EVOLUTION OF HI FROM Z=5 TO THE PRESENT

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Abstract

Studies of damped Lyα systems provide us with a good measure of the evolution of the HI column density distribution function and the contribution to the comoving mass density in neutral gas out to redshifts of $z = 5$. The column density distribution function at high redshift steepens for the highest column density HI absorbers, though the contribution to the comoving mass density of neutral gas remains flat from $2 < z < 5$. Results from studies at $z < 2$ are finding substantial numbers of damped absorbers identified from MgII absorption, compared to previous blind surveys. These results indicate that the contribution to the comoving mass density in neutral gas may be constant from $z \sim 0$ to $z \sim 5$. Details of recent work in the redshift range $z < 2$ work is covered elsewhere in this volume (see D. Nestor). We review here recent results for the redshift range $2 < z < 5$.

1. Introduction

Surveys for damped Lyα absorption systems have been driven historically by the desire to detect galaxies in very early stages of evolution, before most of the gas has turned into stars. Because the gas is neutral and at high column densities ($N_{\rm HI} > 10^{20}$ atoms cm^{-2}) it leaves spectroscopic imprints on the light emitted by background QSOs. These absorbers are identified as damped Lyα absorption systems. Previous studies of the evolution of the neutral gas (e.g. Wolfe *et al.* 1986; Lanzetta *et al.*1991; Lanzetta, Wolfe, & Turnshek 1995; Wolfe *et al.*1995; Storrie-Lombardi *et al.* 1996a; Storrie-Lombardi & Wolfe 2000; Rao & Turnshek 2000) their metal abundances (Lu *et al.* 1996; Pettini *et al.* 1997; Prochaska & Wolfe 1999), their dust content (Fall & Pei 1993; Pei & Fall 1995; Pei, Fall & Hauser 1999), and their kinematics (e.g. Prochaska & Wolfe

1997, 1998a, 1998b) provide compelling evidence that damped absorbers are the progenitors of present day galaxies. However, substantial debate continues over exactly which galaxies these are (e.g. Le Brun *et al.* 1997; Haehnelt, Steinmetz & Rauch 1998; Pettini *et al.* 1999; Prochaska & Wolfe 1998a, 1998b; Rao & Turnshek 1998; Salucci & Persic 1999; Turnshek *et al.* 2001).

2. Result 1

The formation epoch for the highest column density damped absorbers is between $3.5 < z < 4$. We detect a statistically significant steepening in the column density distribution function at redshifts $z > 4.0$. This is evidenced by comparing the damped absorbers detected in the redshift range $1.5 < z < 4$ with the those at $z \geq 4$ as shown in the figure 1. This shows the cumulative distribution, normalized by the absorption distance surveyed. A Kolmogorov-Smirnov (K-S) test gives a probability of only 0.006 that the two redshift samples are drawn from the same distribution. The steepening of the distribution function is due to both fewer very high column density absorbers ($N_{\rm HI} \geq 10^{21}$ atoms cm^{-2}) and more lower column density systems ($N_{\rm HI} = 2 - 4 \times 10^{20}$). No damped systems with column densities log $N_{\rm HI} \geq 21$ have yet been detected at $z > 4$.

A single power law, $f(N) = kN^{-\beta}$ does not provide a good fit to the column density distribution function for damped Lyα absorbers. A single power law fit has the additional problem that if $\beta < 2$, as all current estimates indicate, then the total mass in damped systems diverges unless an upper bound to the HI column density is assumed. An alternative parameterization using a gamma function to describe the HI column density distribution was suggested by Pei & Fall (1995) and adopted by SL96b, Storrie-Lombardi & Wolfe 2000, and Peroux *et al.* 2002. We model the data with a gamma distribution of the form

$$f(N,z) = (f_*/N_*)(N/N_*)^{-\beta} e^{-N/N_*} \quad (1)$$

where f_* is the characteristic number of absorbing systems at the column density N_*, and N_* is a parameter defining the turnover, or 'knee', in the number distribution. For $N << N_*$ the gamma function tends to the same form as the single power law, $f(N) \propto N^{-\beta}$; whilst for $N \gtrsim N_*$, the exponential term begins to dominate. We use a maximum likelihood technique to find a solution over a two-dimensional grid of pairs of values of N_* and β.

The results of fits to the data from Peroux *et al.* 2002 in the redshift ranges $2.4 < z < 3.5$ and $z \geq 3.5$, overplotted on the cumulative distribution of absorbers, are shown in figure 2. Data points for the expected

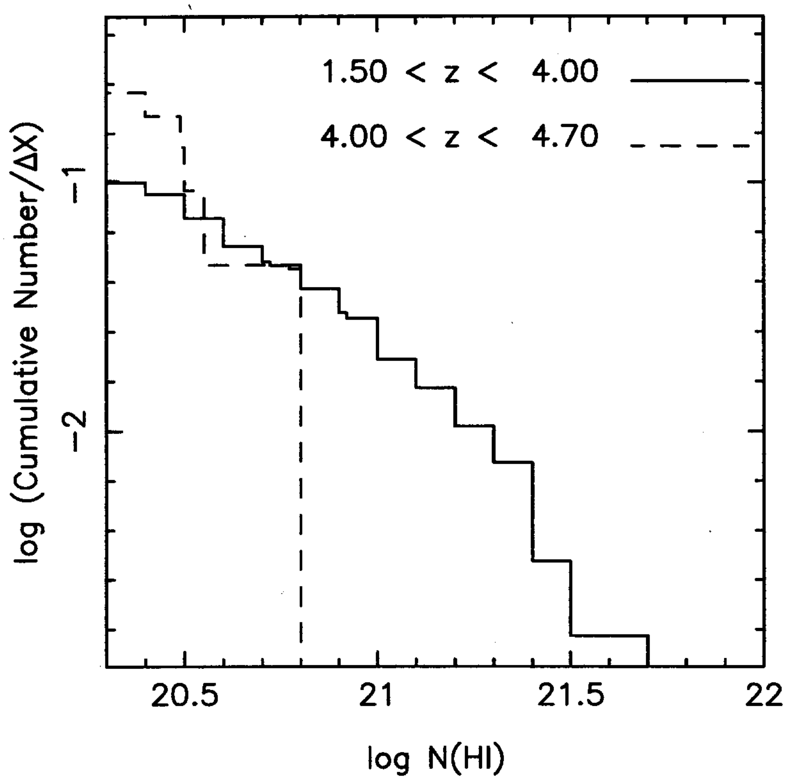

Figure 1 The log of the cumulative number of damped Lyα absorbers versus log column density normalized by the redshift path surveyed, is shown versus log column density for two redshift ranges. The solid lines shows the data for $1.5 < z < 4.0$ and the dashed line shows the data for $z \geq 4.0$. A Kolmogorov-Smirnov (K-S) test gives a probability of only 0.006 that the two redshift samples are drawn from the same distribution (Storrie-Lombardi & Wolfe 1996).

number of Lyman-limit systems that would be detected down to log $N_{\rm HI}$= 17.2 are shown. Lyman-limit systems are defined and detected by the observation of neutral hydrogen (HI) absorption which is optically thick to Lyman continuum radiation for $\lambda < 912$Å, the Lyman limit, corresponding to a column density N(HI)$\geq 1.6\times10^{17}$ cm^{-2} (See Tytler 1982; Sargent, Steidel & Boksenberg 1989; Lanzetta 1991; Storrie-Lombardi *et al.* 1994; Stengler-Larrea *et al.* 1995 for discussions of Lyman Limit systems.) Their contribution is calculated by integrating the number density per unit redshift of Lyman limit systems expected over the redshift path covered by the QSOs in the damped sample. Including the Lyman limit system point provides a longer baseline in column density and allows us to make better estimates of the uncertainties in the fit.

3. Result 2

There is differential evolution with redshift in the number density of lower and higher column density damped absorbers. The highest column density absorbers are disappearing rapidly from $z = 4$ to $z = 1.5$. The number density of absorbers versus redshift, split at a column density of log $N_{\rm HI}$ = 21 is shown in figure 3. The number density of systems with log $N_{\rm HI} > 21$, shown as solid lines, peaks at z $\approx$ 3.5, when the Universe is 15-20% of its present age. These systems then disappear at a much faster rate from z=3.5 to z=1.5 than does the population of damped absorbers as a whole. There is a paucity of very high column density systems at the highest redshifts surveys, which was discussed in result 1. The number density of damped absorbers with column densities log $N_{\rm HI} \leq 21$ decreases from redshifts z $\approx$ 4 to z $\approx$ 3.5 and remains relatively constant towards z = 1.5. The differential evolution with column density suggests:

1 There has been insufficient time at z > 3.5 for the highest column density absorbers to collapse.

2 Once they do form, the highest column density absorbers preferentially form stars before their lower column density counterparts, and hence disappear more rapidly towards lower redshifts.

From the evolution of the HI with redshift alone we are unable to determine if we are watching the evolution of similar systems with redshift or watching some systems disappear and others form.

4. Result 3

The comoving mass density of neutral gas, $\Omega_g(z)$, is not dropping at redshifts $z > 4$. It has been known for some time that $\Omega_g(z)$at

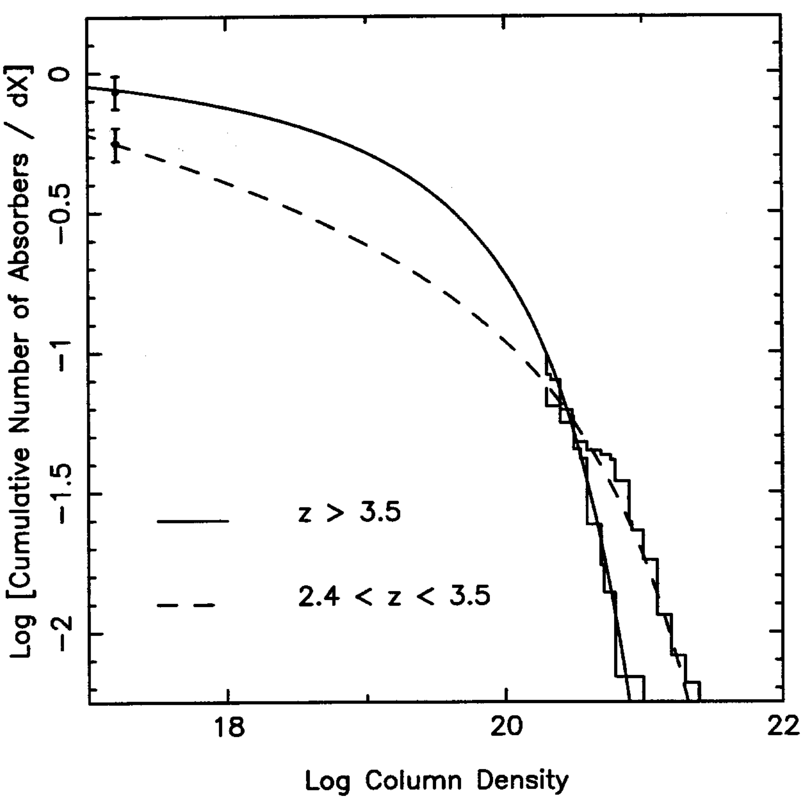

Figure 2 The cumulative number of absorbers per unit absorption distance is plotted in 2 redshift bins. The data points at log $N(HI) = 17.2$ atom cm^{-2} are the *expected number* of LLS derived from the observed number of LLS per unit redshift. The observations are fitted with a Γ-distribution of the form: $f(N,z) = (f_*/N_*)(N/N_*)^{-\beta}\exp(-N/N_*)$.

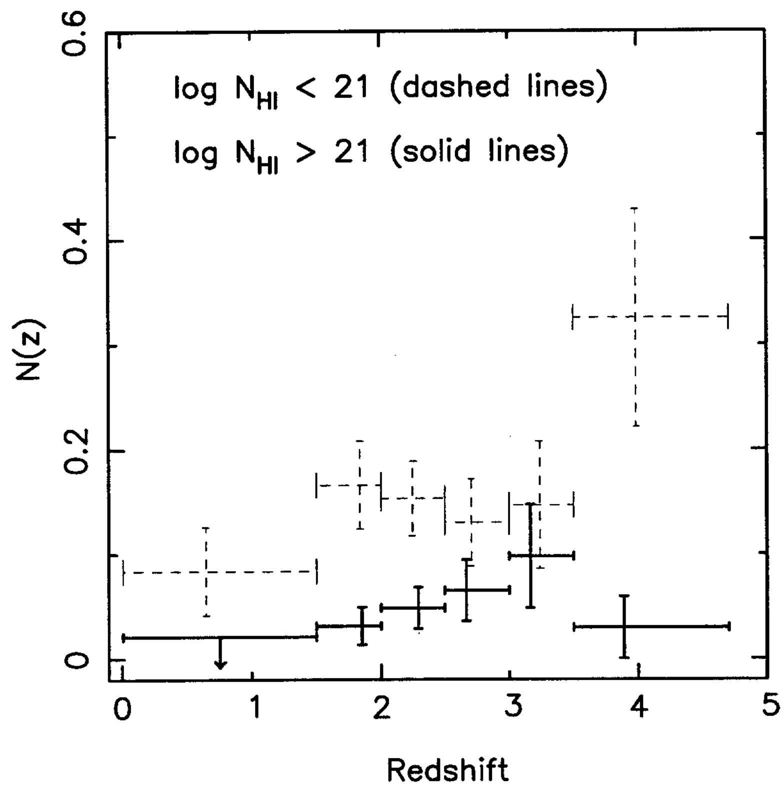

Figure 3 The number density per unit redshift for damped absorbers split into two groups at a column density of log $N_{\rm HI}$ = 21 is shown. The number density of systems with log $N_{\rm HI} > 21$, shown as solid lines, peaks at z $\approx$ 3.5, when the Universe is 15-20% of its present age. These systems then disappear at a much faster rate from z=3.5 to z=1.5 than does the population of damped absorbers as a whole. There is a paucity of very high column density systems at the highest redshifts surveyed. The number density per unit redshift of damped absorbers with column densities log $N_{\rm HI} \leq 21$ peaks at z $\approx$ 4, drops at z $\approx$ 3.5 and remains constant or increases slightly towards z = 1.5.

$z \approx 3$ is comparable to the density of visible matter, i.e. stars in present day galaxies (Ω_*) for an $\Omega = 1$ ($\Lambda = 0$) universe (Rao & Briggs 1993; Wolfe *et al.* 1995; SL96c) but it has taken time to gather enough data to measure the evolution $\Omega_g(z)$ at high redshift. Our estimates of $\Omega_g(z)$ have improved and we now have multiple estimates of Ω_* (Gnedin & Ostriker 1992; Fukugita, Hogan & Peebles 1998; Cole *et al.* 2000).

The first damped Lyα survey to have a substantial high redshift data set hinted at a turnover in $\Omega_g(z)$ at redshifts z > 4 (SL96c), prior to which damped Lyα alpha systems might still be collapsing. The data set analyzed in Storrie-Lombardi & 2000 showed an apparent peak in $\Omega_g$at $3.0 < z < 3.5$, but the uncertainties were still too large to determine the precise shape. The statistics were consistent with a constant value of Ω_g for $2 < z < 4$. The most recent work at high redshift (Peroux *et al.* 2002) shows convincingly that there is no evolution in the *total* amount of neutral gas at $z > 2$. This is shown in figure 4. The high redshift results have been corrected for the HI contribution from absorbers with column densities below the damped system statistical sample threshold. At high redshift, due to the steepening of the column density distribution function, this becomes a correction of nearly a factor of 2.

Combined with the results from Rao & Turnshek 1998, there is no evidence for evolution in $\Omega_g(z)$over the entire redshift range surveyed. One of the most interesting questions generated by these results is how do we reconcile this with the value at $z = 0$ inferred from local HI surveys (Zwaan *et al.* 1997 and Zwaan, this volume).

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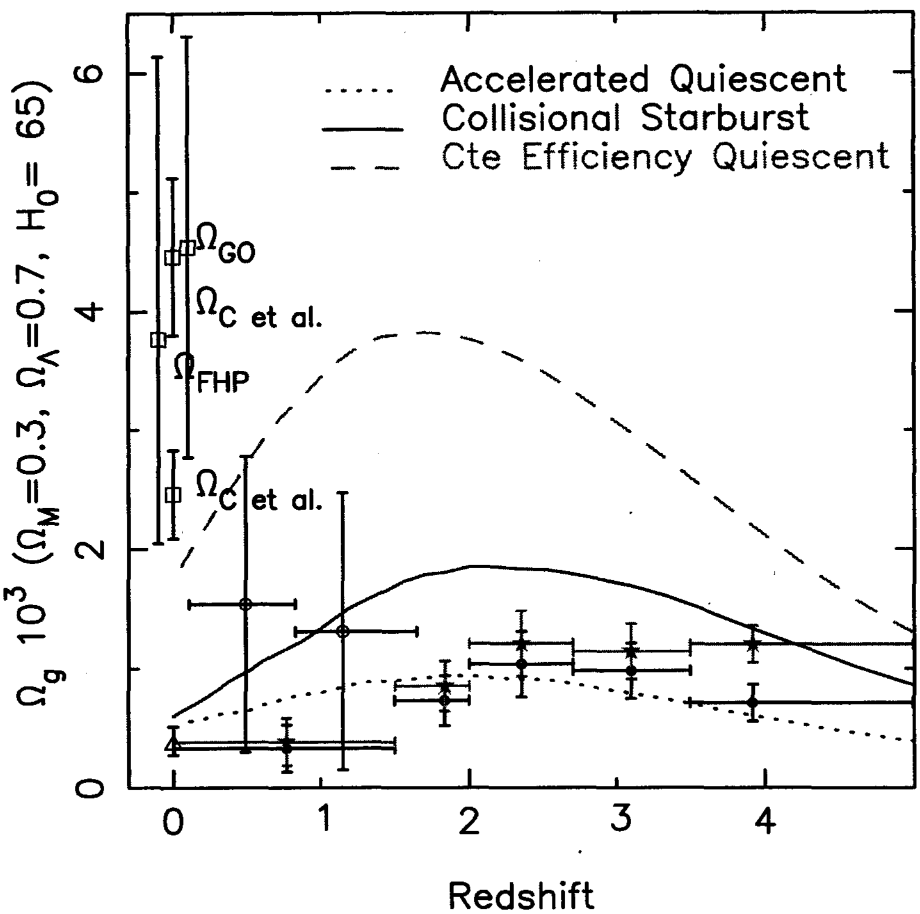

Figure 4 This figure from Peroux *et al.* 2002 shows the comoving mass density in neutral gas, $\Omega_g(z)$, in an $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ and $h = 0.65$ Universe. The vertical error bars correspond to 1-σ uncertainties and the horizontal error bars indicate the bin sizes. The two highest data points at $z < 2$ are the measurements from Rao & Turnshek (2000). The lower data points with dark lines are the uncorrected values. The upper data points with light lines are corrected for the HI contribution from absorbers with column densities below the damped system statistical sample threshold. The triangle at $z = 0$ is the local HI mass measured by Zwaan *et al.* 1997. The squares, Ω_{FHP}, Ω_{GO} and $\Omega_{Cetal.}$ (Fukugita, Hogan & Peebles 1998, Gnedin & Ostriker 1992 and Cole *et al.* 2001 respectively) are $\Omega_{baryons}$ in local galaxies. Semi-analytical models which vary in their recipe for star formation are overplotted (Somerville, Primack & Faber 2000). These represent the cold gas (molecular plus neutral) and thus should lie above the observations.

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