RevMexAA (Serie de Conferencias), **17**, 275–278 (2003)

LESSONS ON GALAXY FORMATION FROM OBSERVATIONS OF THE IGM

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RESUMEN

Las observaciones de alta resolución y alta S/R del bosque de Lyman se extienden ahora desde corrimientos al rojo de 0 hasta 6, dándonos una nueva visión de las condiciones físicas del medio intergaláctico y de su evolución durante más del 90% del tiempo cósmico. La expansión universal, la radiación UV de fondo y la condensación gravitatoria de estructuras son los factores que determinan la densidad por número y la distribución de densidades columnares de los absorbedores. La contribución de fotones UV producida por galaxias resulta ser importante para reproducir el patrón evolutivo observado a z's muy altos y bajos. El bosque de Lyman contiene la mayor parte de los bariones, por lo menos a $z > 1.5$, y actúa como un reservorio para la formación de galaxias. Las mediciones muestran que el parámetro Doppler típico a una densidad columnar fija crece levemente al decrecer z, pero la temperatura que se infiere a la densidad media crece con z. Tentativamente se han identificado en el bosque de Lyman los rasgos característicos de la re-ionización del HeII y de la retro- alimentación de la formación de las estructuras galácticas.

ABSTRACT

High-resolution, high-S/N observations of the Lyman forest extend now from redshift zero to six, providing new insight into the physical conditions of the intergalactic medium and its evolution over more than 90% of the cosmic time. The universal expansion, the UV ionizing background and the gravitational condensation of structures are the driving factors shaping the number density and the column density distribution of the absorbers. A (limited) contribution of UV photons produced by galaxies is found to be important to reproduce the observed evolutionary pattern at very high and low redshift. The Lyman forest contains most of the baryons, at least at $z > 1.5$, and acts as a reservoir for galaxy formation. The typical Doppler parameter at a fixed column density is measured to slightly increase with decreasing redshift, but the inferred temperature at the mean density is increasing with redshift. The signatures of HeII reionization and feedback from the formation of galactic structures have possibly been detected in the Lyman forest.

Key Words: **COSMOLOGY — INTERGALACTIC MEDIUM**

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

1. INTRODUCTION

Through the analysis of the absorption lines imprinted in the spectra of distant sources (quasars, gamma-ray bursters or galaxies) by gas intervening along the line of sight we can study the spatial distributions, motions, chemical enrichment, and ionization histories of gaseous structures from redshift six and hopefully beyond until the present. It is an exciting game: as in a Sherlock Holmes novel, from few details of little apparent significance, one can deduce a surprisingly important number of conclusions about our Universe, especially when we link the information provided by absorption lines with the complementary information derived from the evolutionary properties of luminous galactic structures. In particular, thanks to observations of the IGM, it is possible to address issues like: What were the physical conditions of the primordial universe? What fraction of the matter was in a diffuse medium and what fraction and how early did it condense in clouds? Where are most of the baryons at the various redshifts? When and how did the formation of galaxies and large scale structure start? How early and in what amount were metals produced? What was the typical radiation field, how homogeneous was it, and what was producing it? When and how, after the Dark Ages following recombination, did the Universe get reionized? Does the standard big bang model make the correct predictions about primordial element abundances and CMB evolution? Do fundamental constants of Physics (e.g. the fine structure constant) vary with cosmic time? Obviously, I can address only a few of these items. I will focus mainly on results recently obtained with the UVES spectrograph (D'Odorico et al. 2000) at the VLT, without forgetting the great contribution of the Keck telescope with HIRES and ESI.

2. THE NUMBER DENSITY OF Lyman-α LINES

The swift increase of the number of absorptions (and the average opacity) with increasing redshift is the most impressive property of the Lyman-α forest. Fig. 1 shows the number density evolution of the

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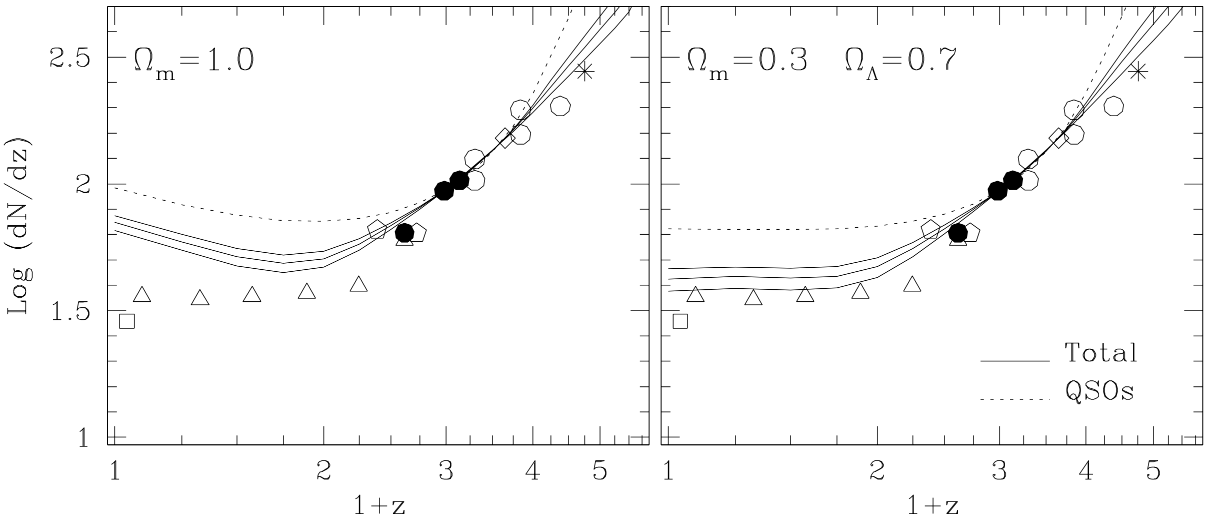

Fig. 1. Number density evolution of the Lyα forest with $N_{HI} = 10^{13.64-16}$ cm^{-2}. Dotted lines refer to the evolution compatible with an ionising UV background due only to QSOs. Solid lines show the expected evolution when both QSOs and galaxies contribute to the background, for models with $f_{\rm esc}$=0.05 (upper line), 0.1 and 0.4 (lower line). Data points come from several observations in the literature, as given by (Kim, Cristiani & D'Odorico 2001). The modelled evolution has been normalized to the observed evolution in the redshift range $2 < z < 3$. (Bianchi, Cristiani & Kim 2001)

Lyman-α lines (Kim, Cristiani & D'Odorico 2001; Kim et al. 2002) in the column density interval [4] $N_{HI} = 10^{13.64-16}$ cm^{-2}. The maximum-likelihood fit to the data at $z > 1.5$ with the customary power-law parametrization provides $N(z) = N_0(1+z)^\gamma = (6.5 \pm 3.8)\,(1+z)^{2.4\pm0.2}$. The UVES observations imply that the turn-off in the evolution does occur at $z \sim 1$, not at $z \sim 2$ as previously suggested.

While the opacity is varying so fast, the column density distribution stays almost unchanged. The differential density distribution function measured by UVES (Kim, Cristiani & D'Odorico 2001; Kim et al. 2002), that is, the number of lines per unit redshift path and per unit N_{HI} as a function of N_{HI}, basically follows a power-law $f(N_{HI}) \propto N_{HI}^{-1.5}$ extending over 10 orders of magnitude with little, but significant deviations: the slope β of the power-law in the range $14 \lesssim \log N_{HI} \lesssim 16$ goes from about -1.5 at $<z>= 3.75$ to -1.7 at $z < 2.4$. Recent HST STIS data (Davé & Tripp 2001) confirm that this trend continues at lower redshift, measuring a β of -2.0 at $z < 0.3$.

3. THE EVOLUTION OF THE Lyman-α FOREST AND THE IONIZING BACKGROUND

The evolution of the $N(z)$ is governed by two main factors: the Hubble expansion and the metagalactic UV background (UVB). At high z both the expansion, which decreases the density and tends to increase the ionization, and the UVB, which is increasing or non-decreasing with decreasing redshift, work in the same direction and cause a steep evolution of the number of lines. At low z, the UVB starts to decrease with decreasing redshift, due to the reduced number and intensity of the ionizing sources, counteracting the Hubble expansion. As a result the evolution of the number of lines slows down.

Up to date, numerical simulations (Theuns et al. 1998) have been remarkably successful in qualitatively reproducing the observed evolution; however they predict the break in the dN/dz power-law at a redshift $z \sim 1.8$ that appears too high in the light of the new UVES results. This suggests that the UVB implemented in the simulations may not be the correct one: it was thought that at low redshift QSOs are the main source of ionizing photons, and, since their space density drops below $z \sim 2$, so does the UVB. However, galaxies can produce a conspicuous ionizing flux too, possibly more significant than it was thought(Steidel, Pettini & Adelberger 2001). The galaxy contribution can keep the UVB relatively high until at $z \sim 1$ the global star formation rate in the Universe quickly decreases, determining the qualitative change in the number density of lines.

Under relatively general assumptions, it is possible to relate the observed number of lines above a given threshold in column density or equivalent

[4] This range in N_{HI} has been chosen to allow a comparison with the HST Key-Programme sample at $z < 1.5$ (Weymann et al. 1998) for which a threshold in equivalent width of 0.24 Å was adopted.

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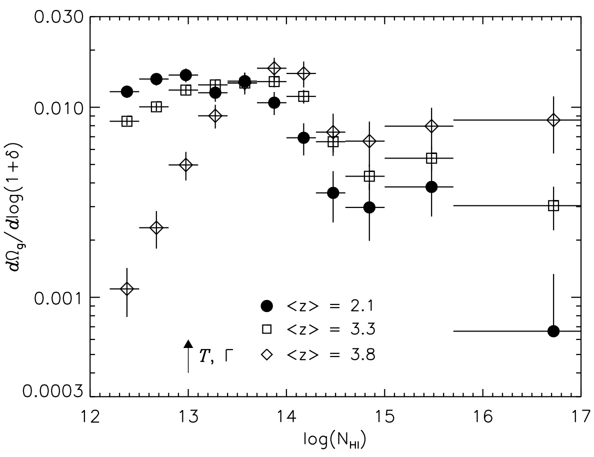

Fig. 2. The differential mass density distribution of the Lyman-α forest as a function of N_{HI}. The arrow indicates the direction towards which the points move if the temperature or the ionization rate increase (Kim et al. 2002),

width to the expansion, the UVB, the distribution in column density of the absorbers and the cosmology (Davé et al. 1999):

$$\left(\frac{dN}{dz}\right)_{>N_{HI,\mathrm{lim}}} = C\left[(1+z)^5\Gamma_{\mathrm{HI}}^{-1}(z)\right]^{\beta-1} H^{-1}(z), \quad (1)$$

where Γ_{HI} is the photoionization rate and β the power-law index of the N_{HI} distribution.

To estimate Γ_{HI} we have investigated the contribution of galaxies to the UVB (Bianchi, Cristiani & Kim 2001), exploring three values for the fraction of ionizing photons that can escape the galaxy interstellar medium, $f_{esc} = 0.05, 0.1$ and 0.4 (the latter value corresponds to the Lyman-continuum flux detected by Steidel, Pettini & Adelberger (2001) in the composite spectrum of 29 Lyman-break galaxies). Measurements of the UVB based on the proximity effect at high-z and on the Hα emission in high-latitude galactic clouds at low-z provide an upper limit on $f_{esc} \lesssim 0.1$, consistent with recent results on individual galaxies both at low-z (Deharveng et al. 2001; Heckman et al. 2001) and at $z \sim 3$ (Giallongo et al. 2002). Introducing a contribution of galaxies to the UVB, the break in the Lyman-α dN/dz can be better reproduced than with a pure QSO contribution (Bianchi, Cristiani & Kim 2001). The agreement improves considerably also at $z \gtrsim 3$. Besides, models with $\Omega_\Lambda = 0.7, \Omega_M = 0.3$ describe the flat evolution of the absorbers much better than those with $\Omega_M = 1$. A consistency check is provided by the evolution of the lower column density lines. For $\log N_{HI} \lesssim 14$ the N_{HI} distribution follows a flatter slope β, and according to Eq. 1 this translates directly into a slower evolutionary rate, which is consistent with the UVES observations(Kim, Cristiani & D'Odorico 2001): $\mathrm{dN/dz}_{(13.1<N_{HI}<14)} \propto (1+z)^{1.2\pm0.2}$. Another diagnostic can be derived from the spectral shape of the UVB and its influence on the intensity ratios of metal lines (Savaglio et al. 1997; Songaila 1998).

4. MAPPING THE COLUMN DENSITY DISTRIBUTION INTO THE MASS DISTRIBUTION OF THE GAS

It is instructive to transform the observed column density distribution into the mass distribution of the photoionized gas (Fig. 2) and interpret it, following Schaye(Schaye 2001), as a function of the matter density contrast: 1) the flattening at $\log N_{HI} \lesssim 13.5$ is partly due to line crowding and partly to the turnover of the density distribution below the mean density; 2) the steepening at $\log N_{HI} \gtrsim 14$, with a deficiency of lines that becomes more and more evident at lower z, reflects the fall-off in the density distribution due to the onset of rapid, non-linear collapse; 3) the flattening at $N_{HI} \gtrsim 10^{16}$ cm^{-2} can be attributed to the flattening of the density distribution at density contrast $\gtrsim 10^2$ due to the virialization of collapsed matter. The differential mass density distribution has a sort of universal form when plotted as a function of the density contrast. A given density contrast, however, corresponds to lower and lower column densities with decreasing redshift, and this causes a shift of the mass density distribution (Fig. 2) towards the left with decreasing redshift, which explains the steepening of the slope β reported in Sect.2. Hydrodynamical simulations successfully reproduce this behaviour, indicating that the derived matter distribution is indeed consistent with what would be expected from gravitational instability.

5. THE COSMIC BARYON DENSITY

The amount of baryons required in a given cosmological scenario to produce the observed opacity of the Lyman forest can be computed (Weinberg et al 1997) under general assumptions. A lower-bound to the cosmic baryon density can be derived from the mean Lyman-α flux decrement, $\overline{D}$,(Oke & Korcyansky 1982) and/or from the distribution of the Lyman-α optical depths. The limits derived from the effective optical depths measured in the UVES spectra at $1.5 < z < 4$ are reported in Tab. 1. They are consistent with the BBN value for a low D/H primordial abundance. Most of the baryons reside in the Lyman forest at $1.5 < z < 4$ with little change in the contribution to Ω as a function of z. Conversely,

TABLE 1

LOWER LIMITS TO $\Omega_B H^{1.5}$ DERIVED FROM THE UVES SPECTRA AT $1.5 < Z < 4$ (FOR A UNIVERSE WITH $\Omega_M = 0.3, \Omega_\Lambda = 0.7$)

UVB	$T = 2 \cdot 10^4$ K	$T = 6 \cdot 10^3$ K
QSOs	0.017	0.011
QSOs + GALs ($f_{esc} = 0.1$)	0.028	0.018

given the observed opacity, a higher UVB requires a higher Ω_b. As pointed out by (Haehnelt et al. 2001), an escape fraction as large as 0.4, as measured by Steidel, Pettini & Adelberger (2001), would result in an $\Omega_b \sim 0.06$ in conflict either with the primordial D/H abundance or, in general, with the BBN or with the Lyman-α opacity measurements.

6. THE TEMPERATURE OF THE IGM

If the Lyman-α forest is in thermal equilibrium with the metagalactic UV background, the line width of the absorption lines, described by the b parameter of the Voigt profile, is directly related to the gas temperature of the absorbing medium determined by the balance between adiabatic cooling and photo-heating: $b = \sqrt{2kT/m_{ion}}$. Additional sources of broadening exist, such as the differential Hubble flow across the absorbers, peculiar motions, Jeans smoothing. However, there is a lower limit to the line widths, set by the temperature of the gas, that is in principle measurable. In practice the situation is slightly more complex because for a photoionized gas there is a temperature-density relation, the so-called equation of state: $T = T_0\,(1+\delta_b)^{\gamma_T - 1}$, where T is the gas temperature, T_0 is the gas temperature at the mean gas density, δ_b is the baryon over-density, $(\rho_b - \overline{\rho}_b)/\overline{\rho}_b$ and γ_T is a constant which depends on the ionization history. The equation of state translates into a lower cutoff $b_c(N_{HI})$ in the N_{HI}–b distribution.

The observed cut-off Doppler parameter at a fixed column density of $\log_{N_{HI}} = 13.6$, $b_c(13.6)$ is measured to increase with decreasing redshift, while the slope of the cutoff does not change significantly. A typical value of $b_c \sim 18$ km s^{-1} at $1.5 < z < 4$ corresponds to a reference temperature of $2 \cdot 10^4$K. This does not mean that the temperature of the IGM increases with decreasing z: on the contrary, taking into account the equation of state and the fact that a given column density corresponds to higher and higher over-densities with decreasing redshift, it turns out that the temperature at the mean density is actually decreasing with decreasing z. Furthermore, evidence has been found (Theuns et al. 2002) for a general increase of the temperature around redshift $z = 3.3 \pm 0.15$, attributed to the reionization of HeII. Temperature and ionization fluctuations are also expected due to feedback processes from the formation of galactic structures (Theuns, Mo & Schaye 2001) and might have ocurred (Kim, Cristiani & D'Odorico 2001).

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