CARBON IONIZATION STATES AND THE COSMIC FAR-UV BACKGROUND WITH He II ABSORPTION

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ABSTRACT

We constrain the spectrum of the cosmic ultraviolet background radiation by fitting the observed abundance ratios of carbon ions at \( z \sim 2–3 \) with those expected from different models of the background radiation. We use the recently calculated modulation of the background radiation between 3 and 4 Ryd due to resonant line absorption by intergalactic He II and determine the ratios of C III to C IV expected at these redshifts, as functions of metallicity, gas density, and temperature. Our analysis of the observed ratios shows that “delayed reionization” models, which assume a large fraction of He II at \( z \sim 3 \), are not favored by data. Our results suggest that He II reionization was inhomogeneous, consistent with the predictions from recent simulations.

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

1. INTRODUCTION

Cosmological simulations of the intergalactic medium (IGM) have been used in recent years to determine many important aspects of structure formation and reionization. One important input for these simulations, the cosmic ultraviolet background radiation, however, has remained uncertain. Our knowledge of the cosmic UV background (its intensity and spectrum and evolution with time) still lacks the precision that is needed to make the interpretations from cosmological simulations robust.

It is believed that He II reionization occurred much after the reionization of H I and He I, with the help of hard UV photons from quasars, whose activity peaked around redshift \( z \sim 3 \). This is because of the relatively high ionization threshold of He II (54.4 eV; e.g., Madau & Meiksin 1994; Sokasian et al. 2002). Some recent observations may have found evidence for the He II Gunn–Peterson (GP) trough in the spectra of quasars at \( z \gtrsim 2.8 \) (e.g., Jakobsen et al. 1994; Schaye et al. 2000; Smette et al. 2002). Numerical simulations of He II reionization (McQuinn et al. 2009) also predict that the process is likely to be inhomogeneous and accompanied by heating of the IGM. There is some evidence for such a heating from recent observations, although the interpretations are not yet clear (e.g., Ricotti et al. 2000; Schaye et al. 2000; Theuns et al. 2002; Bernardi et al. 2003).

Recently, Madau & Haardt (2009) pointed out an important aspect of the evolution of UV background radiation in the context of He II reionization. They calculated the effect of resonant absorption by He II Lyman series that is likely to significantly change the shape of the UV background radiation between 3 and 4 Ryd, whose magnitude depends on the abundance of He II in the IGM. This modulation can be an important probe of the UV background radiation when combined with the observations of absorption lines from metal ions such as C III whose ionization potential lies between energies corresponding to 3 and 4 Ryd.

In this paper, we use the data from Agafonova et al. (2007) of column densities of C III and C IV in the redshift range of \( z \sim 2–3 \) to constrain the spectrum of the UV background radiation. Agafonova et al. (2007) used their observations to recover the shape of the spectrum with a Monte Carlo procedure, but their assumption for the shape of the spectrum did not include the possible attenuation between 3 and 4 Ryd. They claimed a sharp reduction in the flux of the UV background between 3 and 4 Ryd, which was interpreted as a sign of the He II GP effect. In this regard, it is important to study the ionic ratios, especially those involving C III, whose ionization potential falls between 3 and 4 Ryd, and the effect of background radiations of different spectra on these ratios. One of the predictions made by Madau & Haardt (2009) was that the modulation of the spectrum by He II absorption would significantly change the abundance ratio of C III/C IV at \( z \sim 3 \), and a large C III/C IV ratio could be explained without any need to invoke the He II GP effect. We test these ideas in this paper.

2. CALCULATIONS OF IONIC STATES

We study the thermal and ionization evolution of gas exposed to external ionizing radiation. Our calculation of the evolution of gas is similar to Gnat & Sternberg (2007, 2009). A detailed description of thermal and ionization evolution of gas can be found in E. O. Vasiliev (2010, in preparation). Here, we briefly describe the method of calculation, present several tests of our code, and discuss the choice of initial conditions.

2.1. The Description of the Code

A gas parcel is assumed to be optically thin for the ionizing radiation. We consider the time-dependent equations for all ionization states of H, He, C, N, O, Ne, and Fe, including all relevant atomic processes. Namely, we take into account the following major processes: photoionization, collisional ionization, radiative, and dielectronic recombination as well as charge transfer in collisions with hydrogen and helium atoms and ions. Atomic data for the photoionization cross section are adopted from Verner et al. (1996) and Verner & Yakovlev (1995); Auger effect probabilities are taken from Kaastra & Meive (1993); the recombination rate for radiative recombination is taken from Verner & Ferland (1996), Pequignot et al. (1991), Arnaud & Raymond (1992), and Shull & van Steenberg (1982), for dielectronic recombination the rate is adopted from Mazzotta et al. (1998); the collisional ionization rate is adopted from Voronov (1997); and the charge transfer rates of ionization and recombination with hydrogen and helium are adopted from Arnaud & Rothenflug (1985) and Kingdon & Ferland (1996).

This system of time-dependent ionization state equations should be complemented by the temperature equation, which accounts for all relevant cooling and heating processes. Here,
we assume that a gas parcel cools isochorically; i.e., the cooling time is shorter than any dynamical timescale. Note that in the temperature equation we neglect the change in the number of particles in the system (which for a fully ionized plasma of temperature equation we neglect the change in the number of...
In the photoionization calculations, the extragalactic ionizing spectrum without traditionally includes the most recent atomic data. So we assume that such a difference may be mainly explained by small changes in thermal evolution. For example, it is well known that the dielectronic recombination depends exponentially on temperature, so we expect that for higher temperature and lower metallicity this difference becomes smaller (see Figure 3).

Second, we should note that both equilibrium and time-dependent collisional ionic composition have no dependence on gas density, because all processes are two body. In contrast, the ionic composition in the photoionization case strongly depends on gas density. Moreover, the ionizing radiation forces the ionic composition of gas to settle on to equilibrium. In low-density gas, the ionic composition in the time-dependent photoionization case is expected to strongly differ from that in the collisional, both equilibrium and time-dependent, cases, but it tends to the ionic fractions in the photoequilibrium. In high-density gas, we expect that the time-dependent photoionization ionic composition tends to the time-dependent collisional one, whereas the photoequilibrium ionic fractions should be close to those in the CIE. In addition, the ionic composition strongly depends on metallicity. For low metallicity, the difference between time-dependent and equilibrium ionic fractions is expected to be small, but it increases with metallicity.

In Figure 3, one can see that the C\textsc{iii} fraction in the time-dependent photoionization model does not fully coincide in the whole temperature range with either the photoionization equilibrium or pure collisional models. For example, at low metallicity, \(Z = 10^{-3} Z_\odot\), for a high-density value, \(n = 10^{-2} \text{ cm}^{-3}\), the time-dependent photoionization C\textsc{iii} fraction shows some difference from the photoequilibrium case. In contrast, for \(n = 10^{-4} \text{ cm}^{-3}\), the C\textsc{iii} fractions in the time-dependent photoionization and photoequilibrium cases are close to each other in the entire temperature range. For solar metallicity, the difference between time-dependent and equilibrium photoionization becomes more significant for both number density values. Also, one should note from the right panels of Figure 3 that there is almost no dependence on metallicity in the equilibrium photoionization case. The difference between the C\textsc{iii} fraction for \(10^{-3} Z_\odot\) and solar metallicities is only in the value of temperature reached in the cooling process: for higher cooling rates (solar metallicity), this temperature is lower.

As is expected for a higher density value, \(n = 10^{-2} \text{ cm}^{-3}\), the C\textsc{iii} photoionization fractions are close to the collisional ones in both equilibrium and time-dependent cases in a wide temperature range. For example, the ion fractions in time-dependent collisional (thick solid line) and time-dependent photoionization cases (thick dotted line) almost coincide for \(\log T \gtrsim 4.7\) at \(Z = 10^{-3} Z_\odot\) and for \(\log T \gtrsim 4.18\) at solar metallicity. In summary, both time-dependent collisional and photoequilibrium cases in the presence of a significant ionizing radiation flux like the extragalactic background models produce ionic composition, which differs from that in the time-dependent photoionization model. Due to the very nonlinear dependence of ionic fractions on temperature, metallicity, and density, it is difficult to say where it is possible to use time-dependent collisional or photoequilibrium models, so in the present work we use the more complex, but more adequate time-dependent photoionization model.

### 2.3. Dependence on the Initial Temperature

Here, we should consider a choice of the initial temperature and ionic composition for our study of absorbers at the redshift range \(z = 2–3\). Many cosmological simulations (Davé et al., 2001; Cen & Fang, 2006; Bertone et al., 2008) show that the intergalactic gas at \(z = 2–3\) mainly resides in the diffuse phase with a typical temperature \(T \lesssim 10^5 K\) and overdensity \(\delta < 1000\), and a small part of gas (in the best model this fraction is less than 5\%); see, e.g., Davé et al., 2001) can be found in the warm-hot phase with \(10^6 K \lesssim T \lesssim 10^7 K\). It is expected that a gas enriched by metals and expelled from galaxies would have passed through strong shock waves. Since the typical velocity of intergalactic winds varies from several tens to hundreds \(\text{km s}^{-1}\), the intergalactic gas enriched by metals is likely to go through such shock waves. We assume that such a gas was initially heated by shocks up to the temperature \(T \gg 10^5 K\). We are interested in the subsequent evolution of this shock-heated gas. Here also, we should note, first, that the heating rate produced by the strong ionizing background at \(z = 2–3\) does not allow low-density gas with \(n \sim 10^{-3} \text{ cm}^{-3}\) to cool effectively below \(T \sim 3.5 \times 10^4 K\), and second, that here we do not include adiabatic cooling due to the expansion of the universe, which dominates over the radiative cooling for very low density gas, \(n \sim 10^{-3} \text{ cm}^{-3}\) at \(z = 3\).

In the following set of calculations, we study the dependence of the ionic composition evolution of a gas on the initial temperature \(T_i\). We vary the initial temperature in a wide range \(T_i = 5 \times 10^4–10^8 K\). Here, we follow the evolution of gas irrespective of the time needed to cool from \(T_i\) to the temperature value, when our stopping criterion (mentioned above) is reached. Further, we compare the cooling time with the comoving Hubble time at \(z = 2–3\). The gas cooling is strongly determined by both initial conditions of the gas (density, metallicity, and temperature) and the UV background radiation. We assume that the initial ionic composition corresponds to \(T_0 = 2 \times 10^4 K\). Taking such conditions, we simulate a gas...
parcel with \( T_0 = 2 \times 10^4 \) K that initially passes through a strong shock wave front with \( T_s \gg T_0 \). Because of the short ionization timescale of metals (the ionization fraction of hydrogen almost reaches unity for \( T_0 = 2 \times 10^4 \) K in both the CIE and time-dependent cases), the ionization composition of a gas passed through a shock front with temperature \( T_s \gg T_0 \) is expected to tend to that with \( T_s = 10^8 \) K at \( T < T_s \). Certainly, if the initial temperature is low enough, then the ionization composition should strongly depend on the initial temperature value.

Figure 4 presents the C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) fraction (upper panels) and the C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) ratio (lower panels) for different starting temperature values and the ionization composition initially corresponding to that in the CIE at \( T_0 = 2 \times 10^4 \) K. In the upper panels (the left is for \( Z = 10^{-3} Z_\odot \) and the right is for the solar metallicity), the significant deviation from the C\( ^{\text{III}} \) fraction for the evolutionary track with \( T_i = 10^8 \) K is found for \( T < 10^6 \) K, whereas the C\( ^{\text{III}} \) fraction for tracks with \( T_i = 10^6 \) K and \( T_i = 10^8 \) K almost coincides. The time needed for cooling a gas from \( T_i \sim 10^8 \) K with \( n \sim 10^{-4} \) cm\(^{-3} \) and \( Z \sim 10^{-3} Z_\odot \) is comparable with the comoving Hubble time at \( z = 3 \) (\( t_H(z = 2) \approx 1.1 \times 10^9 \) s). The cooling time from \( T_i \sim 10^8 \) K is slightly shorter than the Hubble time at \( z = 3 \), but the C\( ^{\text{III}} \) fraction strongly differs from that for \( T_i = 10^8 \) K. But here we are interested in the ionic ratios and not the column densities of individual ionic species.

In the lower panels of Figure 4, the C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) ratio demonstrates a weak dependence on the initial temperature. The ratio for \( T_i = 4 \times 10^5 \) K almost coincides with that for higher temperature values. For the lower temperature value, \( T_i = 5 \times 10^4 \) K, considered in this set of calculations, the ionic ratio settles to the common trend almost at the same temperature \( T \lesssim 5 \times 10^4 \) K for \( n = 10^{-4} \) cm\(^{-3} \) (in this case at the beginning the photoheating is significant) and at \( T \lesssim 3.2 \times 10^4 \) K for \( n = 10^{-3} \) cm\(^{-3} \).

One can see the vertical parts of the C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) ratio tracks. However, the time needed for settling on the common trend (the time at the vertical part of the track) is significantly lower than the time needed for reaching the stopping criterion. For instance, for a gas with \( n = 10^{-4} \) cm\(^{-3} \) and \( Z = 10^{-3} Z_\odot \), such a timescale is about \( 2 \times 10^{15} \) s in the case of the initial temperature \( T_i = 5 \times 10^4 \) K, whereas the time of the calculation before the stopping criterion reached is more than an order greater, \( \sim 5.2 \times 10^{10} \) s \( \simeq 0.7 T_H(z = 3) \). The timescales for higher density or metallicity are smaller. Thus, for \( T \lesssim 4 \times 10^4 \) K (which is consistent with the line widths inferred by Agafonova et al. 2007), the C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) ratio in a gas with initial temperature \( T_i \gtrsim 5 \times 10^4 \) K almost coincides with that for \( T_i = 10^6-10^8 \) K, and the timescale of calculation needed for reaching our stopping criterion is smaller than the comoving Hubble time at \( z = 2-3 \). In light of this, we can start our calculations from temperature \( T = 10^6 \) K and consider the obtained C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) ratio. We should emphasize that we are interested in the temperature range \( T \lesssim 4 \times 10^4 \) K, where the ionic ratios for \( T_i = 5 \times 10^4-10^8 \) K are very close (see lower panels of Figure 4), thus, our conclusions are almost independent of the initial temperature value, if this value is greater than \( 5 \times 10^4 \) K. Further analysis of the dependence of ionic composition on the initial conditions is not within the scope of this paper and will be done elsewhere.

3. C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) RATIO

In this section, we study the influence of the extragalactic ionizing background with and without He\( ^{\text{II}} \) absorption on the C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) ratio. Nonequilibrium ionization states are calculated for ultraviolet (UV) spectra at redshifts \( z = 1.87, 2.48, 2.65, 2.83, 3 \) (all spectral data were kindly provided by F. Haardt) for three models presented in Madau & Haardt (2009, hereafter MH09): the abbreviations of models are the same as in MH09: (1) absorption in the He\( ^{\text{II}} \) resonant lines was neglected—HM model, (2) the sawtooth modulation was added—HM+S model, where He\( ^{\text{II}} \)/H\( ^{\text{I}} \) = 35 in optically thin absorbers, and (3) the model where the He\( ^{\text{II}} \)/H\( ^{\text{I}} \) ratio was artificially increased to 250—delayed reionization (DR) model (for details, see MH09).

Note that the MH09 spectra differ from the Haardt & Madau (1996, 2001) spectra. First, MH09 spectra include quasar contribution only and, second, in the UV background calculations a quasi-stellar object luminosity function from Hopkins et al. (2007) is used, which produces a very steep decline of the ionizing flux at high redshifts. Figure 1 shows the far UV part of the MH09 spectra for \( z = 2.48 \).

The left panel of Figure 5 shows C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) ratios in the equilibrium calculation (using CLOUDY) for \( Z = 10^{-3} Z_\odot \) (but there is no dependence on metallicity in the equilibrium, see Section 2.2 and right panels of Figure 3). The two middle panels of Figure 5 show C\( ^{\text{III}} \)/C\( ^{\text{IV}} \) ratios in the nonequilibrium calculation (using our program for nonequilibrium calculation) for \( Z = 10^{-3} Z_\odot \) and solar metallicities, respectively, for UV background spectrum at \( z = 2.48 \). The difference between models without (HM) and with (HM+S) the inclusion of the sawtooth modulation is small for the whole range of metallicities and densities. The ratios for the HM and HM+S models differ from each other only by a factor of \( \sim 1.3 \) for low density at \( T \lesssim 10^5 \) K and they almost coincide for \( n = 10^{-2} \) cm\(^{-3} \) or \( T \gtrsim 10^6 \) K. In the DR model, the N(C\( ^{\text{III}} \))/N(C\( ^{\text{IV}} \)) ratio is greater than those in the HM and HM+S models by a factor of \( \sim 10 \) at \( T \lesssim 10^5 \) K. This factor decreases with the increase of density and metallicity. For example, for \( n = 10^{-2} \) cm\(^{-3} \) a significant difference can be found only at \( T \lesssim 6 \times 10^4 \) K for \( Z = 10^{-3} Z_\odot \) and \( T \lesssim 2 \times 10^4 \) K for solar metallicity.

For high density (\( n \gtrsim 10^{-2} \) cm\(^{-3} \)), the ratio is close to that in the collisional limit at \( T \gtrsim 5 \times 10^4 \) K. One can therefore conclude that large sawtooth modulation as present in the DR...
model leads to higher abundances of C\textsc{iii} ions by a factor of 10–1.3 for gas density $n = 10^{-5}$–$10^{-3}$ cm$^{-3}$, respectively. The increase of C\textsc{iii} and C\textsc{iv} abundances in the DR model arises from the decrease of C\textsc{iv} and C\textsc{v} abundances, because of lower ionization flux in the energy range ~50–500 eV in comparison with the other two models, so the growth of the C\textsc{iii} abundance is higher than that of C\textsc{iv} making the C\textsc{iii}/C\textsc{iv} ratio higher.

Our results first show that the ratio of C\textsc{iii}/C\textsc{iv} is not significantly changed by the sawtooth modulation of He\textsc{ii}, as supposed by Madau & Haardt (2009). Since the ionization threshold of C\textsc{iii} (47.9 eV) lies within the Ly\$β$ absorption feature from He\textsc{ii}, and that of C\textsc{iv} lies well beyond the range where He\textsc{ii} resonant absorption changes the spectrum, it was expected that observations of the C\textsc{iii}/C\textsc{iv} ratio along with the theoretically calculated spectrum would be a good probe of the physical conditions in the IGM at $z \sim 3$. Our detailed calculations confirm the Madau & Haardt (2009) claim that the ionization rate of C\textsc{iii} does not significantly differ between the “HM” and “HM+S” spectra, although the “DR” spectrum does make a difference. In other words, the C\textsc{iii}/C\textsc{iv} ratio is a good probe only for distinguishing between the extreme cases of “HM” or “DR” and not for probing the attenuation caused by standard abundances of He\textsc{ii} in the IGM.

### 4. Statistical Analysis

Agafonova et al. (2007) give measurements of C\textsc{iii} and C\textsc{iv} column densities for 10 absorbers in the redshift range 2 < $z$ < 3. We use the ratio $R = N(\text{C}\textsc{iii})/N(\text{C}\textsc{iv})$ to constrain the ionizing radiation in the far-UV range (Table 1).

For our analysis, we consider three models of ionizing radiation, as discussed in the previous section, in the redshift range 2 < $z$ < 3, the metallicity in the range $Z = 10^{-3}$–1, the number density in the range $n = 10^{-4}$–$10^{-2}$ cm$^{-3}$, and temperature $T \leq 4 \times 10^4$ K. This range of temperature is consistent with the line widths inferred by Agafonova et al. (2007).

The measured ratio $R_{\text{obs}}$ depends on the parameters $n$, $T$, $Z$, and the model of ionization. One expects the $Z$, $n$, and $T$ to vary appreciably from one absorber to another and therefore the usual $\chi^2$ approach cannot be applied. Only the background ionizing flux can be assumed to vary slowly with redshift. In light of these assumptions, we define, for each absorber, $\epsilon = |R_{\text{obs}} - R_{\text{cal}}|/|\Delta R|$, where $R_{\text{obs}}$ are the observed values, and $\Delta R$ are the corresponding errors on these measurements (Table 1). For each absorber, we search the entire parameter space of $T$, $n$, and $Z$, for a given model of ionizing radiation corresponding to the redshift of the absorber. For any absorber, a model is deemed acceptable if $\epsilon \leq \sqrt{5}$ (that corresponds to $5\sigma$ level of the theoretical model).

Our results for the three models are shown in Tables 2–4. As seen from the tables, the models HM and HM+S can fit well for 8 out of the 10 data points of Agafonova et al. (2007). However, the DR model is acceptable for only 6 out of the 10 absorbers. One absorber is not fit well by any of the models (absorber 4).

### Table 1
| Absorber | $z_{\text{abs}}$ | $R = N(\text{C}\textsc{iii})/N(\text{C}\textsc{iv})$ | Error in $R$ |
|----------|----------------|---------------------------------|-------------|
| 1        | 2.379          | 1.438                           | 0.160       |
| 2        | 2.433          | 6.944                           | 0.449       |
| 3        | 2.438          | 2.680                           | 0.082       |
| 4        | 2.568          | 1.000                           | 0.083       |
| 5        | 2.735          | 3.083                           | 0.076       |
| 6        | 2.739          | 15.681                          | 1.782       |
| 7        | 2.741          | 3.158                           | 0.499       |
| 8        | 2.875          | 4.750                           | 0.025       |
| 9        | 2.839          | 16.363                          | 2.645       |
| 10       | 2.944          | 21.765                          | 0.311       |

### Table 2
| Absorber | $T$ (K) | $n$ (cm$^{-3}$) | $\epsilon$ | $T$ (K) | $n$ (cm$^{-3}$) | $\epsilon$ |
|----------|---------|----------------|------------|---------|----------------|------------|
| 1        | 40000   | 0.001          | 4          | 31622   | 0.001          | 2.1        |
| 2        | 27200   | 0.01           | 0.1        | 39810   | 0.001          | 8.2        |
| 3        | 30300   | 0.001          | 0.073      | 31622   | 0.001          | 1.82       |
| 4        | 21740   | 0.0001         | 6.9        | 31622   | 0.001          | 9.2        |
| 5        | 35460   | 0.001          | 0.02        | 39810   | 0.001          | 2.5        |
| 6        | 33300   | 0.01           | 0.027      | 19952   | 0.01           | 0.18       |
| 7        | 36370   | 0.001          | 0.005      | 39810   | 0.001          | 0.24       |
| 8        | 37920   | 0.01           | 0.136      | 39810   | 0.001          | 58         |
| 9        | 12840   | 0.01           | 0.006      | 25118   | 0.01           | 0.2        |
| 10       | 31730   | 0.01           | 0.15       | 25118   | 0.01           | 1.5        |

### Table 3
| Absorber | $T$ (K) | $n$ (cm$^{-3}$) | $\epsilon$ | $T$ (K) | $n$ (cm$^{-3}$) | $\epsilon$ |
|----------|---------|----------------|------------|---------|----------------|------------|
| 1        | 39870   | 0.001          | 5.7        | 31622   | 0.001          | 2.83       |
| 2        | 28210   | 0.01           | 0.12       | 39810   | 0.001          | 6.68       |
| 3        | 34930   | 0.001          | 0.07       | 25118   | 0.001          | 0.85       |
| 4        | 23800   | 0.0001         | 6.1        | 31622   | 0.001          | 10.7       |
| 5        | 30200   | 0.001          | 0.1        | 39810   | 0.001          | 2.29       |
| 6        | 36310   | 0.01           | 0.04       | 19952   | 0.01           | 0.4        |
| 7        | 29410   | 0.001          | 0.02       | 39810   | 0.001          | 0.37       |
| 8        | 23400   | 0.001          | 0.4        | 39180   | 0.001          | 31.0       |
| 9        | 13670   | 0.01           | 0.032      | 19552   | 0.01           | 0.012      |
| 10       | 37070   | 0.01           | 0.015      | 39810   | 0.01           | 0.12       |

### Notes
Columns 2–4 present results for the nonequilibrium model. The next three columns show the results for the equilibrium model.
In Tables 2–4, we also show the results for the equilibrium models using CLOUDY (Figure 3). The results in the two cases have qualitative similarities, e.g., absorber 4 is ruled out by all models. However, there are also quantitative differences. Many of the absorbers ruled out by the nonequilibrium models are now allowed or vice versa. An interesting departure between the two results is that the DR model is ruled out for as many as eight absorbers. Our results suggest that it is possible to explain the ionic ratios of C\textsc{iii}/\textsc{iv} between 3 and 4 Ryd by continuum \textsc{He} \textsc{ii} absorption or a \textsc{He} \textsc{ii} GP effect. Agafonova et al. (2007) used their data to reconstruct the far-UV background radiation spectrum and claimed a value of $\tau_{\text{GP}(\textsc{He} \textsc{ii})} \sim 2.5$–3. This was compared with other direct observations of the \textsc{He} \textsc{ii} GP absorption trough, at $z = 2.87$, with opacity $\tau_{\text{GP}(\textsc{He} \textsc{ii})} \sim 2.09 \pm 0.1$ (Reimers et al. 2005). It is difficult to disentangle the effects of absorption from a continuous IGM and an ensemble of clouds, as in the case of the H\textsc{i} GP effect (see Becker et al. 2007), although McQuinn (2009) has argued that the case for the \textsc{He} \textsc{ii} GP effect is stronger than this, owing to the low abundance of \textsc{He} \textsc{ii} compared to H\textsc{i}.

In light of the difficulty of identifying a true GP effect, our results of explaining the ionic ratios of C\textsc{iii}/\textsc{iv} with standard attenuation from \textsc{He} \textsc{ii} absorption suggest that the observations of Agafonova et al. (2007) do not necessarily need a \textsc{He} \textsc{ii} GP effect, although it cannot be completely ruled out.

Our results also clearly show that it is difficult to select one model of far-UV flux from the observed data. It is possible that the measured ratios are sensitive to the local conditions inside the cloud. It is also possible that the far-UV radiation field is inhomogeneous over the redshift of the probe. Available data from \textsc{He} \textsc{ii} measurements suggest that the Str"{o}mgren spheres corresponding to this species might just be merging at $z \approx 3$ (Jakobsen et al. 1994; Smette et al. 2002). Numerical simulations by McQuinn et al. (2009) have also shown that the reionization of \textsc{He} \textsc{ii} remains patchy even at $z \approx 3$. Therefore, it is entirely conceivable that it is inhomogeneous reionization and not fluctuation in the density, metallicity, and temperature that is responsible for the wide range of observed C\textsc{iii}/\textsc{iv} ratios.

However, a bigger data set involving different ionic ratios is needed to address some of these questions in detail and confirms the patchiness of the \textsc{He} \textsc{ii} reionization process. Also, to put better constraints on the spectrum profile, we need to study the ionization structure of a cloud coupled with gas dynamics and radiation transfer. Radiation transfer effects would particularly affect large H\textsc{i} column density clouds and change the predictions of ionic ratios in them, but these effects are outside the scope of the present paper. Furthermore, the predicted ionizing background depends on the spectrum and luminosity function of sources, and this introduces an additional uncertainty in analysis of the kind we have presented here. It is possible that the effect of these uncertainties would be mitigated by studying different ionic ratios, and we will report the advantages of using other ions in a future paper.

### 6. CONCLUSIONS

In this paper, we used the data of Agafonova et al. (2007) for the abundance ratio of C\textsc{iii} to C\textsc{iv} in quasar absorption systems at $z \approx 2.4–2.9$, to constrain the spectrum of the cosmic UV background radiation. We have used the spectrum calculated by Madau & Haardt (2009) which took into account the modulation from \textsc{He} \textsc{ii} Lyman series lines, and also models which assume a large abundance of \textsc{He} \textsc{ii} by artificially increasing the \textsc{He} \textsc{ii}/H\textsc{i} ratio. Our results can be summarized as follows.

1. The ratio between C\textsc{iii}/C\textsc{iv} is not a sensitive probe of the attenuation of the far-UV spectrum between 3 and 4 Ryd for standard abundance of \textsc{He} \textsc{ii} in the IGM.
2. The observed data do not favor the models with additional abundance of \textsc{He} \textsc{ii} in the IGM (the “DR” models).
3. There is a large variation in the fitted values of density and temperature for the absorption systems. This is indicative of an inhomogeneous reionization of \textsc{He} \textsc{ii} at these epochs,

### Table 4

| Absorber | $T$ (K) | $n$ (cm$^{-1}$) | $\epsilon$ | $T$ (K) | $n$ (cm$^{-1}$) | $\epsilon$ |
|----------|---------|----------------|-----------|---------|----------------|-----------|
| 1        | 39810   | 0.0001         | 0.24      | 31622   | 0.001          | 42        |
| 2        | 31100   | 0.001          | 0.02      | 31622   | 0.001          | 3.1       |
| 3        | 16840   | 0.0001         | 3.8       | 31622   | 0.001          | 68        |
| 4        | 39810   | 0.0001         | 5.7       | 31622   | 0.001          | 87        |
| 5        | 16840   | 0.001          | 9.4       | 31622   | 0.001          | 68        |
| 6        | 37830   | 0.001          | 0.01      | 39810   | 0.001          | 0.14      |
| 7        | 16840   | 0.0001         | 1.6       | 31622   | 0.001          | 10        |
| 8        | 39990   | 0.01            | 10.8     | 31622   | 0.001          | 142       |
| 9        | 16710   | 0.01            | 0.001    | 39810   | 0.001          | 0.16      |
| 10       | 39630   | 0.01            | 0.015     | 39810   | 0.001          | 18        |

Same as Table 2 for the Model DR.
that has been suggested from numerical simulations, and our results lend support to these models.

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