He I and its Tales

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ABSTRACT

We propose using He I to make a direct measurement of the temperature of intergalactic medium (IGM). While the temperature of the IGM is believed to be in the range of $1 - 3 \times 10^4 K$ there is yet a direct measurement confirming this result. With a new generation of space-based high resolution UV spectrometer such as the Cosmic Origins Spectrograph (COS) coming online within the next few years, it might become possible to study absorption features of the He I Lyα forest.

By simultaneously measure the H I and the He I b value of the same system we hope to directly measure the temperature of the absorbing system without making any assumptions about the ionization history or its equation of state. We will explore some of the possibilities in this discussion.

Subject headings: intergalactic medium: equation of state, quasar: absorption lines, cosmology: observation, HeI

1. Introduction

Since the groundbreaking work by Gunn and Peterson (1965) and Bahcall and Salpeter (1965) on the absorption of photons from distant quasar by the neutral hydrogen in the diffuse intergalactic medium (IGM) creating the so called Lyα forest, we have learned a great deal about its physics and its usefulness as a cosmological probe. It has become our most sensitive probe of the low density matter distribution at redshift $z < 5$ and so far it has been our only tool for studying the dynamical properties of the IGM at such redshifts. When complemented by numerical simulations, the Lyα forest is an valuable tool in the study of structure formation and the ionization history of our universe.

In recent years, with the developement of high resolution, high signal to noise spectrometers such as the Keck/HIRES and the VLT/UVES, we are able to study many more quasars in more exquisite details than ever before. These technological developments have led to extensive investigations and literatures published on the Lyα forest and the IGM. Through these studies we are able to established several key empirical properties of the forests such as their hydrogen column
density distribution, redshift distribution, the b distribution, and the b cutoff dependence on column density. These properties allow us to construct Lyα forest ourselves that is statistically the same to the real ones we observe.

On the theoretical front there has also been dramatic developments as well. Most notably, the picture of the forest has evolved from that of individual clouds to that of a continuous density fluctuation of matter. Hydrodynamic simulations show that majority of the luminous and dark matter appears to gravitationally collapse into highly asymmetrical filamentary structures interconnecting highly overdense regions such as dark matter halos and galaxy clusters. As these structures evolve and space expands, the underdense regions become more underdense while the overdense regions attract more matter and becoming more overdense. Quite remarkably, people have found an analytical form for describing the matter density of the universe, even after its evolution has turned non-linear ($\delta < 100$). Works by Coles and Jones (1991); Bi and Davidsen (1996); Kayo et al. (2001) show that the lognormal (LN) random field provides a good characterization of the matter density fluctuations. Although the reason for the success of lognormal description is not entirely clear, its usefulness in many cases cannot be denied.

Nevertheless, there are still many questions about the IGM that past studies in Lyα forest have not been able to answer. For example, we cannot yet do a direct measurement of the temperature of the IGM using the Lyα forest. The ionization history of the IGM is also only roughly known at this moment. Key question such as how uniform was the reionization remain unanswered. And finally the ionization state of the IGM, especially for helium, is not well constrained. All of these issues have been tackled theoretically using both analytical methods and numerical simulations. What we need now is observational evidence. The goal of our project is to help shed light on some of these issues.

A consistent difficulty in the study of absorption lines in the Lyα forest has been determination of the non-thermal contributions to the absorption line width. This uncertainty has prevented accurate measurement of the temperature IGM using the b value of the absorption lines. While people have demonstrated various characterizations of the non-thermal component of the line width (Weinberg et al. 1997), there have been very little direct observational evidence to compare with. As of now, our knowledge of the temperature of the IGM is primary grounded indirectly in studies of nonequilibrium chemistry and gas cooling processes.

However, with a new generation of space-based UV spectrometer such as the Cosmic Origins Spectrograph (Green, J. C. 2000) coming online within the next few years, we expect breakthrough in finding the answer to some of these questions. For example, it might for the first time be possible to study the He I Lyα forest. If we can make simultaneous measurement of the same absorption features in the H I Lyα forest and the He I Lyα forest, then we would be able to determine the temperature of the intergalactic medium directly, without having the the need to know the non-thermal contribution or to make any assumptions about the equation of state or the ionization history. In addition, this approach will allow us to constrain the ionization state of the absorbing
system, which when combined with He II measurements can also help us constrain the ionization history.

The observational questions we’d like to address are: (1) what is the probability of observing He I lines in a typical QSO spectra and how to maximize this probability, (2) how many spectras do we need to produce statistically meaningful results, (3) how much telescope time does our observation need, (4) and finally what kind of constraints do we expect to place on temperature and the the equation of state/ionization history of the IGM.

This paper is organized as follow, first in section 2, we will discuss the general plan of observation. in section 3, we will discuss the construction of random lines of sight, in section 4, we will discuss the calculation of HeI and HeII relative abundance and their b value and column densities, and finally in section 5, we will discuss the possible constraints on equation of state and ionization history of the intergalactic medium using HeI observations and their cosmological implications.

2. Helium Observations

The rest frame He I and He II resonant absorption line are located at 584.33 Å and 303.78 Å respectively. At redshift z = 2, the observed He I line would be located at 1753 Å and the He II line at 911.34 Å. These lines are located far in the UV spectrum and observing them would certainly require space based telescope. Due to He II higher relative abundance, the current generation of UV instruments such as STIS aboard hubble and Far Ultraviolet Spectraph Explorer (FUSE) are already capable of observing its Lyα forest (Smette et al. 2002). Observing He I, as we will see, is much more difficult, and the current telescopes do not have the necessary signal to noise ratio to carry out the observation. The only planned UV instrument that will offer the necessary capability of observing He I Lyα lines is the Cosmic Origins Spectrograph (COS) (Green, J. C. 2000). The instrument has two spectrograph channels, the Far Ultraviolet (FUV) and the Near Ultraviolet (NUV), covering wavelength from 1150 Å to 3200 Å. The FUV has three gratings, each covering a different wavelength range. The parameters of the instrument are listed in Table 1.

We need to pick the appropriate instrument and grating for our observation of He I Lyα lines so that we can observe the corresponding H I lines using a ground based telescope. The atmospheric cutoff for UV photon occurs around 3200 Å, therefore we can only choose QSO’s at redshift $z = 3200/1215.67 - 1 = 1.63$ or higher. On the other hand, the maximum wavelength of the FUV’s high S/N G160M grating is 1775 Å which translates into an upper redshift limit $z = 1775/584.33 - 1 = 2.04$. Fortunately, a significant number observable QSO’s lie in this redshift range. In the following sections we will construct a number of random LOS and show likelihood of observing an He I line.
3. Constructing Lines of Sight

There are several methods of constructing random lines of sight for the IGM. The method that is more commonly used and arguably produces lines with the richest information is taking random lines of sight through hydrodynamic N-body simulation boxes. (Davé et al. 1997; Machacek et al. 2000) This method not only reproduces the statistical characteristics of the observed lines but also their dynamical behavior as well, such as clustering and proximity effects. It is ideally suited for checking hydrodynamic simulations against real observation of the forest.

Hydrodynamical simulations, however, are very computationally expensive and its effectiveness and accuracy are sometimes critically dependent on the resolution and size of the simulations. (Machacek et al. 2000) For certain class of problems, simulating Ly\(\alpha\) lines by N-body simulation might not be the best approach.

For our study, where we are mostly interested in the statistical properties of the lines, we will employ a simple statistical method. Each absorption feature in the Lya forest can be characterized by three parameters: its width, depth/strength and location. The width is typically characterized by the so called ‘\(b\)-parameter’. The \(b\) composes of three major components. There is a thermal component due to the thermal motion of the gas, a turbulent component that basically includes all non-thermal and non-instrumental contributions, finally there is the instrumental component due to the finite resolution, resolving power and other imperfection of the instrument. The strength of a line is usually characterized by its optical depth \(\tau \equiv N \lambda f\), where \(N\) is the column density, \(\lambda\) is the wavelength of atomic transition, and \(f\) is the oscillator strength. The higher the optical depth, the more the absorption. The optical depth is directly proportional to the observable quantity column density and the constant of proportionality is the oscillator strength. Finally, the location of the absorber along the LOS is determined by its redshift, \(z\).

Since each absorption line can be fully characterized by three parameters: redshift, \(b\) value, and column density, we can obtain a line list by randomly draw these three parameters from their respective probability distribution functions (PDF) until we have the needed number of lines. This method has the advantage of being simple and easy to implement. We need to be careful however, when using this method, because it is not immediately obvious how we obtain some features of real lines such as the \(N_{HI} - b_c\) relation.

In the next section we will next discuss the probability distribution function for each of the three parameters.

3.1. \(b\)-parameter distribution

The \(b\) parameter is the characterization of the width of a line. Using a linear perturbative analysis of the optical depth fluctuation, Hui and Rutledge (1999) developed a single parameter characterization of the \(b\) distribution. The model describes both the \(b^{-5}\) high velocity tail and the
low velocity cutoff. The normalized $b$ distribution is given as

$$ \frac{dN}{db} = \frac{4b_0^4}{b^5} \exp\left(-\frac{b_0^4}{b^4}\right) $$

(1)

where $b_0$ is the fit parameter of the observed distributions.

Although $b_0$ is an convenient parameter to use in the analytical characterization of the $b$ distribution, it is not what we measure directly. What we see when we plot $b$ versus column density for a large number lines is a cutoff that marks the minimum $b$ for a given column density. Let us define this $b$ cutoff or $b_c$ to be the $b$ value for which 95% of the lines in the $b$ PDF would have values higher than it. It is this $b_c$ that we usually measure.

Fortunately, it is easy to relate $b_c$ to $b_0$. We simply integrate the PDF from some $b$ to infinity for a fixed $b_0$, the $b$ that integrates to 95% would be our desired $b_c$. We found that the ratio $b_c/b_0 = 0.760106$. This is extremely convenient because we now have a simple way of calculating $b_c$ from $b_0$ and vice versa, which in turn allows us to simulate the $b$-cutoff behavior in our lines.

Hui and Rutledge (1999) showed that the equation of state of the IGM in the low-density limit can be written as:

$$ T = T_0 (1 + \delta)^{\gamma - 1} $$

(2)

If we assume that the broadening of Ly$\alpha$ absorption lines is partially due to thermal motion of the absorber, then for a given temperature there should be a nominal line width due mostly to the thermal motion. In this sense, $b_c$ is a quantitative characterization of the minimum thermal broadening of the line. We can write an equation for $b_c$ as a function of column density:

$$ b_c = b_0 (N_{HI})^{\Gamma - 1} $$

(3)

If we can relate overdensity to column density, we should be able to relate the equation of state and the above equation as well (Schaye 2001). Kim et al. (2002) provides fit to the $b$ cutoff equation for a set of eight QSO’s at various redshifts. The fit parameters of the five lowest redshift QSO’s are listed in Table 2. We see that the two fit parameters $\log(b_0)$ and $\Gamma - 1$ can vary a good deal with redshift. Unfortunately, the values do not appear to exhibit any monotonic dependence with redshift. For the purpose of this study where we are not interested in providing the best fit to individual observations, we will simply take the average of the fit parameters given in Table 2. The following parameters are used for our simulation.

$$ \Gamma_{avg} = 1.168, \log(b_0)_{avg} = -1.022 $$

(4)

Knowing $\Gamma$ and $\log(b_0)$, we can calculate $b_c$ and $b_0$. We have now fully characterized the $b$ value PDF. Figure 1 shows a sample $b$ distribution with $N_{HI} = 10^{13.6} cm^{-2}$. 
3.2. column density distribution

The column density distribution is usually given in terms of the differential density distribution, \( f(N_{HI}) \) which is defined as number of lines per column density per absorption path.

\[
f(N_{HI}) = \frac{d^2N}{dX\,dN_{HI}} = AN_{HI}^{-\beta}
\]

(5)

where \( X \) is the absorption path length and \( X(z) = \frac{2}{3}[(1 + z)^{3/2} - 1] \) for \( q_0 = 0.5 \). \( A \) and \( \beta \) are obtained by fitting \( f(N_{HI}) \) to quasar spectra. Kim et al. (2002) performed power-law fit of the above distribution function to three quasars near the redshift of \( z = 2 \). We use the averaged the fit parameters obtained for the column density range \( N_{HI} = 10^{12.8-14.3}\,cm^{-2} \) in our calculation of the column density distribution. Figure 2 shows the plot of \( f(N_{HI}) \).

Next we want to express \( f(N_{HI}) \) in terms of \( dz \) instead of \( dX \). Plugging \( X(z) \) into expression for \( f(N_{HI}) \) we get:

\[
\frac{d^2N}{dz\,dN_{HI}} = \frac{dX}{dz} \frac{d^2N}{dX\,dN_{HI}} = (1 + z)^{1/2}f(N_{HI})
\]

(6)

To obtain the cumulative distribution function (CDF) for column density, we integrate \( f(N_{HI}) \) with respect to \( N_{HI} \). The integral is normalized to unity for \( N_{HI} = 10^{12-17}\,cm^{-2} \). Finally we have:

\[
CDF = 1.00317\,(1 - \sqrt{10^{12-N_{HI}}})
\]

(7)

3.3. redshift distribution

Because the universe was smaller and structures had less time to form and merge at higher redshift, we expect a higher fraction baryons to exist in the IGM than we do today. If we have a telescope with infinite resolving power and very large collecting area, we would expect to see more lines at higher redshift than at lower redshift. The redshift distribution of Ly\( \alpha \) forest is defined as

\[
\frac{dn}{dz} = \frac{(dn/dz)_0}{(1 + z)^\gamma}
\]

(8)

where \( (dn/dz)_0 \) is the local comoving number density of the forest The best fit parameter is \( \frac{dn}{dz} = 9.06 \pm 0.40 \) and \( \gamma = 2.19 \pm 0.27 \) for \( N_{HI} = 10^{13.64-16}cm^{-2} \) (Kim et al. 2002). The redshift distribution is plotted in Figure 3. To obtain the CDF of our distribution, we integrate the above equation with respect to \( z \), and as before, normalize the integral to unity in the column density range \( N_{HI} = 10^{12-17}cm^{-2} \).

4. Simulated lines

We perform Monte Carlo simulation to create a simulated Ly\( \alpha \) spectrum. Each line is drawn from the PDF’s of the three parameters as discussed above. Our lines are created in the redshift range \( 1.5 < z < 4 \) and H I column density range \( 10^{12} < n_{HI} < 10^{17} \).
First we need to determine the number of lines per line of sight in the our redshift and column density range. We start with the differential density distribution function which is a function of the form $AN^{-\beta}_{HI}$. We then integrate $f(N_{HI})$ over the observed column density range (i.e. $N_{HI} = 10^{13.64-16}$ (Kim et al. 2002)) at a fixed redshift and compare it with the number we get from integrating over our desired column density ($N_{HI} = 10^{12-17} cm^{-2}$) at the same redshift and compare the two numbers. the ratio of the column densities provides the normalization for $dN/dz$. Using this method we estimate that there should be about 3000 lines per LOS. Once we determine the number of lines per line of sight, we just continue to draw lines from the distribution until the desired number is reached. We constructed 500 line lists in this fashion.

5. HeI and HeII relative abundance

Having made the simulated line lists, we now can estimate how much He I and He II absorptions we expect to see. Before we go into the calculations of He I and He II lines, however, let us ask ourselves what we intuitively expect. We already know that helium is much less abundant than hydrogen ($n_{He} = 0.08n_H$). On top of that we also know that most of the helium in the universe have been ionized at redshift $z < 3$ (). We therefore expect a very small percentage of helium exist in its neutral form. Finally, as icing on the cake, the oscillator strength for atomic excitation of He I is half that of H I, which would make the optical depth of He I three times less than H I:

$$\frac{\tau_{HI}}{\tau_{HeI}} = \frac{\lambda_{HI}f_{HI}}{\lambda_{HeI}f_{HeI}} = \frac{0.4161215.67}{0.285584.33} = 3.04$$

All of these factors combined would make He I especially hard to observe compare to H I. We will see that this is indeed the case.

The story with He II, on the other hand, is more interesting. Even though the ratio of helium to hydrogen remains unchanged, the relative abundance of He II can be much higher compare to He I at redshift $z \sim 2$. We will see that this is so much so that even though the oscillator strength of He II and H I is the same which would make the optical depth of H I four times larger than He II, we still see much more He II absorptions than H I absorptions. This fact makes He II an ideal probe matter fluctuation in extreme underdense regions (). The argument, however, begs the question what happens when He II reionization takes place and turns He II into He III. For example, we can ask what effects does He II reionization have on He I abundance, or how does it influence the ionizing background, or does our assumption of photoionization equilibrium for all species of helium still holds true. It is not entire clear what the answers to those questions are. Nevertheless, for our current study we will still assume a fixed ionizing background and assume that photoionization equilibrium for hydrogen and helium holds, leaving those questions for a future study.
5.1. Equations of photoionization equilibrium

In exactly the same manner as in H I Lyα forest, each line in the helium Lyα forest is characterized by three parameters: redshift, column density, and $b$ value. To obtain an estimation for the He I and He II column density and the He I $b$ value we will assume the mean temperature of the IGM at $z = 2$ to be $2 \times 10^4 K$ for all of our calculations. We will also assume an equation of state of the form discussed earlier.

To determine the amount of He I and He II in the IGM, we solve a set of photoionization equilibrium equations for a system containing only hydrogen and helium. We assume that the system of interest is optically thin so that effects such as shielding can be ignored. This is a reasonable assumption for systems with $N_{HI} < 10^{17} cm^{-2}$ (). We also assume a constant UV background as given by Haardt and Madau (1996). This assumption is reflected in the ionization coefficient and recombination rate as discussed later.

The following set of equations describes the photoionization of hydrogen and helium:

$$\Gamma_{HI} n_{HI} = n_e n_{HII} \alpha_{HII}$$ (10)
$$\Gamma_{HeI} n_{HeI} = n_e n_{HeII} \alpha_{HeII}$$ (11)
$$\Gamma_{HeII} n_{HeII} = n_e n_{HeIII} \alpha_{HeIII}$$ (12)
$$n_e = n_{HeII} + 2 n_{HeIII} + n_{HII}$$ (13)
$$\frac{n_{HeII} + n_{HeIII} + n_{HeI}}{n_{HII} + n_{HII}} = 0.08$$ (14)

where the $\Gamma$’s are the photoionization parameters for hydrogen and helium, and the $\alpha$’s are the recombination coefficients for hydrogen and helium.

Although we will solve the above system of equations for the individual ionization states of hydrogen and helium, the algebraic manipulation is very complicated and require a computer to solve. We can, however, obtain an elegant expression that relates the abundance of He I to the abundance of He II in a straightforward way by making certain approximates. We will show this now. From study of distant quasar spectra people have concluded that the universe reionized at redshift $z > 6$ (Fan et al. 2002), thus for most of the Lyα absorption systems we study at redshift $1.5 < z < 3$ we can safely assume that most of hydrogen atoms are in their ionized state. Furthermore, He I reionization also must have taken place before $z \sim 3$, for it must occur before He II reionization which took place around $z \sim 3$ (Theuns et al. 2002; Bernardi et al. 2002). We will therefore assume that most of the helium in the universe at redshift $z < 3$ are ionized as well, existing as either He II or He III. We will therefore assume $n_H = n_{HII}$ and $n_{He} = n_{HeII} + n_{HeIII}$. This will allow us to rewrite the above system of equations as follow.

$$\frac{n_{HeI}}{n_{HI}} = \frac{\Gamma_{HI} \alpha_{HeII} n_{HeII}}{\Gamma_{HeI} \alpha_{HII} n_{HII}}$$ (15)
$$\frac{n_{HeII}}{n_{HI}} = \frac{\Gamma_{HI} \alpha_{HeIII} n_{HeII}}{\Gamma_{HeII} \alpha_{HII} n_{HII}}$$ (16)
The ionization balance is given by

$$\frac{n_{\text{He} II} + n_{\text{He} III}}{n_{\text{H} II}} = 0.08 \quad (17)$$

we then let \( \Gamma_{\text{HI}} \alpha_{\text{He} I} \) = \( C_1 \) and \( \Gamma_{\text{He} II} \alpha_{\text{He} III} \) = \( C_2 \), and solve for \( \frac{n_{\text{He} I}}{n_{\text{H} I}} \) in terms of \( \frac{n_{\text{He} II}}{n_{\text{H} I}} \). We get:

$$\frac{n_{\text{He} I}}{n_{\text{H} I}} = \frac{C_1}{C_2} \left( 0.08 C_2 - \frac{n_{\text{He} II}}{n_{\text{H} I}} \right) \quad (18)$$

This equation is extremely nice because it says He I abundance is a simple function of He II abundance, thus if we have one value, we have the other as well. We will test this relation later once we have solved for \( \frac{n_{\text{He} I}}{n_{\text{H} I}} \) and \( \frac{n_{\text{He} II}}{n_{\text{H} I}} \).

As mentioned earlier, it is a difficult algebraic exercise solving the set of photionization equations exactly. We use Mathematica (Wolfram Research 2001) to assist us solving for the various ionization states of hydrogen and helium (i.e. \( n_{\text{H} I}/n_{\text{H}} \), \( n_{\text{He} I}/n_{\text{H} I} \), and \( n_{\text{He} II}/n_{\text{H} I} \)). They are expressed in terms of \( n_{\text{H}} \) and the ionization and recombination parameters. We will study the solutions below.

### 5.2. Photoionization Coefficients and Recombination Rates

Before we can plot the solutions, we need to calculate the ionization coefficients and recombination rates for hydrogen and helium. In the case of hydrogen and helium, they have been studied by others, here we will mostly employ previous results. Haardt and Madau (1996) provides an expression for the photoionization coefficients for hydrogen and helium:

$$\Gamma(z) = A(1 + z)^B \exp\left(-\frac{(z - z_c)^2}{S}\right) \quad (19)$$

where \( A, B, z_c, \) and \( S \) are the fit parameters. H I and He I have the same ionization coefficients. Ionization parameters as functions for redshift are plotted in Figure 4 H I, He I and He II.

Similarly, the recombination rates can also be expressed in a simple analytic form ():

$$\alpha(T) = a\left( \sqrt{\frac{T}{T_0}} - b\sqrt{\frac{T}{T_1}} \right)^{-1} \left( 1 + \sqrt{\frac{T}{T_0}} \right)^{1-b}\left( 1 + \sqrt{\frac{T}{T_1}} \right)^{1+b} \quad (20)$$

where \( T_0, T_1, a, \) and \( b \) are the fit parameters. The fit parameters are calculated by Verner and Ferland (1996) and are plotted as function of temperature in Figure 5.

### 5.3. Solutions

For all of the plots, we take the mean temperature of the IGM \( T = 2 \times 10^4 \) and \( z = 2.4 \) unless otherwise noted.
5.3.1. from number density to column density

Because most theoretical calculations are done using number density while most observations are recorded in column density, it is important to be able to draw a direct connection between the two quantities. Schaye (2001) introduces a notion of “Jeans column density”, $N_{H,J}$ and provides a simple expression connecting Jeans column density with number density $n_H$.

$$N_{H,J} \equiv n_H L_J \sim 1.6 \times 10^{21} cm^{-2} n_H^{1/2} T_4^{1/2} \left( \frac{f_g}{0.16} \right)^{1/2}$$

(21)

Figure 6 is a plot of $N_{H,J}$ vs $n_H$

5.3.2. HI abundance compare to total hydrogen

We expect H to be mostly ionized except at very high density, therefore the ratio $n_{HI}/n_H$ should remain small except at very large $n_H$. Figure 7 plots the H I abundance we calculated and an approximate expression given by Schaye (2001). It shows that our solutions are consistent with each other. Figure 8 shows the same plot with column density on the x-axis.

5.3.3. HeI abundance

Figure 9 shows the He I abundance relative to H I. As expected, He I is indeed very rare, especially for low density systems. We will find out what does this exactly mean when we look at the He I line lists in the next section.

5.3.4. HeII abundance

Figure 10 shows the He II abundance relative to H I. Not surprisingly, it is significantly more abundant than H I, which is why its Lyα forest is often saturated. The plot shows a plateau at 43 at lower densities. This number is consistent with the measurement done using FUSE spacecraft (Kriss et al. 2001), whose observed ratio of He II to H I is $\sim 80$.

5.3.5. how much HeIII?

For curiosity sake, we calculated how much helium is in its fully ionized state as a function of hydrogen column density. It appears at sufficiently low density, most of the helium exists in the He III state. I will not pound about it further since time...all gone!
6. IGM temperature and its equation of state

The idea of a direct temperature measurement of the IGM is very simple. It exploits the fact that whatever non-thermal contribution there is in the measured $b$ of H I, it is also giving the same non-thermal contribution to the $b$ of He I. The measured $b$ value can be expressed as the sum of a thermal component and a non-thermal component as in the expression below.

$$b_{meas}^2 = b_t^2 + b_{nt}^2 \quad (22)$$

where $b_t = \sqrt{kT/m}$ is the thermal component of $b$ and $b_{nt}$ is the non-thermal component of $b$. If we can make a simultaneous measurement of the H I $b$ and the He I $b$ for the same system, we can eliminate the non-thermal component and obtain the temperature for the line.

$$T_{line} = \frac{\mu}{k}(b_{HI}^2 - b_{HeI}^2) \quad (23)$$

where $\mu$ is the reduced mass of hydrogen and helium and $k$ is Boltzmann constant. You might now ask why do we not do the same with He II? We can, of course, except for the fact that the He II forests are very easily saturated due to its high abundance. It is very hard to tell the He II lines apart from one another, making this measurement impossible.

So what is our chance of observing H I lines and He I lines for the same structure? Let us count our observational constraints. We require the line to lay between redshift of $1.63 < z < 2.039$. We need the He I column density to be at least $10^{13} cm^{-2}$. We also require that the H I column density to be less than $10^{17} cm^{-2}$ so that high energy UV photon at least have a chance of getting here. Finally, we require that the $b$ values for both H I and He I must not be too large ($b < 100 km/s$), else even if there is an absorption, we would have a hard time identifying it. Given all these requirement, our simulations show that we expect to see about one He I line per LOS observation if reionization took place at sufficient long time ago such that the equation of state of the IGM has slope of $\gamma = 5/3$ at $z < 2$. On the other hand, if the IGM is still going under significant cooling such that the slope of the equation of state is smaller than $5/3$, we will be able to see more He I lines. Figure 12 and Figure 13 show the location of these lines on a $b_{HeI}$ versus $b_{HI}$ plot for the case of $\gamma = 1$ and $\gamma = 5/3$ respectively.

REFERENCES


Kim, T.-S., Cristiani, S., and D’Odorico, S. 2001, à, 373, 757


Rauch, M. 1998, Annual Reviews


Wolfram Research, Inc. 2001, Mathematica ver. 4.1

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### Table 1. COS FUV gratings

<table>
<thead>
<tr>
<th>Gratings</th>
<th>Wavelength Range (Å)</th>
<th>Coverage per Exposure (Å)</th>
<th>Dispersion (Å/pixel)</th>
<th>Resolving Power</th>
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<td>G130M</td>
<td>1150–1449</td>
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<td>0.0094</td>
<td>20000–24000</td>
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<td>1406–1775</td>
<td>375</td>
<td>0.0118</td>
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<tr>
<td>G140L</td>
<td>1230–2050</td>
<td>820</td>
<td>0.0865</td>
<td>2500–3500</td>
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### Table 2. Power law fit to the $N_{HI} - b$ distributions

<table>
<thead>
<tr>
<th>$z$</th>
<th>log($b_0$)</th>
<th>$\Gamma$-1</th>
<th>$b_c$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.61</td>
<td>−0.92±0.13</td>
<td>0.16±0.04</td>
<td>20.3±1.1</td>
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<td>1.98</td>
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<td>0.20±0.01</td>
<td>19.1±1.0</td>
</tr>
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<td>0.16±0.03</td>
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<td>2.1</td>
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<td>0.15±0.04</td>
<td>19.2±1.0</td>
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Fig. 1.— $b$ distribution for $N_{HI} = 10^{13.6} cm^{-2}$. 
Fig. 2.— Differential density distribution as function of $\log(N_{\text{HI}})$. 
Fig. 3.— redshift distribution for $N_{HI} = 10^{12−17} cm^{-2}$.
Fig. 4.— Ionization rate versus redshift. The solid line represents H I ionization rate, the crosses represent He I ionization rate, and the diamonds represent the He II ionization rate.
Fig. 5.— Recombination coefficient versus temperature. The solid line represents H II, the crosses represent He II, and the diamonds represent He III.
Fig. 6.— Plot of Eqn. (4) in Schaye (2001). By the argument that $t_{sc} \sim t_{dyn}$, the column density and number density follows a nice linear log-log relationship.
Fig. 7.— As expected, H is mostly ionized at redshift $z < 4$, except at very high density where optically thin approximation breaks down and other effect such as self shielding plays a role. The dotted line is our exact solution and the solid line is equation (6) of Schaye (2001). They agree very well.
Fig. 8.— Plot of HI ionization fraction as a function of Jean column density $N_{H,J}$. 
Fig. 9.— HeI abundance compare to HI.
Fig. 10.— HeII abundance compare to HI.
Fig. 11.— HeIII ionization fraction.
Fig. 12.— $b_{He} \text{vs} b_{HI}$ for ten LOS observations, $\Gamma = 1$. The crosses are lines within our observational constraints.
Fig. 13. — $b_{\text{He}}$ versus $b_{\text{H}}$ for ten LOS observations, $\Gamma = 5/3$. The crosses are lines within our observation constraints.