SOFT X-RAY ABSORPTION BY HIGH-REDSHIFT INTERGALACTIC HELIUM

JORDI MIRALDA-ESCUDE

Department of Physics and Astronomy, University of Pennsylvania, David Rittenhouse Laboratory, 209 South 33d Street, Philadelphia, PA 19104; jordi@llull.physics.upenn.edu

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ABSTRACT

The Ly$\alpha$ absorption from intergalactic, once-ionized helium (He ii) has been measured with the Hubble Space Telescope in four quasars over the last few years in the redshift range $2.4 < z < 3.2$. These observations have indicated that the He ii reionization may not have been completed until $z \approx 2.8$ and that large fluctuations in the intensity of the He ii--ionizing background were present before this epoch. The detailed history of He ii reionization at higher redshifts is, however, model-dependent and difficult to determine from these observations, since the intergalactic medium (IGM) can be completely optically thick to Ly$\alpha$ photons when only a small fraction of the helium remains as He ii. In addition, finding quasars in which the He ii Ly$\alpha$ absorption can be observed becomes increasingly difficult at higher redshift owing to the large abundance of hydrogen Lyman limit systems. It is pointed out here that He ii in the IGM should also cause detectable continuum absorption in the soft X-rays. The spectrum of a high-redshift source seen behind the IGM when most of the helium was He ii should recover from the He ii Lyman continuum absorption at an observed energy of $\sim0.1$ keV. Galactic absorption will generally be stronger, but not by a large factor; the intergalactic He ii absorption can be detected as an excess over the expected Galactic absorption from the 21 cm H i column density. In principle, this method allows a direct determination of the fraction of helium that was singly ionized as a function of redshift if the measurement is done on a large sample of high-redshift sources over a range of redshifts.

Subject headings: galaxies: formation — intergalactic medium — large-scale structure of universe — quasars: absorption lines

1. INTRODUCTION

The Ly$\alpha$ absorption by intergalactic He ii has now been observed in four quasars at redshifts $2.4 < z < 3.2$ (Jakobsen et al. 1994; Davidsen, Kriss, & Zheng 1996; Reimers et al. 1997; Anderson et al. 1999; Heap et al. 1999). While it is known that hydrogen (together with He i) was ionized at redshift $z \approx 5$, given the presence of transmitted flux to the blue of the hydrogen Ly$\alpha$ wavelength in sources up to that redshift, the double ionization of helium can take place at a lower redshift. The reason is simple: even though there are only about eight helium atoms for every 100 hydrogen atoms, He ii recombines at a rate 5.5 times faster than hydrogen. Consequently, if a large number of recombinations for each helium ion take place, then the He ii reionization will be delayed relative to the hydrogen reionization as long as the number of photons emitted to the intergalactic medium (IGM) above 54.4 eV is less than 0.44 times the number of photons emitted above 13.6 eV. This condition is satisfied by the known sources of ionizing radiation (quasars and galaxies). In practice, the mean number of recombinations of He ii may not be very large: for the uniform IGM, the He ii recombination rate is $\sim 4$ times the Hubble rate at $z = 4$, and then a somewhat softer emission spectrum is required for a delayed He ii reionization. However, the recombination rate is enhanced by the clumping factor of the ionized gas, which increases as progressively denser gas is reionized, as described recently in Miralda-Escudé, Haehnelt, & Rees (1999, hereafter MHR).

The present state of the observations of intergalactic He ii can be summarized as follows: at redshift $z \leq 2.8$, there is an He ii "Ly$\alpha$ forest" with a flux decrement that is consistent with the hydrogen Ly$\alpha$ forest flux decrement and a background spectrum produced by quasars, plus a possible contribution from galaxies to increase the ratio $J_{\odot}/J_{\odot}$ of intensities at the H i and He ii ionization edges (Davidsen et al. 1996; Miralda-Escudé et al. 1996; Bi & Davidsen 1997; Croft et al. 1997). At $z \geq 2.8$, the He ii Ly$\alpha$ spectra appear to be divided into two different types of regions: those in which transmitted flux is still observed (with a similar $J_{\odot}/J_{\odot}$ implied for the ionizing background) and those in which the transmitted flux is undetectable or, at least, much smaller (see Heap et al. 1999 and references therein). The regions with greater transmitted flux occupy a small fraction of the spectrum at $z \geq 3$, and they have typical widths of $\sim 10^4$ km s$^{-1}$. Some of them can be attributed to the proximity effect of the source being observed (e.g., Hogan, Anderson, & Rugers 1997).

These observations are not yet conclusive in clarifying the ionization history of He ii in the IGM. The reason is that the optical depth of a homogeneous medium with the mean baryon density of the universe, in which all the helium is He ii, is very large:

$$\tau_{0, \text{He ii}} = 1.7 \times 10^3 \frac{\Omega_b h Y H_0 (1 + z)^{3/2}}{0.007 H(z)} \left(\frac{1 + z}{4}\right)^{3/2}.$$  \hspace{1cm} (1)

Therefore, if only a fraction $\sim 10^{-3}$ of the average IGM helium density is in the form of He ii, the flux transmission can already be reduced to very low levels. Even when the line of sight crosses a void with density $\rho = 0.1 \bar{\rho}$ (about the lowest densities in the photoionized IGM at $z = 3$ according to numerical simulations of cold dark matter models; see MHR and references therein), the void will still be optically thick to He ii Ly$\alpha$ photons if its He ii fraction is greater than $\sim 0.01$. The implication is that even a very stringent upper limit to the He ii Ly$\alpha$
flux transmission does not imply that most of the He II had not yet been reionized at the observed redshift.

Although the observations quoted earlier could be simply interpreted as revealing an IGM with a patchy ionization of He II, with He III regions surrounding luminous quasars and a pure He II IGM filling the volume between the He III regions, the correct picture is probably much more complicated. In the regions in which no transmitted flux is detected, the helium might also be doubly ionized over most of the volume, although with a much lower ionizing background intensity than in the regions near luminous quasars. The higher He II fraction implied in the regions with low intensity, although still much smaller than unity, could be enough to completely absorb the Lyα photons. The presence of this low-intensity, but widespread, background above the He II edge is quite plausible, as discussed in MHR, if there is a modest contribution to the emissivity from sources of luminosity much lower than quasars.

A more direct observational probe to the mean fraction of He II in the IGM at different redshifts would be highly valuable to test models for the reionization history, which is in turn important for the history of galaxy formation owing to the strong heating of the IGM gas produced by the He II reionization (e.g., Efstathiou 1992; Miralda-Escudé & Rees 1994). It is shown in this Letter that this new probe may be found in the soft X-ray continuum absorption spectra of high-redshift quasars.

The distributed He II in the IGM should cause, in addition to the He II forest absorption in Lyα and the other Lyman series lines, the continuum absorption (due to photoionization) below a rest-frame wavelength of 228 Å. This continuum absorption should be very large near the edge, but the flux should recover at shorter wavelengths. We shall see that when most of the helium in the IGM is He II, this recovery of the flux should occur at ~0.5 keV or an observed frequency of ~0.1 keV at z = 4.

2. X-RAY ABSORPTION BY INTERGALACTIC HELIUM

Let $F(z)$ be the mean fraction of helium in the IGM in the form of He II as a function of redshift. For the moment, we consider a homogeneous IGM [with a uniform fraction $F(z)$], but because we shall consider continuum absorption only, the results will be valid also for a clumpy IGM as long as the clumps have a large covering factor. The continuum absorption spectrum by He II on a source at redshift $z_s$ is given by

$$
\tau(\nu) = \int_0^{z_s} dz' \frac{dl}{dz'} n_{He,0}(1+z)^3 F(z') \sigma_{He} [\nu(1+z')],
$$

(2)

where $dl$ is the proper length element along the line of sight, $n_{He,0}$ is the mean primordial helium density extrapolated to the present epoch, $\sigma_{He}(\nu)$ is the photoionization cross section of He II, and $\nu$ is the observed frequency. If He II is highly ionized at low redshift, most of the contribution to $\tau(\nu)$ will be from high redshift, where we can use $dl/dz = c H_0 \Omega_0^{1/2} (1+z)^{-3/2}$. We also define $\Sigma_{He}(\nu) = \sigma_{He}(\nu) \nu / n_{He}$, where $\nu_{He}$ is the frequency at the ionization edge of He II (the function $\Sigma$ varies only slowly with frequency and is plotted in Fig. 1).

As an example, we consider the simple case of a sudden and complete reionization of He II at $z = z_r$: $F = 1$ at $z > z_r$, and $F = 0$ at $z < z_r$. The integral in the above equation is then well approximated as $(z_s - z_r)/(1+z_s)^{3/2}$ (for small $z_s - z_r$). For $z_s = 3$ and $z_r = 4$, $\tau(\nu) = 10 (\nu_{He}/\nu)^3$, so the optical depth reaches unity at an observed frequency $\nu = 0.12$ keV.

3. COMPARISON TO GALACTIC ABSORPTION

Any extragalactic source will also be absorbed in soft X-rays by Galactic hydrogen and helium, with a hydrogen column density $N_H$ that can be determined from the H I 21 cm emission.
The absorption optical depth is

$$\tau_{c}(\nu) = N_{H,I} \sigma_{H,I}(\nu) + 0.084 \sigma_{He,i}(\nu) \equiv N_{H,I} \sigma_{H,I}(\nu) R_{He}(\nu), \quad (5)$$

where the ratio of helium to hydrogen atoms is \((Y/3.97)/(1 - Y) = 0.084, \sigma_{H,I} \text{ and } \sigma_{He,i},\) are the photoionization cross sections of \(H \text{ and } He \text{, and we have defined the quantity } R_{He}(\nu).\) At the frequencies that will be of interest to us, \(h\nu = 0.2 \text{ keV},\) this quantity is \(R_{He}(\nu) \approx 3\) (this is shown in detail in Fig. 1).

Dividing the optical depth due to the high-redshift IGM from equation (4) by the Galactic optical depth in equation (5), we obtain the ratio to be

$$\frac{\tau(\nu)}{\tau_{c}(\nu)} = \frac{56}{N_{H,I,20} R_{He}(\nu)} \frac{\Sigma_{He} [\nu(1 + z_{i})]}{\Sigma_{He} (4\nu)} \times$$

$$\int_{0}^{z_{i}} dz F(z) \frac{\Sigma_{He} [\nu(1 + z)]}{(1 + z)^{5/2} \Sigma_{He} [\nu(1 + z)]} \quad (6)$$

where \(N_{H,I,20} = N_{H,I}/(10^{20} \text{ cm}^{-2}).\) This fiducial \(H \text{ column density is around that which is usually reached at high Galactic latitude (e.g., Laor et al. 1997). Using the same example as in § 2, where the integral is given by \((z_{i}, - z_{i}))/ (1 + z_{i})^{5/2} \approx 0.018,\) we find \(\tau(\nu)/\tau_{c}(\nu) \approx 1/[N_{H,I,20} R_{He}(\nu)] \approx 1/(3N_{H,I,20}).\) Thus, we conclude that the absorption by high-redshift intergalactic helium should be smaller than the Galactic absorption only by a factor of \(\sim 3\) when the Galactic column density has the lowest value normally found in sources, \(N_{H,I} \approx 10^{20} \text{ cm}^{-2}.\)

Laor et al. (1997) measured the Galactic column densities in a sample of 23 low-redshift quasars from the absorption in soft X-rays. Comparing the column densities they derived with those measured from the 21 cm emission, they show that there are no significant differences within observational error. In particular, the two quasars with the smallest error (10%) in the column density determined from the soft X-ray spectrum by Laor et al. also agree with the 21 cm column density (see their Fig. 2). Provided that the Galactic absorption can be subtracted from the measured X-ray absorption on a high-redshift quasar, given the column density measured from 21 cm emission, it should be possible to detect the continuum absorption of intergalactic helium in the soft X-rays.

A natural question to ask here is if the shape of the absorption can be used to distinguish Galactic absorption from the high-redshift \(He \beta \text{ absorption. Unfortunately, the shape is almost identical in the two cases, as we shall now see. In Figure 1, the solid line is the hydrogen cross section \(\sigma_{H,I}(\nu),\) multiplied by \((\nu p_{\beta I})^3,\) and the dashed line is \([\sigma_{H,I}(\nu) + n_{He}/n_{H,I} \sigma_{He,i}(\nu)](\nu p_{\beta I})^3,\) [so the ratio of the dashed line to the solid line is \(R_{He}(\nu),\) defined in eq. (5)]. We have used the exact analytical expression for \(\sigma_{He,i}(\nu)\) (e.g., Spitzer 1978) and the fit of Verner et al. (1996) for \(\sigma_{He,i}(\nu).\) The dashed line is therefore the expected shape of the Galactic absorption, except for the fact that some of the ionized gas in the Galaxy may not have the helium doubly ionized, and there could then be some additional \(He \beta \text{ absorption at } z \approx 0.\) This is shown by the dotted line, equal to \(\sigma_{He,i}(\nu)(\nu p_{\beta I}/n_{H,I} p_{\beta I})^3,\) and we see that it has almost the same slope as the dashed line at energies \(\approx 0.15 \text{ keV}.\)

The intergalactic \(He \beta \text{ absorption should have the same shape as the solid line, at redshift } z = 3\) (because the \(He \beta \text{ cross section is identical to the } H \beta \text{ cross section shifted to a frequency 4 times higher.}\) Notice from equation (4) that the frequency dependence of \(\tau(\nu)\) is basically the same as the redshifted cross section \(\sigma_{He,i}(\nu).\) Thus, we see from Figure 1 that the high-redshift absorption has a slightly steeper cross section than the Galactic one. In the range from 0.1 to 0.2 keV, the Galactic cross section is \(\sigma \approx r^{-1.15}\) and the intergalactic helium cross section is \(\sigma_{He} \approx r^{-3.15}.\) In practice, it will be extremely difficult to reach the high signal-to-noise ratio required to distinguish between these two slopes; moreover, the intrinsic emission spectrum of the source introduces an additional uncertainty. Therefore, the high-redshift helium absorption can probably be detected only as an excess of absorption over that expected from the Galactic column density derived from the 21 cm emission.

4. A REIONIZATION MODEL

In any realistic model, the reionization of all the \(He \beta \text{ in the universe will take place over a substantial length of time, of the order of a Hubble time. In the reionization model proposed in MHR, the low-density gas is ionized earlier and reionization advances outside-in. The stage of reionization depends at every redshift on the gas overdensity } \Delta_{He} \text{ up to which the helium is mostly ionized to } He \beta.\text{ Using results of numerical simulations for the density distribution and the photon mean free path in the IGM, the model in MHR predicts the } He \beta \text{ Ly} \alpha \text{ flux decrement and the fraction of gas at overdensities greater than } \Delta_{He} \text{, assumed to be still in the form of } He \beta.\text{ The observed flux decrement of } \approx 0.7 \text{ at } z = 2.6 (\text{Davidsen et al. 1996) requires } \Delta_{He} \approx 70, \text{ implying a fraction of } He \beta \text{ F } = 0.2 \text{ (see Figs. 2 and 9 in MHR).} \text{ At the slightly higher redshift } z = 3.1, \text{ a flux decrement as high as 0.99 (see Heap et al. 1999) requires } \Delta_{He} \approx 12 \text{ and the fraction of gas at greater overdensities increases only to } F = 0.3, \text{ showing how a small increase in } He \beta \text{ ionization can result in a dramatic decline of the transmitted flux due to the effect that the most underdense voids rapidly become optically thick to the } He \beta \text{ Ly} \alpha \text{ photons.}\)

As an example of a reasonable model matching the above conditions, in which the } He \beta \text{ reionization takes place over an extended period of time, we consider the simple case } F = [(1 + z)/7]^{5/2}, \text{ where the first } He \beta \text{ sources would turn on at } z = 6. \text{ For this case, equation (6) yields (neglecting the ratios of the function } \Sigma_{He}) \text{ } \tau(\nu)/\tau_{c}(\nu) = 0.43 z_{i}/N_{H,I,20}/R_{He}(\nu) \text{ (for } z_{i} < 6).\text{ It must be borne in mind here that whatever contribution arises from low redshifts to the integral in equation (6) should originate mostly in dense systems, in which the helium is self-shielded and remains in the form of } He \beta \text{ (these are the observed Lyman limit and damped absorption systems). When the mean free path between these absorption systems is not much smaller than the Hubble length (i.e., when the absorbers do not have a large covering factor), the } He \beta \text{ column density on a particular line of sight will no longer be equal to the mean value, but will have large fluctuations: it will most often be smaller than the mean value, but it will exceed this mean value when a rare, strong absorption system is intersected. The presence of these rare absorption systems, which should dominate the total } He \beta \text{ content of the universe at low redshift only, can in principle be determined independently for every line of sight from observations of the } H \beta \text{ absorption spectrum. In practice, though, the Lyman limit absorption from higher redshift systems, and the } He \beta \text{ Ly} \alpha \text{ absorption itself, will prevent the}
determination of the H I column density of any low-redshift absorber in a high-redshift source. The absence of strong metal lines can still be a good indication that a strong H I absorber is not present.

In order for a low-redshift absorber to cause soft X-ray absorption comparable to that of the high-redshift IGM, it must have a column density $N_{H_1} \approx 10^{19.5}(1+z)^4$ cm$^{-2}$. Only $\sim 20\%$ of the lines of sight have an absorber with this strength (e.g., Storrie-Lombardi, Irwin, & McMahon 1996). Nevertheless, the fluctuation in the low-redshift absorption will be an additional source of uncertainty (especially if the low-redshift H I Ly$\alpha$ absorption cannot be measured), implying that the excess soft X-ray absorption will need to be detected in several sources before one can be sure that the effect of the helium in the low-density IGM at high redshift has been detected.

The fluctuations in the He II column density due to high-redshift absorbers of high column density are less important because these absorbers do not contain a large fraction of the baryons. For example, at $z = 3$ we need an absorber with $N_{H_1} \sim 10^{21}$ cm$^{-2}$ to produce an absorption similar to the IGM. These absorbers are rare, and they can also be readily identified in the H I Ly$\alpha$ spectrum when their redshift is not much lower than the source redshift.

5. CONCLUSIONS

Soft X-ray absorption can be a new powerful tool for measuring the fraction of helium in the form of He II as a function of redshift. This direct determination of the He II fraction provides a straightforward test of any model of reionization based on the observed emitting sources (quasars and galaxies). Although the observations of the He II Ly$\alpha$ absorption spectra provide a much greater wealth of information, their interpretation is more complicated because of the complexities introduced by the highly inhomogeneous IGM and the fluctuating intensity of the ionizing background.

The main challenge in detecting this effect will be to find enough high-redshift, X-ray–bright sources and to accurately measure the 21 cm H I column density, so that the Galactic contribution to the soft X-ray absorption can be precisely subtracted. A systematic uncertainty that will be faced is the possible existence of some Galactic He II along the line of sight, which can also produce excess soft X-ray absorption not accounted for by the Galactic H I column density. In addition, extragalactic damped Ly$\alpha$ absorbers at low redshifts can also make a significant contribution, which may be difficult to correct for in high-redshift sources. These systematic uncertainties can be put under control once the effect is measured in many sources over a wide range of redshifts.

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