$^{-1}$ in this range based on the present state–of–the–art detector on the Space Infrared Telescope Facility (SIRTF). To estimate the sky background, we use the minimum observed sky brightness tabulated from DIRBE data in the range

2 Detectability of HeII recombination lines

The escape fraction $f_{\text{esc}}^{\text{HeII}}$ of HI ionizing photons from galaxies in the local universe is inferred to be small, $\sim 3 - 6\%$ (Leitherer et al 1995, Bland-Hawthorn & Maloney 1999, Dove, Shull & Ferrara 2000) and is expected to further decrease with increasing redshift (Wood & Loeb 2000, Ricotti & Shull 2000). The escape fraction $f_{\text{esc}}^{\text{HeII}}$ of HeII ionizing photons is likely to be even smaller: all the sources of ionizing radiation we consider have $\eta < 1$, since the probability that any ionizing photon is likely to be even smaller: all the sources of ionizing radiation we consider have $\eta < 1$. In addition, we have assumed ionization balance of ionizing radiation we consider have $\eta = 1$. The luminosity in a line $j$ is given by

$$L_j \equiv \frac{\alpha_j}{\nu_j} \left( N_{\text{ion}}^{\text{HeII}} / n_{\text{HeII}} \right) \left( t_{\text{rec,HeII}} / t_{\text{rec,HI}} \right) \left( \alpha_{\text{HeII}/\alpha_{\text{HI}}} \right) = 0.5$$

Assuming the BH emits radiation at the Eddington rate, the ionizing radiation from quasars is able to ionize HeII. The luminosity in the line $j$ is given by

$$L_j = 4\pi j_{\nu_j} V = (4\pi j_{\nu_j} / (n_{\text{HeII}} n_{\text{HeII}})) \times \left( N_{\text{ion}}^{\text{HeII}} / (\alpha_{\text{HeII}}) \right),$$

where $4\pi j_{\nu_j}$ is the emissivity coefficient (in erg cm$^{-3}$ s$^{-1}$). $V$ is the emitting volume, and we have assumed ionization balance for species $k$, which implies $N_{\text{ion}}^{\text{HeII}} = \alpha_{\text{HeII}} n_{\text{HeII}} V$. Thus, we can normalize the line luminosity of a helium recombination line to the H$\alpha$ luminosity via $L_j = Q_{j_\alpha} L_{\text{H}\alpha}$, where

$$L_{\text{H}\alpha} = \frac{\text{H}\alpha \text{ luminosity}}{\text{HeII line}}$$

and we obtain the quantities $j_{\alpha} / n_{\text{HeII}} n_{\text{HeII}}$ and $j_{\alpha} / n_{\text{HeII}} n_{\text{HeII}}$ from Seaton (1978). Note that the similar temperature scaling of the HI, HeII emission and recombination coefficients implies that $\alpha_i \propto T^{0.15}$ depends only weakly on the assumed temperature, varying by at most $\sim 10\%$ across a plausible temperature range. We are only interested in the HeII recombination lines longward of HI Ly$\alpha$, which will not redshift into HI Ly$\alpha$ and be resonantly scattered in the IGM. The three strongest such recombination lines are: HeII(4 $\rightarrow$ 3), HeII(3 $\rightarrow$ 2), and HeII(5 $\rightarrow$ 3), with rest frame wavelengths $\lambda = 4686\AA, 1640\AA, 3203\AA$, and luminosities relative to the H$\alpha$ line of $f_{\lambda 4686} = 0.74, f_{\lambda 1640} = 4.7, f_{\lambda 3203} = 0.30$ respectively.
1.25μm-12μm (Hauser et al. 1998, Table 2). We find that this background contributes \( \sim 20 - 50\% \) of the noise in the 1-5.5 μm range, while it is less important ( \( \lesssim 10\% \)) compared to the increased detector noise at \( \lambda > 5.5\mu m \).

The sky background is dominated by the zodiacal light, and might be substantially reduced for NGST compared to DIRBE, depending on NGST’s orbit.

The increase of the detector noise beyond \( \lambda > 5.5\mu m \) affects the relative detectability of the HeII and Hα lines. For a source at redshift \( z_{\alpha,i} < 32, 16, 11 \), the He \( \lambda 1640, \lambda 2026, \lambda 6563 \) lines lie in the favorable 1-5.5 μm range; by contrast, the Hα line redshifts to \( \lambda > 5.7\mu m \) for \( z_{\alpha,i} > 7 \).

Thus, in the redshift range \( 7 < z < z_{\alpha,i} \), the relative signal to noise is \( (S/N)_{\text{He},i}/(S/N)_{\text{Hα}} \approx 0.5(Q/0.05)/(q/1.2) \).

As an example, for a metal–free stellar population with a Salpeter IMF, the detection of the brightest line, HeII \( \lambda 1640 \), would require an integration time \( \approx 4 \) times longer than that required for Hα; a quasar with \( q = 1 \) would an integration time \( \sim 6 \) times shorter for HeII \( \lambda 1640 \) than for Hα. More generally, for redshifts below \( z_{\alpha,i} \), a day’s integration for a HeII line yields

\[
\frac{S}{N} \approx 10 \left( \frac{q}{1.2} \right) \left( \frac{R}{1000} \right) \left( \frac{1+z}{10} \right)^{-1} \left( \frac{t}{10^5 s} \right)^{1/2} \times \\
\left( \frac{\Omega}{0.01 \text{arcsec}^{-2}} \right)^{-1/2} \left( \frac{Q}{0.05} \right) \left( \frac{4-\alpha}{0.25} \right) \times \\
\left( \frac{\text{SFR}}{(1M_\odot \text{yr}^{-1})} \right) \left( \frac{M_{\text{bh}}}{5 \times 10^4 M_\odot} \right) 
\]

(3)

where the left figures in square brackets are to be used for metal-free stars and the right figures are to be used for mini–quasars. Assuming that \( f_{\text{star}} \sim 10\% \) of the gas is processed into stars, and \( f_{\text{HeII}} \sim 0.3\% \) collapses to the central BH (see the models for high-redshift starbursts and mini–quasars by Haiman & Loeb 1997, 1998), the requirement of \( S/N=10 \) corresponds to dark halos with total mass \( M_{\text{halo}} \sim 10^9 M_\odot \) at \( z = 9 \) (note that \( f_{\text{star}}, f_{\text{HeII}} \) should be regarded as adjustable parameters uncertain to within an order of magnitude). We assume that gas in sources collapes to form discs with angular scale \( r_{\text{disc}} \sim \lambda_{\text{vir}} \), where \( \lambda \sim 0.5 \) is the spin parameter; thus, most photons are converted to recombination line photons in the dense cores of halos. In this case most sources remain spatially unresolved, and subtend a solid angle \( \Omega \approx \max[1, (\lambda/3.5\mu m)^2] \times 0.01 \text{arcsec}^2 \).

From the observed recombination line fluxes, one can determine the relative number of HI and HeII ionizing photons: \( Q_{\text{obs}} = (1/q)(J_{\text{HeII}}/J_{\text{Hα}}) \). There is, however, an upper limit to the observable ratio of HeII and Hα line strengths. Ionizing photon ratios in excess of \( N_{\text{ion}}^{\text{HeII}}/N_{\text{ion}}^{\text{HI}} \sim 1 \) do not further increase the observed line ratios, because \( \approx 50\% \) of the opacity at \( E = 54.4\text{eV} \) is contributed by HI rather than HeII, inhibiting the growth of a HeIII region further than the extent of the HII region. In practice, this limit can be approached only by unusually hard sources with a spectral index such that \( F_\nu \approx \text{const} (\alpha \approx 0) \).

The relative intensities are also proportional to the relative escape fractions: \( Q_{\text{obs}} \propto J_{\text{HeII}}/J_{\text{Hα}} \propto (1 - f_{\text{esc}})^{-1} / (1 - f_{\text{esc}}^\prime) \); thus, unequal escape fractions would lead to incorrect inferred \( Q \). However, as long as the escape fraction for both HI and HeII ionizing photons is small, \( f_{\text{esc}} < 10\% \), this is a small effect. Furthermore, while the inferred values of \( N_{\text{HeII}}/N_{\text{HeI}} \) from \( J_{\text{HeII}}, J_{\text{HeI}} \) are subject to uncertainties about the electron temperature and dust scattering, their ratio is much more robust. In particular, the inferred value of \( Q \) has only a \( T^{-0.15} \) dependence on the electron temperature and is largely insensitive to interstellar reddening (Garnett et al 1991).

### 3. NUMBER OF DETECTABLE HALOS

It is interesting to ask how many sources are expected to be bright enough for detection in HeII emission by NGST. Based on equation 3, the minimum halo mass associated with a detectable source is at least \( \sim 10^9 M_\odot \). The gas in these halos have virial temperatures \( T_{\text{vir}} > 10^4 \text{K} \), allowing efficient atomic line cooling and subsequent star or BH formation. We now make further simple assumptions about the efficiency of star and BH formation to compute the expected number counts, based on the abundance of dark halos. The mass function of halos has recently been determined accurately (to within \( \sim 20\% \)) in large three–dimensional simulations (Jenkins et al. 2000), and we adopt their fitting formula (their eq. 9). The halo masses relevant here are factor of a few above the “knee” of the mass function, where the abundance of halos is slightly larger than in the standard Press-Schechter (1974) theory. We also adopt a flat cold dark matter (CDM) cosmology with a cosmological constant, i.e. \( \Lambda \)CDM with \( (\Omega_M, \Omega_\Lambda, h, \sigma_{8h^{-1}}, n) = (0.7, 0.3, 0.04, 0.7, 1, 1) \).

The estimate of the number of detectable metal–free starbursts is difficult, since the length of the epoch of completely metal–free star formation is not known. Even trace enrichment of star forming regions to low metallicities \( Z \sim 10^{-3} \) results in stars with significantly softer spectra (Tumlinson & Shull 2000), with a production rate of HeII ionizing photons lower by 5 orders of magnitude, from which HeII recombination radiation would be unobservable. It is possible that such trace enrichment could take place very quickly, on timescales of order the lifetime of the first generation of stars. To circumvent this uncertainty, we simply assume that some fixed fraction \( f_* \) of the baryonic mass of every halo with \( T_{\text{vir}} > 10^4 \text{K} \) undergoes a metal–free starburst. Of course, in reality \( f_*(M_{\text{halo}}) \) is likely a function of both halo mass and redshift, and in particular declines with redshift as stars pollute the IGM with metals. Our ansatz is therefore valid only at high redshift \( z > z_{\text{pollute}} \) before metal pollution becomes widespread; at lower redshifts the counts are overestimates. For detection with NGST to be feasible \( z_{\text{pollute}} \) must be low, either because metal mixing is inefficient or widespread star formation only takes place at low redshift.

We define the efficiency parameter \( \epsilon = (f_*/0.1)(Q/0.05) \), and in Figure 3 we show the number of detectable objects in the three HeII lines, as a function of redshift, for two different values of \( \epsilon = 1 \) and 0.1. We require \( S/N=10 \), and adopt the field of view of \( 4' \times 4' \) of NGST. The curves are obtained by computing the total abundance of halos brighter than the \( S/N \) threshold, and multiplying by the duty–cycle \( t_\nu/1H(z) \), where \( t_H(z) \) is the age of the universe at redshift \( z \), and \( t_* = 10^7 \) or \( t_* = 10^6 \) years is the duration of the burst. Note that since the underlying mass function is steeper than \( M^{-1} \), shorter, and therefore for a fixed \( f_* \) brighter, bursts (upper set of three curves) yield
a larger number of detectable sources than longer bursts (middle set of three curves). Note further that for a low star formation efficiency of $f_s = 1\%$ (and $Q = 0.05$), one source is still detectable per field out to $z \sim 13$ in the brightest line (lower solid curve).

shifts, where the underlying halo mass function is steep (cf. the upper vs. the middle set of three curves). The lower set of three curves demonstrate that for a relatively soft spectrum $\alpha = 1.8$, a few mini–quasars would still be visible out to $z \sim 14$.

FIG. 1.—The number of sources in a 4' × 4' NGST field per unit redshift, detectable as a 1σ fluctuation in the three brightest HeII line, in a $t = 10^5$ s exposure at spectral resolution $R = 1000$. The sources are assumed to remain unresolved. The middle set of three (solid, dashed and dotted) curves correspond to the efficiency parameter $\epsilon = (f_s/0.1)(Q/0.05) = 1$ and a burst duration of $t_b = 10^5$ years. The upper and lower set of three curves show variations from this model when $t_b = 10^6$ years or $\epsilon = 0.1$ is assumed, respectively. The sharp cutoff in the counts for the $\lambda 4686\AA$ line for $z > 11$ is due to the increased detector noise at $\lambda > 5.5 \mu$m.

To estimate the number of detectable mini–quasars, we assume that a fraction $3 \times 10^{-4}(\Omega_b/\Omega_m)$ of the halo mass collects into a central BH, which shines for $t_Q = 10^7$ years. Alternatively, we assume that the BH’s are 10 times more massive than this, but shine only for $10^9$ years. Both of these relations produce the same amount of total quasar light, and the latter relation is similar to the Haiman & Loeb (1998) model, which was explicitly calibrated to fit the Pei (1995) luminosity function at redshifts below $z \lesssim 5$ (see Haehnelt et al. 1998 and Haiman & Hui 2000 for a discussion on the quasar lifetime, and the calibration of the ratio of BH to halo mass). Note that while the low-redshift empirical relation $M_{\text{bh}} \propto L_{\text{halo}}$ (Magorrian et al 1998) has large scatter, the relation $M_{\text{bh}} \propto \sigma^3$ has recently been shown to be much tighter, with scatter largely accounted for by observational errors (Gebhardt et al 2000, Ferrarese et al 2000). This new result is in line with our assumptions, since at a given formation redshift the correlation $M_{\text{halo}} \propto \sigma^3$ is much tighter than the correlation $M_{\text{halo}} \propto L_{\text{halo}}$ (the latter being subject to larger scatter in gas cooling and star formation efficiency). Nevertheless, we must regard the $M_{\text{bh}} \propto M_{\text{halo}}$ scaling as an uncertain ansatz motivated by lower–redshift observations. In Figure 2 we show the expected number of detectable sources in these two models in the three strongest HeII lines. Similar to the starburst case, shorter and brighter mini–quasars would be more numerous, especially at the highest redshifts, where the underlying halo mass function is steep (cf. the upper vs. the middle set of three curves). The lower set of three curves demonstrate that for a relatively soft spectrum $\alpha = 1.8$, a few mini–quasars would still be visible out to $z \sim 14$.

FIG. 2.—Same as Fig. 1, but for mini–quasars. The middle set of three curves describe a model with BH to halo mass ratio of $3 \times 10^{-4}(\Omega_b/\Omega_m)$, a quasar lifetime of $t_Q = 10^7$ years, and spectral index $\alpha = 1$. The upper and lower set of three curves show variations from this model when $t_Q = 10^6$ years (with $M_{\text{BH}}/M_{\text{halo}} = 3 \times 10^{-3}[\Omega_b/\Omega_m]$) or $\alpha = 1.8$ is assumed, respectively.

4. DISCUSSION

Our simple estimates suggest that hard ionizing radiation from either metal–free stellar populations or from mini–quasars would produce HeII emission lines that are detectable with NGST. Our results, shown in Figures 1 and 2, reveal that there could be ~ 10 suitably bright sources from redshift $z \gtrsim 10$ in an NGST field in a $10^5$ sec exposure. The distinction between metal–free starbursts and mini–quasars is best performed with observations with greater signal–to–noise than HeII recombination lines—e.g. on the basis of broad–band colors as has been successfully used to select high–redshift quasars (Fan 1999), Ho line widths (with mini–quasars displaying much broader line widths $\sigma \sim 1000$ km s$^{-1}$ due to line broadening by the accretion disc), and the fact that the brightest mini–quasars can be seen in X–ray emission with CXO (see discussion below).

HeII recombination radiation could also arise from other sources of hard photons, such as supernova remnants. Indeed, HeII recombination emission has been detected in several nearby extragalactic HII regions, and have been used to infer values of $Q$ of order $Q \approx 3\%$ (e.g., Garnett et al 1991). The interpretation of these results is still uncertain, with suggested emission mechanisms for HeII ionizing radiation ranging from Wolf–Rayet stars to X–ray binaries and shocks. Suffice it to say that if such hard sources are also present at high redshift, their HeII recombination will also be detectable by NGST, and their presence has important implications for the reionization process.

For
processes which scale with the star formation rate such as Wolf-Rayet stars, XRB and supernova shocks, their detectability can be estimated simply by inserting the appropriate value of $Q$ in equation (1): the empirically derived value of $Q \approx 3\%$ yields fluxes about a factor of 2 below that assumed for metal-free stars. Thus, HeII recombination lines might be visible from star-forming regions even after widespread metal pollution.

Candidate objects for HeII emission lines can be imaged with NGST in broad bands at rest-frame energies below 13.6 eV. However, strong absorption within the source, and by the neutral IGM, will render the ionizing continuum inaccessible to direct observation. High-redshift quasars are also much more difficult to detect in X–rays than in the HeII lines. To detect a redshift $z = 10$ source with the Chandra satellite in $5 \times 10^5$ seconds at $S/N = 5$, the BH mass needs to be at least about $10^8 M_\odot$ (Haiman & Loeb 1999). By contrast, NGST could detect the HeII line signal from a BH as small as $\sim$ NGST value of appropriate value of $Q$ (Haiman & Loeb 1999). Thus, HeII recombination lines might be visible from star-forming regions even after widespread metal pollution.

It is worth noting that the measured value of $Q$ does not uniquely constrain the importance of hard photons for the reionization of the universe. Photons with energies above $E \gtrsim 270(N_{HI}/10^{21} \text{cm}^{-2})^{1/3}$eV can escape unimpeded from a halo with a neutral hydrogen column density of $N_{HI}$, and would not produce HeII recombinations (and would therefore not affect the measurement of $Q$). Nevertheless, these hard photons can contribute to the reionization of the universe by multiple secondary ionizations far away from the source, since a fully neutral IGM is optically thin only for $E \gtrsim 1.5(1+z)/10^{1/2}(x_{HI})^{1/3}$keV. Such photons are more important for HI ionizations rather than HeII ionizations, since each photon contributes at most one HeII ionization but multiple HI ionizations (secondary ionizations have little effect on HeII ionization, Shull & van Steenberg 1985). Thus, hard sources of radiation, such as non-thermal emission from supernova remnants, can produce low levels of HeII recombination line flux and yet potentially play an important role in the reionization of the universe (Oh 2000a).

5. CONCLUSIONS

The unparalleled sensitivity of NGST will make it possible to image the first luminous sources in near and mid IR, corresponding to rest frame UV emission longward of the Lyman limit (e.g. Haiman & Loeb 1997, 1998). However, the most important part of the spectrum for models of reionization, the ionizing continuum, will likely be inaccessible to direct observation. Provided that the escape fraction of ionizing photons is indeed small, the recombination line fluxes can serve as an important proxy for this part of the spectrum. This technique has already been successfully applied to extragalactic HII regions (Garnett 1991). The Balmer $\alpha$ flux is relatively easily detectable from high-redshift sources (Oh 1999), and probes their intrinsic spectrum in the range 13.6–54 eV. In this paper, we have shown that the HeII recombination lines are also detectable for redshifts exceeding $z \sim 10$, and provide a measure of the source luminosity above 54 eV. The most promising line is HeII(3 → 2) (1640 Å), with the HeII(4 → 3) (4686 Å) and HeII(5 → 3) (3203 Å) lines fainter by a factor of $\sim 2$ and $\sim 8$ respectively. Combining the measured He and HeII fluxes can serve as an important probe of the hardness of the spectrum, largely independent of the electron temperature and interstellar reddening. Such a measurement will shed light on the nature and emission mechanism of these first luminous sources, with important astrophysical consequences for the reheating and reionization of the IGM.

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