Dependences of QSO Ly$\alpha$ absorption line statistics on cosmological parameters

Tom Theuns,$^1$* Anthony Leonard,$^2$ Joop Schaye$^1$ and George Efstathiou$^1$

$^1$Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
$^2$Department of Physics, Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH

Accepted 1998 December 21. Received 1998 December 14; in original form 1998 September 28

ABSTRACT

We have performed high-resolution hydrodynamic simulations of the Ly$\alpha$ forest in a variety of popular cold dark matter dominated cosmologies, including a low density and a vacuum-dominated model. The fluctuation amplitude of these models is chosen to match the observed abundance of galaxy clusters at low redshift. We assume that the intergalactic medium is photoionized and photoheated by a uniform ultraviolet background with the required amplitude to give the observed mean hydrogen absorption. We produce simulated spectra, analyse them by fitting Voigt profiles and compare line statistics with those obtained from high-resolution observations. All models give column density distributions in good agreement with observations. However, the distribution of line widths (the $b$-parameter distribution) reflects differences in the temperature of the intergalactic medium between the models, with colder models producing more narrow lines. All the models with a low baryon density, $Q_b h^2 \approx 0.0125$, are too cold to produce a $b$-parameter distribution in agreement with observations. Models with a higher baryon density, $Q_b h^2 = 0.025$, are hotter and provide better fits. Peculiar velocities contribute significantly to the line widths in models with low matter density, and this improves the agreement with observations further. We briefly discuss alternative mechanisms for reconciling the simulations with the observed $b$-parameter distributions.

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

1 INTRODUCTION

Neutral hydrogen in the intergalactic medium produces a forest of Ly$\alpha$ absorption lines blueward of the Ly$\alpha$ emission line in quasar spectra (Bahcall & Salpeter 1965; Gunn & Peterson 1965). Hydrodynamic simulations of hierarchical structure formation in a cold dark matter (CDM) dominated universe have been shown to be remarkably successful in reproducing a variety of properties of the observed forest (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, Leonard & Efstathiou 1998a; Theuns et al. 1998b; Davé et al. 1998; Bryan et al. 1998). The simulations show that the weaker Ly$\alpha$ lines (neutral hydrogen column density $N_{H\text{I}} \approx 10^{14}$ cm$^{-2}$) are predominantly produced in the filamentary and sheet-like structures that form naturally in this structure formation scenario. Higher column density lines occur where the line of sight intersects a halo.

These models assume that the intergalactic medium (IGM) is photoionized and photoheated by ultraviolet (UV) light from quasars. The characteristic break in the rate of evolution of the number of lines below a redshift $z \approx 1.7$, as observed by the Hubble Space Telescope, can then be explained by the decrease in the intensity of this ionizing background, itself a consequence of the rapid decline in quasar numbers towards lower redshifts (Theuns et al. 1998a; Davé et al. 1998).

While the first simulations showed good agreement with the observed line statistics, more detailed studies at higher numerical resolution in a standard CDM universe produced a larger fraction of narrow lines than are observed (Theuns et al. 1998b; Bryan et al. 1998). Theuns et al. suggested that an increase in temperature of the IGM might broaden the absorption lines sufficiently to improve the agreement with observations. A higher gas temperature leads to more thermal broadening and in addition increases the Jeans mass. At low redshifts, the temperature of the gas responsible for the majority of Ly$\alpha$ lines is determined by the balance between adiabatic cooling and photoheating. This causes the gas temperature to be a function of density, and this ‘equation of state’ is well approximated by a power law, $T = T_0 (1 + \delta)^{-1}$, where $\delta$ is the gas overdensity (Hui & Gnedin 1997). $T_0$ can be made higher by

*Present address: Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85740 Garching, Germany.
increasing the photoheating rate, or by heating the gas for longer by increasing the age of the universe. The first can be achieved by increasing the baryon density $\Omega_b h^2$, the latter by decreasing the matter density $\Omega_m$. Using some simplifying assumptions, Hui & Gnedin (1997) obtain the scaling
\[ T_0 \propto \left( \frac{\Omega_b h^2}{\Omega_m h^2} \right)^{1/2+1/2}. \]
Increasing $\Omega_b h^2$ by a factor 2 and using $\Omega_m = 0.3$ instead of 1 increases $T_0$ by a factor $\geq 2$, which might be sufficient to obtain agreement with observations.

In this Letter we use high-resolution hydrodynamic simulations to investigate the dependence of the $b$-parameter distribution on cosmological parameters, for a given reionization history. This complements the work of Haehnelt & Steinmetz (1998), who quantified the dependence of the $b$-parameter distribution on the reionization history, for a critical density universe.

## 2 SIMULATION

We have simulated six different cosmological models, characterized by their total matter density $\Omega_m$, the value of the cosmological constant $\Omega_{\Lambda}$, the rms of mass fluctuations in spheres of $8h^{-1}$ Mpc, $\sigma_8$, the baryon density $\Omega_b h^2$ and the present-day value of the Hubble constant, $H_0 = 100h \text{ km s}^{-1}\text{Mpc}^{-1}$. The parameters for these models are summarized in Table 1. Note that the Sb, Ob and Lb models have a baryon density slightly higher than the value $\Omega_b h^2 = 0.0193 \pm 0.0014$, advocated by Burles & Tytler (1998) from measurements of the deuterium abundance in quasar spectra. Rauch et al. (1997) required a similarly high value $\Omega_b h^2 \approx 0.017$ in order to make the measured flux decrement of the Ly$\alpha$ forest consistent with the observed intensity of ionizing photons from quasars.

We model the evolution of a periodic, cubical region of the universe of comoving size $2.5h^{-1}$Mpc. The code is used based on a hierarchical P3M implementation (Couchman 1991) for gravity and smoothed particle hydrodynamics (SPH; Lucy 1977; Gingold & Monaghan 1977, see e.g. Monaghan 1992 for a review) for hydrodynamics. It is a hybrid between the HYDRA code of Couchman, Thomas & Pearce (1995) and the APMSPH code, which were described in detail in Theuns et al. (1998b). In particular, we use the APMSPH method for consistently computing SPH densities for particles in underdense regions. These simulations use 64$^3$ particles of each species, so the SPH particle masses are $1.65 \times 10^8 (\Omega_b h^2/0.0125) (h/0.5)^{-2} \text{M}_\odot$ and the CDM particles are more massive by a factor $\Omega_{DM}/\Omega_b$. This resolution is sufficient to simulate linewidths reliably (Theuns et al. 1998; note that numerical convergence will be even better in the hotter simulations). The simulations of Bryan et al. (1998) indicate that the absence of long waves will produce a small, but for our purposes unimportant, underestimate of the widths of the absorption profiles. All our simulations were run with the same initial phases to minimize cosmic variance when comparing the different models.

### Table 1. Models simulated.

| Name | $\Omega_m$ | $\Omega_{\Lambda}$ | $\sigma_8$ | $\Omega_b h^2$ | $h$ | $\Gamma_H$ |
|------|------------|-------------------|-----------|---------------|----|-----------|
| 1    | S          | 1                 | 0         | 0.5           | 0.0125 | 0.5 | HM/2     |
| 2    | O          | 0.3               | 0         | 0.85          | 0.0125 | 0.65 | HM/2     |
| 3    | L          | 0.3               | 0.7       | 0.90          | 0.0125 | 0.65 | HM/2     |
| 4    | Sb         | 1                 | 0         | 0.50          | 0.025  | 0.5  | HM       |
| 5    | Ob         | 0.3               | 0         | 0.85          | 0.025  | 0.65 | HM       |
| 6    | Lb         | 0.3               | 0.7       | 0.90          | 0.025  | 0.65 | HM       |

We assume that the IGM is ionized and photoheated by an imposed uniform background of UV photons that originate from quasars, as computed by Haardt & Madau (1996). This flux is redshift dependent, due to the evolution of the quasar luminosity function. Haardt & Madau (1996) give two fits to the hydrogen ionization rate $\Gamma_H$, as a function of redshift. We have used their $q_0 = 0.5$ fit for the critical density models and their $q_0 = 0.1$ fit for the open ones. This amplitude of the flux is indicated as HM in the $\Gamma_H$ column of Table 1. In addition, for the low $\Omega_b h^2$ models, we have divided the ionizing flux by two, indicated as HM/2. The dependence on $q_0$ reflects small differences in the completeness corrections of the observed quasar luminosity functions and is relatively unimportant for the simulations described here. The detailed expressions for the heating and cooling rates as a function of temperature and ionizing flux are taken from Cen (1992) with some minor modifications (Theuns et al. 1998). Our analysis differs slightly from that in Theuns et al. in that we do not impose thermal equilibrium but solve the rate equations to track the abundances of $H_1$, $H_2$, $H_3$, $H_4$, $H_5$ and $\text{He}^+$. We assume a helium abundance of $Y = 0.24$ by mass.

We have used cmbfast (Seljak & Zaldarriaga 1996) to compute the linear matter transfer function for each model. The amplitude of the transfer function is normalized to the observed abundance of galaxy clusters at $z = 0$ using the fits $\sigma_8 = 0.52\Omega_m^{0.46+0.13}$ for $\Omega_m = 0$ and $\sigma_8 = 0.52\Omega_m^{0.52+0.13}$ for $\Omega_m = 1 - \Omega_m$, as computed by Eke, Cole & Frenk (1996).
At several output times we compute simulated spectra along lines of sight through the simulation box. Each spectrum is convolved with a Gaussian with full width at half maximum of FWHM = 8 km s\(^{-1}\), then re-sampled on to pixels of width 3 km s\(^{-1}\) to mimic the instrumental profile and characteristics of the HIRES spectrograph on the Keck telescope. We rescale the background flux in the analysis stage such that the mean effective optical depth at a given redshift in all models is the same as for the Ob model. The latter model has a mean absorption in good agreement with observations (Ob has \(\bar{\tau}_{\text{eff}} = 0.93, 0.33\) and 0.14 at \(z = 4, 3\) and 2). Finally, we add to the flux in every pixel a Gaussian random signal with zero mean and standard deviation \(\sigma = 0.02\) to mimic noise. We fit the continuum of the spectra using the method described in Theuns et al. (1998b). The absorption features in these mock observations are then fitted with Voigt profiles using an automated version of VPFIT (Carswell et al. 1987).

3 RESULTS AND DISCUSSION

A comparison between the observed and simulated column density distribution functions (CDDFs) is shown in Fig. 1. The CDDFs for the different models are almost indistinguishable and in addition are...
very similar to the observed distribution at both redshifts 2 and 3. In principle, the slope of the CDDF is sensitive to the amplitude of the mass fluctuations on small scales (e.g. Gnedin 1998). Fig. 1 then shows that demanding consistency of the model with the observed abundance of galaxy clusters at $z = 0$ automatically guarantees good agreement with the observed CDDF, for the CDM dominated cosmological models examined here.

The distribution of linewidths for the different models is compared with observation in Fig. 2. We have selected those lines with column density $N_{\text{HI}} > 10^{13} \text{ cm}^{-2}$ that have an estimated error from vpfit $b_{\text{err}} < 0.25 b$. For the data we have applied the same column density cut, and used the published uncertainties in $b$ for each fitted Ly$\alpha$ line, where available.

The models have different temperature–density relations at $z = 4$, yet all of them provide $b$-parameter distributions which are in good agreement with the observed distribution at this redshift. However, at $z = 3$ there is a significant overproduction of narrow lines in all models with $\Omega_b h^2 = 0.0125$, compared to the data. The models with the higher value $\Omega_b h^2 = 0.025$ agree much better with the observed $b$-distribution, although the critical density $S_b$ model still peaks at lower values than the observed distribution. The open models $O_b$ and $L_b$, on the other hand, produce $b$-parameter distributions which fit the observed distribution reasonably well. At redshift $z = 2$, the quality of the data is lower since the Keck spectrograph becomes less efficient in the blue. The high baryon models produce $b$-parameter distributions which fit the observed distribution at $z = 2$ better than the low $\Omega_b h^2$ models. Again, the critical density model peaks at significantly lower $b$ than the observed distribution.

We illustrate the main reasons for the cosmology dependence of the $b$-parameter distribution in Fig. 3. We have recomputed simulated spectra for model $S$ after imposing the equation of state of the significantly hotter model $O_b$. We did this by increasing the temperature of SPH particles when they were cooler than the temperature given by the required equation of state. We then rescaled the flux so that the mean decrement was again the same as for the $O_b$ model. Comparing this new model $S$-hot with $S$ and $S_b$, we see that the main reason for the broader lines in $S_b$ as compared to $S$ is the higher temperature of the IGM in model $S_b$. However, the $b$-distribution of model $S$-hot still peaks at lower values than that of model $O_b$. The reason for the remaining differences is the contribution of peculiar velocities to the linewidth for model $O_b$, as shown in Fig. 3. Model $O_b$-vel is identical to model $O_b$, except that we have put all peculiar velocities to zero. This increases the fraction of narrow lines and the $b$-distribution of this new model is almost identical to that of models $S_b$ and $S$-hot. The right panel in Fig. 3 shows that neglecting peculiar velocities in model $S_b$ decreases the fraction of narrow lines for this cosmology, as shown by model $S_b$-vel. Consequently, the open model $O_b$ has broader lines than the critical model $S_b$ because of the different way that peculiar velocities contribute to line broadening between the two models. The effects of peculiar velocity are similar in models $L_b$ (not shown) and $O_b$.

In summary, we have investigated the properties of the simulated Ly$\alpha$ forest in three popular cosmologies (critical, open and vacuum-dominated) and compared simulated spectra analysed in terms of Voigt profiles with observations. When the power spectrum is normalized to the abundance of galaxy clusters and the amplitude of the ionizing background is normalized to match the observed mean absorption, then all investigated models produce column density distributions which are well matched to the observations, at $z = 2$ and 3. However, the distribution of $b$-parameters is sensitive to the baryon density as well as to the matter density of the universe. Models with a higher baryon density $\Omega_b h^2$ are hotter and hence the increased thermal broadening and Jeans smoothing shift the $b$-parameter distribution towards larger $b$ values, providing a better fit to the observations. Peculiar velocities contribute significantly to the broadening of absorption lines with column density $N_{\text{HI}} \sim 10^{13} \text{ cm}^{-2}$, in low matter density models. This broadening improves the agreement with observations further. In contrast, peculiar velocities narrow the lines in a critical density universe. The $b$-distributions for our open and vacuum-dominated models with $\Omega_m = 0.3$ are almost identical. Of all our simulated models, the one that fits best has $\Omega_b h^2 = 0.025$ and $\Omega_m = 0.3$ and produces significantly more broad lines than the other models, yet there is a hint that the observed distribution has an even larger fraction of broad lines. It is not clear whether the present data are sufficiently reliable that this is a real discrepancy. For example, some of the remaining differences may be a result of differences in the Voigt profile-fitting procedures between vpfit and HKCSR or owing to uncertainties in the continuum fitting (Rauch et al. 1993), although it seems unlikely that these effects would be large enough to reconcile our model with the data. If the discrepancy is real, then it is possible that feedback from e.g. star formation, not included in this investigation, might contribute to broadening the lines. Alternatively, a larger contribution from helium heating than assumed in our model might be required to boost the temperature further.

ACKNOWLEDGMENTS

AL thanks PPARC for the award of a research studentship, JS thanks the Isaac Newton Trust, St John’s College and PPARC for support and GE thanks PPARC for the award of a senior fellowship. We also thank M. Haehnelt for many stimulating discussions and R. Carswell for helping us with vpfit.

REFERENCES

Bahcall J. N., Salpeter E. E., 1965, ApJ, 142, 1677
Bryan G. L., Machacek M., Anninos P., Norman M. L., 1998, preprint (astro-ph/9805340)
Burles S., Tytler D., 1998, ApJ, 499, 699
Carswell R. F., Webb J. K., Baldwin J. A., Atwood B., 1987, ApJ, 319, 709
Cen R., 1992, ApJS, 78, 341
Cen R., Miralda-Escudé J., Ostriker J. P., Rauch M., 1994, ApJ, 437, L83
Couchman H. M. P., 1991, ApJ, 368, L23
Couchman H. M. P., Thomas P. A., Pearce F. P., 1995, ApJ, 452, 797
Davé R., Hernquist L., Katz N., Weinberg D., 1998, preprint (astro-ph/9807177)
Eke V. R., Cole S., Frenk C. S., 1996, MNRAS, 282, 263
Gingold R. A., Monaghan J. J., 1977, MNRAS, 181, 375
Gnedin N., 1998, MNRAS, 299, 392
Gunn J. E., Peterson B. A., 1965, ApJ, 142, 1633
Haardt F., Madau P., 1996, ApJ, 461, 20
Haehnelt M., Steinmetz M., 1998, MNRAS, 298, L21
Hernquist L., Katz N., Weinberg D., Miralda-Escudé J., 1996, ApJ, 457, L51
Hu E. M., Kim T., Cowie L. L., Songaila A., Rauch M., 1995, AJ, 110, 1526
(HKCSR)
Kim T., Hu E. M., Cowie L. L., Songaila A., 1997, AJ, 114, 1 (HKCS)
Hui L., Gnedin N., 1997, MNRAS, 292, 27
Lu L., Sargent W. L. W., Womble D. S., Takada-Hidai M., 1996, ApJ, 472, 509
Lucy L. B., 1977, AJ, 82, 1023
Miralda-Escudé J., Cen R., Ostriker J. P., Rauch M., 1996, ApJ, 471, 582
Monahan J. J., 1992, ARA&A, 30, 543
Petitjean P., Webb J. K., Rauch M., Carswell R. F., Lanzetta K., 1993, MNRAS, 262, 499 (PWRC)
Rauch M., Carswell R. F., Webb J. K., Weymann R. J., 1993, MNRAS, 260, 589
Rauch M. et al., 1997, ApJ, 489, 7
Seljak U., Zaldarriaga M., 1996, ApJ, 469, 437
Theuns T., Leonard A., Efstathiou G., 1998a, MNRAS, 297, L49
Theuns T., Leonard A., Efstathiou G., Pearce F. R., Thomas P. A., 1998b, MNRAS, 301, 478
Wadsley J., Bond J. R., 1996, in Clarke D., West M., eds, ASP Conf. Ser. Vol. 123, Computational Astrophysics, Proc. 12th Kingston Conference, Halifax, October 1996. Astron. Soc. Pac., San Francisco
Zhang Y., Anninos P., Norman M. L., 1995, ApJ, 453, L57
Zhang Y., Anninos P., Norman M. L., Meiksin A., 1997, ApJ, 485, 496

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.