Probing Galaxies through Quasar Absorption Lines
Proceedings IAU Colloquium No. 199, 2005
P.R. Williams, C. Shu, and B. Ménard, eds.

DOI: 00.0000/X000000000000000X

Constraints on the metagalactic hydrogen ionization rate from the Lyman-α forest opacity

James S. Bolton[1], **Martin G. Haehnelt**[1], **Matteo Viel**[1] **and Volker Springel**[2]

[1]Institute of Astronomy, University of Cambridge, Madingely Road, Cambridge, CB3 0HA, UK

[2]Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, Garching bei München, Germany

Abstract. Understanding the sources responsible for reionizing the Universe is a key goal of observational cosmology. A discrepancy has existed between the metagalactic hydrogen ionization rate, $\Gamma_{\rm HI}$, predicted by early hydrodynamical simulations of the Lyman-α forest if scaled to appropriate assumptions for the IGM temperature, when compared to values predicted from the proximity effect. We present new estimates for $\Gamma_{\rm HI}$ in the redshift range $2 < z < 4$ based on hydrodynamical simulations of the Lyman-α forest opacity. Within the current concordance cosmology, and assuming updated QSO emissivity rates, a substantial contribution to the UV background from young star-forming galaxies appears to be required over the entire redshift range. Our results are consistent with lower-end estimates from the proximity effect. It is also found that the errors on the ionization rate are dominated by uncertainties in the thermal state of the intergalactic medium and the r.m.s fluctuation amplitude at the Jeans scale.

Keywords. methods: numerical, hydrodynamics, diffuse radiation, intergalactic medium, quasars: absorption lines

1. Introduction

The series of low column density ($10^{12.5} < N_{\rm HI} < 10^{14.5}$ cm^{-2}) Lyα absorption features seen blue-ward of the Lyα emission line in high redshift quasi-stellar object (QSO) spectra trace the distribution of neutral hydrogen in the intergalactic medium (IGM). This forest of absorption lines provides a unique, unbiased probe of the thermal and ionization history of the IGM along the QSO line-of-sight. This has motivated many authors to use hydrodynamical simulations of structure formation, calibrated to reproduce the observed properties of the forest obtained from high resolution QSO spectra, to infer the amplitude of the metagalactic UV background (see the seminal paper by Rauch *et al*. 1997, and most recently Tytler *et al*. 2004). Consequently there are a wide range of estimates for the hydrogen ionization rate per atom, $\Gamma_{\rm HI}$, inferred from the Lyα forest opacity using numerical simulations with different assumptions. This complicates the comparison with determinations of the ionization rate from estimates of the integrated emission from observed QSOs and/or galaxies (*e.g.* Haardt & Madau 1996, hereafter HM96; Madau, Haardt & Rees 1999) and estimates using the proximity effect (*e.g.* Scott et al. 2000) which both also have rather large uncertainties. Furthermore, Steidel *et al*. (2001), in a study of Lyman break galaxies at $z \simeq 3.4$, suggested that the intensity of the ionizing background may be a factor of a few larger than in the model of HM96 due to a large contribution from star-forming galaxies.

We discuss new estimates of the metagalactic hydrogen ionization rate presented in Bolton *et al.* (2005), inferred from state-of-the-art hydrodynamical simulations of the Lyα forest. These estimates are consistent with a substantial contribution from galaxies to the amplitude of the UV background at the hydrogen ionization edge, and are in agreement with other observational estimates of the dimensionless quantity $\Gamma_{-12} = \Gamma_{\rm HI}/10^{-12}{\rm s}^{-1}$.

2. Numerical code and convergence

We use a suite of 21 high resolution hydrodynamical simulations run using a new version of GADGET (Springel, Yoshida & White, 2001) to investigate in detail the dependence of $\Gamma_{\rm HI}$ on physical and numerical parameters (for a detailed description of the simulations see Bolton *et al.* 2005). The cosmological parameters for our adopted fiducial model are:

$$(\Omega_{\rm m}, \Omega_{\rm b}h^2, h, \sigma_8) = (0.26 \pm 0.04, 0.024 \pm 0.001, 0.72 \pm 0.04, 0.85 \pm 0.05),$$

consistent with the results of Spergel et al. (2003), assuming a flat, vacuum energy dominated cosmological model. We assume $n = 0.95$ and a helium mass fraction of $Y = 0.24$. In addition, we adopt fiducial values for the thermal state of the gas at mean cosmic density; $T_0 = [11200, 17800, 12500] \pm 5000$ K at $z = [2, 3, 4]$ and $\gamma = 1.3 \pm 0.3$ for the index of the gas effective equation of state (Hui & Gnedin 1997), based on the results of Schaye *et al.* (2000). We linearly rescale the opacity of the artificial Lyα forest spectra we construct to match the central values for the Lyα forest effective optical depth taken from the fitting formula of Schaye *et al.* (2003): $\tau_{\rm eff} = [0.130 \pm 0.021, 0.362 \pm 0.036, 0.805 \pm 0.070]$. We treat the amplitude of the UV background as a free parameter, so rescaling the neutral hydrogen opacity corresponds to linearly rescaling the hydrogen ionization rate by the same amount.

We initially run 7 simulations of our fiducial model with differing box size and resolution to assess the degree of numerical convergence. We find simulations with less than 400^3 gas particles within a $30h^{-1}$ comoving Mpc box do not achieve adequate numerical convergence. We take our fiducial model to have 200^3 gas particles within a $15h^{-1}$ comoving Mpc box; we estimate the value of Γ_{-12} we infer will be systematically high by around 8 per cent due to the combined error from box size and resolution.

3. Scaling relations for Γ_{-12} from simulated absorption spectra

When inferring Γ_{-12} from hydrodynamical simulations and subsequently rescaling with different parameters, it is generally assumed that (*e.g* Rauch *et al.* 1997):

$$\Gamma_{-12} \propto \Omega_{\rm b}^2 h^3 T^{-0.7} \Omega_{\rm m}^{-0.5}. \tag{3.1}$$

It is implicit in this relation that the density and velocity distribution, along with the effective equation of state of the Lyα absorbers remain unchanged for different values of $\Omega_{\rm b}$, h, $\Omega_{\rm m}$, T and Γ_{-12}. We test the validity of equation 3.1 using 14 simulations in addition to our fiducial model, by varying the parameters T, $\Omega_{\rm m}$ and σ_8 in each run. We also rescale to different values for the temperature-density relation index γ and the effective optical depth in post-processing. We do not discuss the scaling with $\Omega_{\rm b}$ and h, since our analysis revealed that equation 3.1 holds extremely well for these parameters.

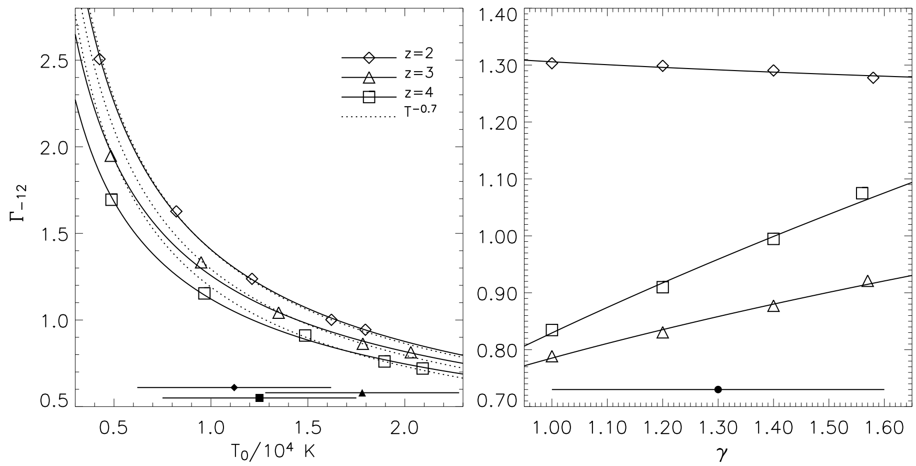

Figure 1. *Left:* The dependence of Γ_{-12} on the gas temperature at mean density T_0 at the three different redshifts indicated on the plot. Solid curves show a least squares fit and the dotted curves shows the $T^{-0.7}$ scaling due to the temperature dependence of the recombination coefficient. The filled symbols show the fiducial temperatures and their uncertainties. *Right:* The dependence of Γ_{-12} on the index of the temperature density relation γ. The filled circle shows our fiducial value of γ and its uncertainty.

Table 1. The redshift dependent indices from our scaling relation of Γ_{-12} with several cosmological and astrophysical parameters.

	T	γ	$\Omega_{\rm m}$	σ_8	$\tau_{\rm eff}$
z	$x_1(z)$	$x_2(z)$	$x_3(z)$	$x_4(z)$	$x_5(z)$
2	-0.68	-0.04	-1.00	-0.90	-1.44
3	-0.62	0.34	-1.04	-0.99	-1.61
4	-0.59	0.55	-1.16	-1.26	-1.68

Figures 1 and 2 and Table 1 summarise the main results of this study. We find that Γ_{-12} scales around our fiducial model as:

$$\Gamma_{-12} \propto \Omega_{\rm b}^2 h^3 T^{x_1(z)} \gamma^{x_2(z)} \Omega_{\rm m}^{x_3(z)} \sigma_8^{x_4(z)} \tau_{\rm eff}^{x_5(z)}, \tag{3.2}$$

where we tabulate the indices of equation 3.2 in Table 1. We stress that this scaling relation is likely to be somewhat model dependent and should not be applied to models with parameters very different from our fiducial model without further checks. However, it does provide a clear picture of the degeneracies which exist between Γ_{-12} and other parameters within our simulations, and is independent of assumptions about the gas distribution, effective equation of state and ionized gas fraction of the low density IGM. In particular, the Lyα optical depth at fixed r.m.s. fluctuation amplitude σ_8 is more strongly dependent on $\Omega_{\rm m}$ than equation 3.1 suggests due to changes in the gas density distribution. Thermal broadening also produces a deviation from the scaling of equation 3.1 for temperature, although this change is much less dramatic. Consequently, we urge caution when using equation 3.1, especially if comparing models with differing $\Omega_{\rm m}$. We also find

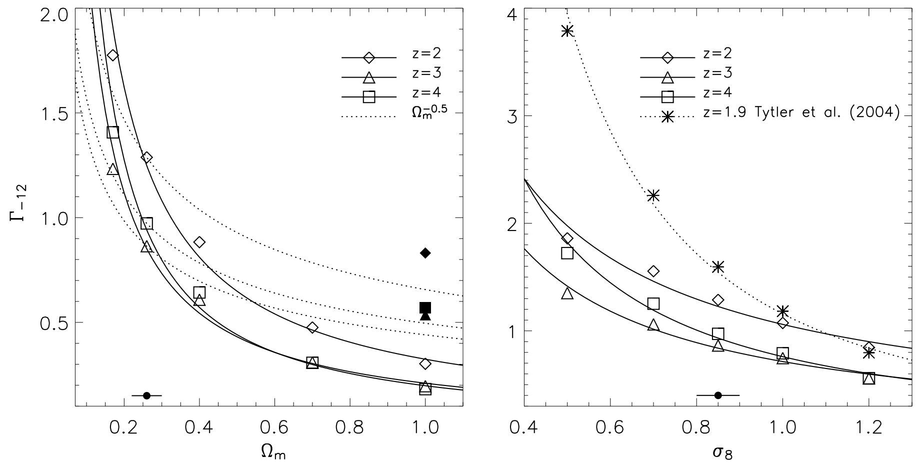

Figure 2. *Left:* The dependence of the estimated Γ_{-12} on $\Omega_{\rm m}$ for the three different redshifts indicated on the plot. The solid curves are a least-square fit. The dotted lines show the $\Omega_{\rm m}^{-0.5}$ scaling. Filled points are obtained for a model with $\Omega_{\rm m} = 1.0$ and the the same r.m.s. fluctuation amplitude at a scale of 30 $\rm kms^{-1}$ as our fiducial model. The filled circle shows our fiducial value of $\Omega_{\rm m} = 0.26$ and its uncertainty. *Right:* The dependence of Γ_{-12} on σ_8. The dotted curve shows the result of Tytler et al. at $z = 1.9$, assuming $\langle F\rangle_{\rm obs} = 0.882 \pm 0.01$. The filled circle shows our fiducial value of σ_8 and its uncertainty

a strong dependence of Γ_{-12} on the effective optical depth of the Lyα forest which the simulated spectra are scaled to match.

4. Results

Using our scaling relations, we estimate the error on the values of Γ_{-12} from our fiducial simulation using the uncertainties on our fiducial parameter values taken from the literature. The error budget is listed in Table 2. We find the largest contribution is from the uncertainty in the gas temperature. There is also a large contribution from the uncertainty in the effective optical depth, especially at $z = 2$. Interestingly, the uncertainty in $\Omega_{\rm m}$ also gives a substantial contribution to the total error budget. This is primarily due to the sensitivity of Γ_{-12} on $\Omega_{\rm m}$ due to changes in the r.m.s. fluctuations of the gas density at the Jeans scale. Other uncertainties are less important, in particular $\Omega_{\rm b}h^2$, σ_8 and h. Using our fiducial model, we find the Lyα effective optical depth of the IGM at $z = [2, 3, 4]$ is reproduced by $\Gamma_{-12} = [1.29\pm^{0.80}_{0.46}, 0.86\pm^{0.34}_{0.26}, 0.97\pm^{0.48}_{0.33}]$.

We compare our results with other observational estimates of Γ_{-12} in fig. 3. The filled triangles show the metagalactic hydrogen ionization rate computed from the updated UV background model of Madau, Haardt & Rees (1999), hereafter MHR99 (Francesco Haardt, private communication), based on the contribution from QSOs and re-processing by the IGM (*e.g.* HM96). Our data appear to be inconsistent with the IGM being kept ionized by QSOs at $z \leqslant 4$. For comparison, the filled squares give Γ_{-12} calculated using the QSO rate above, plus an additional source in the form of Young Star Forming Galaxies (YSFGs). These ionization rates are in good agreement with our results, suggesting that a substantial contribution from galaxies appears to be required at all redshifts.

Constraints on Γ_{-12} from the proximity effect measurements of Scott *et al.* (2000) are shown by the hatched box. Our results are consistent with the lower end of these

Table 2. Percentage error budget for Γ_{-12} from estimates of various cosmological and astrophysical parameters, listed approximately in order of importance. The total error is obtained by adding the individual errors in quadrature.

Parameter	$z = 2.00$	$z = 3.00$	$z = 4.00$
T	$^{+50}_{-22}$	$^{+23}_{-14}$	$^{+35}_{-18}$
$\Omega_{\rm m}$	$^{+18}_{-13}$	$^{+19}_{-14}$	$^{+21}_{-15}$
$\tau_{\rm eff}$	$^{+29}_{-19}$	$^{+18}_{-14}$	$^{+17}_{-13}$
Numerical	±10	±10	±10
γ	±1	$^{+7}_{-9}$	$^{+12}_{-13}$
$\Omega_{\rm b}h^2$	$^{+9}_{-8}$	$^{+9}_{-8}$	$^{+9}_{-8}$
σ_8	$^{+6}_{-5}$	±6	$^{+8}_{-7}$
h	±6	±6	±6
Total	$^{+62}_{-36}$	$^{+39}_{-30}$	$^{+49}_{-34}$

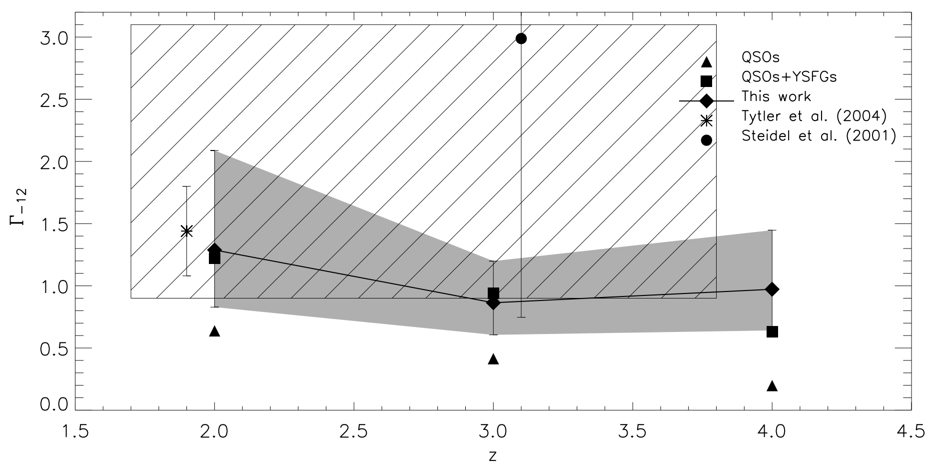

Figure 3. Comparison of our best estimate for Γ_{-12} at $z = [2, 3, 4]$ with constraints from observations. Our data are plotted with filled diamonds, and the grey shaded area shows the error bounds. The filled squares and triangles show the estimated contribution to the metagalactic ionization rate from QSOs+galaxies and QSOs alone, based on estimates from the updated model of Madau, Haardt & Rees (1999) including UV photons from re-processing by the IGM. The hatched box gives the constraint on Γ_{-12} from the proximity effect (Scott *et al.* 2000) and the estimate from Lyman-break galaxies assuming a global spectral index of $\alpha = 1.8$ is plotted with a filled circle (Steidel *et al.* 2001). The data point has been offset from $z = 3$ for clarity, and the upper error limit is not shown. The star shows the best estimate of Γ_{-12} at $z = 1.9$ from Tytler *et al.* (2004), including their errors from the uncertainty in $\tau_{\rm eff}$, σ_8 and $\Omega_{\rm b}$.

estimates. The filled circle gives the Γ_{-12} we calculate assuming a spectral index of $\alpha = 1.8$ using the metagalactic ionizing radiation intensity inferred from Lyman-break galaxies (Steidel *et al.* 2001). Finally we also plot the value of Γ_{-12} inferred by Tytler *et al.* in their study of the Lyα forest at $z = 1.9$. The error bars include the uncertainties in $\tau_{\rm eff}$, σ_8 and $\Omega_{\rm b}$, based on scaling from their hydrodynamical simulations. Our data is in reasonable agreement with the Tytler et al. result, allowing for differences between the exact gas temperatures and numerical method.

5. Conclusions

In recent years, compelling observational evidence has led to the acceptance of a standard cosmological model which is flat, has low matter density and a substantial contribution of vacuum energy to the total energy density. Within this 'concordance' cosmological model the current generation of hydrodynamical simulations predict values for the metagalactic hydrogen ionization rate, required to reproduce the effective Lyα optical depth of the IGM in the range $z = 2 - 4$, which are about a factor of four larger than those in an Einstein-de Sitter model with the same r.m.s. density fluctuation amplitude σ_8. The ionization rates estimated from the Lyα forest opacity are more than a factor two larger than estimates from the integrated flux of optically/UV bright observed QSOs alone. This discrepancy increases with increasing redshift. We confirm the findings of Tytler et al. (2004) at $z \sim 1.9$ that the estimated ionization rates from simulations of a ΛCDM concordance model are in reasonable agreement with the estimates of the integrated ionizing flux from observed QSOs plus a significant contribution from galaxies as in the model of MHR99. The estimates of the ionization rate are also in agreement with the lower end of the range of values from the proximity effect. This new agreement appears to be in part due to the currently favoured low value of $\Omega_{\rm m}$, which increases the required value of $\Gamma_{\rm HI}$, and more accurate measurements of the Lyα forest opacity. We also find that the uncertainty on the magnitude of $\Gamma_{\rm HI}$ inferred from simulations is greater than previously estimated, with the primary contribution to this error coming from the temperature of the low density gas in the IGM. Better constraints on the thermal history of the IGM are required. Additional physics such as radiative transfer, galactic feedback and metal enrichment may need to be incorporated into simulations in a more realistic fashion. However, our estimate of the error on Γ_{-12} most likely accounts for the modest changes expected from these processes, suggesting we have obtained a consistent constraint on the metagalactic hydrogen ionization rate.

Acknowledgements

We are grateful to Francesco Haardt for making his updated UV background model available to us. The simulations were run using the Altix 3700 supercomputer COSMOS at the Department of Applied Mathematics and Theoretical Physics in Cambridge. COSMOS is a UK-CCC facility which is supported by HEFCE and PPARC. We acknowledge support from the European Community Research and Training Network "The Physics of the Intergalactic Medium", NSF Grant No. PHY99-07949 and PPARC. JSB and MV also thank the IAU for financial assistance.

References

Bolton J.S., Haehnelt M.G., Viel M. & Springel V. 2005, *MNRAS* 357, 1178
Haardt F. & Madau P. 1996, *ApJ* 461, 20
Hui L. & Gnedin N. 1997, *MNRAS* 292, 27
Madau P., Haardt F. & Rees M.J. 1999, *ApJ* 585, 34
Rauch M. *et al.* 1997, *ApJ* 489, 7
Schaye J., Theuns T., Rauch M., Efstathiou G. & Sargent W.L.W. 2000, *MNRAS* 318, 817
Schaye J., Aguirre A., Kim T.-S.,Theuns T., Rauch M & Sargent W.L.W. 2003, *ApJ* 596, 768
Scott J., Bechtold J., Dobrzycki A. & Kulkarni V.P. 2000, *ApJS* 130, 67
Spergel D.N. *et al.* 2000, *ApJS* 148, 175
Springel V., Yoshida N. & White S.D.M. 2001, *New Astron.* 6, 79
Steidel C.C, Pettini M. & Adelberger K.L. 2001, *ApJ* 546, 665
Tytler D. *et al.* 2004, *ApJ* 617, 1