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# He II ABSORPTION AND THE SAWTOOTH SPECTRUM OF THE COSMIC FAR-UV BACKGROUND

Piero Madau[1] and Francesco Haardt[2]
[1] Department of Astronomy & Astrophysics, University of California, Santa Cruz, CA 95064, USA
[2] Dipartimento di Fisica e Matematica, Universitá dell'Insubria, Via Valleggio 11, 22100 Como, Italy
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## ABSTRACT

Cosmic ultraviolet background radiation between 3 and 4 Ryd is reprocessed by resonant line absorption in the Lyman series of intergalactic He II. This process results in a sawtooth modulation of the radiation spectrum from the He II Ly$\alpha$ frequency to the Lyman limit. The size of this modulation is a sensitive probe of the epoch of helium reionization and of the sources that keep the intergalactic medium (IGM) highly ionized. For large absorption opacities, the background intensity will peak at frequencies just above each resonance, go to zero at resonance, and fluctuate greatly just below resonance. The He II sawtooth modulation may be one of the missing ingredients needed in the modeling of the abundances of metal ions such as C III and Si IV observed in the IGM at redshift 3.

*Key words:* cosmology: theory – diffuse radiation – intergalactic medium – quasars: general

## 1. INTRODUCTION

The intensity and spectrum of the cosmic ultraviolet background are two of the most uncertain yet critically important astrophysical input parameters for cosmological simulations of the intergalactic medium (IGM) and early reionization. Theoretical models of such a diffuse radiation field can help interpret quasar absorption-line data and derive information on the distribution of primordial baryons (traced by H I, He I, He II transitions) and of the nucleosynthetic products of star formation (C III, C IV, Si III, Si IV, O VI, etc.). Because of the high ionization threshold (54.4 eV) and small photoionization cross section of He II, and of the rapid recombination rate of He III, the double ionization of helium is expected to be completed by hard UV-emitting quasars around the peak of their activity at $z \approx 3$ (e.g., Madau & Meiksin 1994; Madau et al. 1999; Sokasian et al. 2002), much later than the reionization of intergalactic H I and He I. Several observations have provided controversial evidence for a transition in some properties of the IGM around the predicted epoch of helium reionization, from the He II Gunn–Peterson trough measured in the spectra of $z > 2.8$ quasars (e.g., Jakobsen et al. 1994; Reimers et al. 1997; Heap et al. 2000; Smette et al. 2002), to the possible detection of an increase in the temperature of the IGM (e.g., Ricotti et al. 2000; Schaye et al. 2000; McDonald et al. 2001; Zaldarriaga et al. 2001; Theuns et al. 2002; Bernardi et al. 2003), to the claimed sharp evolution in the column density ratios of metal line absorbers (Songaila 1998; Boksenberg et al. 2003; Agafonova et al. 2007).

With the imminent installation of the Cosmic Origins Spectrograph on board the *Hubble Space Telescope*, the quantity and quality of far-UV observations of the IGM will improve significantly. Numerical simulations of patchy He II reionization (Paschos et al. 2007; McQuinn et al. 2008) are already shedding new light on the nature of such a late reheating process and its potential impact on observables. In this Letter, we return to the theory of cosmological radiative transfer and to the atomic processes that shape the spectrum of the far-UV background. We address a hitherto unnoticed effect, resonant absorption by the He II Lyman series, and show that this process will produce a sawtooth modulation of the radiation spectrum between 3 and 4 Ryd. The size of this modulation depends sensitively on the abundance of He II in the IGM, and may in turn be a crucial factor in determining the abundance of metal ions such as C III, Si III, and Si IV in the IGM. The analogous modulation between 0.75 and 1 Ryd from hydrogen line absorption was first studied by Haiman et al. (1997) in the limiting case of a fully neutral IGM.

## 2. SPECTRAL FILTERING BY THE IGM

We treat the radiation field $J_\nu(z)$ as a uniform, isotropic background, and include the reprocessing of UV radiation in a clumpy IGM (Haardt & Madau 1996, hereafter HM96). The specific intensity (in erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$) at redshift $z_o$ and observed frequency $\nu_o$ is given by

$$J_{\nu_o}(z_o) = \frac{c}{4\pi}\int_{z_o}^{\infty} \frac{dt}{dz} dz \frac{(1+z_o)^3}{(1+z)^3} \epsilon_\nu(z) e^{-\bar{\tau}}, \quad (1)$$

where $\nu = \nu_o(1+z)/(1+z_o)$, $(dt/dz) = [H(z)(1+z)]^{-1}$, $H(z)$ is the Hubble parameter, $e^{-\bar{\tau}} \equiv \langle e^{-\tau}\rangle$ is the average cosmic transmission over all lines of sight, and $\epsilon_\nu$ (in erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$) is the proper volume emissivity. The effective continuum (LyC) optical depth between $z_o$ and $z$ from Poisson-distributed absorbers is

$$\bar{\tau}(\nu_o) \equiv \bar{\tau}_c = \int_{z_o}^{z} dz' \int_0^\infty dN_{\rm HI}\, f(N_{\rm HI}, z')(1-e^{-\tau_c}), \quad (2)$$

where $f(N_{\rm HI}, z')$ is the bivariate distribution of absorbers in redshift and column density along the line of sight, and $\tau_c$ is the LyC optical depth through an individual cloud of hydrogen and helium column densities $N_{\rm HI}$, $N_{\rm HeI}$, and $N_{\rm HeII}$. The effective line absorption optical depth is instead

$$\bar{\tau}_n(z) = \frac{(1+z)\nu_n}{c} \int dN_{\rm HI}\, f(N_{\rm HI}, z) W_n, \quad (3)$$

where $\nu_n$ is the frequency of the $1s \to np$ Lyman series transition ($n > 2$) and $W_n$ is the rest equivalent width of the line expressed in wavelength units.

### 2.1. *Resonant He II Absorption*

The far-UV metagalactic flux has long been known to be partially suppressed by the He II and H I continuum opacity of the IGM (e.g., Miralda-Escudé & Ostriker 1990; Madau 1992), but

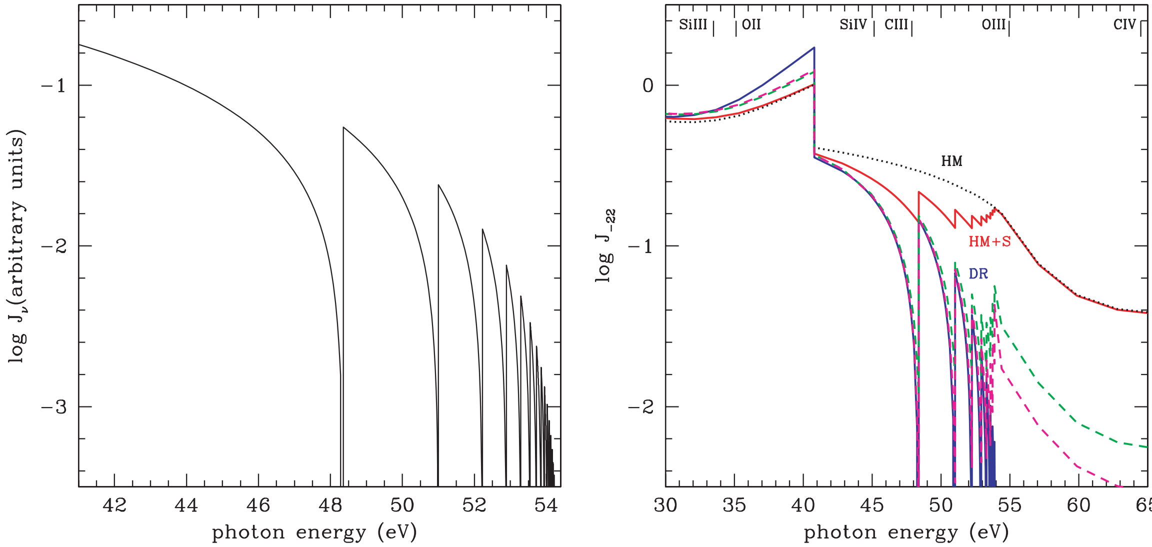


**Figure 1.** Left: the sawtooth modulation of the metagalactic flux between 3 and 4 Ryd produced by resonant absorption in the Lyman series of intergalactic He II. The background specific intensity was computed assuming negligible continuum absorption, large line opacities, an integrand in Equation (1) independent of redshift, and a proper emissivity $\epsilon_\nu \propto \nu^0 =$ const. Right: the far-UV background intensity (in units of $10^{-22}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$) at redshift 3 from quasar sources, computed using the radiative transfer code CUBA. Several models are compared: (1) "HM," where resonant absorption from the Lyman series of singly ionized helium was neglected (dotted line); (2) "HM+S," where the sawtooth modulation of He II was added (solid red line). Both these models assume photoionization equilibrium with a uniform radiation field following HM96, and yield a value He II/H I = 35 in optically thin absorbers; and (3) "DR" (for "delayed reionization"), where the He II/H I ratios were artificially increased to 160 (dashed green line), 250 (dashed magenta line), and 530 (solid blue line). All five models assume the quasar emissivity and absorbers' distribution given in Equations (6) and (7) of the text. The positions of the ionization thresholds of different ions are indicated by the tick marks.

little attention has been given to He II line absorption. Photons passing through the He II Ly$\alpha$ resonance are scattered until they redshift out of resonance, without any net absorption: aside from the photoionization of H I and He I, the only other He II Ly$\alpha$ destruction mechanism, two-photon decay, is unimportant in the low-density IGM at the redshifts of interest.[3] This is not true, however, for photons passing through a He II Lyman series resonance between the Lyman limit at energy $h\nu_L = 4$ Ryd and the He II Ly$\beta$ at $h\nu_\beta = 3.56$ Ryd. If the opacity of the IGM in the Lyman series lines is large, Ly$\beta$ and higher Lyman line photons will be absorbed and degraded via a radiative cascade rather than escaping by redshifting across the line width. The net result is a sawtooth modulation of the spectrum between 3 and 4 Ryd, and a large discontinuous step at the He II Ly$\alpha$ frequency, as we show below.

Consider, for example, radiation observed at frequency $\nu_o < \nu_\beta$ and redshift $z_o$. The resonant absorption cross section is a narrow, strongly peaked function, different lines dominate the opacity at different absorption redshifts, and the line and continuum transmission can be treated as independent random variables (e.g., Madau 1995). Photons emitted between $z_o$ and $z_\beta = (1 + z_o)(\nu_\beta/\nu_o) - 1$ can reach the observer without undergoing resonant absorption. Photons emitted between $z_\beta$ and $z_\gamma = (1+z_o)(\nu_\gamma/\nu_o) - 1$ pass instead through the He II Ly$\beta$ resonance at $z_\beta$ and are absorbed. Photons emitted between $z_\gamma$ and $z_\delta = (1 + z_o)(\nu_\delta/\nu_o) - 1$ pass through both the He II Ly$\beta$ and the Ly$\gamma$ resonances before reaching the observer. The background intensity can then be written as

$$J_{\nu_o}(z_o) = I(z_o, z_\beta) + I(z_\beta, z_\gamma)e^{-\bar{\tau}_\beta} + I(z_\gamma, z_\delta)e^{-\bar{\tau}_\beta - \bar{\tau}_\gamma} + \cdots + I(z_L, \infty)e^{-\sum_n \bar{\tau}_n}, \quad (4)$$

where we denote with the symbol $I(z_i, z_j)$ the right-hand side of Equation (1) integrated between $z_i$ and $z_j$ with $\bar{\tau} \equiv \bar{\tau}_c$. Here, $z_L = (1 + z_o)(\nu_L/\nu_o) - 1$, the LyC opacity $\bar{\tau}_c$ in all $I$ integrals except the last (where He II must be added) includes only H I and He I absorption, and $\bar{\tau}_\beta, \bar{\tau}_\gamma, \bar{\tau}_\delta, \ldots$ are the He II Lyman series effective opacities at redshift $z_\beta, z_\gamma, z_\delta, \ldots$. Equation (4) is easily generalized to higher frequencies, e.g., for $\nu_\beta < \nu_o < \nu_\gamma$ the first two terms must be replaced by the integral $I(z_o, z_\gamma)$.

The effect of the sawtooth modulation is best depicted in the idealized case of negligible continuum absorption, $\bar{\tau}_c \to 0$, and large line opacity, $\bar{\tau}_n \to \infty$ (this is similar to the hydrogen case studied by Haiman et al. (1997)). The ensuing radiation flux is shown in Figure 1, where we have also assumed for simplicity that the integrand in Equation (1) is independent of redshift and the proper emissivity is $\epsilon_\nu \propto \nu^0 =$ const. Note how only sources between the observer and the "screen" redshift $z_n = (1 + z_o)(\nu_n/\nu_o) - 1$ corresponding to the frequency of the nearest Lyman series line above $\nu_o$ are not blocked from view: the background flux peaks at frequencies just above each resonance, as the first integral in Equation (4) extends over the largest redshift path, and goes to zero only at resonance.

### 2.2. *He II Ly$\alpha$ Re-emission*

The usual assumption that each photon entering a Lyman series resonance causes a radiative cascade that terminates in a Ly$\alpha$ photon requires full $l$-mixing of the $2s - 2p$ levels (Seaton 1959). Collisions are infrequent in the low-density IGM, however, and most radiative cascades from an $np$ state terminate instead in two-photon $2s \to 1s$ emission (Hirata 2006). The fraction, $f_n$, of decays that generates Ly$\alpha$ photons can be determined from the selection rules and the decay probabilities, and it is $f_n = (1, 0, 0.2609, 0.3078, 0.3259...)$ for $n = (2, 3, 4, 5, 6...)$ (Pritchard & Furlanetto 2006). Without $l$-mixing, the quantum selection rules forbid Ly$\beta$ photons from being converted into Ly$\alpha$, while at large $n$ the conversion

[3] Another conversion process of He II Ly$\alpha$ photons, the O III Bowen fluorescence mechanism (Kallman & McCray 1980), can be neglected in nearly primordial intergalactic gas.

fraction asymptotes to 0.36. Let now $J_{\nu_\gamma}(z_\alpha)$ be the background intensity measured just above the He II Ly$\gamma$ resonance at redshift $z_\alpha = (1+z_o)(\nu_\alpha/\nu_o)-1$. The flux that is absorbed and converted into He II Ly$\alpha$ is then $f_4 \times J_{\nu_\gamma}(z_\alpha)[1-e^{-\bar{\tau}_\gamma(z_\alpha)}]$. The additional flux observed at frequency $\nu_o \leqslant \nu_\alpha$ and redshift $z_o$ from this process is then

$$\Delta J_{\nu_o}(z_o) = \left(\frac{\nu_o}{\nu_\alpha}\right)^3 e^{-\bar{\tau}_c(\nu_o, z_o, z_\alpha)} \left[f_4 \times J_{\nu_\gamma}(z_\alpha)\left(1-e^{-\bar{\tau}_\gamma(z_\alpha)}\right)\right]. \quad (5)$$

When summing up over all He II Lyman series lines, the term in square brackets must be replaced by $\sum_{n>3}[f_n \times J_{\nu_n}(z_\alpha)(1-e^{-\bar{\tau}_n(z_\alpha)})]$.[4]

## 3. UV METAGALACTIC FLUX

We now compute the integrated far-UV background from quasar sources at redshift 3, including the effect of He II resonant absorption. We parameterize the recent determination of the *comoving* quasar emissivity at 1 Ryd by Hopkins et al. (2007) as

$$\varepsilon_{\rm ion}(z) = (4\times 10^{24}\ {\rm erg\ s^{-1}\ Hz^{-1}\ Mpc^{-3}})\,(1+z)^{4.68} \times \frac{e^{-0.28z}}{e^{1.77z}+26.3}. \quad (6)$$

At $z = 3$, this yields a value that is 1.4 times lower than that used in Madau et al. (1999). Assuming a power-law far-UV spectrum with spectral index $-1.57$ (Telfer et al. 2002), the adopted *proper* emissivity becomes $\epsilon_\nu(z) = (1+z)^3\,\varepsilon_{\rm ion}(z)\,(h\nu/1\,{\rm Ryd})^{-1.57}$. To compute the effective opacity of the IGM we use the standard parameterization for the distribution of absorbers along the line of sight,

$$f(N_{\rm HI}, z) = A\,N_{\rm HI}^{-\beta}\,(1+z)^\gamma, \quad (7)$$

with $(A, \beta, \gamma) = (1.4, 1.5, 2.9)$ over the column density range $10^{11} < N_{\rm HI} < 10^{17.2}$ cm$^{-2}$, and $(A, \beta, \gamma) = (5, 1.5, 1.5)$ for $N_{\rm HI} > 10^{17.2}$ cm$^{-2}$ (e.g., Kim et al. 1997; Hu et al. 1995; Meiksin & Madau 1993; Petitjean et al. 1993; Tytler 1987). Here, the normalization $A$ is expressed in units of $10^7$ cm$^{-2(\beta-1)}$. The high column density distribution agrees with the results of Stengler-Larrea et al. (1995), while the low column density distribution produces an H I Ly$\alpha$ effective opacity at $z = 3$ of 0.41 as in Faucher-Giguere et al. (2008). The detailed redshift evolution of the quasar emissivity and IGM opacity are not important for the problem at hand, since the measured—at 1 Ryd—and inferred—at 4 Ryd—absorption distances for ionizing radiation at redshift 3 are quite small, and the background flux in the relevant energy range is largely determined by local sources.

We have used the cosmological radiative transfer code CUBA to follow the propagation of UV radiation through a partially ionized inhomogeneous medium (HM96). The code uses a multizoned approximation to model the physical conditions within absorbing systems and infer the amount of singly ionized helium that is present along the line of sight from the well-measured $N_{\rm HI}$ distribution. We include the reprocessing into He II Ly$\alpha$ and two-photon continuum from resonant absorption in the Lyman series (as detailed in the preceding section) as well as continuum absorption, and assume photoionization equilibrium with a uniform radiation field. The resulting far-UV background intensity at redshift 3 is shown in Figure 1 for model "HM," where resonant absorption from the Lyman series of He II is neglected, and model "HM+S," where the sawtooth modulation was added. Both these models yield a value of He II/H I = 35 in optically thin absorbers. In the HM+S case, the effective He II Ly$\beta$ line opacity is 0.43, and the sawtooth modulation causes a small decrease in the metagalactic flux, by at most a factor of 2, relative to the old HM spectrum. We have also run three other representative cases, termed "DR" for "delayed reionization." These models ignore the patchy nature of the reionization process and assume that a larger fraction of intergalactic helium at redshift 3 is in He II: this is obtained by artificially increasing the He II/H I ratios computed by CUBA to 160, 250, and 530, respectively. Resonant absorption from the Lyman series now causes a reduction of the background intensity between 3 and 4 Ryd by as much as 1 dex (off-resonance) compared to the HM spectrum.

## 4. DISCUSSION

Since the pioneering work of Chaffee et al. (1986) and Bergeron & Stasinska (1986), many studies have used observations of intervening metal absorption systems to reconstruct the shape of the photoionizing radiation field at $z \lesssim 3$. The many modifications to the HM96 background intensity that have been proposed include: (1) a stronger He II Ly$\alpha$ feature in order to match the observed Si IV/Si II abundance ratios (Levshakov et al. 2003); (2) a depression between 3 and 4 Ryd in order to enhance the predicted C II/C IV and C III/C IV ratios, incorrectly attributed by Agafonova et al. (2007) to a He II Ly$\alpha$ Gunn–Peterson effect; (3) a softer far-UV spectrum in order to predict [O/Si] values that are consistent with theoretical yields (Aguirre et al. 2008). A detailed modeling of the abundances of intergalactic metals is beyond the scope of this Letter: here, we just want to point out that the sawtooth modulation, if as large as computed in the DR models, may provide a better match to the observations. At the top of the right panel of Figure 1 we have indicated the positions of the ionization thresholds of Si III (33.5 eV), Si IV (45.1 eV), C III (47.9 eV), C IV (64.5 eV), O II (35.1 eV), and O III (54.9 eV) ions. The reprocessing of Lyman series and Lyman continuum photons increases He II Ly$\alpha$ in the DR spectra by a factor of 1.7 compared to the HM case. The flux at the Si IV ionization threshold decreases by a factor of 2, boosting the predicted abundance of Si IV. An even larger boost is expected in the abundance of C III, whose the ionization threshold lies exactly within the He II Ly$\beta$ deep absorption feature, and of O III, whose threshold lies just beyond the He II Lyman limit.

The above results show that line absorption from the Lyman series of intergalactic helium may be an important, so far neglected, process shaping the spectrum of the cosmic radiation background above 3 Ryd. The large resonant cross sections for far-UV light scattering make the sawtooth modulation a sensitive probe of the epoch of helium reionization and of the sources that keep the IGM highly ionized. The He II sawtooth may be one of the crucial missing ingredients in the modeling of the abundances of metal ions such as C III and Si IV observed in the IGM at redshift 3. In the case of large line opacities, substantial fluctuations are expected in the far-UV background intensity near each resonance, as the first integral in Equation (4) extends over a small absorption distance, and just a few quasars are expected to contribute to the local

[4] Note that the analogous Equation (7) of Haiman et al. (1997) for the reprocessing of hydrogen Lyman series radiation erroneously includes a term $(\nu_n/\nu_\alpha)$ to account for the conversion of higher energy photons into Ly$\alpha$. This factor is spurious since in the process the specific intensity is conserved.

emissivity. Such fluctuations may cause large variations in, e.g., the observed C III abundances. In future work, we intend to study such fluctuations and address how the contribution of star-forming galaxies to the background may affect the He II/H I ratio in the IGM and the predicted sawtooth modulation.

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