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NUMERICAL SIMULATIONS OF THE INTERGALACTIC MEDIUM

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RESUMEN

El medio intergaláctico a corrimientos al rojo entre 2 y 6 se puede estudiar observacionalmente gracias a los rasgos de absorción que produce en el espectro de los cuasares de fondo. La mayoría de las líneas de absorción UV aparecen en regiones ligeramente más densas, que pueden ser modeladas de manera fiable con las simulaciones hidrodinámicas actuales. La comparación del espectro observado con el simulado nos permite poner límites a los parámetros del modelo.

ABSTRACT

The intergalactic medium at redshifts 2–6 can be studied observationally through the absorption features it produces in the spectra of background quasars. Most of the UV-absorption lines arise in mildly overdense regions, which can be simulated reliably with current hydrodynamical simulations. Comparison of observed and simulated spectra allows one to put contraints on the model's parameters.

Key Words: **COSMOLOGY: OBSERVATIONS — COSMOLOGY: THEORY — GALAXIES: FORMATION — INTERGALACTIC MEDIUM — QUASARS: ABSORPTION LINES**

1. GENERAL

Spectra of quasars contain hundreds of absorption lines, which arise in the mostly smoothly distributed intergalactic medium (IGM) along the line of sight. Most of the lines are due to the absorption by neutral hydrogen, which produces the quasar's 'Lyman-α forest' (Lynds 1971; see Rauch 1998 for a recent review), but transitions of other elements such as C IV, N V and O VI are seen as well (e.g. Cowie et al. 1995).

A fully neutral IGM would block all quasar light below the Lyα- transition, and so the fact that some flux is observed implies that the IGM is very highly ionized (Gunn & Peterson 1965; Bahcall & Salpeter 1965). At redshifts $z \lesssim 3$, quasars produce enough ionizing photons to explain the inferred high ionization levels (e.g. Rauch et al. 1997), but their dwindling numbers at higher redshifts suggest that galaxies must make-up an increasingly important contribution to the background at higher z. The nature of the sources responsible for reionizing the universe is still being debated, as is the epoch of reionization. The recent observations of redshift $z \sim 6$ quasars with a significant stretch of Lyα-forest with zero flux to within the noise (Becker et al. 2001; Djorgovski et al. 2001), are consistent with a detection of the transition from a neutral to a highly ionized IGM.

Hydrodynamical simulations of hierarchical structure formation in a cold dark matter (CDM) dominated universe, have been very successful in reproducing the statistical properties of the observed Lyα-absorption, in the redshift range $0 \lesssim z \lesssim 4$ (see e.g. Efstathiou, Schaye & Theuns 2000 for a recent review). These simulations show that the weaker Lyα-lines are predominantly produced in the filamentary and sheet-like structures that form naturally in this cosmology. These structures have modest densities $0.3 \lesssim \rho/\langle\rho\rangle \lesssim 10$, and so can be reliably simulated, and semi-analytical (Bi & Davidsen 1997) and analytical models (Schaye 2001) provide valuable insight into the dominant processes that shape the lines.

The ionizing radiation photo-heats the gas, and establishes a density-temperature relation $T = T_0(\rho/\langle\rho\rangle)^{\gamma-1}$ (Hui & Gnedin 1997). The gas temperature $T_0(z)$ and the exponent $\gamma(z)$ retain a memory of the reionization history, because the thermal time-scales are long in the low-density IGM (Miralda-Escudeé & Rees 1994; Haehnelt & Steinmetz 1998). The widths of the Lyα-lines can be used to measure T_0 and γ (Schaye et al. 1999). Wavelets provide another way to characterize changes in line-widths (Theuns & Zaroubi 2000). Finally, the mean level of absorption depends on T_0, and this can be exploited as well to search for a sudden change in T_0 which could arise from the epoch of He II reionization (Miralda-Escudé & Rees 1994; Theuns et al. 2002c).

The metals detected in the IGM were presumably synthesized in stars, and later expelled into the surroundings by galactic winds. This process is cur-

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rently not well understood, and difficult to simulate (see e.g. Mac Low & Ferrara 1999), because of the complexity of the interstellar medium in galaxies (McKee & Ostriker 1977). Preliminary simulations of such winds indicate that they can indeed pollute the IGM with enough metals to reproduce the data, without significantly changing the properties of the hydrogen absorption lines (Theuns et al. 2002d).

Section 2 briefly summarizes the current status of IGM simulations, Section 3 discusses constraints on reionization and Section 4 illustrates the effects of galactic winds.

2. SIMULATIONS

Structure formation in a CDM-dominated cosmology is characterized by a set of numbers, namely the density of matter, vacuum-energy and baryons, the Hubble constant h, the amplitude of the power spectrum, and the helium abundance. Recently, most simulations have used small variations around a popular set of $(\Omega_m, \Omega_b h^2, h, \sigma_8, Y)$=(0.3,0.019,0.65,0.9,0.24), and assumed a geometrically flat universe.

Once these numbers are chosen, the linear power spectrum can be computed (e.g. using CMBFAST, Seljak & Zaldarriaga 1996), and a representation of a random realization of such a density field using particles can be generated using the Zel'dovich (1970) approximation. The equations of motion are then integrated into the non-linear regime (see e.g. Efstathiou et al. 1985).

Baryons can be added in a variety of ways, using Smoothed Particle Hydrodynamics (e.g. Hernquist et al. 1996; Haehnelt & Steinmetz 1996; Wadsley & Bond 1996; Theuns et al. 1998), or finite-difference schemes (e.g. Cen & Ostriker 1992; Zhang, Anninos & Norman 1995; Bryan et al. 1999). In addition, the evolution of the ionizing background needs to be specified, either estimated from the simulation itself, or computed separately (e.g. Haardt & Madau 1996) and imposed by hand. Given a UV-background, the photo-ionization equations determine the abundances of ionized hydrogen, helium (and other species). Non-equilibrium effects are important during reionization (Abel & Haehnelt 1999), and need to be modeled separately.

Mock spectra are computed along random sight lines through the simulation box (e.g. Theuns et al. 1998), which can be made to look like observed low or high-resolution spectra by convolving them with a Gaussian to mimic a given spectral resolution, and adding noise (see Theuns, Schaye & Haehnelt 2000 for details). These mock spectra are then analyzed

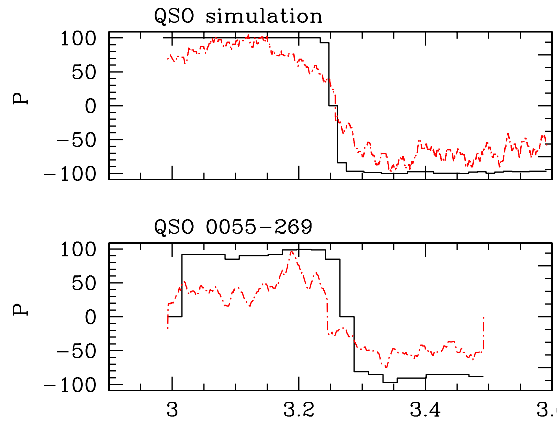

Fig. 1. Application of the wavelet method to a simulated spectrum (top panel) and QSO 0055–269 (bottom panel). In the simulations, the low redshift half is 50 per cent hotter than the high redshift half. This jump is detected at the 99.5 per cent level. A similar jump is seen in the observed spectrum.

with the same tools as the data, e.g. using VPFIT[3] (Webb 1987) to fit Voigt profiles to the absorption features.

3. THE THERMAL HISTORY OF THE IGM AND REIONIZATION

In the simulations, the line-widths of the hydrogen Lyα-lines depend on temperature, in the sense that thermal broadening introduces a cut-off in the line-widths for given column-density (Schaye et al. 1999). Such a cut-off is also clearly seen in observational samples (Kirkman & Tytler 1997). The relation between temperature and cut-off can be calibrated with simulations, and hence the thermal history can be reconstructed (Schaye et al. 2000; Ricotti, Gnedin & Shull 2000; Bryan & Machacek 2000; McDonald et al. 2001). Schaye et al. (2000) found evidence for an increase in T_0 around redshift $z \sim 3$, which they interpreted as evidence for He II reionization. Normal stars do not produce photons that are hard enough to ionize He II, and so the reionization epoch for H I and He II can be quite different, if H I reionization is due to galaxies.

Theuns et al. (2002a) used wavelets as basis functions to characterize Lyα-forest spectra. The amplitude of a narrow wavelet is a measure of the typical widths of the absorption features, and so a change in temperature – as might result from He II reionization – would lead to a change in rms amplitude

[3] http://www.ast.cam.ac.uk/~rfc/vpfit.html

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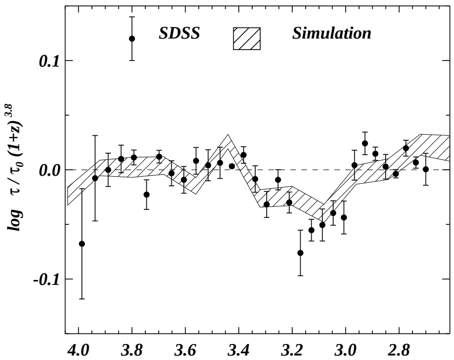

Fig. 2. Deviation of the effective optical depth from a power-law evolution, $\bar{\tau}_{\rm eff}/(1+z)^{3.8}$, for the SDSS data smoothed on 3000km s^{-1}(symbols with error bars) and a hydrodynamical simulation of a ΛCDM model, in which He II reionization starts at $z = 3.4$ (hashed region). The temperature increase associated with He II reionization causes $\bar{\tau}_{\rm eff}$ to drop below the power-law evolution in the simulation. This characteristic dip matches the feature detected in the SDSS data very well .

of the wavelet. Wavelets have the advantage over Voigt profile fitting that the wavelet spectrum of a given signal is unique, since wavelets form an orthogonal basis. In addition, the decomposition into wavelets is extremely fast. Figure 1 shows a measure of the wavelet amplitude for a simulated spectrum in which T_0 increases by 50 per cent at redshift $z = 3.3$ (wavy line), and for the spectrum of quasar 0055–269. There is strong evidence for a sharp increase in T_0 in the observed spectrum. The significance of a given amplitude is denoted by the histogram-like full line (see Theuns et al. 2002a for details). The significance level of the temperature change is more than 99 per cent.

Such a temperature change will also influence the mean absorption $\exp(-\bar{\tau}_{\rm eff})$ in the Lyα-forest. This is because the neutral hydrogen fraction is determined by the balance between photo-ionizations and recombinations, and the recombination coefficient depends on temperature. Figure 2 compares the predicted evolution of the effective optical depth, $\bar{\tau}_{\rm eff}$, with the evolution measured from the Sloan Digital Sky Survey by Bernardi et al. (2002). The good agreement suggests that He II re-ionization has been detected in the SDSS data set (Theuns et al. 2002c).

If this interpretation is correct, then the high values of T_0 inferred above $z \sim 4$, imply that hydrogen reionized relatively late (Theuns et al. 2002b). Figure 3 illustrates how T_0 drops rapidly after H I reionization, and how this can be used to constrain the H I reionization epoch to be below a redshift of 9. If

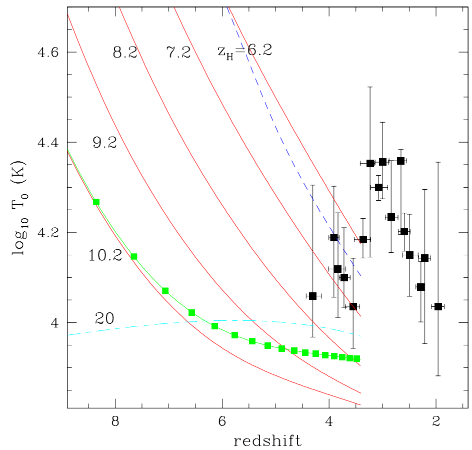

Fig. 3. The temperature evolution of the IGM above redshift 3.4. Symbols with error bars are determined from QSO observations by Schaye et al. (2000). The solid curves indicate the evolution of the temperature at the mean density for various assumed H I reionization redshifts $z_{\rm H}$, as indicated. The post-hydrogen reionization temperature is assumed to be $T_0 = 6 \times 10^4$ K and the hydrogen photo-ionization rate is $\Gamma_{\rm H\,I} = 10^{-13}$ s^{-1} (the short dashed line has $\Gamma_{\rm H\,I} = 10^{-14}$ s^{-1}). The He II photo-ionization rate is adjusted so that the He III abundance $x_{\rm He\,III} \approx 0.1$ at $z = 3.5$. The solid line connecting filled squares is for $z_{\rm H} = 10.2$, and a higher He II photo-ionization rate, $x_{\rm He\,III}(z = 3.5) = 0.6$. Finally, the long dashed line has $z_{\rm H} = 20$, but a still higher He II photo-ionization rate, $x_{\rm He\,III}(z = 3.5) = 0.95$. If, as expected, He is mostly singly ionized at $z \gtrsim 3.5$, then the rapid decrease in T_0 after reionization places an upper limit of $z_{\rm H} < 9$ on the redshift of hydrogen reionization.

H I reionization happened at $z > 9$, then T_0 would have decreased (due to adiabatic expansion) below the values measured around $z \sim 4$.

4. METALS IN THE IGM

Feedback from star formation is thought to play an important role in the formation of galaxies. Observations of star-bursts, both at low and high redshift, show evidence for strong galactic winds with a mass-loss rate comparable to the star-formation rate. Such winds could be responsible for enriching the IGM with metals. Most strong Lyα-lines have associated C IV absorption, and at least at lower z, O VI as well (Carswell, Schaye & Kim 2002). At present it is not clear whether only regions close to galaxies are metal enriched, or if most of the IGM contains metals.

It has been suggested that these metals may have been distributed by an early generation of popula-

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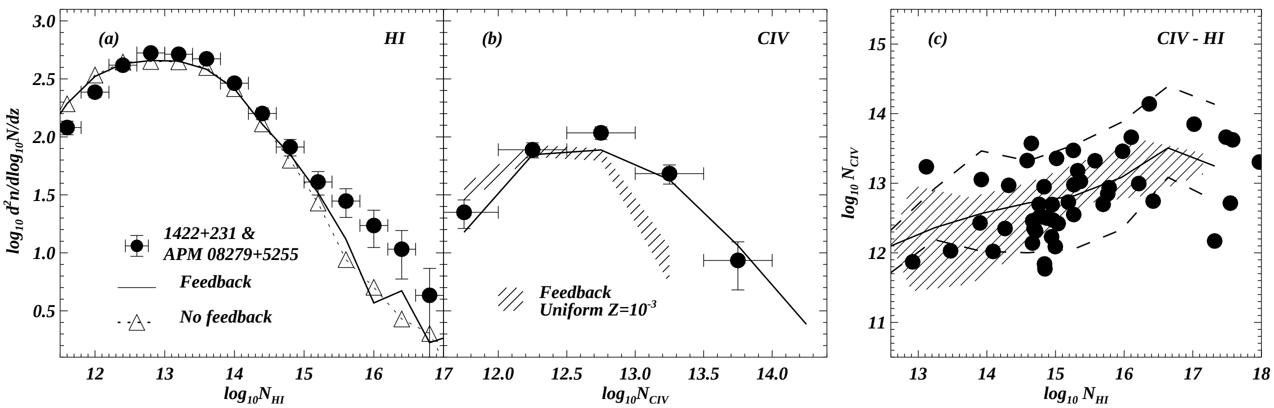

Fig. 4. Column density distribution functions (CDDFs) of H I (panel a), C IV (panel b), and the C IV versus H I column density of systems (panel c). Filled circles refer to the combined-line lists of quasars Q1422+231 (Ellison et al. 2000; $z_{\rm em} = 3.6$) and APM 08279+5255 ($z_{\rm em} = 3.91$), and the solid line indicates the results for the feedback simulation at $z = 3$. Panel (a): The H I CDDF of the feedback simulation is nearly identical to that of the simulation without feedback (dotted line and triangles), and both fit the observations very well for $\log N_{HI} \lesssim 15$. Panel (b): The feedback simulation matches the observed C IV CDDF, but imposing a uniform metallicity ($Z = 10^{-3} Z_\odot$, hashed region) does not work as well. Panel (c): C IV versus H I column density, for systems identified on a smoothing scale of ± 150km s^{-1}. The median for the feedback simulation is indicated with the full line, with dashed lines indicating the 5 and 95 percentiles. The hatched region is the corresponding range for the uniform metallicity case. The feedback simulation reproduces the observed median and scatter better than the uniform Z case.

tion III stars at very high redshifts. One of the arguments for this pre-enrichment scenario is the suspicion that galactic winds at lower redshifts, if they were sufficiently volume-filling to produce the required pollution with metals, would destroy the filaments that produce the Lyα-forest.

We have performed simulations of the IGM in order to investigate this question (Theuns et al. 2002d). In these simulations, star formation generates hot regions that expand in the form of a metal enriched wind. This feedback implementation strongly quenches the star formation rate. Crucially, there is almost no difference in the properties of the Lyα-lines between this simulation and a similar simulation without feedback. This is because the hot bubbles prefer to expand into the lower density surroundings of the galaxies, thereby leaving intact, the filaments that produce most of the H I lines, and because the volume filling factor of the winds is small. The metal enriched gas produces about the observed number of C IV lines, and the same large scatter between H I and C IV column-density as is observed (Fig. 4). It will be interesting to examine in more detail whether the statistics of the simulated metal lines agree with the data.

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