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The depth of the Lyman valley revisited

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Abstract. The severity of the intervening photoelectric absorption out to large redshift due to neutral hydrogen contained in quasar absorption line systems is reassessed in light of improved absorber statistics resulting from the *HST* Quasar Absorption Line Key Project. Compared to previous estimates, the updated statistics imply roughly a doubling of the anticipated fraction of the sky showing a given residual opacity at the wavelength of the He II $\lambda 304$ line. Because of the steepness of the quasar luminosity function, this slight lifting of the intergalactic cloud cover significantly affects the expected appearance of the high redshift quasar population at short far-UV wavelengths, resulting in somewhat more optimistic prospects for carrying out further studies of intergalactic He II absorption beyond the four objects toward which such absorption has been detected so far.

Key words: quasars: absorption lines – intergalactic medium – ultraviolet: galaxies

1. Introduction

The continuum fluxes of quasars at extreme ultraviolet wavelengths ($\lambda < 912$ Å) are astrophysically important for several reasons. The quasar output at ionizing energies is of keen interest in its own right since this radiation provides important clues to the accretion process, powers the emission line region, and is probably responsible for reionizing the intergalactic medium (see Zheng et al. 1997 and references therein). Equally important, UV bright high redshift quasars can be used as background sources for the study of intervening absorption in a number of otherwise inaccessible atomic and ionic species (Reimers et al. 1992; Vogel & Reimers 1995; Köhler et al. 1996) – not least both neutral and singly ionized intergalactic helium (Reimers & Vogel 1993; Jakobsen et al 1994; Tytler et al. 1995; Davidsen et al. 1996; Reimers et al. 1997).

A significant hurdle for observing quasars at rest wavelengths in the Lyman continuum is presented by the cumulative photoelectric absorption in neutral hydrogen contained in the various types of absorption line system intercepted out to large redshift. The statistical properties of this absorption have been discussed by Møller & Jakobsen (1990) and Zuo & Phinney (1993).

The light from a quasar at $z \simeq 3$ will on the average intercept some $\sim 10^3$ Lyman forest systems on its way to Earth. Although optically thin individually ($10^{12}\ \mathrm{cm}^{-2} \lesssim N_{\mathrm{HI}} \lesssim 10^{17}\ \mathrm{cm}^{-2}$), the large number and strong redshift evolution of the Lyman forest systems act together with the $\sigma_{\mathrm{HI}} \propto \nu^{-3}$ dependency of the photoelectric cross section to produce a characteristic and unavoidable 'Lyman valley' spectral imprint on the far-UV quasar spectrum.

A further and even greater source of opacity are the optically thick Lyman limit systems with column densities $N_{\mathrm{HI}} \gtrsim 10^{17}\ \mathrm{cm}^{-2}$. The densest of these – including the damped systems with column densities as large as $N_{\mathrm{HI}} \sim 10^{21}\ \mathrm{cm}^{-2}$ – are capable of completely quenching the quasar EUV flux below the redshifted Lyman edge of the absorber.

Based on the quasar absorber data available at the time, Møller & Jakobsen (1990) assessed the magnitude of the total H I absorption out to large redshift with emphasis on gauging the prospects for carrying out the He II $\lambda 304$ equivalent of the Gunn-Peterson test with *HST* and *FUSE*. These calculations were taken a step further by Picard & Jakobsen (1993) who combined the opacity statistics with available quasar evolution models in order to estimate the number of quasars on the sky whose intrinsic brightness and exceptionally clear lines of sight conspire to make detection of He II $\lambda 304$ absorption feasible.

The severity of the intergalactic absorption anticipated from these calculations has been borne out by *HST* experience. Despite considerable effort (Jakobsen et al. 1993; Reimers et al. 1995; Tytler et al. 1995; Lyons et al. 1995), He II $\lambda 304$ absorption has so far been detected only toward four objects: Q0302−003 ($z = 3.29$; Jakobsen et al. 1994; Hogan et al. 1997); PKS 1935−692 ($z = 3.18$; Tytler et al. 1995); HS1700+6416 ($z = 2.73$; Reimers et al. 1989; Davidsen et al. 1996 and HE2347−4342 ($z = 2.89$; Reimers et al. 1997).

Nonetheless, there is now good reason to believe that the initial calculations may have been somewhat too pessimistic. In particular, the results of the *HST* Quasar Absorption Line Key Project (Stengler-Larrea et al. 1995) have shown there to be fewer high column density Lyman limit systems at low redshift than previously thought. Taking this into account lowers the overall level of the predicted Lyman continuum opacity. Because of the steepness of the quasar luminosity function this, in turn, leads to a significant increase in the number of quasars predicted to display a given far-UV brightness.

Since the total number of 'clear' quasars on the sky has important ramifications for the prospects for carrying out further and more detailed studies of intergalactic He II absorption, it is of some interest to revisit and update the calculations of Møller & Jakobsen (1990) and Picard & Jakobsen (1993) taking the most recent information into account.

2. Revised absorber statistics

Møller & Jakobsen (1990) modeled the Lyman forest ($N_{\rm HI} < 10^{17}\ {\rm cm}^{-2}$) and Lyman limit ($N_{\rm HI} \geq 10^{17}\ {\rm cm}^{-2}$) systems as two separate populations, whose mean number densities evolve in redshift according to the law

$$\frac{dn}{dz}(z) = A(1+z)^{\gamma} \tag{1}$$

and whose distributions in column density are described by a power law

$$\frac{dn}{dN_{\rm HI}} \propto N_{\rm HI}^{-s} \tag{2}$$

This conventional framework still provides an adequate statistical description for the purpose at hand, i.e. only the numerical parameters need to be updated.

Møller & Jakobsen (1990) modeled the Lyman forest systems over the $0 < z < 4$ redshift and $10^{13}\ {\rm cm}^{-2} < N_{\rm HI} < 10^{17}\ {\rm cm}^{-2}$ column density range with normalization, evolution, and spectral slope parameters of $A = 14$, $\gamma = 2.3$ and $s = 1.5$. The most significant findings since then have been the discovery of the 'excess' number of forest systems at low redshift (Bahcall et al. 1991; Morris et al. 1991) and the realization that the Lyman forest population extends down to column densities $N_{\rm HI} \simeq 10^{12}\ {\rm cm}^{-2}$ and possibly lower (Hu et al. 1995; Songaila et al. 1995; Kirkman & Tytler 1997).

While the contribution to the total Lyman continuum opacity from the latter systems is entirely negligible due to their extremely low column densities, the former systems do lead to a slight systematic decrease of the short wavelength slope of the Lyman valley (see Fig. 2 below). In order to take the excess systems into account, the Lyman forest model of Møller & Jakobsen (1990) has been modified by changing the slope of the density law (1) from $\gamma = 2.3$ at redshifts $z \geq 1.5$ to $\gamma = 0.58$ at redshifts $z < 1.5$. With the previous high redshift normalization and column density slope of $A = 14$ and $s = 1.5$ this simple broken power law model reproduces very closely the findings of Bahcall et al. (1996).

A more significant adjustment concerns the optically thick Lyman limit systems, where the results from the *HST* Quasar Absorption Line Key Project have led to a significant revision of the statistics of these systems. In particular, the improved *HST* surveys have confirmed that there are fewer very high column systems at low redshift than previously thought based on the older *IUE* data (Møller 1991). This finding is important in that it eases the total opacity.

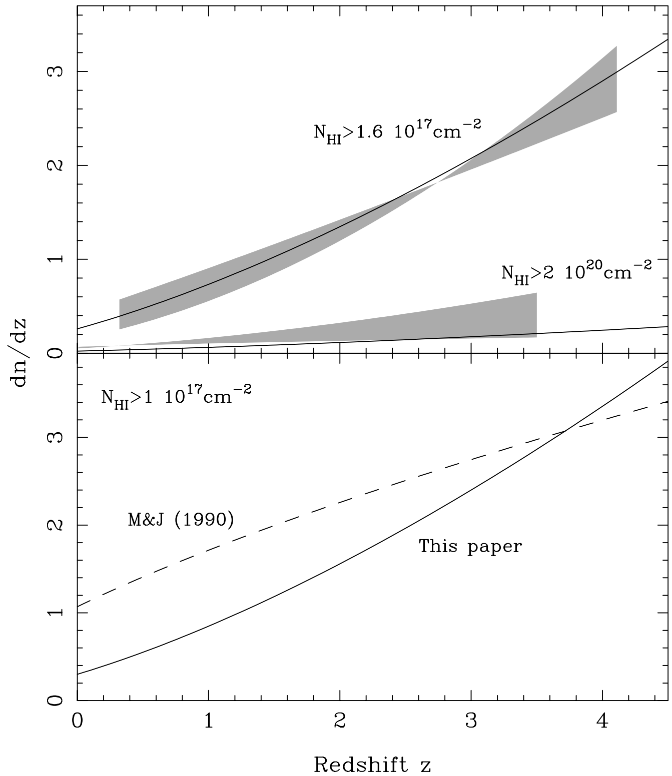

Fig. 1. Comparison of the improved model for the redshift and column density distribution of the Lyman limit systems adopted in this paper with the observations of Stengler-Larrea et al. (1995) and Lanzetta et al. (1995) [top frame] and the previous model adopted in Møller & Jakobsen (1990) [lower frame]. Note the decreased number of systems at low redshift.

Based on the results of Stengler-Larrea et al. (1995), the Lyman limit systems are in this paper modeled as spanning the column density range $10^{17}\ {\rm cm}^{-2} < N_{\rm HI} < 10^{22}\ {\rm cm}^{-2}$ with statistics described by Eqs. (1) and (2) and parameters $A = 0.30$, $\gamma = 1.5$ and $s = 1.3$. These modified parameters imply both a steeper density evolution and a slightly shallower column density spectrum (Petitjean et al. 1993) than assumed by Møller & Jakobsen (1990). The good fidelity of the updated model in reproducing both the observations of Stengler-Larrea et al. (1995) and the damped Lyman alpha system statistics of Lanzetta et al. (1995) is illustrated in Fig. 1. Although the consistency between the Lyman limit and damped Lyman alpha data in Fig. 1 is not perfect and is suggestive of a further flattening of the column density spectrum at very high column, what matters to the opacity calculations is the number of such completely opaque systems – which in principle are included in the Lyman limit statistics.

As in Møller & Jakobsen (1990), the opacity due to photoelectric absorption in He I is ignored in this paper due to the low abundance of this species in the highly ionized systems responsible for the bulk of the absorption (Vogel & Reimers 1995).

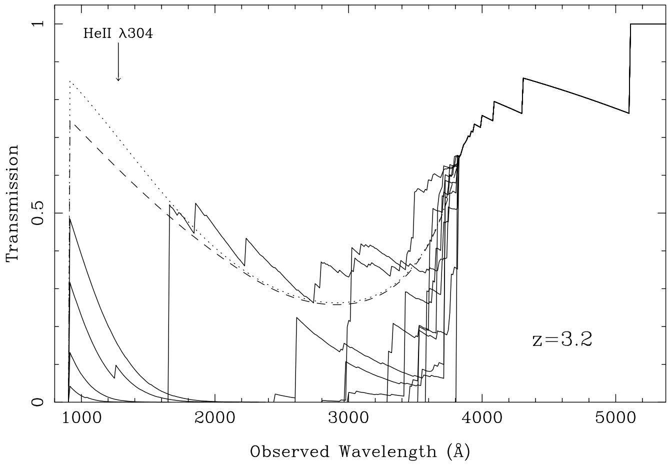

Fig. 2. Ten simulations of the total Lyman valley absorption out to $z = 3.2$ for the revised absorber statistics. For clarity, only the average Lyman series line absorption spectrum is plotted. The dotted and dashed curves show the average Lyman valley absorption due to the forest systems alone calculated from Eq. (9) of Møller & Jakobsen (1990) for the old and revised absorber models, respectively.

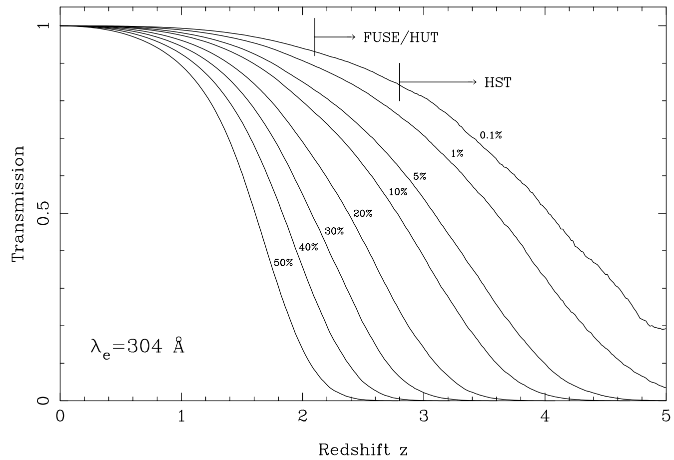

Fig. 3. Updated version of Fig. 6 of Møller & Jakobsen (1990) showing the upper transmission quantiles for the net absorption in intervening Lyman forest and Lyman limit systems at redshifted He II $\lambda 304$ as a function of redshift.

3. The net opacity revisited

The highly variable character of the imprint that the cumulative Lyman continuum opacity makes on quasar spectra is illustrated in Fig. 2, which shows 10 Monte Carlo simulations of detailed absorption spectra out to redshift $z = 3.2$. With the updated absorber statistics, most sightlines are still expected to intercept a dense Lyman limit system capable of completely quenching the far-UV flux. Nonetheless, the fewer number of systems at low redshift does in this case permit 4 of the 10 sightlines to 'recover' at the shortest wavelengths to varying degrees. It is only along the latter class of sightline that intervening He II absorption can be observed.

The detailed statistics of this process are summarized in Fig. 3, which shows the upper quantiles for the residual transmission at the observed He II $\lambda 304$ line as a function of redshift. This figure is an update of Fig. 6 from Møller & Jakobsen (1990) and was calculated using the same Monte Carlo method. The use of a numerical Monte Carlo approach is necessitated by the fact that the more elegant analytical approach of Zuo & Phinney (1993) is unfortunately only tractable in the most simple cases; i.e. cannot readily deal with the two population absorber model adopted above. As in Picard & Jakobsen (1993) a total of 10^4 trials were used per simulation per redshift bin – which is adequate to assure that the uncertainties are systematic in nature and wholly dominated by the astrophysical fidelity of the adopted absorber model.

Compared to the earlier calculations, the revised absorber statistics lead to a factor ~ 2 increase in the fraction of the sky exhibiting a given residual opacity. For example, according to Fig. 3, $\simeq 20\%$ of all sightlines out to $z \simeq 3.1$ are now expected to show a residual transmission of 10% or better, compared to the earlier estimate of $\simeq 10\%$. This easing of the absorption has a significant impact on the appearance of the high redshift quasar population in the far-UV.

4. The number of UV bright quasars revisited

The parameter of interest for absorption line work is not so much the residual opacity, but rather the absolute continuum flux of the background quasar. Because of the well known steepness of the quasar luminosity function, the factor ~ 2 relief in absorption described above leads to a significant increase in the number of quasars predicted to be detectable at a given far-UV brightness.

Fig. 4 shows an updated version of Fig. 6 of Picard & Jakobsen (1993), giving the total expected number of quasars on the sky in the redshift ranges $2.0 < z < 2.9$ and $z > 2.9$ as a function of observed limiting flux at redshifted He II $\lambda 304$. As discussed by Picard & Jakobsen (1993), the two key factors central to this type of calculation are the intrinsic extreme UV spectra of quasars and the drop-off in quasar co-moving density at $z \gtrsim 2$ (Schmidt et al. 1995; Shaver et al. 1996). The latter issue is discussed by Pei (1995), who provides a convenient analytical fit to the quasar luminosity function based on the available quasar counts. Fig. 4 incorporates the $(h, q_0, \alpha) = (0.5, 0.5, -0.5)$ evolutionary model of Pei (1995). This model is very close to the favored 'BSP-H' model of Picard & Jakobsen, (1993) in which the pure luminosity evolution model of Boyle et al. (1988) was combined with a pure density evolution model beyond $z > 2$. For consistency, Fig. 4 assumes an intrinsic quasar spectrum given by a broken power law with index $\alpha_2 = -0.5$ at wavelengths above Lyα. The range of likely spectral slopes below this wavelength is bracketed by the values $\alpha_1 = -2.0$ and $\alpha_1 = -1.5$, in accord with the empirical composite quasar UV spectrum assembled by Zheng et al. (1997).

The locations of the four objects toward which He II absorption has successfully been detected so far are also indicated in Fig. 4. Compared to the previous calculations of Picard & Jakobsen (1993), the updated model presented here leads to

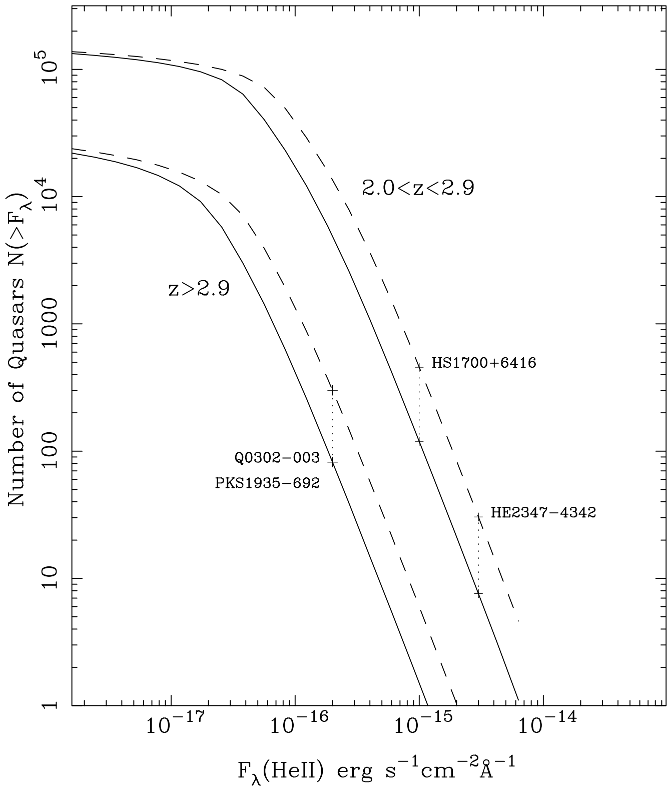

Fig. 4. Updated version of Fig. 6 from Picard & Jakobsen (1993) giving the predicted number of quasars on the sky as a function of detectable flux at redshifted He II $\lambda 304$ for the redshift ranges $2.0 < z < 2.9$ (upper curves) and $z > 2.9$ (lower curves) that can be reached with *FUSE/HUT* and *HST*. The full and dashed curves are calculated for mean extreme UV spectral indices of $\alpha_1 = -2$ and $\alpha_1 = -1.5$, respectively. The four objects toward which He II absorption has so far been successfully detected are also marked.

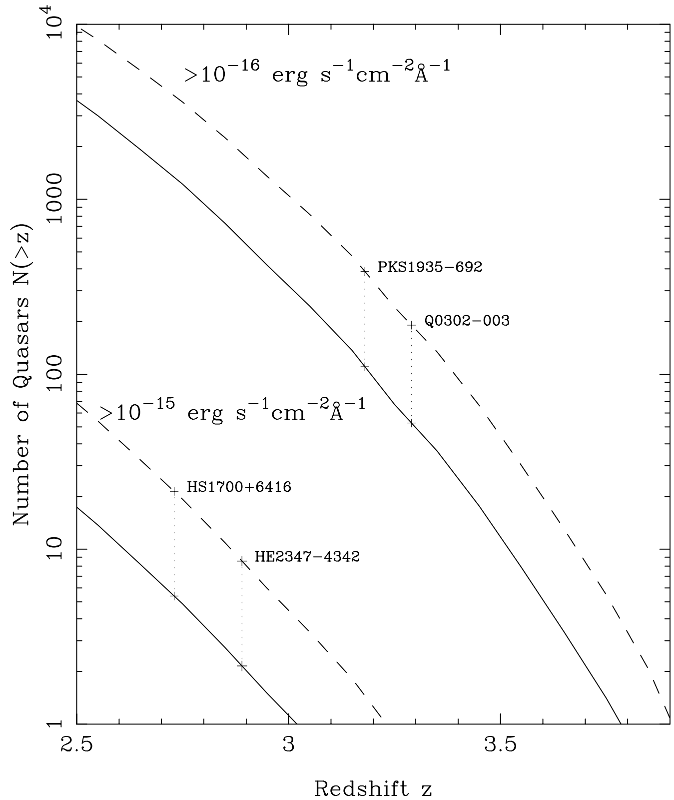

Fig. 5. Predicted cumulative redshift distribution for the total number of quasars on the sky displaying a residual flux at redshifted He II $\lambda 304$ brighter than $F_\lambda = 10^{-16}$ erg s^{-1} cm^{-2} Å^{-1} (upper curves) and $F_\lambda = 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1} (lower curves). The full and dashed curves are refer to mean spectral indices of $\alpha = -2$ and $\alpha = -1.5$, respectively. The four objects toward which He II absorption has so far been successfully detected are also marked.

nearly a ten-fold increase in the predicted availability of UV-bright quasars. In particular, the sky is expected to contain some $\sim 10^2$ quasars a $z > 2.9$ having a UV brightness comparable to that of the two faint high redshift objects Q0302−003 and PKS 1935−692.

At lower redshifts $2.0 < z < 2.9$, a similar number of objects are expected to reach the UV brightness of HS1700+6416, while only some ~ 10 objects are expected to rival the most recent and brightest quasar discovered by the Hamburg group, HE2347−4342. However, the latter two numbers do not tell the entire story, since most of these 'clear' quasars will appear at the lower redshifts. As an expansion on Picard & Jakobsen (1993), Fig. 5 gives the predicted cumulative redshift distribution of quasars showing a flux at He II $\lambda 304$ brighter than 10^{-16} and 10^{-15} erg s^{-1} cm^{-2} Å^{-1}, respectively. It is seen that in reality only a handful of objects as bright as HS1700+6416 and HE2347−4342 are expected at the high redshifts of these objects – a fact that makes their discovery all the more impressive an achievement.

5. Summary and conclusions

Revised numbers for the statistical occurrence of optically thick Lyman limit systems stemming from the *HST* Quasar Absorption Line Key Project (Stengler-Larrea et al. 1995) lead to a factor ~ 2 relief in the predicted severity of the cumulative photoelectric absorption out to large redshift compared to the original estimates of Møller & Jakobsen (1990). This change comes about primarily due to there being fewer high column density systems at low redshifts than previously thought.

When combined with the more recent empirical models for the quasar luminosity function and intrinsic extreme UV spectra, this slight lifting of the intergalactic cloud cover leads to nearly an order of magnitude increase in the expected number of UV bright quasars compared to the earlier estimates of Picard & Jakobsen (1993). The whole sky is predicted to contain of the order of $\sim 10^2$ quasars at $z > 2.9$ similar in brightness to Q0302−003 and PKS1935−692 against which intergalactic He II $\lambda 304$ absorption can be studied from *HST*. A comparable number of ~ 10 times brighter objects similar to HS1700+6414 and HE2347−4342 are predicted to be reachable with *FUSE*, *HUT* or other spectroscopic missions capable of reaching He II at lower redshift at $2.0 < z < 2.9$ – albeit with the bulk of the quasars appearing in the lowermost part of this redshift range.

Although generally more optimistic, these updated predictions still do not change the basic conclusion that the study of He II absorption at $z \sim 3$ is of necessity constrained to take place against background continuum fluxes of order $F_\lambda \simeq 10^{-16}$ erg s^{-1} cm^{-2} Å^{-1}, rising to $F_\lambda \simeq 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1} at $z \sim 2$. In particular, one does not anticipate the discovery of too many more objects similar to the most recent 'clear' quasar discovered by the Hamburg group, HE2347−4342. With a UV continuum reaching $F_\lambda \simeq 3\ 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1} this object is probably close to the brightest Nature is prepared to provide at its redshift of $z = 2.89$.

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