The low-redshift evolution of the Lyman-α Forest

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ABSTRACT
The low-redshift evolution of the intergalactic medium is investigated using hydrodynamic cosmological simulations. The assumed cosmological model is a critical density cold dark matter universe. The imposed uniform background of ionizing radiation has the amplitude, shape and redshift evolution as computed from the observed quasar luminosity function by Haardt & Madau. We have analysed simulated Lyman-α spectra using Voigt-profile fitting, mimicking the procedure with which quasar spectra are analysed. Our simulations reproduce the observed evolution of the number of Lyman-α absorption lines over the whole observed interval of z = 0.5 to z = 4. In particular, our simulations show that the decrease in the rate of evolution of Lyman-α absorption lines at z ≤ 2, as observed by Hubble Space Telescope, can be explained by the steep decline in the photo-ionizing background resulting from the rapid decline in quasar numbers at low redshift.

Key words: cosmology: theory – hydrodynamics – large-scale structure of universe – quasars: absorption lines

1 INTRODUCTION
Neutral hydrogen in the intergalactic medium produces a forest of Lyman-α absorption lines blueward of the Lyman-α emission line in quasar spectra (Lynds 1971). Observations of quasars at redshifts z > 2 show that there is strong cosmological evolution in the number of Lyman-α lines, which can be characterised by a power law dN/dz ∝ (1 + z)γ (Sargent et al. 1980), where N is the number of lines above a threshold rest-frame equivalent width W (typically W > 0.32 Å).

Studies at high resolution using the Keck telescope find γ = 2.78 ± 0.71 for 2 < z < 3.5 (e.g. Kim et al. 1997). At even higher z the evolution is still stronger: Williger et al. (1994) find γ > 4 for z > 4 using the CTIO 4m telescope. In contrast at low redshifts, observations using the Hubble Space Telescope find much less evolution, γ = 0.48±0.62 for z < 1 (Morris et al. 1991, Bahcall et al. 1991, 1993, Impey et al. 1996).

Recently, hydrodynamic simulations of hierarchical structure formation in a cold dark matter (CDM) dominated universe have been shown to be remarkably successful in reproducing this Lyman-α forest in the redshift range z = 4 → 2 (Cen et al. 1994, Zhang, Anninos & Norman 1995, Miralda-Escudé et al. 1996, Hernquist et al. 1996, Wadsley & Bond 1996, Zhang et al. 1997, Theuns et al. 1998). These simulations show that the weaker Lyman-α lines (neutral hydrogen column density NH ≤ 10¹⁴ cm⁻²) are predominantly produced in the filamentary and sheet-like structures that form naturally in this structure formation scenario. Velocity structure in these lines is often due to residual Hubble flow since many of the absorbing structures are expanding. In contrast, the stronger lines (NH > 10¹⁶ cm⁻²) tend to occur when the line of sight passes near a dense virialised halo.

Over the redshift range investigated in these simulations a photo-ionizing background close to that inferred from quasars (Haardt & Madau 1996) is required to explain the properties of the Lyman-α forest. In fact, although most simulations have assumed a critical density, scale-invariant CDM universe, other variants of the CDM model provide acceptable fits with relatively small changes to the ionizing background (Cen et al. 1994, Miralda-Escudé et al. 1996). The general success of CDM-like models in explaining the high redshift (z ≥ 2) properties of the Lyman-α forest is impressive.

In this Letter we investigate using hydrodynamic simulations whether a CDM universe with a photo-ionizing background dominated by quasars can explain the observed transition in the cosmological evolution of the number of Lyman-α lines at z ≤ 2.

2 SIMULATION
We model the evolution of a periodic, cubical region of a critical density Einstein-de Sitter universe (Ω = 1, ΩΛ = 0). We use a simulation code based on a hierarchical P3M implementation (Couchman 1991) for gravity and smoothed

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particle hydrodynamics (Lucy 1977, Gingold & Monaghan 1977, see e.g. Monaghan 1992 for a review) for hydrodynamics (Theuns et al. 1998). The comoving size of the simulation box is \( L/(2h) \) Mpc, where the Hubble constant today is written as \( H_0 = 100h \) km s\(^{-1}\) Mpc\(^{-1}\). We will assume \( h = 0.5 \) throughout and describe simulations with \( L = 5.5 \) and 22.22 Mpc. A fraction \( \Omega_B h^2 = 0.0125 \) of the matter density is assumed to be baryonic, consistent with limits from nucleo-synthesis (Walker et al. 1991, but note the continuing debate on the deuterium abundance derived from quasar matter linear transfer function from Bardeen et al. 1997).

For the starting redshift \( z = 0 \) we use the fit to the cold dark matter linear transfer function from Bardeen et al. (1986) and normalise it such that the linearly extrapolated value of \( \sigma_8 = 0.7 \) at the present day. These simulations use \( 64^3 \) particles of either species hence the gas mass resolutions are \( 1.5 \times 10^8 M_\odot \) and \( 2.2 \times 10^8 M_\odot \) for \( L = 22.22 \) and \( L = 5.5 \) Mpc, respectively.

Gas in these simulations is ionized and photo-heated by an imposed uniform background of ionizing photons assumed to originate from quasars as computed by Haardt & Madau (1996). This flux is redshift dependent, mimicking the evolution of the quasar luminosity function. Gas can also cool by interacting with microwave background photons and through collisional cooling. The detailed rates for all these processes as a function of temperature are taken from Cen & Madau (1996). This flux is redshift dependent, mimicking the evolution of the quasar luminosity function.

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The effective mean optical depth \( \bar{\tau} \) from the simulations, with this set of parameters, is significantly lower than the observed value. Consequently, we have reduced the amplitude \( \Gamma_{\text{HI}} \) of the ionizing radiation given by Haardt & Madau (1996) by a factor of two. Here, \( \Gamma_{\text{HI}} \) is the amplitude of the radiation spectrum at the hydrogen Lyman edge. Since \( \bar{\tau} \) scales approximately as \( \tau \propto (\Omega_B h^2)^{2/3} h \Gamma_{\text{HI}} \) (Rauch et al. 1997), we would obtain the same results by keeping the original value of \( \Gamma_{\text{HI}} \) from Haardt & Madau but increase \( \Omega_B h^2 \) from 0.0125 to 0.0177, which is still well within the range allowed by nucleo-synthesis.

At several output times we compute simulated spectra along lines of sight through the simulation box. Each spectrum is convolved with a Gaussian with FWHM = 8 km s\(^{-1}\), then re-sampled onto pixels of width 3 km s\(^{-1}\) to mimic the instrumental profile and characteristics of the HIRES spectrograph on the Keck telescope. Artificial noise is introduced by adding a Gaussian random signal with zero mean, and standard deviation \( \sigma = 0.02 \) to every pixel (i.e. a SNR of 50 for pixels at the continuum). The absorption lines in these mock observations are then fitted with Voigt profiles using an automated version of VPFIT (Carswell et al. 1987).

### 3 RESULTS AND DISCUSSION

We show in figure 1 examples of simulated spectra at \( z = 3, 2, 1 \) & 0.5 for the \( L = 22.22 \) Mpc lower resolution simulation. Fluctuations in neutral hydrogen density, caused by gas tracing dark matter potential wells, produce absorption features similar to those in observed spectra. At low redshifts, there are large regions of the spectrum with very low absorption. These regions are separated by prominent absorption features, most of which are just a single strong line. At higher redshifts, there is considerable absorption over most of the spectrum and many lines are blended. Many of the strong lines at \( z = 0.5 \) can be traced back to higher redshifts. There is a clear decrease in the comoving number of lines with decreasing redshift.

The evolution of the column density distribution with redshift is illustrated in figure 2. There is clear evolution in the simulated column density distribution with redshift. The rate of change depends on column density, with higher column density lines undergoing stronger evolution leading to steepening of the distribution. At \( z = 2 \), the column density distribution is \( \propto N_{\text{HI}}^{-1.6} \) whereas this has steepened to...
The rate of evolution also depends on redshift, with considerably stronger evolution at higher redshifts. The number of weak Lyman-α lines ($\lesssim 10^{13.1}$ cm$^{-2}$) remains approximately constant. At redshifts 3 and 2, there is good agreement between the simulated column density distribution for our higher resolution simulation ($L = 5.5$ Mpc) and the observed one.

The drop in the number of lines with redshift can be quantified by counting the number of lines within a given column density range. The simulation results are compared to observations in figure 3. The simulations reproduce well the number of lines at a given redshift for all three column density cuts. Crucially, they also match very well the observed number of lines at low redshift. Consequently, the hierarchical picture of galaxy formation in a cold dark matter universe, coupled with the observed evolution in the quasar luminosity function, can explain the observed evolution of the number of Lyman-α lines over the entire observed redshift range.

We have re-analysed the $z = 0.5$ output time after increasing the imposed ionization flux from its $z = 0.5$ value to the value appropriate to $z = 2$. The number of lines with $10^{13.77}$ cm$^{-2} \lesssim N_{\text{HI}} \lesssim 10^{16}$ cm$^{-2}$ is shown by the open pentagon in figure 3. This point falls onto the extrapolation for the number density evolution for $z \geq 2$. Consequently, the dominant reason for the higher number of lines at low $z$ compared to what would be expected by extrapolation from high $z$, is the decrease in ionizing flux from $z = 2$ to $z = 0$, itself a consequence of the evolution of the quasar luminosity function.

An estimate of the reliability of these simulations can be obtained by comparing the two simulations run at different resolutions. The higher resolution simulation produces more lines at all column densities, but the difference between the two simulations is well within the error bars of the observational results. This gives us confidence that we can reliably predict the number of lines from these simulations.

In summary: our numerical simulations show that the properties of the Lyman-α forest are in excellent agreement with what is expected in a cold dark matter universe with a photo-ionizing background dominated by quasar light. In particular, our simulations show that the observed decrease

\[ \propto N_{\text{HI}}^{-2.1} \] at $z = 0.5$ (see figure 3). The rate of evolution also depends on redshift, with considerably stronger evolution at higher redshifts. The number of weak Lyman-α lines ($\lesssim 10^{13.1}$ cm$^{-2}$) remains approximately constant. At redshifts 3 and 2, there is good agreement between the simulated column density distribution for our higher resolution simulation ($L = 5.5$ Mpc) and the observed one.

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Figure 2. Evolution of the column density distribution with redshift, for $z = 3, 2, 1, 1.5$ and 0.5. Distributions for $z = 2$ and $z = 3$ are from the higher resolution ($L = 5.5$ Mpc) simulation, the others are for the lower resolution ($L = 22.22$ Mpc) simulation. Observational data from Hu et al. (1995, HKCSR), Petitjean et al. (1993, PWRCL) and Kim et al. (1997, KHCS) are shown for comparison, and their mean redshifts are indicated. Sca lings $d^2N/dz/dN_{\text{HI}} \propto N_{\text{HI}}^{-1.6}$ and $N_{\text{HI}}^{-2.1}$ are shown.

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