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# Quasar absorption lines as a cosmological probe: exploring the Lyman forest with VLT/UVES

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## 1 Observations and Data Reduction

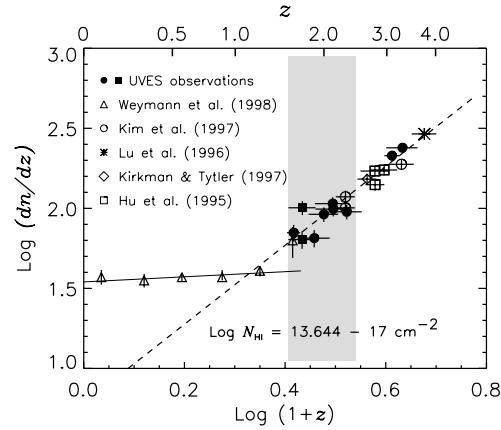
The remarkable efficiency of the Ultra-Violet Echelle Spectrograph (UVES) at the VLT has made it possible to push high-resolution, high-S/N ground observations of the Ly $\alpha$  forest down to  $z \sim 1.5$ , gaining new insight into the physical state of the intergalactic medium (IGM) and its evolution over more than 90% of the cosmic time. The results presented here are based on recent UVES observations of eight QSOs spectra, covering the Ly $\alpha$  forest at  $1.5 < z_{\text{Ly}\alpha} < 3.6$  with S/N  $\sim 40$ –50 and resolution  $R \sim 45\,000$  [1,2]. The absorption lines of the normalized spectra were fit to the Voigt profiles to derive the three line parameters: absorption redshift,  $z$ , the HI column density,  $N_{\text{HI}}$  in  $\text{cm}^{-2}$ , and the Doppler parameters,  $b$  in  $\text{km s}^{-1}$ .

## 2 The Number Density Evolution of the Ly $\alpha$ forest

Fig. 1 shows the evolution of the line number density per unit redshift,  $dn/dz$ , in the interval  $N_{\text{HI}} = 10^{13.6-17} \text{ cm}^{-2}$ . The maximum-likelihood fit to the  $z > 1.5$  data is  $dn/dz = 6.1 (1+z)^{2.5 \pm 0.2}$  (dashed line). The evolution of the Ly $\alpha$  forest with  $z$  is mainly governed by two physical processes: the Hubble expansion and the ionizing ultraviolet background flux (UVB,[3]). At higher  $z$ , the Hubble expansion and the non-decreasing UVB cause a rapid evolution of  $dn/dz$ . At lower  $z$ , HST observations have shown a slow-down in  $dn/dz$  (solid line in Fig. 1,[4]), which can be explained with a decrease of the UVB flux in the local universe. The UVES observations imply that the turn-off in the evolution occurs at  $z \sim 1$ . The evolution and the redshift of the turn-off are consistent with an UVB to which galaxies contribute as much as QSOs or more, as long as a fraction  $f_{\text{esc}} \geq 0.05$  of the UV flux can escape the internal absorption in a galaxy [5].

## 3 The cosmic baryon density

A lower-bound to the cosmic baryon density can be derived from the distribution of the Ly $\alpha$  optical depths [6]. For a UVB with a contribution from galaxies ( $f_{\text{esc}} = 0.1$ ), the effective optical depths measured in the UVES spectra at  $1.5 < z < 4$  implies  $\Omega_b h^{1.5} > 0.028$  (assuming IGM temperature  $T = 2 \cdot 10^4 \text{K}$ ,  $\Omega_m = 0.3$ ,  $\Omega_A = 0.7$ ). This value is consistent with the BBN value for a low D/H



**Fig. 1.** The number density evolution of the Ly $\alpha$  forest

primordial abundance. Most of the baryons reside in the Lyman forest at  $1.5 < z < 4$  with little change in the contribution to  $\Omega$  as a function of  $z$ . Conversely, given the observed opacity, a higher UVB requires a higher  $\Omega_b$ . As pointed out by Haehnelt et al. [7], values of  $f_{\text{esc}}$  as large as 0.4 [8], would result in too large  $\Omega_b$  values.

## 4 The Temperature of the IGM

Absorption lines in the Ly $\alpha$  forest are broadened by gas thermal motion and other processes, therefore the minimum  $b$  value can provide an upper limit on the temperature. The minimum  $b$  is found to increase as  $z$  decreases [9]. When the column densities are converted into over-densities, this implies that the temperature at the mean ISM density decreases with  $z$ . The large fluctuations in the minimum  $b$  value and in its dependence on  $N_{\text{HI}}$ , even at a similar redshift, suggest that the temperature of the intergalactic medium might fluctuate. A large fluctuation seen at  $z \sim 3.1$  is probably due to the HeII reionization [10,9].

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