THE IMPLICATIONS OF GUNN–PETERSON TROUHS IN THE He II Lyα FOREST

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ABSTRACT

Many experts believe that the z ∼ 3 He II Lyα forest will suffer from the same saturation issues as the z ∼ 6 H I Lyα forest and, therefore, will not be a sensitive probe of He II reionization. However, there are several factors that make He II Lyα absorption more sensitive than H I Lyα. We show that observations of He II Lyα and Lyβ Gunn–Peterson troughs can provide a relatively model-independent constraint on the volume-averaged He II fraction of x_{He II} > 0.1. This bound derives from first using the most underdense regions in the He II forest to constrain the local He II fraction and, then, assuming photoionization equilibrium with the maximum allowed photoionization rate to calculate the ionization state of nearby gas. It is possible to evade this constraint by a factor of ∼ 2, but only if the He II were reionized recently. We argue that He II Lyα Gunn–Peterson troughs observed in the spectra of Q0302−003 and HE2347−4342 signify the presence of > 10 comoving Mpc patches in which x_{He II} > 0.03. This is a factor of 20 improvement over previous constraints from these spectra and 100 times stronger than the tightest constraint on the H I volume-filling fraction from the z > 6 H I Lyman forest.

Key words: diffuse radiation – intergalactic medium – quasars: absorption lines

1. INTRODUCTION

Most experts do not believe that effective optical depths of τ_{eff} ∼ 5 measured in the z ∼ 6 H I Lyα forest imply that H I reionization was occurring (e.g., Becker et al. 2007). Observations of the z ∼ 3 He II Lyα forest also find τ_{eff} ∼ 5 in select regions, and again the view of experts is that these observations do not necessarily indicate that He II reionization is happening (e.g., Fardal et al. 1998; Miralda-Escudé et al. 2000). However, there are several key differences that make He II Lyα absorption at z ∼ 3 a more sensitive probe of diffuse He II than H I Lyα absorption at z > 6 is of diffuse H I: (1) the abundance of helium is ∼ 14 times smaller than that of hydrogen, (2) a photon redshifts through the He II resonance four times faster than the H I resonance, and (3) the intergalactic medium (IGM) is less dense and has more voids at z ∼ 3 than z ∼ 6.

Previous theoretical studies of the He II Lyα forest modeled this absorption as a set of discrete absorbing clouds and/or focused on the τ_{eff} statistic (Giroux & Shull 1997; Fardal et al. 1998; Miralda-Escudé et al. 2000). This Letter employs better-suited techniques to study He II Lyα absorption near saturation. The discrete-cloud approximation works best in overdense regions. The low-density IGM is better approximated as a less clumpy continuum of gas that has not decoupled from the Hubble flow, and it is the absorption in the least dense regions that are the most constraining with regard to He II reionization. Furthermore, the local measure for the He II fraction studied here is more powerful than global measures like τ_{eff}(z), for which what redshift evolution indicates about He II reionization is highly model-dependent. Our measure uses H I absorption to target the He II absorption in the most evacuated voids, where one is sensitive to the largest He II fractions. The advantages of using the H I absorption were realized in many observational studies of the He II forest (Davidson et al. 1996; Hogan et al. 1997; Anderson et al. 1999; Heap et al. 2000; Smette et al. 2002), and we argue here that this information can be used to obtain tighter constraints on the amount of intergalactic He II than previous analyses have found.

This study is timely because the Hubble Space Telescope (HST) reserving mission installed the Cosmic Origins Spectrograph (COS) in 2009 May. COS will enable absorption measurements at 2.76 < z < 3.05 for He II Lyα and at 3.46 < z < 3.8 for He II Lyβ, where z_{QSO} is the redshift of the quasar. It is able to achieve higher signal-to-noise ratios and higher spectral resolutions than previous instruments on ∼ 4 existing He II Lyα sightlines, in addition to providing > 10 new sightlines.

In this Letter, we assume a flat ΛCDM cosmology with h = 0.71, Ω_b = 0.046, Ω_m = 0.27, σ_8 = 0.8, and Y_{He} = 0.24, consistent with recent measurements (Komatsu et al. 2009).

2. THE He II LYMANY-SERIES FOREST

In contrast to H I Lyα Gunn–Peterson absorption at z ∼ 6, which saturates for neutral fractions of ∼ 10^{-3}, the Gunn–Peterson optical depths for a photon to redshift through the He II Lyα, Lyβ, and Lyγ resonances are

$$\tau_{GP}(\alpha, \beta, \gamma) = (3.4, 0.7, 0.2) \frac{(x_{\text{He II}}/0.01)}{(1 + z)} \frac{1 + z}{4} \left(\frac{\Delta_b}{0.1}\right)^{3/2},$$

where Δ_b is the gas density in units of the cosmic mean and x_{He II} is the local fraction of helium in He II. Note that damping wing absorption from He II in dense systems or from intergalactic He II is not significant.

The focus of this Letter is on absorption in underdense regions and what this absorption implies about the ionization state of denser, neighboring regions. Approximately 13% of the volume has Δ_b < 0.2 at z = 3, 5% has Δ_b < 0.15 (Miralda-Escudé et al. 2000), and a larger fraction in redshift space. Equation (1), combined with the knowledge that the least dense regions in the z ∼ 3 IGM have Δ_b ∼ 0.1, suggests that the He II Lyα forest is sensitive to He II fractions in such underdensities of the order 1% (and higher series lines to ∼ 10%).

3 Underdense regions will be expanding faster than the Hubble flow such that Equation (1) will be an overestimate. Accounting for peculiar velocities does not change our constraints on x_{He II}, because peculiar velocities have the same effect on both τ_{He II} and τ_{HI}. 
In order to achieve such constraints, the locations of underdense regions must be known. The H I Lyα forest reveals this information. The H I Lyα Gunn–Peterson optical depth is

$$\tau_{\text{HI}}(x) \approx 0.7 \Delta_b^{-0.7(y-1)} \left( \frac{T_0}{20,000} \right)^{-0.7} \Gamma_{12}^{-1} \left( \frac{1}{4} \right)^{9/2},$$

where we have assumed photoionization equilibrium with $\Gamma_{12}$—the H I photoionization rate in units of $10^{-12}$ s$^{-1}$—and a power-law temperature–density relation given by $T = T_0 \Delta_b^{-\gamma}$, where $\gamma < 1.6$ (Gnedin & Hui 1998). The term $\Delta_b^{0.7(y-1)}$ in Equation (2) arises from the temperature dependence of the recombination rate. Our results depend weakly on $y$ and $T_0$, and we adopt the values $y = 1.3$, $T_0 = 18,000$ K, and $\Gamma_{12} = 0.8$, consistent with observations (McDonald et al. 2001; Faucher-Giguère et al. 2008a). $\Gamma_{12}$ is expected to be nearly spatially invariant owing to the long mean free path (mfp) of hydrogen-ionizing photons and the large number of sources within a mfp.

The smaller the value of $\Delta_b$ that can be reliably located in the H I Lyα forest, the better one can constrain the He II fraction from the H I Lyman forest. However, the continuum fitting tends to artificially remove flux such that the flux in the lowest density pixels is set to zero, thereby preventing one from distinguishing between small values of $\Delta_b$. Faucher-Giguère et al. (2008) estimated that continuum fitting on average removes 3% of the transmission at $z = 3$. Therefore, a value of $\Delta_b = 0.15$, which yields $\tau_{\text{HI}} \approx 0.03$ or 3% absorption, is approximately the minimum density contrast over 0 that can be discriminated at $z \sim 3$. While a more rigorous derivation of the minimum $\Delta_b$ would be worthwhile, we employ $\Delta_b = 0.15$ for this study.

Figure 1 shows the H I Lyα spectrum (dotted curve, $R = 1000$) and He II Lyα spectrum (thick solid curve, $R = 800$) of the $z = 3.29$ quasar Q0302–003 (Worseck & Wisotzki 2006), one of the most-studied He II Lyα forest sightlines. Note that for $3.1 < z < 3.2$—a region spanning

\[ \approx 100 \text{ comoving Mpc} (\text{cMpc}) \sim \frac{2}{3} \] (except perhaps near $z = 3.1$) such that there is no significant He II Lyα transmission. The short-dashed horizontal line in Figure 1 represents the transmission and provides a similar bound.

Many of the elements with $\tau < 4$ in He II Lyα absorption admit $\sim 100\%$ H I Lyα transmission (see the cyan highlighted regions in Figure 1). These regions should have $\Delta_b \lesssim 0.15$ from the above discussion. Equation (1) and the limit $\tau < 4$ implies that the underdense elements with $\Delta_b < 0.15$ have $x_{\text{He II}} > 0.008$.4 Throughout this Letter, we adopt this bound on $x_{\text{He II}}$ for the most underdense, saturated elements in the He II Lyα spectrum of Q0302–003, although a more detailed analysis could improve upon it. Another well-studied He II forest sightline, the $z = 2.89$ quasar HE2347–4342 (not shown), has a Gunn–Peterson trough at $z \approx 2.85$ with no detected He II Lyα transmission and provides a similar bound.

3. He II PHOTOIONIZATION

Sometime before $z \approx 2.8$, the second electron of intergalactic helium was reionized by a source of ultraviolet photons (most probably quasars), and afterward the helium was kept doubly ionized by the metagalactic radiation background. If a gas parcel is exposed to a radiation background with He II photoionization rate $\Gamma_{\text{He II}}$, the He II fraction as a function of elapsed time $\Delta t$ is

$$x_{\text{He II}}(t) \approx x_{\text{He II}, \text{eq}} + (x_{\text{He II}, 0} - x_{\text{He II}, \text{eq}}) \exp(-\Delta t / \tau_{\text{eq}}),$$

where $x_{\text{He II}, 0}$ is the He II fraction at $\Delta t = 0$, $\tau_{\text{eq}} \equiv (\Gamma_{\text{He II}} + \alpha n_e)^{-1}$,

$$x_{\text{He II}, \text{eq}} = \frac{\alpha (T) n_e}{\Gamma_{\text{He II}} + \alpha (T) n_e}.$$  

$n_e$ is the electron density, and $\alpha(T)$ is the recombination coefficient.3 The $z \sim 3$ recombination time $(\alpha(T) n_e)^{-1}$ is roughly half the Hubble time $H(z)^{-1}$ at mean density. Figure 2 plots $x_{\text{He II}, \text{eq}}$ as a function of $\Gamma_{\text{He II}}$ for $\Delta_b = 0.15$ and $\Delta_b = 1$.}

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4 We have checked that this bound holds if we instead use the $R = 40,000$ Keck HIRES H I Lyα forest spectrum of Q0302–003.

5 Note that $\Delta_b$ appears implicitly in $\alpha (T) n_e$ and $\alpha$ is the case A recombination coefficient.
4. A NEW METHOD TO ESTIMATE $X_{\text{He} \text{II}}$

We have shown that a measurement with percent-level precision of the He $\text{II}$ Ly$\alpha$ forest can be used to set a percent-level constraint on the He $\text{II}$ fraction in underdense regions that are opaque to He $\text{II}$ Ly$\alpha$ photons. In this section, we argue that such a measurement can place an even stronger limit on the local He $\text{II}$ fraction in a $\gtrsim 10$ cMpc region surrounding such underdensities.

Our argument requires two propositions to hold:

1. The ionization state of gas elements in a volume that is exposed to the same $\Gamma_{\text{He} \text{II}}(t)$ scales as $X_{\text{He} \text{II}} \propto \Delta_b^{-1.07(\gamma-1)}$, the scaling expected for photoionization equilibrium.$^6$
2. A $\gtrsim 10$ cMpc region surrounding an underdensity in the forest is exposed to approximately the same $\Gamma_{\text{He} \text{II}}(t)$ as the underdensity.

From these two propositions, one can place an interesting lower bound on $x_{\text{He} \text{II}}$ in $\gtrsim 10$ cMpc regions. To see this, let us take our constraint of $x_{\text{He} \text{II}} > 0.008$ at $\Delta_b = 0.15$ (Section 2). Using the two propositions and Equation (4) to infer the ionization state of neighboring gas elements (which provides the scaling $X_{\text{He} \text{II}} \propto \Delta_b^{-0.7(\gamma-1)}$), we find that nearby elements with $\Delta_b = 1$ should have $X_{\text{He} \text{II}} > 0.034$. See the intersection of the solid vertical line in Figure 2 with the thick solid curve. In addition, the intersection of this vertical line with the two dashed curves in Figure 2 represents the lower limit on the volume- and mass-weighted He $\text{II}$ fractions in the region surrounding the opaque voids with $x_{\text{He} \text{II}} > 0.008$ at $\Delta_b = 0.15$, or $x_{\text{He} \text{II},V} > 0.026$ and $x_{\text{He} \text{II},M} > 0.052$ (excluding $\Delta_b > 10$ in these averages). This calculation of the volume- and mass-weighted He $\text{II}$ fractions uses the gas density probability distribution function (PDF) measured from simulations in Miralda-Escudé et al. (2000), and it uses the fact that a $\gtrsim 10$ cMpc region is fairly representative of the IGM at $z = 3$.$^7$

It is clear that these constraints can be improved with a more careful analysis and better data. We expect that the constraint $X_{\text{He} \text{II},V} > 0.1$ in a $\gtrsim 10$ Mpc region is possible by utilizing smaller $\Delta_b$ (probably in a statistical manner) or by using higher Lyman-series resonances. For example, the measurement of $\tau > 4$ at $\Delta_b = 0.15$ in Ly$\beta$ absorption would constrain $X_{\text{He} \text{II},V} > 0.1$ (dashed vertical curve in Figure 2). We have shown that if two propositions hold, the He $\text{II}$ Lyman forest can place strong constraints on $x_{\text{He} \text{II}}$ in a region. Next, we argue that the two propositions are generally satisfied.

4.1. Proposition 1: $x_{\text{He} \text{II}} \propto \Delta_b^{-1.07(\gamma-1)}$

We define He $\text{II}$ reionization as being over in a region when $X_{\text{He} \text{II}} \ll 1$ and $\Gamma(t)$ is much greater than a $\Delta_b$, such that the region never significantly recombines. The scaling $x_{\text{He} \text{II}} \propto \Delta_b^{-1.07(\gamma-1)}$ will apply a few equilibrium times after He $\text{II}$ reionization ends in such a region even if photoionization equilibrium does not to a precision of $\delta x_{\text{He} \text{II}} \propto \exp(-\Delta_b / \Gamma)$ (Equation 3), where $\Delta_b / \Gamma$ represents a time average from the time He $\text{II}$ reionization ended, $\Delta_b$. Furthermore, once this scaling is achieved after He $\text{II}$ reionization, this scaling is maintained even if photoionization equilibrium is not.

6 This proportionality omits the $\Delta_b$ factors that appear in the denominator of Equation (4) for notational convenience (see footnote 5). Our calculations include this additional scaling, which increases in importance with density.

7 In linear theory in the assumed cosmology, the standard deviation of $\Delta_b$ averaged over a sphere of radius $5 ~(10)$ cMpc is 0.4 (0.2) at $z = 3$.

Figure 3. Illustration of possible scenarios in the $\Delta_b$ vs. $x_{\text{He} \text{II}}$ plane at $z = 3$. The solid curves assume equilibrium with $\Gamma_{\text{He} \text{II}} = 6 \times 10^{-13}$ s$^{-1}$ and $6 \times 10^{-16}$ s$^{-1}$. The long- (short-) dashed curves take $\Gamma_{\text{He} \text{II}}$ to be 3 (10) times these values, but assume that equilibrium has not been reached and $x_{\text{He} \text{II},0} = 1$. The arrows represent this Letter’s constraint and an estimated future constraint, probably using Ly$\beta$. The shaded region is $\Delta_b$ times the gas density PDF, arbitrarily normalized.

During or a few $t_{eq}$ after He $\text{II}$ reionization this scaling may not be achieved, but it is still difficult to significantly evade the constraint on $x_{\text{He} \text{II}}$ that assumes this scaling. To see this, let us consider a region with uniform $\Gamma_{\text{He} \text{II}}(t)$ that has an initial He $\text{II}$ fraction of $x_{\text{He} \text{II},0} \sim 1$ and is being reionized ($x_{\text{He} \text{II}}$ is decreasing). In this case, assuming photoionization equilibrium and using underdense regions to infer the largest allowed photoionization rate $\Gamma_{\text{He} \text{II}}$ would result in an overestimate of the He $\text{II}$ fraction if the incident He $\text{II}$ fraction is larger than the corresponding solid curve (which assumes equilibrium). However, it is unlikely that a region will have $\Gamma_{\text{He} \text{II}} \gg \Gamma_{\text{He} \text{II}}$ because the timescale to reach the new equilibrium state is $\sim \Gamma_{\text{He} \text{II}}^{-1}$, which is typically much less than $H(z)^{-1}$. For example, the constraint $x_{\text{He} \text{II}} = 0.1$ at $\Delta_b = 1$ and $z = 3$ would imply $t_{eq} < \Gamma_{\text{He} \text{II}}^{-1} \approx 0.05 H(z)^{-1}$.

Figure 4 illustrates this argument for a toy example where $\Gamma_{\text{He} \text{II}}$ is taken as constant after He $\text{II}$ reionization begins. Plotted are contours of fixed He $\text{II}$ fraction in the $\Gamma_{\text{He} \text{II}}$ versus $\Delta_{\text{rec}}$ plane, where $\Delta_{\text{rec}}$ is the time since the beginning of He $\text{II}$ reionization in the region. The top thick solid curve represents our constraint $x_{\text{He} \text{II}} = 0.008$ at $\Delta_b = 0.15$. Only the colored area left of this curve is allowed. The dashed curves represent $X_{\text{He} \text{II},V} = 0.01, 0.02, 0.04, 0.08$, and 0.16. This illustrates that in order for $X_{\text{He} \text{II},V}$ to be significantly less than the limit we set assuming photoionization equilibrium (or $X_{\text{He} \text{II},V} = 0.026$; Section 4), the He $\text{II}$ needs to have been recently reionized. For example, to evade this limit such that $X_{\text{He} \text{II},V} = 0.015$, the He $\text{II}$ in the region must have been reionized over the last 100 Myr ($\Delta \approx 0.1$).

4.2. Proposition 2: $\Gamma_{\text{He} \text{II}}$ Fluctuates on $\gtrsim 10$ cMpc

This proposition holds because the mfp of a He $\text{II}$-ionizing photon, which sets the correlation length for $\Gamma_{\text{He} \text{II}}$, should be $\gtrsim 10$ cMpc. The mfp for a He $\text{II}$ Lyman-limit photon to be absorbed in diffuse gas at $z = 3$ is $\sim 0.8 x_{\text{He} \text{II},V}$ cMpc (assuming a homogeneous IGM), which is $\gtrsim 10$ cMpc for the value of $X_{\text{He} \text{II},V}$. This effect is
by contribution to $\Gamma_{\text{He} \, \text{II}}$, is three and seven times larger than the Lyman-limit mfp for photon spectral indexes of 2.5 (expected in the case of no absorption) and 1.5, respectively. In addition, estimates for the mfp of He ii-ionizing photons to be absorbed in dense systems in the manner of Haardt & Madau (1996) are similar at the $\Gamma_{\text{He} \, \text{II}}$ that yield $x_{\text{He} \, \text{II}, \text{eq}, \text{V}} < 0.1$ (Appendix A in McQuinn et al. 2009 plus follow-up work). In agreement with this proposition, the He ii reionization simulations of McQuinn et al. (2009) find $\Gamma_{\text{He} \, \text{II}}$-fluctuations on $\gtrsim 10$ cMpc scales (even in He ii regions; see their Figure 5).

The previous paragraph argued that $\Gamma_{\text{He} \, \text{II}}$ fluctuates as $\gtrsim 10$ cMpc when our bound on $x_{\text{He} \, \text{II}, \text{V}}$ is saturated. However, $x_{\text{He} \, \text{II}, \text{V}}$ could be larger than our lower bound immediately around the underdensity such that the fluctuation scale is $< 10$ cMpc. One could then design a situation in which the average $x_{\text{He} \, \text{II}}$ in a 10 cMpc region around an underdensity is less than our bound. However, the situation would have to be very contrived in order to significantly evade our bound, especially since current spectra show saturated voids throughout their Gunn–Peterson troughs.

In apparent contradiction to this proposition, Shull et al. (2004) detected large fluctuations in $\Gamma_{\text{He} \, \text{II}}$ on $\sim 1$ cMpc scales in the spectra of HE2347−4342, with the least dense pixels yielding smaller $\Gamma_{\text{He} \, \text{II}}$. However, Bolton et al. (2005) replicated the Shull et al. (2004) analysis on mock data with the same noise properties, and they showed that the observed $\Gamma_{\text{He} \, \text{II}}$-fluctuations could be explained by Poissonian fluctuations in the distribution of quasars and by a 30 cMpc mfp. While not explicitly stated, it appears the reason that a $\sim 1$ cMpc correlation length is inferred in Bolton et al. (2005) owes to noise in the He ii forest spectrum, which often results in a large overestimate for $\Gamma_{\text{He} \, \text{II}}$ in pixels with $\tau > 0.05$. In fact, Fechner & Reimers (2007) demonstrated the presence of this bias and, when it was corrected for, estimated a fluctuation scale for $\Gamma_{\text{He} \, \text{II}}$ of $\geq 8$–24 cMpc from HE2347−4342.

Related to Proposition 2 is the misconception that $\Gamma_{\text{He} \, \text{II}}$ should correlate strongly with the density of an absorber. The rays from a quasar will traverse many (essentially uncorrelated) absorption systems prior to traveling $\sim 10$ cMpc to a typical absorber, making it implausible that the typical overdense element will be exposed to a larger $\Gamma_{\text{He} \, \text{II}}$ from these sources than an underdense one. This argument ignores that overdense absorbers are more likely to exist closer to a quasar where there is more radiation. However, the correlation between the locations of $\sim L_*$ quasars ($\sim 1$ per 30$^3$ cMpc$^3$) and the density of a typical absorber is negligible (McQuinn et al. 2009). Even if $\sim L_*$ quasars were not the primary source for $\Gamma_{\text{He} \, \text{II}}$ (contrary to what the quasar luminosity function and the amplitude of $\Gamma_{\text{He} \, \text{II}}$-fluctuations in the He ii forest suggest; McQuinn et al. 2009; Bolton et al. 2005), it would be difficult to make $\Gamma_{\text{He} \, \text{II}}$ correlate strongly with the density of absorbers: as the number density of the sources increases, the fluctuations in $\Gamma_{\text{He} \, \text{II}}$ should decrease.

5. CONCLUSIONS

This Letter showed that current He ii Ly$\alpha$ forest data imply that $x_{\text{He} \, \text{II}, \text{V}} > 0.03$ in regions surrounding opaque voids, while $x_{\text{He} \, \text{II}, \text{V}} \gtrsim 0.1$ should be possible with future He ii Lyman forest data. These limits derive from assuming photoionization equilibrium and that the maximum allowed $\Gamma_{\text{He} \, \text{II}}$ in an underdense gas element is also the maximum in a surrounding $\gtrsim 10$ cMpc region—the expected fluctuation scale for $\Gamma_{\text{He} \, \text{II}}$. They may be weakened somewhat, but only if the region in question is being reionized.

Our constraint of $x_{\text{He} \, \text{II}, \text{V}} > 0.03$ is a significant improvement over previous efforts, which set the bound $x_{\text{He} \, \text{II}, \text{V}} > 1.3 \times 10^{-3}$ in the regions of highest opacity (Heap et al. 2000). Our constraint on $x_{\text{He} \, \text{II}, \text{V}}$ in select regions is 100 times stronger than the tightest constraint on the volume-averaged H i fraction from the $z > 6$ HI Ly$\alpha$−$\gamma$ forests of $x_{\text{He} \, \text{II}, \text{V}} \gtrsim 3 \times 10^{-4}$ (Fan et al. 2006). It can be improved by better observations, by including redshift-space effects, by measuring $x_{\text{He} \, \text{II}}$ in pixels with $\Delta b < 0.15$, or by utilizing absorption information from higher Lyman-series resonances.

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