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Evolution of neutral gas at high redshift: implications for the epoch of galaxy formation

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ABSTRACT

Although observationally rare, damped Lyα absorption systems dominate the mass density of neutral gas in the Universe. 11 high-redshift damped Lyα systems covering $2.8 \leq z \leq 4.4$ were discovered in 26 QSOs from the APM $z > 4$ QSO survey, extending these absorption system surveys to the highest redshifts currently possible. Combining our new data set with previous surveys, we find that the cosmological mass density in neutral gas, Ω_g, does not rise as steeply prior to $z \sim 2$ as indicated by previous studies. There is evidence in the observed Ω_g for a flattening at $z \sim 2$ and a possible turnover at $z \sim 3$. When combined with the decline at $z > 3.5$ in number density per unit redshift of damped systems with column densities $\log N_{\rm H\,I} \geq 21$ atom cm^{-2}, these results point to an epoch at $z \gtrsim 3$ prior to which the highest column density damped systems are still forming. We find that, over the redshift range $2 < z < 4$, the total mass in neutral gas is marginally comparable to the total visible mass in stars in present-day galaxies. However, if one considers the total mass visible in stellar discs alone, i.e. excluding galactic bulges, the two values are comparable. We are observing a mass of neutral gas that is comparable to the mass of visible disc stars. Lanzetta, Wolfe & Turnshek found that $\Omega(z \approx 3.5)$ was twice $\Omega(z \approx 2)$, implying that a much larger amount of star formation must have taken place between $z = 3.5$ and 2 than is indicated by metallicity studies. This created a 'cosmic G-dwarf problem'. The more gradual evolution of Ω_g that we find alleviates this. These results have profound implications for theories of galaxy formation.

Key words: galaxies: evolution – galaxies: formation – quasars: absorption lines – cosmology: miscellaneous.

1 INTRODUCTION

While the baryonic content of spiral galaxies that are observed at the present epoch is concentrated in stars, in the past this must have been in the form of gas. The principal gaseous component in spiral galaxies is H I, which has led to surveys for absorption systems detected by the damped lines that they produce [Wolfe et al. 1986 (WTSC); Lanzetta et al. 1991 (LWTLMH); Lanzetta, Wolfe & Turnshek 1995 (LWT); Wolfe et al. 1995]. Damped Lyα absorption systems have neutral hydrogen column densities of $N_{\rm H\,I} > 2 \times 10^{20}$ atom cm^{-2} and they dominate the baryonic mass contributed by H I. We extend the earlier work on damped Lyα systems to higher redshifts using 26 QSOs from the APM Damped Lyα Survey [Storrie-Lombardi et al. 1996a (SMIH); Storrie-Lombardi, Irwin & McMahon 1996b (SIM)], with 11 candidate or confirmed damped Lyα absorption systems covering the redshift range $2.8 \leq z \leq 4.4$ (eight with $z > 3.5$). These data more than triple the redshift path surveyed at $z > 3$, and allow the first systematic study up to $z = 4.7$.

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2 EVOLUTION OF Ω_g: BARYONS IN NEUTRAL GAS

The mean cosmological mass density contributed by Lyα absorbers can be estimated as

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$$\langle\Omega_g\rangle = \frac{H_0 \mu m_H}{c\rho_{crit}} \int_{N_{min}}^{\infty} Nf(N,z)\,dN, \tag{1}$$

giving the current mass density in units of the current critical density (LWTLMH). μ is the mean molecular weight of the gas which is taken to be 1.3 (75 per cent H and 25 per cent He by mass), m_H is the mass of the hydrogen atom, ρ_{crit} is the current critical mass density, N_{min} is the low end of the H I column density range being investigated, and $f(N, z)$ is the column density distribution function. Unfortunately, $f(N, z)$ is not a simple function, and its evolution with redshift is difficult to quantify accurately (LWT; SIM). The integral in equation (1) can be estimated using

$$\int_{N_{min}}^{\infty} Nf(N,z)\,dN = \frac{\sum_i N_i(\text{H I})}{\Delta X}, \tag{2}$$

where ΔX is the absorption distance interval. The absorption distance X is used to remove the redshift dependence in the sample and put everything on a comoving coordinate scale. If the population of absorbers is non-evolving (i.e. the product of their space density multiplied by their cross-section does not change with redshift), they have a constant number density per unit absorption distance. In a standard Friedmann universe X is defined as

$$X(z) = \begin{cases} \frac{2}{3}[(1+z)^{3/2}-1] & \text{if } q_0 = 0.5, \\ \frac{1}{2}[(1+z)^2-1] & \text{if } q_0 = 0 \end{cases} \tag{3}$$

(Bahcall & Peebles 1969; cf. Tytler 1987). The errors in Ω_g are also difficult to estimate without knowing $f(N, z)$. LWTLMH used the standard error in the distribution of $N_{\text{H I}}$, which yields zero error if all the column densities in a bin are the same. We have estimated the fractional variance in Ω_g by comparing the observed distribution of $f(N, z)$ with the equivalent Poisson sampling process. This gives

$$\left(\frac{\Delta\Omega_g}{\Omega_g}\right)^2 = \sum_{i=1}^{p} N_i^2 \Bigg/ \left(\sum_{i=1}^{p} N_i\right)^2, \tag{4}$$

and $1/\sqrt{p}$ fractional errors if all the column densities included in a bin are equal. To address uncertainties in $f(N, z)$ we have also calculated a maximum likelihood estimate of the errors in the H I column density. We used the power law with an exponential turnover form of the column density distribution function, i.e. the gamma-distribution from SIM:

$$f(N,z) = (f_*/N_*)(N/N_*)^{-\beta} e^{-N/N_*}, \tag{5}$$

with $\log N_* = 21.63 \pm 0.35$, $\beta = 1.48 \pm 0.30$ and $f_* = 1.77 \times 10^{-2}$. Unlike a pure power law, this form has a finite integral mass. The maximum likelihood estimates of the errors agree well with the fractional variance.

LWT found that Ω_g inferred from studies of damped systems rises with increasing redshift for $0.008 < z < 3.5$. For the range $3.0 < z < 3.5$, which included four damped systems and was the highest redshift bin in the study, $\Omega_g(z \approx 3.5)$ was twice $\Omega_g(z \approx 2)$. This implied that a much larger amount of star formation must have taken place between $z = 3.5$ and 2 than is indicated by metallicity studies. Specifically, Pettini et al. (1994) measured a low mean metallicity in damped Lyα systems at $z \approx 2.2$, inferring that they are observed prior to the bulk of star formation in the disc. The LWT result also implied that the bulk of stars in nearby galaxies should be metal-poor, whereas only a small fraction of disc stars in the solar neighbourhood are metal-poor. This result presented a 'cosmic G-dwarf problem' similar to the 'G-dwarf problem' described by Schmidt (1963) that comes about if bright and faint stars formed at the same rate and there was no accretion on to the disc of the Galaxy. LWT concluded that the characteristic epoch of metal production in galaxies occurred after the characteristic epoch of star formation, and that damped Lyα absorbers might trace disc as well as spheroid evolution. Fall & Pei (1993; and Pei & Fall 1995) have argued that obscuration caused by dust in damped Lyα systems could lead to significant underestimates of the neutral gas fraction at all redshifts, particularly in the range $1 \le z \le 2$, also possibly explaining these results.

To investigate these issues further, the high-redshift confirmed and candidate damped Lyα systems discovered in the APM Damped Lyα Survey (SMIH; SIM) have been combined with lower redshift samples (WTSC; LWTLMH; LWT) to study the evolution of Ω_g over the range $0.008 < z < 4.7$. The combined data set includes 44 absorbers in 366 quasars. The results are tabulated in Table 1 and shown in Figs 1(a) for $q_0 = 0$ and 1(b) for $q_0 = 0.5$ ($H_0 = 50$ km s^{-1} Mpc^{-1}), following the format presented by Wolfe et al. (1995). The solid bins include the entire data set and the dashed bins exclude the new high-redshift APM data.[1] The region Ω_{star} is the $\pm 1\sigma$ range for the mass density in stars in nearby galaxies (Gnedin & Ostriker 1992). The point at $z = 0$ is the value inferred from 21-cm emission from local galaxies (Fall & Pei 1993; Rao & Briggs 1993). The most striking result is that Ω_g does not rise as steeply prior to $z \sim 2$ as indicated by previous studies. There is now evidence for a flattening in Ω_g at $z \sim 2$ and a possible turnover at $z \sim 3$. This result, combined with the decline at $z > 3.5$ in number density per unit redshift of damped systems with column densities $\log N_{\text{H I}} \ge 21$ atom cm^{-2} (SIM), points to an epoch at $z \gtrsim 3$ prior to which the largest damped systems are still forming. The decrease in number density at high redshift of the highest column density absorbers is in marked contrast to the more numerous lower column density systems, e.g. Lyman-limit systems ($N_{\text{H I}} \sim 10^{18}$ atom cm^{-2}) (Storrie-Lombardi et al. 1994; Stengler-Larrea et al. 1995) and Lyα forest absorbers ($N_{\text{H I}} \sim 10^{13}$–$10^{15}$ cm^{-2}) (Williger et al. 1994).

The inclusion of the APM survey data for $z > 3$ reduces significantly the value previously found for Ω_g in the bin $3 < z < 3.5$. Only one damped system is added to the existing four in this redshift range, but the absorption distance is doubled, which comes in to the calculation of Ω_g in the denominator in equation (2) (see Table 2). The additional redshift path added by the APM survey is shown graphically by the sensitivity function in fig. 6 of SMIH. We find that, over the redshift range $2 < z < 4$, the total mass in neutral gas (Ω_g) is marginally comparable to the total visible mass in stars in present-day galaxies (Ω_{star}) for $q_0 = 0.5$. However, if one considers the total mass visible in stellar discs alone, i.e. excluding galactic bulges, the two values are comparable.

[1]Excluding the new APM data effectively yields the data set analysed by LWT.

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Table 1. Data for figures.

Bin Redshift Range	DLA ⟨z⟩	Δz	# of DLA in bin	QSO	$q_0=0$ ΔX	$q_0=0$ Ω_g [$\times h_{50} 10^3$]	$q_0=0.5$ ΔX	$q_0=0.5$ Ω_g [$\times h_{50} 10^3$]
.008-1.5	0.64	47.8	4	186	73.1	0.56±0.32	58.5	0.70±0.40
1.5-2.0	1.89	27.9	4	126	79.5	1.21±0.71	47.1	2.05±1.19
2.0-3.0	2.40	120.2	22	176	415.9	1.50±0.49	223.4	2.79±0.91
3.0-3.5	3.17	24.3	5	82	102.0	1.48±0.72	49.8	3.04±1.48
3.5-4.7	4.01	19.2	9	32	93.8	0.85±0.34	42.5	1.87±0.75
Dashed bins, excluding high redshift data.								
2.0-3.0	2.38	114.6	21	154	394.8	1.56±0.52	212.6	2.90±0.96
3.0-3.5	3.19	11.8	4	56	48.9	2.79±1.47	24.0	5.68±3.00

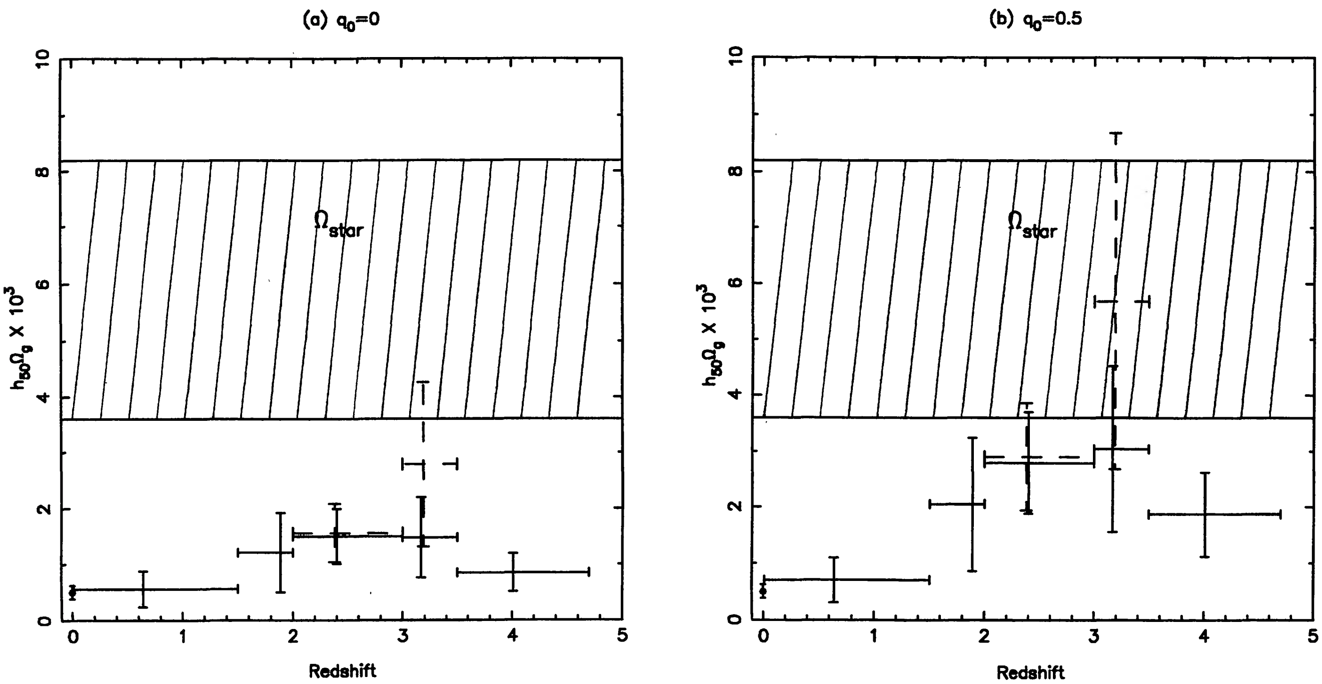

Figure 1. The mean cosmological mass density in neutral gas, Ω_g, contributed by damped Lyα absorbers for $0.008 \leq z \leq 4.7$, for (a) $q_0=0$ and (b) $q_0=0.5$. The solid bins include the combined data set and the dashed bins exclude the new APM high-redshift data. The region $\Omega_{\rm star}$ is the $\pm 1\sigma$ range for the mass density in stars in nearby galaxies (Gnedin & Ostriker 1992). The point at $z=0$ is the value inferred from 21-cm emission from local galaxies (Fall & Pei 1993; Rao & Briggs 1993). These results are tabulated in Table 1.

Using the result from Schechter & Dressler (1987) that galactic discs and bulges contribute equally to the mass density of the Universe, we are observing a mass of neutral gas comparable to the mass of visible disc stars, i.e. $\Omega_g \sim \Omega_{\rm disc\ stars}$. We note that the uncertainty in the total mass in visible stars in the local Universe is comparable to our estimates of the mass in neutral gas at $z>2$. Given this, and the fact that we do not know if damped systems are the precursors to galactic discs, bulges, or both, these results are difficult to interpret. If we made a plausible correction for obscuration by dust as advocated by Pei & Fall (1995), the Ω_g points shown in Fig. 1(b) would migrate to the positions of the open circles shown in Fig. 2. More work is needed to determine the severity of dust obscuration in optically selected QSO surveys. An estimated 20 per cent correction for the neutral gas not in damped Lyα systems is shown by the open squares.

3 IMPLICATIONS FOR GALAXY FORMATION THEORIES

The shape of the Ω_g curve has been used by numerous authors to constrain theories of galaxy formation and cosmological models (Klypin et al. 1995; Kauffmann &

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Table 2. Redshift path and absorption distance.

Data Set	Δz	ΔX ($q_0 = 0$)	ΔX ($q_0 = 0.5$)
$3.0 < z < 3.5$			
APM Damped Lyα Survey	12.5	53.1	25.8
WTSC + LWTLMH + LWT	11.8	48.9	24.0
Combined	24.3	102.0	49.8
$z > 3$			
APM Damped Lyα Survey	30.5	141.2	65.5
WTSC + LWTLMH + LWT	13.0	54.6	26.7
Combined	43.5	195.8	92.2
$0 < z < 4.7$			
APM Damped Lyα Survey	36.1	162.3	76.5
WTSC + LWTLMH + LWT	203.4	602.1	344.8
Combined	239.5	764.4	421.3

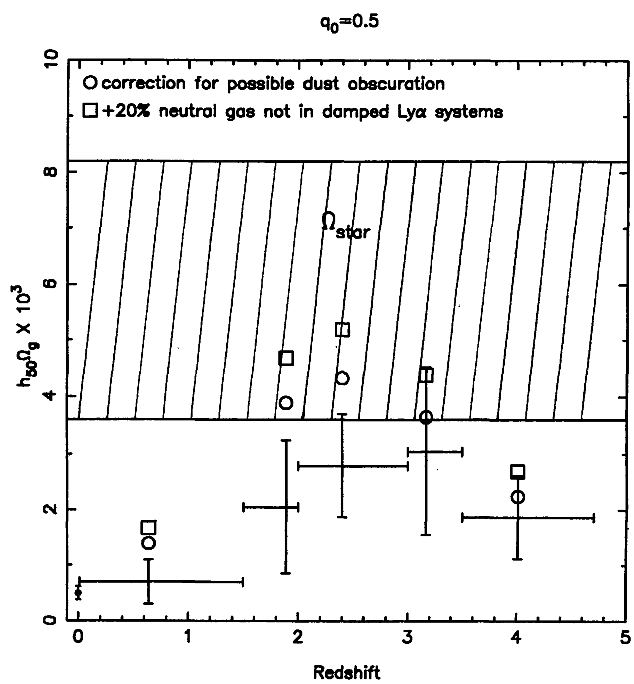

Figure 2. The mean cosmological mass density in neutral gas, Ω_g, contributed by damped Lyα absorbers for $0.008 \le z \le 4.7$. The solid bins are the combined data set shown in Fig. 1(b) for $q_0 = 0.5$. The circles show the observed data points corrected for possible dust obscuration using values determined from the closed-box/outflow models shown in fig. 4(b) of Pei & Fall (1995). The squares add an estimated 20 per cent correction for neutral gas not in damped Lyα absorbers. The region $\Omega_{\rm star}$ is the $\pm 1\sigma$ range for the mass density in stars in nearby galaxies (Gnedin & Ostriker 1992). The point at $z = 0$ is the value inferred from 21-cm emission from local galaxies (Fall & Pei 1993; Rao & Briggs 1993).

Charlot 1994; Ma & Bertschinger 1994; Mo & Miralde-Escudé 1994). They have found that cold + hot dark matter (CHDM) models are incompatible with the previous results from the damped Lyα systems at $z \sim 3$, as they predict too few galactic haloes. These models need to be re-evaluated now that the value of $\Omega_g(z=3)$ indicated from our new observations has changed significantly. For example, Klypin et al. (1995) show a peak in Ω_g at $z=3$ for various CHDM models. Although the error bars on Ω_g are still far too large to discriminate accurately between details of cosmological models, the overall shape has implications for structure formation.

4 SUMMARY

Combining the new data from the APM high-redshift survey with previous results extends studies of the cosmological mass density in neutral gas, Ω_g, to $z = 4.7$. We find evidence for a flattening in Ω_g at $z \sim 2$ and a possible turnover at $z \sim 3$. Although the turnover is not formally significant, when combined with the decline at $z > 3.5$ in number density of damped systems with column densities $\log N_{\rm H\,I} \ge 21$ atom cm^{-2}, these results point to an epoch prior to which the largest damped systems are still forming.

Previous studies indicated that $\Omega_g(z \approx 3.5)$ was twice $\Omega_g(z \approx 2)$, implying that a much larger amount of star formation must have taken place between $z = 3.5$ and 2 than is indicated by metallicity studies. The more gradual evolution that we find in Ω_g alleviates this problem. The results are consistent with observations of damped Lyα systems at $z \approx 2.2$ that show a low mean metallicity, suggesting that they are observed prior to the bulk of star formation in the disc. We have also made an estimated correction to Ω_g to account for bias in optically selected quasar samples due to possible obscuration by dust in foreground absorbers. Theories of galaxy formation and constraints on cosmological models utilizing Ω_g should be re-evaluated in light of the new observational results presented here. The error bars are still very large at high redshift, and, to differentiate between a peak and a flattening in the Ω_g curve, larger samples of bright $z > 3.5$ quasars are needed to discover damped Lyα systems with $z > 3$.

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