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Intergalactic He II absorption and the baryonic content of the Lyman forest

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Abstract. Intervening intergalactic HeII λ304 absorption has so far been detected toward four high redshift quasars by *HST* and *HUT*. The quantitative interpretation of these data provides a measure of the ionization in the absorbing gas in the form of the ratio of residual HeII ions to HI atoms. Assuming a standard Big Bang helium abundance, this ratio can be used to derive a lower limit on the baryonic content of the Lyman forest without reference to the intensity of the ionizing background flux. It is shown that the HeII detections are consistent with the ionized component of the Lyman forest being a dominant carrier of baryonic matter at high redshift. If the detected HeII absorption is attributed exclusively to the known population of Lyman forest clouds with HI column densities $N_{\rm HI} \gtrsim 10^{12}$ cm^{-2}, then lower limits for the cosmological density of the Lyman forest of $\Omega_{\rm b} h_{75} \gtrsim 1\ 10^{-2}$ at $\langle z \rangle \simeq 2.4$, and $\Omega_{\rm b} h_{75} \gtrsim 9\ 10^{-2}$ at $\langle z \rangle \simeq 3.0$, are implied by the *HUT* and *HST* data, respectively. Both these lower limits are uncomfortably large compared to recent determinations of $\Omega_{\rm b}$ based on the D/H ratio in the forest clouds, but can be lowered by adding a contribution from more diffuse gas, either in the form of very low column density forest clouds or a uniform intergalactic medium. While good consistency between the HeII and D/H values of $\Omega_{\rm b}$ can be reached in the $\langle z \rangle \simeq 2.4$ case in this way, the very strong HeII absorption seen at $\langle z \rangle \simeq 3.0$ is only barely reconcilable with the D/H data. This suggests that the underlying assumption of photoionization equilibrium may not apply to HeII at this redshift, thereby providing further indirect evidence for HeII reionization occurring at $z \simeq 2.9$.

Key words: quasars: absorption lines – intergalactic medium

1. Introduction

Due not least to a series of recent observations obtained with the *W. M. Keck Telescope* and *HST*, very rapid progress is presently being made toward unraveling the nature of the intervening intergalactic gas giving rise to the forest of narrow Lyα lines seen in the spectra of all high redshift quasars.

The availability of the *Keck* HIRES spectrograph (Vogt et al. 1994) – with its two order of magnitude improvement in minimum detectable column density – has led to a number of key results: the detection of CIV and SiIV absorption in a large fraction of the forest systems (Tytler et al. 1995; Cowie et al. 1995; Songaila & Cowie 1996); the extension of the forest cloud population to column densities as low as $N_{\rm HI} \simeq 10^{12}$ cm^{-2} (Hu et al. 1995; Songaila et al. Cowie 1995; Kirkman & Tytler 1997); and the first detections of deuterium in the forest gas (Songaila et al. 1994; Tytler et al. 1996).

In addition to exploring the redshift evolution and nature of the Lyman forest absorbers at low redshift (Lanzetta et al. 1996; Bahcall et al. 1996 and references therein), other noteworthy contributions from *HST* to this topic include establishing the huge apparent angular extent of Lyman forest clouds through the study of quasar pairs (Dinshaw et al. 1995), and the first detections of intense redshift-smeared singly ionized HeII λ304 absorption from the forest and possibly the diffuse IGM at $z \simeq 3$ (Jakobsen et al. 1994; Tytler et al. 1995, Hogan et al. 1997; Reimers et al. 1997). Another key result is the HeII detection obtained with the *Hopkins Ultraviolet Telescope* flown on the *Astro-2* mission (Davidsen et al. 1996), which augments and extends the *HST* observations to lower redshifts.

The standard qualitative picture of the Lyman forest has largely been validated by these recent results. Ever since the Lyman forest was first discovered in the mid-1970s, it has been widely suspected that the forest material is held photoionized by the diffuse meta-galactic background flux due to the integrated light of quasars and/or young galaxies, and consequently that the detectable HI lines therefore represent only the tip of the iceberg of the total amount of matter contained in these systems (cf. Sargent et al. 1980). The notion of a highly ionized forest later gained further indirect support through the so-called proximity effect (Carswell et al. 1982; Murdoch et al. 1986; Bajtlik et al. 1988; Lu et al. 1991; Bechtold 1994) – and has now been established unequivocally by the recent detections of HeII, CIV and SiIV absorption mentioned above.

In their seminal paper, Sargent et al. (1980) estimated that, in spite of their probably being ionized to one part in $\sim 10^4$, the mass present in the forest clouds represents a 'trifling' cosmological density of order $\Omega_b \sim 10^{-3}$. However, as the statistics and physical properties of the forest absorbers have become better determined and the observations pushed to ever lower column density clouds, this estimate has slowly crept upward, while the nucleosynthesis appraisals of Ω_b have decreased (e.g. Walker et al. 1991) – to the point where several authors have commented parenthetically that the Lyman forest may in fact be the dominant depository of ionized baryonic matter at high redshift (Petitjean et al. 1993, Meiksin & Madau 1993; Shapiro et al. 1994; Madau & Meiksin 1994; Giroux et al. 1995). One of the first explicit discussions of this possibility was been given by Rauch & Haehnelt (1995) who argued that the megaparsec sizes for the forest clouds found by Dinshaw et al. (1995), taken together with the ionizing flux implied by the proximity effect, points to such a high ionization parameter that the forest clouds have to be highly flattened filamentary structures for their inferred baryonic content not to exceed the primordial nucleosynthesis values. This same point has also been discussed by Madau & Shull (1996).

The first measurements of deuterium in the forest clouds themselves have reopened the discussion of the nucleosynthesis constraints on Ω_b. In particular, the high D/H ratio measured by Songaila et al. (1994) suggests a baryon density as low as $\Omega_b(\mathrm{D/H})h_{75}^2 \simeq 0.011$ whereas the low value of D/H found by Tytler et al. (1996) corresponds to $\Omega_b(\mathrm{D/H})h_{75}^2 \simeq 0.043$. Hence there may be a need to account for more dark baryonic matter than previously thought.

The purpose of this paper is to point out the implicit connection between the question of the baryonic content of the Lyman forest and the quantitative interpretation of the recent *HST* and *HUT* detections of intergalactic HeII absorption. The key open question surrounding the HeII measurements is whether the amount of HeII absorption detected can be quantitatively accounted for by unresolved line absorption in the HeII equivalent of the Lyman forest, or whether a contribution from true Gunn-Peterson absorption from a more diffuse intergalactic medium is also required (Jakobsen et al. 1994; Madau & Meiksin 1994; Songaila et al. 1995; Giroux et al. 1995; Davidsen et al. 1996; Hogan et al. 1997). Although recent theoretical work has blurred the distinction between the Lyman forest and the diffuse IGM (Cen et al. 1994; Zhang et al. 1995; Hernquist et al. 1996; Bi & Davidsen 1997; Croft et al. 1997), since a heavily clumped or smooth absorbing medium produces a vastly different amount of absorption for a given number of absorbing ions, the assumed geometry of the absorbing HeII matters greatly when assessing empirically the total amount of gas detected from the observational data.

In the following, it is shown that the quantitative interpretation of the HeII data permits a strict lower limit on Ω_b of the Lyman forest to be derived without the need to assume a value for the intensity of the ionizing background. Although still somewhat model dependent, this analysis serves to demonstrate that the HeII observations also require that the ionized component of the Lyman forest be a substantial, if not dominant, reservoir of baryonic matter at high redshift.

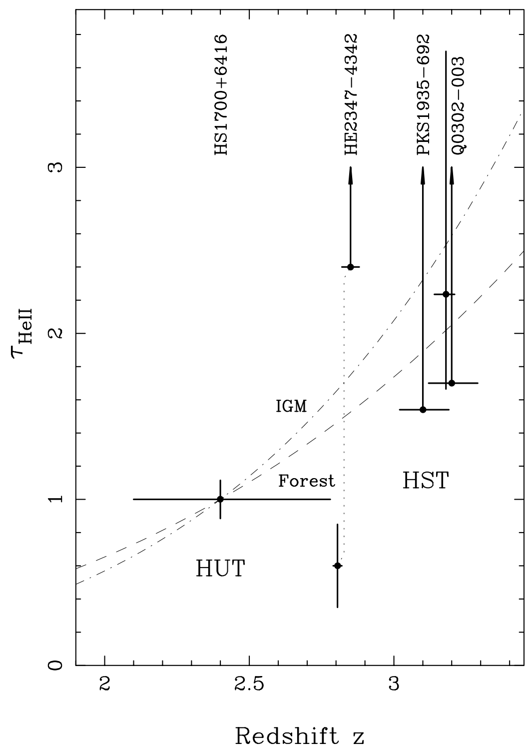

Fig. 1. Available measurements of the HeII optical depth as determined by *HUT* and *HST* (see text). The horizontal bars denote the redshift range spanned by each data point. For reference, the dashed and dot-dashed lines respectively show the smooth evolution in τ_{HeII} expected from the Lyman forest and diffuse gas in the case of a non-evolving ionizing background.

2. HeII detections to date

Singly ionized HeII absorption has so far been detected toward only four quasars: twice at $z \gtrsim 3$ with *HST* (Jakobsen et al. 1994; Tytler et al. 1995); once at $z \simeq 2.4$ with *HUT/Astro-2* (Davidsen et al. 1996); and most recently at the intermediate redshift $z \simeq 2.85$ by Reimers et al. (1997) using *HST*. It is important to appreciate that because of the very faint UV fluxes involved, these observations push present space instrumentation to the limit – HeII absorption cannot presently be observed at anywhere near the level of detail that the Lyman forest can be observed from the ground. Although individual strong HeII lines have been convincingly detected in a few cases (Hogan et al. 1997; Reimers et al. 1997), even the best quality spectra do not have the spectral resolution nor signal to noise ratio required to fully resolve the HeII forest. What is primarily observed is the total redshift-smeared absorption shortward of the HeII line in the quasar rest frame due to the combined HeII opacity of both the forest and any diffuse IGM, and the quantitative strength of this absorption as measured by its wavelength-averaged effective optical depth, τ_{HeII}. A synopsis of the available data is given in Fig. 1 where τ_{HeII} is plotted against the redshift range probed by each detection.

Strong HeII absorption was first detected toward the $z = 3.29$ quasar Q0302−003 by Jakobsen et al. (1994) using the COSTAR-corrected FOC in the objective prism mode. The far-UV spectrum of Q0302−003 is seemingly completely absorbed on the blue side of the redshifted HeII line with no detectable flux seen in the HeII trough. The inferred HeII optical depth toward Q0302−003 is $\tau_{\rm HeII} = 3.2^{+\infty}_{-1.1}$ at $\langle z \rangle \simeq 3.2$. The corresponding 90% confidence bound of $\tau_{\rm HeII} > 1.7$ is shown in Fig. 1.

Follow-up GHRS observations of Q0302−003 obtained by Hogan et al. (1997) have confirmed the initial FOC results and revealed several subtle details in the spectrum that provide important clues as to the nature of the absorbing gas (see Sect. 3 below). These authors also report the possible detection of a weak residual flux in the HeII trough of Q0302−003 at redshifts far from the quasar. The corresponding estimate of $1.5 \lesssim \tau_{\rm HeII} \lesssim 3.0$ quoted by Hogan et al. is also shown in Fig. 1. However, the reality of the reported upper limit on $\tau_{\rm HeII}$ is rather uncertain in view of the difficulty of background subtraction in the GHRS detectors at very low signal levels.

A high value of $\tau_{\rm HeII}$ at $z \simeq 3$ is also implied by the second *HST* detection of HeII absorption toward PKS 1935−692 ($z = 3.18$). Although the first FOS observations of PKS 1935−692 initially suggested less intense HeII absorption ($\tau_{\rm HeII} \simeq 1$) than seen toward Q0302−003 at slightly higher redshift (Tytler et al. 1995), this has not been confirmed by follow-up observations of PKS 1935−692 taken with the FOC objective prism (unpublished results from Program DD 6156). The FOC prism spectrum of PKS 1935−692 reveals that this object also displays seemingly 'black' absorption below the redshifted HeII line, corresponding to $\tau_{\rm HeII} = 2.4^{+2.3}_{-0.6}$ at $\langle z \rangle \simeq 3.1$ ($\tau_{\rm HeII} > 1.5$ at 90% confidence). It is believed that the discrepancy with the initial FOS observations can be attributed to residual background/stray light in the FOS at the extremely faint signal levels involved.

The third successful measurement of HeII absorption was carried out toward HS1700+6416 ($z = 2.73$) with *HUT/Astro-2* (Davidsen et al. 1996). In contrast to the two *HST* cases at $z > 3$, the *HUT* spectrum of HS1700+6416 reveals a finite flux in the HeII trough and a lower HeII opacity over the lower $2.0 \lesssim z \lesssim 2.7$ redshift range sampled by the *HUT* data. The inferred 90% confidence value of $\tau_{\rm HeII} = 1.0 \pm 0.1$ at $\langle z \rangle = 2.4$ quoted by Davidsen et al. (1996) is plotted in Fig. 1.

Very recently, Reimers et al. (1997) have successfully detected HeII absorption toward the exceptionally bright 'clear' quasar HE2347−4342. This object has a redshift of $z = 2.89$ and bridges the gap between HS1700+6416 and the two detections toward Q0302−003 and PKS 1935−692. The spectacular GHRS spectrum of HE2347−4342 reveals that the HeII absorption at $z \simeq 2.8 - 2.9$ is patchy, consisting of alternating ∼Mpc sized regions of finite optical depth ($\tau_{\rm HeII} \simeq 0.7$) and regions of apparently black absorption ($\tau_{\rm HeII} = 4.8^{+\infty}_{-2.0}$).

As discussed by Reimers et al., the HE2347−4342 observations strongly suggest that the HeII opacity does not evolve smoothly with redshift, but rather in the abrupt and patchy 'overlapping Strömgren sphere' manner expected if the HeII-ionizing output of quasars is responsible for reionizing the intergalactic helium (cf. Meiksin & Madau 1993; Shapiro et al. 1994; Miralda-Escudé & Rees 1994). When combined with the previous detections at both higher and lower redshift, a rather compelling picture emerges in which the patchy HeII absorption seen in HE2347−4342 is associated with 'breakthrough' and the rapid onset of the integrated $E > 54$ eV quasar flux at a redshift of $z \simeq 2.9$. In this interpretation, the deep absorption troughs seen in HE2347−4342 represent remnants of the intense HeII absorption seen previously at $z > 3$ toward Q0302−003 and PKS 1935−692. Although already highly ionized in hydrogen, the helium in these regions is effectively locked in singly ionized form due to the lack of HeII ionizing flux. The patches of low HeII absorption seen in HE2347−4342 are interpreted as bubbles of fully exposed ionized gas destined to merge into the more uniform finite opacity seen previously at $z < 2.8$ toward HS1700+6416. Further evidence for a rapid change in the spectrum of the ionizing background at high energies near $z \sim 3$ comes from the study of the metal lines in the forest (Songaila & Cowie 1996; Savaglio et al. 1997)

In the following, the astrophysical consequences of the observed opacity of these two types of HeII absorption regions will be explored. The *HUT* measurement of $\tau_{\rm HeII} = 1.0 \pm 0.1$ at $\langle z \rangle = 2.4$ is adopted as representative of the low redshift case. For simplicity, the two FOC measurements toward Q0302−003 and PKS 1935−692 are combined statistically with the HE2347−4342 measurement to yield a conservative 90% confidence limit of $\tau_{\rm HeII} \gtrsim 2.4$ at $\langle z \rangle \simeq 3.0$ for the high redshift case.

3. Clouds and/or diffuse IGM?

A key issue surrounding the quantitative interpretation of the HeII detections has been whether the observed HeII opacity can be fully accounted for by HeII $\lambda 304$ absorption in the known Lyman forest cloud population or whether a contribution from true Gunn-Peterson absorption from a uniform IGM is also required to explain the data. The total observed value of $\tau_{\rm HeII}$ is the sum of these two components

$$\tau_{\rm HeII} = \tau^{\rm LF}_{\rm HeII} + \tau^{\rm GP}_{\rm HeII} \qquad (1)$$

The wavelength-averaged contribution to $\tau_{\rm HeII}$ from HeII line absorption in the Lyman forest systems can be written (Møller & Jakobsen 1990)

$$\tau^{\rm LF}_{\rm HeII}(z) = \frac{\rm dn}{\rm dz}(z)\frac{\langle W_\lambda \rangle}{\lambda_l}(1+z) \qquad (2)$$

where dn/dz is the number of forest lines per unit redshift and $\langle W_\lambda \rangle$ is the average HeII $\lambda 304$ equivalent width of the forest systems averaged over their distribution in column density.

The expression for the Gunn-Peterson absorption trough produced by a smooth IGM having HeII volume density $n_{\rm HeII}(z)$ in an $\Omega = 1$ universe is (Gunn & Peterson 1965)

$$\tau^{\rm GP}_{\rm HeII}(z) = \left[\frac{c}{H_0}\right] n_{\rm HeII}(z)\sigma_l(1+z)^{-\frac{3}{2}} \qquad (3)$$

where H_0 = 75 h_{75} km s^{-1} Mpc^{-1} is the Hubble constant and $\sigma_l = \lambda_l \frac{\pi e^2}{m_e c^2} f_{ij} = 1.1\times10^{-18}$ cm^2 is the integrated cross section of the HeII λ304 transition.

Both contributions to $\tau_{\rm HeII}$ are expected to evolve rapidly with redshift. In the simplest case of an IGM held photoionized by a background flux of constant intensity and spectral shape, it is easy to show that Eq. (3) predicts that $\tau^{\rm GP}_{\rm HeII}$ should evolve as $\tau^{\rm GP}_{\rm HeII} \propto (1+z)^{9/2}$. Similarly, since the Lyman forest line density evolves as dn/dz(z) $\propto$ (1 + z)$^\gamma$ where $\gamma \simeq 2.4$ (see below), the same assumptions lead to the prediction $\tau^{\rm LF}_{\rm HeII} \propto (1+z)^{3.4}$. The relative increases in $\tau_{\rm HeII}$ expected between the *HUT* and *HST* redshift ranges in these two naive evolution models are shown for reference in Fig. 1. Although both models are consistent with the trend of the observations, the patchy absorption detected in HE2347−4342 clearly points to a more complicated picture.

The question of the relative contributions from HeII forest lines and diffuse gas can be addressed by numerically evaluating the likely range of values for $\tau^{\rm LF}_{\rm HeII}$ based on the known properties the corresponding Lyman forest absorption. This 'translation' of the HI opacity to HeII can either be done on an individual 'line by line' basis using high quality spectra of the quasars in question (Songaila et al. 1995; Hogan et al. 1997; Reimers et al. 1997; Kirkman & Tytler 1997), or statistically from Eq. (2) using generic Lyman forest parameters (Miralda-Escudé 1993; Jakobsen et al. 1994; Madau & Meiksin 1994; Giroux et al. 1995; Davidsen et al. 1996).

Of key importance to this problem is the *Keck* discovery that the column density spectrum of Lyman forest clouds extends uninterrupted down to $N_{\rm HI} \simeq 10^{12}$cm^{-2} and possibly lower (Songaila et al. 1995; Tytler et al. 1995; Kirkman & Tytler 1997). This 'underbrush' to the Lyman forest is very important to the HeII opacity problem since the ionization conditions are almost certainly such that the low column population dominates the HeII absorption. Direct evidence for this can be found the higher resolution GHRS spectrum of Q0302−003 obtained by Hogan et al.(1997), which shows that the well-known 'void' in the Lyman forest of this quasar (Dobrzycki & Bechtold 1991) is seemingly not mimicked in the HeII absorption. As discussed by Hogan et al. this implies that the HeII opacity is dominated by gas more diffuse than the Lyman forest systems having $N_{\rm HI} \gtrsim 10^{13}$cm^{-2} which define the void – a hypothesis that is further supported by the 'proximity effect' displayed by the HeII absorption at redshifts very close to the quasar. This diffuse gas could either be in the form of even lower column density forest clouds or very low-density volume filling gas.

Useful insight into the character of the HeII forest component of the absorption can be gained from examination of the recipe for evaluating Eq. (2) in the statistical approach. The first factor, the number density of Lyman forest systems, is customarily parameterized as

$$\frac{\rm dn}{\rm dz}(z) = A(1+z)^\gamma \quad (4)$$

where $\gamma \simeq 2.4$, and the normalization constant A depends on the column density cut-off one adopts for the forest population.

The HI column density spectrum of Lyman the forest clouds is well-described by the simple power law

$$\frac{\rm dn}{\rm dN_{HI}} \propto N_{\rm HI}^{-s} \quad (5)$$

with $s \simeq 1.5$ (Tytler 1987; Petitjean et al 1993). This spectrum is now known to extend down to at least $N_{\rm HI} \simeq 10^{12}$ cm^{-2}, the present *Keck* detection limit (Hu et al. 1995). The density of the Lyman forest at $z \simeq 3$ counting these newly-discovered low-column systems is approximately one Lyα line per Å, corresponding to $A \simeq 50$ in Eq. (4).

For the spectrum given by Eq. (5), the expression for the average HeII λ304 equivalent width appearing in Eq. (2) is

$$\langle W_\lambda \rangle = \int W_\lambda(N_{\rm HeII}) N_{\rm HI}^{-s}\, {\rm dN_{HI}} \Big/ \int {\rm N_{HI}^{-s}\, dN_{HI}} \quad (6)$$

where $W_\lambda(N_{\rm HeII})$ is the HeII λ304 equivalent width of a forest cloud having HI column $N_{\rm HI}$ and the integral extends over the assumed span in forest cloud $N_{\rm HI}$.

A pivotal assumption in these calculations is that the forest clouds are highly photoionized, so the ratio of HeII ions to HI atoms is given by

$$\left[\frac{\rm HeII}{\rm HI}\right] = \left[\frac{\rm He}{\rm H}\right] (\frac{\alpha_{\rm HeIII}}{\alpha_{\rm HII}})(\frac{\sigma^o_{\rm HI}}{\sigma^o_{\rm HeII}}) S_L \simeq 1.9 S_L \quad (7)$$

where [He/H] $\simeq$ 0.08 is the Big Bang helium abundance by number; $(\alpha_{\rm HeIII}/\alpha_{\rm HII}) \simeq 6$ and $(\sigma^o_{\rm HI}/\sigma^o_{\rm HeII}) = 4$ the ratios between the HeII and HI recombination coefficients and photoionization cross sections at threshold; and $S_L = J_\nu({\rm HI})/J_\nu({\rm HeII})$ is the ratio of HI to HeII ionizing photons (Jakobsen et al. 1993; Miralda-Escudé 1993; Madau & Meiksin 1994). Since $\left[{\rm HeII/HI}\right]$ depends only on the shape of the ionizing background spectrum, the relationship between the HI and HeII column density can be assumed to be

$$N_{\rm HeII} \simeq \left[\frac{\rm HeII}{\rm HI}\right] N_{\rm HI} \quad (8)$$

where $\left[{\rm HeII/HI}\right]$ is a constant applicable to all optically thin forest clouds.

In addition to the conversion factor in Eq. (8), evaluation of Eq. (6), also requires knowledge of the curve of growth of the HeII λ304 line. The velocity widths of the forest lines as measured in Lyα are now well-established by *Keck* observations and show a narrow distribution around an average value of b(H) $\simeq$ 30 km s^{-1} (Hu et al. 1995, Tytler et al. 1995). The anticipated b-value for the helium lines is b(He) $\simeq \xi b$(H), where ξ = 0.5 if the forest cloud velocity dispersion is purely thermal in origin and ξ = 1.0 if turbulence dominates. Detailed studies of CIV lines in the forest (Cowie et al. 1995) suggest that both processes are at work, and that an intermediate value of $\xi \simeq 0.8$ corresponding to b(He) $\simeq$ 25 km s^{-1} therefore is a likely value.

Fig. 2 shows the run of $\tau^{\rm LF}_{\rm HeII}$ as a function of $\left[{\rm HeII/HI}\right]$ calculated for the adopted parameters A = 50, γ = 2.4, s = 1.5 and b(HeII) = 25 km s^{-1} for the redshifts $\langle z \rangle \simeq 2.4$ and $\langle z \rangle \simeq 3.0$

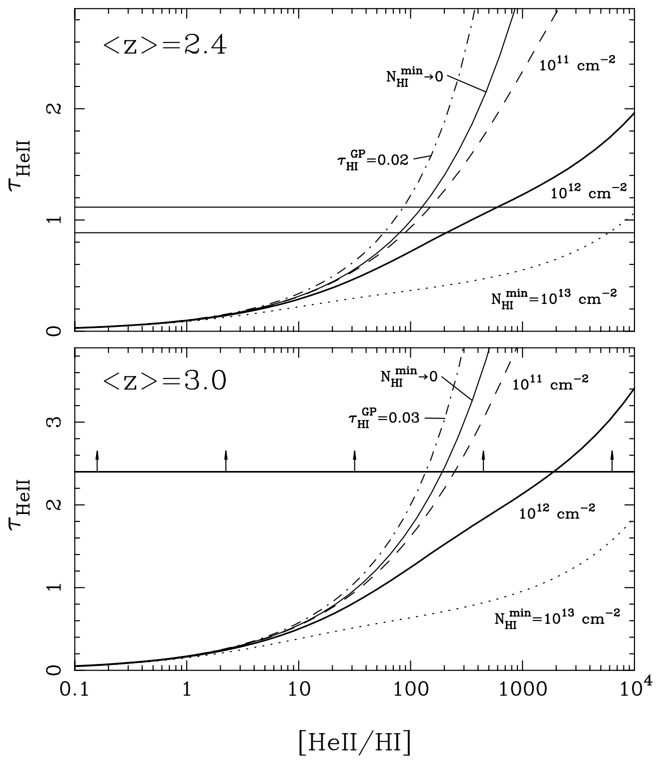

Fig. 2. The predicted HeII optical depth of the Lyman forest as a function of $\left[\mathrm{HeII}/\mathrm{HI}\right]$ for $\langle z\rangle \simeq 2.4$ (*HUT*) and $\langle z\rangle \simeq 3.0$ (*HST*). Also shown are the 90% confidence limits on $\tau_{\rm HeII}$ inferred from the *HUT* and *HST* observations. The thick full curves correspond to the known population of Lyman forest clouds with HI column $N_{\rm HI} \gtrsim 10^{12}\mathrm{cm}^{-2}$. The dotted curves give the contribution from systems with $N_{\rm HI} \gtrsim 10^{13}\mathrm{cm}^{-2}$, while the dashed and thin full curves show the HeII opacity calculated by extrapolating the forest column density distribution to $N_{\rm HI}^{\rm min} = 10^{11}\mathrm{cm}^{-2}$ and zero, respectively (b(HeII) = 25 km s^{-1} assumed in all cases). The dash-dotted curves show the effect of adding a Gunn-Peterson component to the $N_{\rm HI}^{\rm min} = 10^{12}\mathrm{cm}^{-2}$ cases (see text).

appropriate to the *HUT* and *HST* data, respectively. These plots are essentially updated versions of Fig. 3 of Jakobsen et al. (1994), revamped to include both the *HUT* and updated *HST* observations, the low column forest clouds and the larger assumed value of b(He). Similar curves for the high redshift *HST* case can be found in the papers of Madau & Meiksin (1994), Giroux et al. (1995) and Kirkman & Tytler (1997).

The importance of the low column forest clouds in dramatically increasing the forest opacity in HeII is evident from Fig. 2. As discussed by Miralda-Escudé (1993), the reason for this is that the integral in Eq. (7) is always dominated by the contribution from the marginally optically thick systems having HeII column density $N_{\rm HeII} \simeq 10^{14}$ cm^{-1}, with both lower and higher column density systems contributing relatively little to the net opacity. Depending of the value of $\left[\mathrm{HeII}/\mathrm{HI}\right]$, the parameter $\tau_{\rm HeII}^{\rm LF}$ therefore samples different regions of the power law distribution in $N_{\rm HI}$ than does $\tau_{\rm HI}^{\rm LF}$. The dependence of $\tau_{\rm HeII}^{\rm LF}$ on these parameters can be gauged from Eq. (6) in the 'saturated' limit where the extrapolation in $N_{\rm HI}$ is taken to zero column (Miralda-Escudé 1993)

$$\tau_{\rm HeII}^{\rm LF} = \xi^{2-s}\left(\frac{1}{4}\left[\frac{\rm HeII}{\rm HI}\right]\right)^{s-1}\tau_{\rm HI}^{\rm LF} \qquad (9)$$

An alternative approach to extrapolating the cloud spectrum to low column is instead to add a contribution from true Gunn-Petersen absorption. The relationship between the HI to HeII optical depth in this case is simply

$$\tau_{\rm HeII}^{\rm GP} = \frac{1}{4}\left[\frac{\rm HeII}{\rm HI}\right]\tau_{\rm HI}^{\rm GP} \qquad (10)$$

where $\left[\mathrm{HeII}/\mathrm{HI}\right]$ in the photoionized case can be assumed to be the same in both the diffuse and forest components.

The dash-dotted curves in Fig. 2 show the effects of adding a HeII Gunn-Petersen component to the $N_{\rm HI}^{\rm min} = 10^{12}\mathrm{cm}^{-2}$ forest absorption case. In order to be consistent with the optical constraints (e.g. Webb et al. 1992; Giallongo et al. 1992) the magnitude of this component was conservatively constrained to be $\tau_{\rm HI}^{\rm GP} = 0.1\tau_{\rm HI}^{\rm LF}$; i.e. 10% of the total Lyman decrement corresponding to $\tau_{\rm HI}^{\rm GP} = 0.02$ and $\tau_{\rm HI}^{\rm GP} = 0.03$ at $z = 2.4$ and $z = 3.0$ respectively. It is apparent that adding a true Gunn-Peterson component of this magnitude produces an effect very similar to extrapolating the cloud spectrum to low column.

The main conclusion to be drawn from Fig. 2 is that in spite of the various uncertainties, the shear strength of the detected HeII absorption with respect to its HI counterpart implies a high value of $\left[\mathrm{HeII}/\mathrm{HI}\right]$ for the intergalactic gas. If, as suggested by Madau & Meiksin (1994), Songaila et al. (1995) and Giroux et al. (1995), the HeII opacity is to be solely explained by unresolved line absorption in the known population of forest clouds with $N_{\rm HI} \gtrsim 10^{12}$ cm^{-2}, then the ionizing background spectrum needs to be sufficiently soft so that $\left[\mathrm{HeII}/\mathrm{HI}\right] \simeq 350$ at $z \simeq 2.4$, rising to $\left[\mathrm{HeII}/\mathrm{HI}\right] \gtrsim 1900$ at $z \simeq 3$. By adding a further diffuse component to the absorbing gas, either in the form of very low column density clouds or more uniformly distributed gas, these numbers can be reduced to $\left[\mathrm{HeII}/\mathrm{HI}\right] \simeq 100$ and $\left[\mathrm{HeII}/\mathrm{HI}\right] \gtrsim 200$, respectively.

4. The baryonic content of the forest

The high value of $\left[\mathrm{HeII}/\mathrm{HI}\right]$ inferred from the analysis of the HeII data carries important information on the degree of ionization of the Lyman forest and thereby its baryonic content.

The expression for the contribution to the cosmological baryonic density in an $\Omega = 1$ Universe from a population of absorbers having average total hydrogen column density $\langle N_{\rm H}\rangle$ and line of sight density dn/dz can be written

$$\Omega_{\rm b} = \frac{\mu m_{\rm H}}{\rho_{\rm crit}}\left[\frac{H_0}{c}\right]\langle N_{\rm H}\rangle\,\frac{\rm dn}{\rm dz}(z)(1+z)^{-\frac{1}{2}} \qquad (11)$$

where $\rho_{\rm crit} = 6.32\ 10^{-6}h_{75}^{2}m_{\rm H}$ cm^{-3} is the critical density and the mean molecular weight is $\mu m_{\rm H} = 1.32 m_{\rm H}$ for a standard helium to hydrogen ratio by number of $\left[\mathrm{He}/\mathrm{H}\right] \simeq 0.08$.

It has been appreciated for some time (e.g. Sargent et al. 1980) that the neutral hydrogen content of the Lyman forest adds up to a very small contribution to Ω_b. The mean HI column density for the spectrum given by Eq. (5) averaged over the range 10^{12} cm^{-2} $\lesssim N_{HI} \lesssim 10^{17}$ cm^{-2} is $\langle N_{HI}\rangle = 3.2\ 10^{14}$ cm^{-2}. Inserting this value for $\langle N_{HI}\rangle$ in Eq. (11) together with dn/dz given by Eq. (4) leads to $\Omega_b(\mathrm{HI})\ h_{75} \simeq 3.7\ 10^{-6}$ at $z \simeq 3$. This number is dominated by the very highest column density clouds. With the cloud spectrum of Eq. (5) and $s = 1.5$, 90% of the mass of the forest is carried by the systems with column densities $N_{HI} \gtrsim 10^{15}$ cm^{-2}.

In order to arrive at the total mass in the forest Ω_b(HI) must be divided by the residual neutral fraction of the forest clouds, $\left[\mathrm{HI/H}\right]$

$$\Omega_b = \left[\frac{\mathrm{HI}}{\mathrm{H}}\right]^{-1} \Omega_b(\mathrm{HI}) \tag{12}$$

Up until now, the forest ionization could only be conjectured from uncertain photoionization calculations involving an assumed ionization parameter based on considerations of typical clouds dimensions and estimates of the absolute ionizing background flux based on quantitative analysis of the proximity effect. However, the values of $\left[\mathrm{HeII/HI}\right]$ resulting from the interpretation of the HeII data yield a complementary and more direct measure of the forest cloud ionization. Specifically, the ionization correction in Eq. (12) can be written

$$\left[\frac{\mathrm{HI}}{\mathrm{H}}\right]^{-1} = \left[\frac{\mathrm{HeII}}{\mathrm{HI}}\right]\left[\frac{\mathrm{He}}{\mathrm{H}}\right]^{-1}\left[\frac{\mathrm{HeII}}{\mathrm{He}}\right]^{-1} \tag{13}$$

where $\left[\mathrm{He/H}\right] \simeq 0.08$ is the (assumed) cosmological helium abundance by number. In general, the ionization level of a given forest cloud will depend on its gas density. However, since $\left[\mathrm{HeII/HI}\right]$ can be assumed constant in the case of a uniform ionizing flux, and the (density sensitive) relative HeII fraction is constrained by $\left[\mathrm{HeII/He}\right] \leq 1$, Eq. (13) implies the following inequality valid for any optically thin component of the intergalactic medium:

$$\left[\frac{\mathrm{HI}}{\mathrm{H}}\right]^{-1} \geq \left[\frac{\mathrm{He}}{\mathrm{H}}\right]^{-1}\left[\frac{\mathrm{HeII}}{\mathrm{HI}}\right] \tag{14}$$

With the values of $\left[\mathrm{HeII/HI}\right] \gtrsim 10^2 - 10^3$ from in the previous section, this inequality implies that the Lyman forest clouds must be ionized to a level $\left[\mathrm{HI/H}\right] \lesssim 10^{-3} - 10^{-4}$. Consequently, the estimate of Ω_b(HI) for the forest given above can be raised by the inverse factor to $\Omega_b(\mathrm{HeII})\ h_{75} \gtrsim 0.01 - 0.1$ – i.e. to values well within range of those suggested by the recent deuterium measurements.

Figs. 3 and 4 plot in more detail, for the respective *HUT* and *HST* cases, the values of Ω_b(HeII) calculated from Eqs. (11), (12) and the inequality Eq. (14) as a function of $\tau^{\mathrm{LF}}_{\mathrm{HeII}}$ given by Eq. (2). It is seen that in order for the known population of Lyman forest clouds having HI column densities in the range 10^{12} cm^{-2} $\gtrsim N_{HI} \gtrsim 10^{17}$ cm^{-2} to produce sufficient opacity to account for all the HeII absorption detected by *HST* and *HUT*, it follows that these clouds must carry a total mass equivalent to $\Omega_b(\mathrm{HeII}) h_{75} \gtrsim 1\ 10^{-2}$ at $\langle z\rangle \simeq 2.4$, and $\Omega_b(\mathrm{HeII}) h_{75} \gtrsim 9\ 10^{-2}$ at $\langle z\rangle \simeq 3.0$. Both limits are uncomfortably large with respect to the D/H-derived values for the total baryonic density. The lower limit in the $z = 2.4$ case corresponds to the 'high D/H' value for Ω_b(D/H), leaving little or no room for an unseen component of fully ionized HeIII. This discrepancy is even greater at $z = 3.0$ where Ω_b(HeII) exceeds even the 'low D/H' Ω_b(D/H) value.

As illustrated by the dashed curves in Figs. 3 and 4, the derived values of Ω_b(HeII) can be lowered by factors of ~ 3 and ~ 10 respectively by either extrapolating the forest cloud spectrum to columns below the present detection limit of $N_{HI} \simeq 10^{12}$ cm^{-2} or adding a small Gunn-Peterson component to the absorption consistent with the optical constraints. The seemingly paradoxical situation where adding material to the forest leads to a lowering of the implied Ω_b(HeII) reflects the strongly non-linear nature of the line absorption. All other factors being equal, having more weak forest clouds make up a given value of $\tau^{\mathrm{LF}}_{\mathrm{HeII}}$ lowers the required value of $\left[\mathrm{HeII/HI}\right]$ without significantly raising the base value of Ω_b(HI) since the latter is determined by the high column systems.

Adding an additional diffuse component to the HeII absorption decreases the estimate of Ω_b(HeII) in the $\langle z\rangle \simeq 2.4$ case to a level where the intergalactic helium at this redshift can be nearly fully photoionized (up to $\left[\mathrm{HeII/He}\right] \sim 0.1$) and still be consistent with the Ω_b(D/H). In other words, the finite HeII opacity detected at $z \lesssim 2.9$ is consistent with the picture of a highly photoionized intergalactic medium in which the Lyman forest clouds contain most of the baryonic mass of the Universe.

At $\langle z\rangle \simeq 3.0$, however, the lowered value of Ω_b(HeII) is still uncomfortably large with respect to Ω_b(D/H) – especially considering that the actual optical depth at high redshift is very likely to be greater than the adopted conservative lower limit of $\tau_{\mathrm{HeII}} > 2.4$. Rather than imply a serious conflict with Ω_b(D/H), this inconsistency most likely signals a breakdown of the basic assumption of photoionization and the implied constancy of $\left[\mathrm{HeII/HI}\right]$.

Simply put, the method of estimating Ω_b(HeII) outlined in this paper boils downs to deriving a value of $\left[\mathrm{HeII/HI}\right]$ from knowledge of the properties of the low column systems with $N_{HI} \lesssim 10^{13}$ cm^{-2} (which dominate the HeII absorption) and the intermediate systems with $N_{HI} \simeq 10^{14}$ cm^{-2} (which dominate the HI absorption), and then applying this implied degree of ionization to the high column density forest systems with $N_{HI} \gtrsim 10^{14}$ cm^{-2} (which carry the mass). This extrapolation over some five decades in forest cloud column density is permissible only in the highly photoionized case where the parameter $\left[\mathrm{HeII/HI}\right]$ is the same for all optically thin clouds.

In the case where the ionizing background does not extend to energies $E > 54$ eV, the ionization of HI and HeII is no longer locked and Eq. (7) is replaced by

$$\left[\frac{\mathrm{HeII}}{\mathrm{HI}}\right] \simeq \left[\frac{\mathrm{He}}{\mathrm{H}}\right]\left[\frac{\mathrm{HI}}{\mathrm{H}}\right]^{-1} = \left[\frac{\mathrm{He}}{\mathrm{H}}\right]\left(\frac{c\sigma^o_{\mathrm{HI}}}{\alpha_{\mathrm{HII}}}\right)\left(\frac{\alpha}{\alpha+3}\right)U \tag{15}$$

where α is the spectral index of the ionizing background and $U \simeq (4\pi/hc\alpha)(J_\nu(\mathrm{HI})/n_{\mathrm{H}})$ is the ionization parameter gov-

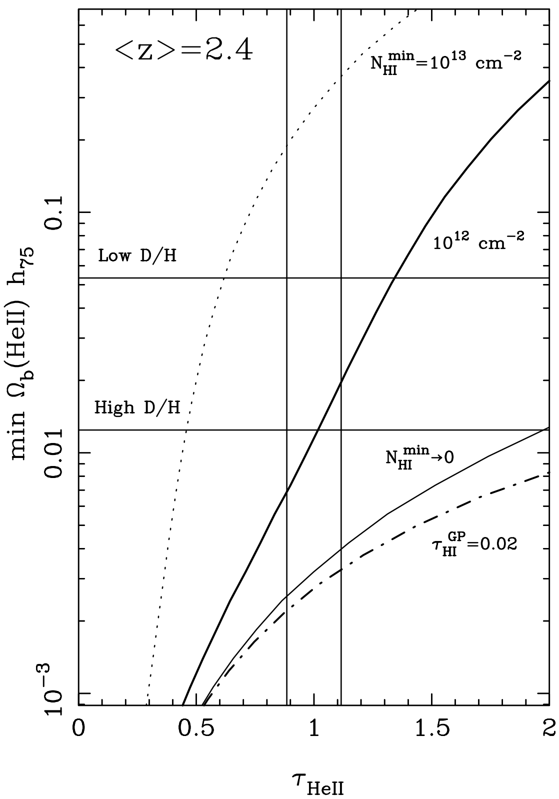

Fig. 3. The minimum baryonic content of the Lyman forest as a function of $\tau_{\rm HeII}$ calculated for $\langle z\rangle \simeq 2.4$ and b(HeII) = 25 km s^{-1}. The thick full, dotted, and thin full curves correspond to assumed minimum forest HI columns of $N_{\rm HI}^{\rm min}$ = 10^{12}cm^{-2}, 10^{13}cm^{-2} and zero, respectively. The dot-dashed line shows the effect of adding a diffuse component having an HI Gunn-Peterson optical depth of $\tau_{\rm HI}^{\rm GP}$ = 0.02 to the $N_{\rm HI}^{\rm min}$ = 10^{12}cm^{-2} case. The value of $\tau_{\rm HeII} = 1.0 \pm 0.1$ measured from the *HUT* detection is also indicated, as is the range in total $\Omega_{\rm b}$ suggested by recent measurements of deuterium in the forest clouds.

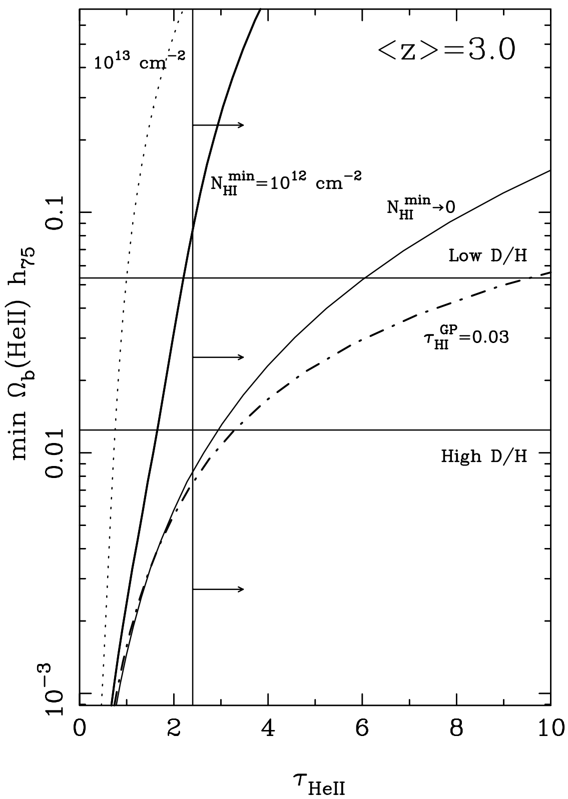

Fig. 4. As Fig. 3, but calculated for $\langle z\rangle \simeq 3.0$, $\tau_{\rm HI}^{\rm GP}$ = 0.03 and the limit $\tau_{\rm HeII} > 2.4$ inferred from the combined *HST* observations.

erning the ionization of hydrogen. Since U is inversely proportional to gas density, the simplifying assumption of constant $\left[\rm HeII/HI\right]$ is no longer valid. In particular, the value of $\left[\rm HeII/HI\right]$ derived from $\tau_{\rm HeII}$ need not apply to the high $N_{\rm HI}$ systems which carry the forest mass. If, as is likely, the large column density forest systems have a higher density than the low column density systems, this will lead to $\Omega_{\rm b}$(HeII) being overestimated by a factor of order of the relative span in forest cloud density. The mismatch between the limits on $\Omega_{\rm b}$(HeII) for the $\langle z\rangle \simeq 2.4$ and $\langle z\rangle \simeq 3.0$ cases in Figs. 3 and 4 can therefore be interpreted as providing further indirect evidence for the delayed HeII reionization scenario with HeII reionization having occurred between these two redshifts.

As a corollary, Eq. (15) predicts $\left[\rm HeII/HI\right] \gtrsim 2000$ for a conservative estimate of $U \gtrsim 10^{-1}$ for the low density gas. Consequently, the true optical depth of regions of 'black' HeII absorption at $z \gtrsim 2.9$ is expected to reach at least $\tau_{\rm HeII} \gtrsim 7$. Hence, if confirmed, the finite flux in the HeII trough of Q0302−003 reported by Hogan et al. (1997) might pose a problem for the late HeII reionization hypothesis.

5. Discussion

Despite being somewhat model dependent, the limits on $\Omega_{\rm b}$(HeII) shown in Figs. 3 and 4 clearly support the concept of the Lyman forest clouds being a significant depository of baryonic matter at high redshift, easily exceeding the damped Lyα systems in importance (cf. Lanzetta et al. 1995). How robust is this inference?

One key unknown is obviously the assumed helium abundance $\left[\rm He/H\right]$. Because of the large and uncertain ionization corrections involved in Eq. (7), the helium abundance of the Lyman forest material cannot be derived from the HeII (or HeI; see Reimers & Vogel 1993) absorption data at any level of accuracy of interest for nucleosynthesis calculations. However, other observations and theory point to a primordial helium in the narrow range $\left[\rm He/H\right] \simeq 0.08 \pm 0.01$ (cf. Walker et al. 1991; Olive & Steigman 1995).

The other critical parameters are those that enter into the determination of $\left[\rm HeII/HI\right]$. For example, because of the shallowness of the curves in Fig. 2, a 20% change in the adopted value of A (or $\tau_{\rm HeII}$) leads to a factor ~ 2 change in the inferred value of $\left[\rm HeII/HI\right]$ and thereby $\Omega_{\rm b}$(HeII). This sensitivity and the slightly different assumptions made explains why the inferred values of $\left[\rm HeII/HI\right]$ derived in this paper are slightly higher than those inferred previously for the high redshift *HST* case by Madau & Meiksin (1994), Songaila et al. (1995) and

Giroux et al. (1995), but somewhat lower than the estimates of Kirkman & Tytler (1997).

A useful consistency-check on the adopted forest model is to compare the calculated and observed total redshift-smeared optical depth of the forest in the Lyα line. Such measurements are available for two of the quasars against which HeII absorption has been detected. Songaila at al. (1995) quote $\tau_{\rm HI}^{\rm LF} = 0.31$ at $\langle z \rangle \simeq 2.9$ toward Q0302−003 and Davidsen et al. (1996) quote $\tau_{\rm HI}^{\rm LF} = 0.22$ at $\langle z \rangle \simeq 2.4$ toward HS1700+6416. The corresponding expected values calculated using the above expressions and the parameters $A = 50$, $\gamma = 2.4$, $s = 1.5$ and b(H) = 30 km s^{-1} are $\tau_{\rm HI}^{\rm LF} = 0.33$ and $\tau_{\rm HI}^{\rm LF} = 0.21$, respectively. This good agreement notwithstanding, this calculation really only validates the fidelity of the forest model at the intermediate column densities ($N_{\rm HI} \sim 10^{14}$ cm^{-2}) which dominate the forest absorption in Lyα – whereas the HeII λ304 opacity is dominated by the systems having HI columns a factor $\left[\rm HeII/HI\right]/4 \sim 50$ times lower. The latter very low column systems provide a negligible contribution to the net HI opacity as measured by $\tau_{\rm HI}^{\rm LF}$.

A further uncertainty related to the forest cloud spectrum is the possible steepening of the spectrum at high column densities $N_{\rm HI} \gtrsim 1\ 10^{15}$ cm^{-2} discussed by Petitjean et al. (1993) and Hu et al. (1995). Taking this potential complication into account decreases the number of high density systems with respect to Eq. (5) by a factor 2-3, thereby lowering $\Omega_{\rm b}$(HeII) by roughly the same factor.

Lastly, a more basic uncertainty concerns the validity of the adopted paradigm of a two component intergalactic medium consisting of well-defined clouds, possibly embedded in a uniform medium. It is presently not obvious what biases this simplistic, but mathematically convenient geometry introduces compared to the more sophisticated CDM simulations of the structure of the intergalactic medium (Cen et al. 1994; Zhang et al. 1995; Hernquist et al. 1996; Miralda-Escudé et al. 1996; Croft et al. 1997). Nonetheless, given that the values of $\Omega_{\rm b}$ being discussed in the latter work are comparable to those inferred above, this bias is unlikely to change the main conclusions of this paper.

6. Summary and conclusions

The quantitative interpretation of the detections of intergalactic HeII λ304 absorption obtained by *HST* and *HUT*, when combined with measurements of the matching HI forest absorption in Lyα, provide a value for the ratio of singly ionized HeII ions to neutral HI atoms in the Lyman forest. For a given absolute helium abundance, the value of $\left[\rm HeII/HI\right]$ derived in this manner is a direct measure of the minimum ionization level of the absorbing gas, which can be used to place a lower limit on the total baryonic content of the Lyman forest. This simple method of 'weighing the Lyman forest by counting the helium' rests on the tacit assumption that the intergalactic gas is highly photoionized and that $\left[\rm HeII/HI\right]$ therefore is constant and applicable to all optically thin components of the intergalactic medium, not least the forest systems up to column density $N_{\rm HI} \simeq 10^{17}$ cm^{-2} which carry most of the mass. The method also requires an assumed geometry for the absorbing medium in order that the strong saturation effects in the HI and HeII absorption can be taken into account.

If interpreted within the framework of the conventional discrete cloud model, the shear strength of the detected HeII absorption compared to its Lyα counterpart requires a large value for the baryonic content of the Lyman forest – to the point where uncomfortably high constraints of $\Omega_{\rm b}$(HeII)$h_{75} \gtrsim 1\ 10^{-2}$ at $\langle z \rangle \simeq 2.40$ rising to $\Omega_{\rm b}$(HeII)$h_{75} \gtrsim 9\ 10^{-2}$ at $\langle z \rangle \simeq 3.0$ are inferred in the case where the HeII opacity is assumed to be exclusively made up of unresolved HeII line absorption in the known population of Lyman forest clouds with $N_{\rm HI} \gtrsim 10^{12}$cm^{-2} as suggested by Madau & Meiksin (1994); Songaila et al. (1995) and Giroux et al. (1995). These constraints can be lowered to values more compatible with the estimates of $\Omega_{\rm b}$(D/H) resulting from measurements of the D/H ratio in the forest by assigning a portion of the detected HeII absorption to more diffuse gas in the form of a population of very low column density forest clouds and/or a homogeneous intergalactic medium at a level consistent with the observational constraints measured in Lyα. Direct evidence for such a component to the HeII absorption in Q0302−003 is provided by the observations of Hogan et al. (1997).

The recent discovery by Reimers et al. (1997) that the HeII absorption is highly patchy at redshift $z \simeq 2.9$ raises the strong possibility that complete reionization of the intergalactic medium in HeII did not occur until after this redshift. If so, then the *HUT* HeII measurements at $\langle z \rangle \simeq 2.40$ and the *HST* measurements at $z \gtrsim 3$ sample quite distinct physical conditions. In particular, the seemingly 'black' HeII absorption detected in the troughs of HE2347−4342 and toward Q0302−003 and PKS 1935−692 cannot be interpreted in the simple photoionization model, and the above technique for constraining $\Omega_{\rm b}$(HeII) is not applicable. That the discrepancy between $\Omega_{\rm b}$(HeII) and $\Omega_{\rm b}$(D/H) is largest for the $\langle z \rangle \simeq 3.0$ case provides indirect support for the delayed HeII reionization scenario.

The various uncertainties and sensitivity to assumptions notwithstanding, the simple considerations of this paper do serve to demonstrate that the HeII detections are entirely consistent with the hypothesis that the ionized component of the Lyman forest is a significant, if not dominant, carrier of baryonic matter at high redshift.

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