THE EVOLUTION OF INTERGALACTIC HYDROGEN CLOUDS: CONFUSION RESOLVED

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1. INTRODUCTION

It is now widely accepted that a population of intergalactic hydrogen clouds is responsible for the plethora of absorption lines seen at wavelengths shorter than Ly α emission in all high-z QSOs. The question of whether the comoving number density of such clouds evolves with redshift has been somewhat controversial. It is usually assumed that

$$\frac{dN}{dz} \propto (1+z)^{\gamma} \qquad \text{for } W \equiv \frac{W_{obs}}{1+z} \geq 0.32\ \text{Å}.$$

For a non-evolving population of clouds we expect $\gamma \leq 1$ for $q_o \geq 0$.

The results obtained for γ have varied widely depending on the method of analysis used, particularly where the range of z is limited. This may be seen clearly in Table 1, especially for the results of Carswell et al. (1982). Their last method gives the weighted mean of maximum likelihood (ML) estimates for each QSO separately. We aim to apply rigorous statistical methods to test for evolution and to attempt to explain the variety of results previously obtained.

Table 1: Various estimates of γ for the SYBT* sample

Author(s)	γ	Method
SYBT	+0.48 ± 0.54	ML
Our analysis	+0.45 ± 0.69	ML
Phillipps and Ellis (1983)	-0.1 ± 1.0	Own
Peterson (1983)	+1.6 ± 1.3	Peterson
Carswell et al. (1982)	+1.4 ± 0.7	Peterson
	+0.6 ± 0.6	ML
	-2.1 ± 1.5	$\bar{\gamma}$

* SYBT = Sargent et al. (1980); sample of 5 QSOs with 187 lines. Carswell et al. add a further 25 lines from 2 QSOs.

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2. OUR APPROACH

We form a homogeneous sample of QSOs observed at comparable resolution (∿1 Å) by adding 2000-330 (z=3.78; Hunstead et al. 1986) and 0215+015 (z=1.7; Blades et al. 1985) to the 9 QSOs of the Young, Sargent and Boksenberg (1982; YSB) sample. This gives the widest range of z (1.5 - 3.78) currently achievable. We exclude all lines in known heavy-element systems, including Ly α, since these probably form a separate population.

We then estimate γ using ML since this method gives a minimum variance for the fitted parameter. Next we apply various statistical tests for the assumed parametric form; this is a very important step. Specifically we test for:

(i) assumed overall power law
(ii) uniformity of dN/dz among QSOs
(iii) uniformity of dN/dz within QSOs
(iv) rank correlation between W and z within individual QSOs for comparison with overall rank correlation (if any).

3. RESULTS AND TESTS

For our sample of 277 lines we find $\gamma = 2.17 \pm 0.36$, which differs from the case of no evolution by ≥3.25 σ for $q_o \geq 0$. A Kolmogorov test shows an excellent fit to the assumed power law and there is no significant overall rank correlation between W and z.

It is essential, however, to apply the remaining tests for the uniformity of the power law expression for dN/dz both among and within QSOs. In Table 2, the χ^2 test is consistent with a uniform distribution

Table 2. Tests for individual QSOs

	Test for uniformity of dN/dz among QSOs			Uniformity of dN/dz within QSOs		Rank correlation W:z for each QSO	
QSO	N_k	$\langle N_k \rangle$	χ^2	$\bar{Q}_k - 0.500$		ρ_k	
2000-330	73	67.6	0.4	+0.016	± 0.030	-0.20	± 0.12
2126-158	52	56.9	0.4	-0.050	0.036	-0.40	0.14
0002-422	34	32.6	0.1	-0.078	0.048	-0.12	0.17
PHL 957	29	35.7	1.3	-0.085	0.056	-0.02	0.19
0453-423	37	25.7	5.0	-0.041	0.051	+0.09	0.17
1225+317	20	20.5	0.0	-0.090	0.064	-0.09	0.30
0421+019	8	13.5	2.3	-0.15	0.11	+0.14	0.38
0119-046	10	9.7	0.0	-0.04	0.09	-0.22	0.33
0002+051	5	8.6	0.3	-0.04		-0.50	
1115+080	2			+0.10		-1.0	
0215+015	7	6.2	0.1	-0.19	0.09	-0.68	0.41
	277	277.0	9.9	-0.046	± 0.017	-0.172	± 0.061

from one QSO to another but the other two tests each indicate a significant departure within individual QSOs from the global trend. The weighted mean values of the test statistics are each significant at a probability level $p \sim 0.003$ in a sense consistent with the alternate test. The Q test (Murdoch et al. 1986) indicates that, compared with the overall trend, there are relatively fewer absorption lines close to the emission redshift, while the rank correlation test for individual QSOs indicates that lines closer to the emission redshift tend to be weaker.

4. THE INVERSE EFFECT

We use this term for the weakening of the global trend for dN/dz within individual QSOs, as shown by the above tests. When lines within the emission line profile are excluded the inverse effect becomes insignificant (and the value of γ is increased). This suggests an effect located close to each QSO. A probable explanation is the increased ionization of the hydrogen clouds which occurs within $\sim$5 Mpc from a luminous QSO; within this range the flux from the QSO is calculated to exceed that from the general QSO background. This explanation is also consistent with the occurrence of high-ionization absorption systems (with N V) at redshifts relatively close to that of the QSO.

The inverse effect is especially important where the overall range of z is small and it can explain the divergence of results reported in Table 1. From Table 3 the improved concordance in the results for the various samples can be seen when we progressively i) exclude Ly α lines in heavy-element systems and then ii) remove the region of spectrum close to Ly α emission. The inverse effect is small in our sample because of the wide overall range of z.

Table 3. Summary of estimates of γ

	SYBT sample	(N)	YSB sample	(N)	Our sample	(N)
Original result :	0.48 ±0.54	(187)	1.81 ±0.48	(214)	...	
Our results:						
incl Ly α in heavy-element systems :	0.45 ±0.69	(187)	1.31 ±0.55	(214)	1.79 ±0.35	(298)
excl Ly α in heavy-element systems :	0.97 ±0.71	(172)	1.72 ±0.57	(197)	2.17 ±0.36	(277)
after removing region under emission line :	1.43 ±0.88	(131)	1.95 ±0.73	(144)	2.31 ±0.40	(222)

5. WHAT HAPPENS TO THE CLOUDS?

We find that, for $W \geqq 0.32$ Å, a good approximation to the combined distribution in z and W is

$$\frac{\partial^2 N}{\partial z\, \partial W} \propto e^{-W/W^*} (1 + z)^{\gamma}.$$

with W^* approximately constant (Murdoch et al. 1986). Clearly there are fewer clouds with W(Ly α) ≧ 0.32 Å at lower z. Hence more lines have left the sample through becoming too weak but the form of the distribution in W remains essentially unchanged. This implies that the evolution of W with z has the form

$$W = \gamma W^* \ln(1 + z) + \text{const.}$$

Since, in the relevant region of the curve of growth, $W \sim k \ln N(\text{H I})$ + const., a consistent expression for the evolution in the column density of neutral hydrogen is given by

$$N(\text{H I}) \propto (1 + z)^{\eta}, \quad \text{with } \eta = \gamma W^*/k.$$

For a typical H I cloud with $b \sim 40$ km s^{-1}, this leads to an indicative value for $\eta \sim 6$. This agrees well with the models of Ikeuchi and Ostriker (1986) and Atwood, Baldwin and Carswell (1985) which predict $\eta \sim 4$ to 7 in the relevant range of z. In these models, clouds with mass $\sim 10^6$ to $10^{8.5}$ $M_{\odot}$ do not collapse to form galaxies but rather expand approximately isothermally (for $z \geqq 2$) in pressure equilibrium with a hot intergalactic medium. Our empirically deduced result should encourage the further development of these models and also provide a useful challenge for competing models.

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DISCUSSION

Malkan : The observation that $\frac{dN}{dZ}$ goes the wrong way in an individual QSO spectrum (i.e. the lack of absorption in the blue wings of the quasar emission lines) was previously noted by Dave Tytler. He suggests that this effect may be explained if the absorbing clouds are often too small to cover the emission line region. Then the observed absorption equivalent widths become 2 or 3 times weaker when seen in the emission line profiles, explaining the effect.

Murdoch : We seriously considered this possibility but believed that is was probably ruled out by the work of Foltz et al. on the size of typical clouds.

Turnshek : Concerning Matt Malkan's comment, I have discussed with Foltz and Weymann their observation of a QSO pair in which they detect coincident Ly-α lines. They are concerned that their observations may have been a bit misinterpreted. They make the point that, while there are Lyα lines in common, there are many that are not, and so there is at least a distribution of smaller cloud sizes. The common lines may just be associated clouds or filaments. In either case, the Lyα emitting region may not be completely occulted giving smaller observed equivalent widths near the emission line.

Murdoch : We would be equally happy with the explanation that the clouds close to the QSO may be too small to cover the emission regions. It is possible that both mechanisms operate, since high ionization heavy element systems are also found close to the QSO.

Segal : You have established the consistency of evolution with certain data, but this by no means implies that the same data may not be consistent with quite different hypotheses, - e.g. chronometric theory with a different model for the origin of absorbing clouds than you have implicitly assumed. Moreover, in part your data appears a posteriori, - it includes that from which your hypothesis emerges. Could you comment ?

Murdoch : We have clearly established that N(HI) or alternately W depend strongly on z. We accept the majority view that z is a measure of epoch. Any alternate thoery needs to explain our specific results.