Aust. J. Phys., 1990, **43**, 211–25

The Lyman α Forest in QSOs: A Window on Intergalactic Clouds at High Redshift*

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Abstract

It is now well established that the number density of Lyα forest absorption lines evolves strongly with redshift. When combined with the observed exponential distribution of equivalent widths, this points to a steep dependence of H I column density on z. New information on the nature of the Lyα clouds has recently been obtained from high-resolution AAT échelle observations (6.5 km s^{-1} FWHM) of the QSO 2206–199N. Profile fits to unblended Lyα lines in the interval $z_{abs} = 2.103 - 2.587$ have established a clear trend between the Doppler velocity dispersion b and column density N, suggesting that b is measuring large-scale motions within the Lyα clouds rather than their temperatures. If correct, cloud temperatures (set by the lowest b values) are probably < 5000 K instead of the 30 000 K usually assumed, implying that the clouds are predominantly neutral. Previous data at lower resolution are shown to be roughly consistent with the new b:N trend, after allowing for the evolutionary dependence of N on z. The new observations are difficult to accommodate within the conventional framework of pressure-confined, low-density, ionised clouds; instead, we suggest that the Lyα clouds may be either in the form of dense, thin sheets or may be gravitationally confined.

1. Introduction

The plethora of narrow absorption lines seen at wavelengths shortward of Lyman α emission is a universal feature of the intermediate-resolution (1 – 2 Å) spectra of high-redshift ($z \gtrsim 1.5$) QSOs. In this region, commonly known as the Lyα forest, the majority of absorption lines are Lyα and the discrete regions of neutral hydrogen giving rise to them are referred to colloquially as Lyα clouds. A minor fraction of the lines can usually be identified with heavy elements in well-defined absorption systems which are thought to arise in intervening galaxies. The Lyα clouds, on the other hand, appear to form an intergalactic population, not associated with galaxies. Whatever their origin and fate, they should be sensitive tracers of the physical conditions in the intergalactic medium (IGM) as a function of redshift and, therefore, may eventually reveal essential clues to the process and epoch of galaxy formation.

* Paper presented at the joint Australia–USSR Workshop on the Early Universe and the Formation of Galaxies held at Mt Stromlo Observatory, 28–29 June 1989.

0004-9506/90/020211$03.00

Since the Lyα forest lines are so numerous and are accessible to ground-based telescopes over a wide range of redshift, $z = 1.5$ to >4, their properties can be examined statistically and trends with redshift can be investigated. As a result, useful progress has been made in understanding their *global* properties, although details of the physical conditions in individual clouds (e.g. temperature, density, ionisation level, large-scale motions) are still sparse due to the observational difficulties. We summarise below the widely-accepted properties of the Lyα clouds, which have been established over the past decade:

(i) In a given redshift interval, the number density of Lyα lines from QSO to QSO is found to be consistent with Poisson statistics (Sargent *et al.* 1980, hereafter SYBT); this argues strongly for a cosmological distribution of the clouds.

(ii) For Lyα lines stronger than a given equivalent width (usually taken to be 0.32 Å in the absorber's frame), there is marked evolution with redshift, z, in the number density of lines, $d\mathcal{N}/dz$ (Murdoch *et al.* 1986, hereafter MHPB), in the sense that the lines were more numerous at higher redshifts. Within individual QSOs, however, MHPB found a countervailing trend (the so-called "inverse effect") arising from a relative deficiency of Lyα absorption lines close to the emission redshift. The favoured interpretation of the inverse effect is that it results from the excess flux of ionising radiation from the QSO over the metagalactic ionising flux (Bajtlik *et al.* 1988), leading to a lower neutral fraction in clouds located within ~ 5 Mpc of a luminous QSO.

(iii) No clustering of Lyα clouds is seen on scales ranging from 300 to 30 000 km s^{-1} (SYBT, Bechtold 1987) although Webb (1987), using data of higher spectral resolution, has claimed that there is evidence for weak clustering on scales of $50-300$ km s^{-1} at low redshift ($\bar{z} = 2.371$), but not at higher redshift ($\bar{z} = 3.390$).

(iv) Whereas the local universe has a sponge-like topology with prominent voids of size $\sim 10-50\,h^{-1}$ Mpc in the galaxy distribution (where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}), there is no evidence for detectable voids on the same scale in the distribution of Lyα clouds at $z \sim 2-4$ (e.g. Duncan *et al.* 1989; Kovner and Rees 1989). Attempts to detect heavy elements associated with Lyα clouds have been unsuccessful (e.g. Sargent and Boksenberg 1983; Chaffee *et al.* 1985, 1986) with limits of typically $Z \leq 0.001\,Z_{\odot}$. It has been assumed, therefore, that the Lyα clouds have a primordial composition and are fundamentally different from the absorption systems containing heavy elements.

In the following sections, we summarise the evidence for redshift evolution in the density of Lyα forest lines observed at intermediate resolution and discuss what this implies for evolution of the column densities of individual clouds. New observations, at the highest spectral resolution yet obtained for a high-z QSO, are introduced and preliminary results for the Lyα lines are presented. These new results suggest that our current ideas about the origin and confinement of the Lyα clouds require drastic revision.

2. Line Density Evolution

(a) Evolution in Number Density

Over the past decade there has been considerable controversy as to whether the Lyα cloud distribution is uniform in comoving space or whether the number density changes with epoch (i.e. z). The background to this controversy and its resolution are discussed in detail by MHPB and Hunstead (1988). For non-evolving clouds of constant cross-section the number density of absorption lines per unit redshift is given by

$$\frac{d\mathcal{N}}{dz} \propto (1+z)(1+2q_o z)^{-1/2}. \qquad (1)$$

Following SYBT, most authors have adopted the functional form

$$\frac{d\mathcal{N}}{dz} \propto (1+z)^{\gamma} \qquad (2)$$

where, for non-evolving clouds, $\gamma = 1$ for $q_o = 0$ and $\gamma = \frac{1}{2}$ for $q_o = \frac{1}{2}$.

A key factor in establishing a strong evolutionary trend in line density with redshift was the extension of the redshift baseline afforded by the $z = 3.78$ QSO 2000–330 (Hunstead *et al.* 1986). Another important factor was the exclusion by MHPB of Lyα lines associated with definite heavy-element systems, on the grounds that they form a separate population with different evolutionary properties (e.g. Sargent *et al.* 1988). The current best estimate for γ is 2.3 ± 0.4 (e.g. Hunstead *et al.* 1988) for lines with rest frame equivalent widths $W_0 > 0.32$ Å.

A high-resolution spectrum of 2000–330 near Lyα emission is shown in Fig. 1 together with the corresponding spectral region for the $z = 2.06$ QSO 1256–175. This figure illustrates graphically the strong evolution in the Lyα cloud population with redshift. Not only is there a dramatic difference in line density between the two spectra but there is also an obvious difference in the average line strength at the two redshifts (ignoring the strong metal-system Lyα in 1256–175).

(b) Evolution in Column Density

It was shown by SYBT that, for $W \geq 0.32$ Å, the distribution of Lyα equivalent widths is well fitted by an exponential function of the form

$$\frac{d\mathcal{N}}{dW} \propto e^{-W/W^*}. \qquad (3)$$

MHPB and Hunstead (1988) explored the equivalent width distribution over a wider range in W, z and spectral resolution. The most surprising feature of the W distribution is its apparent uniformity with redshift and with spectral resolution. MHPB reported a marginal (2σ) trend between W^* and z in the sense of larger W^* (and, therefore, larger average W) at higher redshift; this effect is seen qualitatively in Fig. 1.

Regardless of the processes responsible for the evolution of the neutral hydrogen component of the clouds (e.g. expansion, ionisation, evaporation),

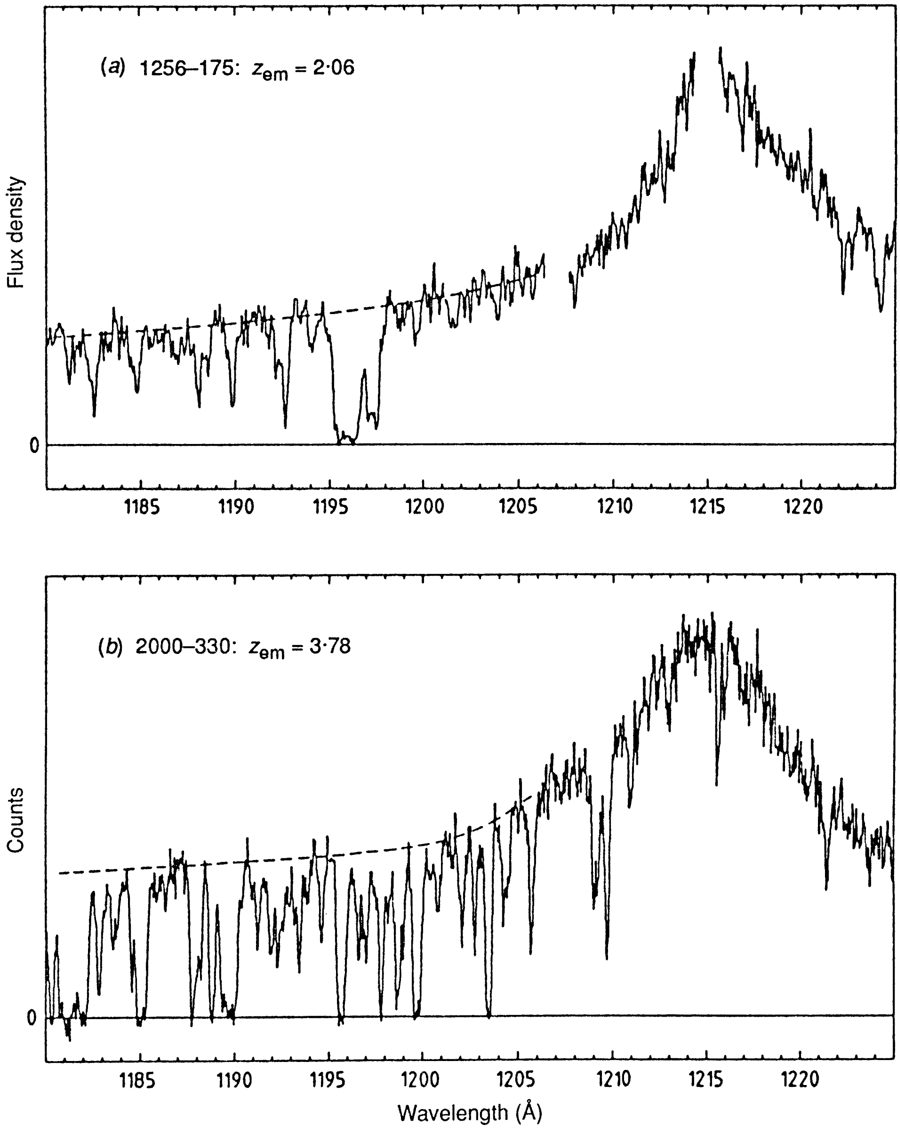

Fig. 1. AAT spectra showing Lyα emission and part of the Lyα forest in two QSOs : *(a)* 1256–175 at $z = 2.06$, and *(b)* 2000–330 at $z = 3.78$. Each spectrum has been shifted to the QSO rest frame and an approximate continuum level is shown. The original resolution was 0.6 Å FWHM. The spectrum of 1256–175 has been edited to remove a strong Si IV $\lambda\lambda$1393,1402 doublet (at $z_{abs} = 1.649$) in the Lyα emission profile; the strong absorption line near 1196 Å is Lyα in a heavy-element system at $z_{abs} = 2.009$ *(from Hunstead 1988).*

the observed increase of $d\mathcal{N}/dz$ with z implies that the Lyα equivalent width of individual clouds must decrease with time, so that for many clouds, W falls below the sample limit (0.32 Å for the MHPB sample) at lower redshift. For constant W^*, the combined distribution of $\mathcal{N}$ with both z and W may then be written

$$\frac{\partial^2 \mathcal{N}}{\partial z \partial W} \propto e^{-W/W^*}(1+z)^{\gamma}. \tag{4}$$

For Doppler velocity dispersion parameter b ($=\sqrt{2}\sigma$) in the range 20–40 km s^{-1} and for most of the range $W = 0.3 - 1.0$ Å, the lines are saturated and the H I curve of growth may be approximated by

$$W = k \ln N + \text{constant}, \tag{5}$$

where N is the H I column density and k depends on b. It then follows that

$$N \propto (1+z)^{\eta}, \tag{6}$$

where $\eta = \gamma W^*/k$. For a typical Lyα cloud with $N \sim 10^{14-15}$ cm^{-2} and $b \sim 30-40$ km s^{-1}, η falls in the range $6-8$, increasing to ~ 10 for smaller b values or if the weak trend between W^* and z is taken into account. Although this estimate of η is only an indicative value (as the assumptions underlying the derivation of (6) apply only to a limited range of W), it nevertheless points to a steep evolution with redshift in the H I column density of individual clouds. Although the physical basis for this evolution is not yet understood, the redshift dependence of the column density distribution may hold the key, provided the inherent difficulties in determining H I column densities can be overcome (Carswell *et al.* 1987).

3. Velocity Dispersion in the Lyα Clouds

(a) Existing Data

High resolution data are needed to resolve the Lyα lines and thereby determine their Doppler velocity dispersion b and column density N. These parameters are essential for constraining models for the Lyα clouds and are estimated by fitting Voigt profiles (convolved with the instrumental profile) to the data. Since few Lyα lines are single when observed at resolutions of 20–30 km s^{-1}, it is often necessary to fit multiple components to complex, blended features; in such cases, the line parameters are only well constrained when higher-order Lyman lines are available. The most extensive measurements of the properties of the Lyα clouds come from the work of Carswell and collaborators (summarised in Carswell 1989) and show a distribution of b values with a broad peak at about $30-35$ km s^{-1} and a range from $\sim 5-100$ km s^{-1}. However, it is not clear how much of the spread is intrinsic and how much is due to blending and measurement errors.

The best evidence for a Lyα cloud with a small b value comes from MMT observations of PHL 957 at a resolution of 12 km s^{-1} FWHM (Chaffee *et al.* 1983). This weak, narrow line at 4442.4 Å ($z_{abs} = 2.654$) has $b = 14.5 \pm 2.5$ km s^{-1}, $N = 1.8 \pm 0.25 \times 10^{13}$ cm^{-2} and is not associated with any identified heavy-element system. If we attribute the Doppler velocity dispersion solely to thermal motions in the H I gas, this defines an upper limit to the temperature of $T = 12\,700 \pm 4000$ K.

As argued by Chaffee *et al.* (1983), the ramifications of such a low temperature in a metal-free primordial cloud are substantial. The equilibrium temperature of an isolated, spherical H I cloud is determined by its density and by the incident ionising flux. Assuming a lower limit for the cloud size of 10^{19} cm (imposed by the requirement that the cloud should occult fully the QSO's broad emission line region) the measured column density of H I implies a density of $\log n(\mathrm{H\ I}) < -6.0$. In their model calculations this leads to $T > 25\,000$ K, well above the upper limit of 16 700 K measured from the line width. This result, which does not depend strongly on the assumed UV ionising flux nor on the assumption of ionisation equilibrium, poses a fundamental dilemma for the conventional view that the Lyα clouds are tenuous and highly-ionised. Even the presence of metals at solar abundance cannot cool the cloud to 12 000 K. The concluding suggestion by Chaffee *et al.* is that the clouds may be in the form of highly-flattened structures or sheets; for the same column density this could allow much higher number densities and hence more efficient cooling.

Although the spectrum of PHL 957 by Chaffee *et al.* (1983) was obtained at higher resolution than all subsequent studies (that is, until now), the significance of their conclusions regarding the λ4442 line appears to have been largely ignored by those involved in theoretical modelling of the Lyα clouds. Perhaps this has been due to a lingering concern that the line may not, after all, be Lyα but an unrecognised heavy-element line.

In modelling the Lyα clouds and their evolution with redshift, it is also important to test for any possible correlation between b and N. Hunstead *et al.* (1987, hereafter HPBM) were first to claim a significant correlation, based on 149 lines spanning the range $z_{abs} = 3.43 - 3.78$ in the $z_{em} = 3.78$ QSO 2000–330; these authors also claimed the existence of Lyα clouds in 2000–330 with b values as low as that reported by Chaffee *et al.* (1983) for the λ4442 cloud in PHL957. Carswell *et al.* (1984) had earlier reported marginal evidence for a b:N correlation in the same sense, based on Anglo-Australian Telescope (AAT) data at a resolution of 20 km s^{-1}, but in a later paper (Atwood *et al.* 1985) they sought to attribute this correlation to line blending. Combining all his Lyα data, Carswell (1989) finds evidence for a weak correlation between b and N when the sample is restricted to the best-determined lines. However, these data (Carswell 1989, Fig. 4) cover a wide range in z (1.85 – 3.75), and any underlying correlation between b and N would tend to be smeared out as a result of the strong evolution of N with z [equation (6)]. At the time of writing, both the existence of a b:N correlation and the reality of low b values (< 20 km s^{-1}) are considered controversial (e.g. Carswell 1988, discussion following paper; Carswell 1989), mainly as a result of different approaches to the deconvolution of complex absorption features in data with barely-adequate resolution.

(b) New Observations of 2206–199N

The $B = 17.5$ QSO 2206–199N ($z_{em} = 2.559$; Savage *et al.* 1978) was observed in 1988 August using the University College London coudé échelle spectrograph (UCLES) on the 3.9 m AAT; the integration time was 37 500 s. The detector was the Image Photon Counting System (IPCS) and the resolution achieved was 6.5

$\mathrm{km\,s^{-1}}$ FWHM, the highest resolution yet applied to the study of QSO absorption lines. The échelle spectrum extends over nine orders from 3730 – 4365 Å, with small gaps ~ 15 Å between adjacent orders. A full description of this observation and the data reduction procedures are given by Pettini *et al.* (1990).

In Fig. 2 we show the same portion of the spectrum of 2206–199N at two resolving powers, differing by a factor ~ 20. The upper panel, obtained at a resolution of 1.5 Å FWHM, is typical of the data used to determine the line density evolution discussed in §2; possibly five absorption lines would have been claimed in this region. The high resolution UCLES data in the lower panel reveal the presence of many more absorption features, including some with very narrow profiles. The majority of these features cannot be identified with any heavy-element systems and are therefore assumed to be individual Lyα forest lines.

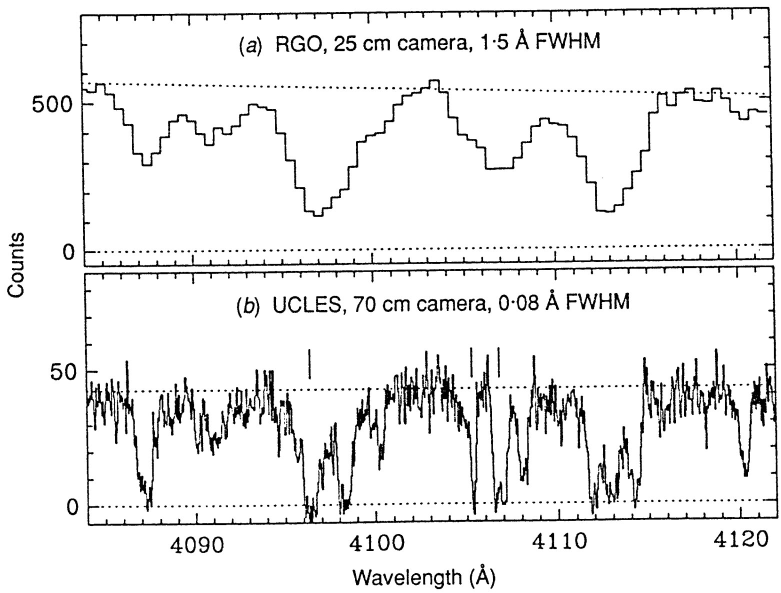

Fig. 2. AAT observations of portion of the spectrum of the QSO 2206–199N at two widely-differing resolutions: *(a)* obtained with the RGO cassegrain spectrograph at a resolution of 1.5 Å FWHM, and *(b)* obtained with the UCL coudé échelle spectrograph at a resolution of 0.08 Å. The lines marked are heavy-element transitions in known absorption systems; the remainder are presumed to be Lyα lines.

(i) Profile fits

Theoretical Voigt profiles were fitted to 41 unblended Lyα lines spanning the redshift interval $z_{abs} = 2.103 - 2.587$, using the Starlink software ALAS. Our aim was to obtain the most reliable set of line parameters and, as a consequence, we did not attempt to fit to saturated lines or to deblend complex features. Most of the lines fall on the linear portion of the curve of growth and are well resolved, making the determination of b and N relatively straightforward.

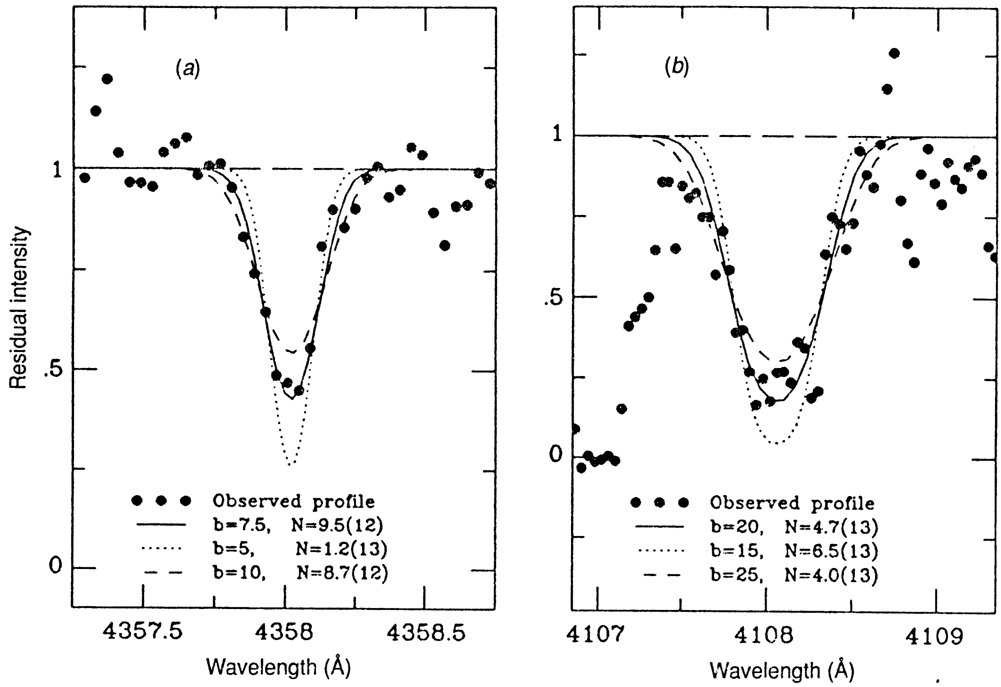

Fig. 3. Examples of Voigt profile fits to two Lyα forest lines in 2206–199N; in each case the solid line is the adopted fit. *(a)* A narrow Lyα line at $z_{abs} = 2.58487$ falling near the peak of the broad Lyα emission line. *(b)* A broader Lyα line at $z_{abs} = 2.37926$ just redward of a strong metal line (see Fig. 2); even though the S/N is lower in this case, the line parameters still have errors of $\leq 20\%$.

It is worth noting, in passing, that several of the presumed Lyα absorption lines in 2206–199N are at redshifts greater than the nominal emission redshift of $z_{em} = 2.559$, which is itself based largely on the observed wavelength of C IV (Sargent *et al.* 1988). The existence of velocity offsets between QSO redshifts determined from high- and low-ionisation emission lines has been discussed by Espey *et al.* (1989). In 2206–199N, the velocity difference between z_{em} and the highest-z Lyα absorption line is 2400 km s^{-1}, well within the range of C IV:Hα offsets found by Espey *et al.*

Examples of profile fits for two of the Lyα lines in 2206–199N are shown in Fig. 3, and demonstrate that the b and N values are quite well constrained by the data. Note also that the b value for the line in Fig. 3*a* is only 7.5 km s^{-1} (the mean instrumental b value is 3.9 km s^{-1}), well below the 14.5 km s^{-1} found by Chaffee *et al.* (1983) for the λ4442 line in PHL 957. The overall properties of the 41 lines fitted are given below:

Mean redshift .... $\overline{z_{abs}} = 2.38$
Median column density .... $\log N$ (cm^{-2}) = 13.4
Median velocity dispersion .... $b = 17$ km s^{-1}.

We found no significant trend in b or N with redshift over the interval $z = 2.103 - 2.587$.

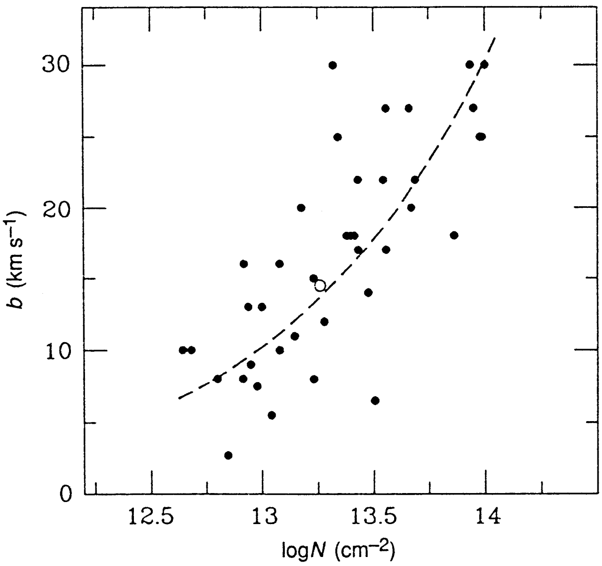

Fig. 4. Plot of Doppler velocity dispersion b versus H I column density N (cm^{-2}) for 41 unblended Lyα lines in the AAT échelle spectrum of 2206–199N; the instrumental b value was 3.9 km s^{-1}. The open circle is the λ4442 Å cloud in PHL 957 from Chaffee *et al.* (1983) (see text) and the dashed line is the unweighted regression of $\log b$ on $\log N$ [see equation (7)].

A plot of b versus $\log N$ for this line sample is shown in Fig. 4. The Chaffee *et al.* (1983) point, plotted as an open circle, is obviously consistent with the new data. The most remarkable feature of Fig. 4 is the strong correlation evident between b and N. An unweighted linear regression of b on $\log N$ yields a correlation coefficient $r = 0.77$, whilst a regression of $\log b$ on $\log N$ gives $r = 0.73$. The latter curve, shown dashed in Fig. 4, has the equation

$$N = A_o \; b^{2.1 \pm 0.3}\,, \tag{7}$$

where N is in cm^{-2}, b is in km s^{-1} and $A_o = 6.9 \times 10^{10}$.

(ii) Selection Effects

Does the correlation in Fig. 4 arise from a selection effect in our 2206–199N line sample? It might be thought that, with data of modest S/N ratio, weak broad lines (which would populate the upper left portion of Fig. 4) could be masked by noise. Simulations indicate that this is not the case: lines with b, N values appropriate to the upper-left triangle of Fig. 4 would have been detected, although much weaker and broader lines would have escaped detection.

Turning now to the lower-right region of Fig. 4, such lines, having small b values, would be narrow and saturated and, therefore, easily recognised. In fact, all lines which would have populated this region of the figure (had they been Lyα) were readily identified as metal lines in known heavy-element systems. In addition, strong saturated lines in the Lyα forest (which we have not fitted here) all have FWHM ≥ 50 km s^{-1}; even though *some* of these strong lines will be blends of narrower components, they would need to exhibit sub-structure radically different from that seen in the weaker Lyα lines in order to account for the absence of the low-b high-N points. A similar dearth of systems with low velocity dispersion ($b < 20$ km s^{-1}) and high H I column density ($N > 3\times10^{13}$ cm^{-2}) was noted by Carswell *et al.* (1984) in their analysis of high-resolution data for the $z_{em} = 2.14$ QSO 1101–264. Finally we note that the second Lyα line fitted by Chaffee *et al.* (1983) (at λ4438, with $b = 40$ km s^{-1}, $\log N = 14.64$) is consistent with an extrapolation of the trend shown in Fig. 4.

(iii) Clustering

A two-point correlation analysis of our complete Lyα sample of 79 lines shows no significant signal on any velocity scale and, in particular, shows no evidence for the clustering (on scales of ≤ 200 km s^{-1}) which was found by Webb (1987) at this redshift. However, the comparison with Webb is not definitive because his total sample was larger than ours, even though our spectral resolution is higher. On the other hand, the absence of significant clustering in our sample suggests that the residual metal-line contamination is low (Bechtold and Schectman 1989).

4. Discussion

(a) Interpretation of the New Data

The picture of the Lyα clouds that is now emerging from the new AAT échelle data for 2206–199N differs in several key respects from the previously accepted one. For the first time in a QSO spectrum, essentially *all* the Lyα lines are well resolved, yielding well-determined values of Doppler velocity dispersion b. The median b value of 17 km s^{-1} is well below the $30-35$ km s^{-1} normally assumed in theoretical models. If we attribute the measured b values entirely to thermal motions in the H I gas, most of the clouds in Fig. 4 have temperatures $T < 30\,000$ K, the canonical temperature adopted for the Lyα clouds. Indeed, there are several clouds with $T < 5000$ K, at which temperature hydrogen is almost entirely neutral.

On the other hand, accepting that a strong correlation exists between b and N, it seems more plausible to associate b values with turbulent rather than thermal motions, since turbulent velocities might be expected to correlate with cloud mass and, therefore, column density, whereas there is no physical basis for expecting a T:N correlation. If this interpretation is correct, cloud temperatures need be no greater than $\sim$ 5000 K, the upper limit for the lowest-b clouds in our sample, which means that *all* the clouds in the interval $\log N = 12.7 - 14.0$ are probably neutral. This conclusion is in stark contrast with the currently-accepted picture of highly-ionised intergalactic clouds at $T \sim 30\,000$ K.

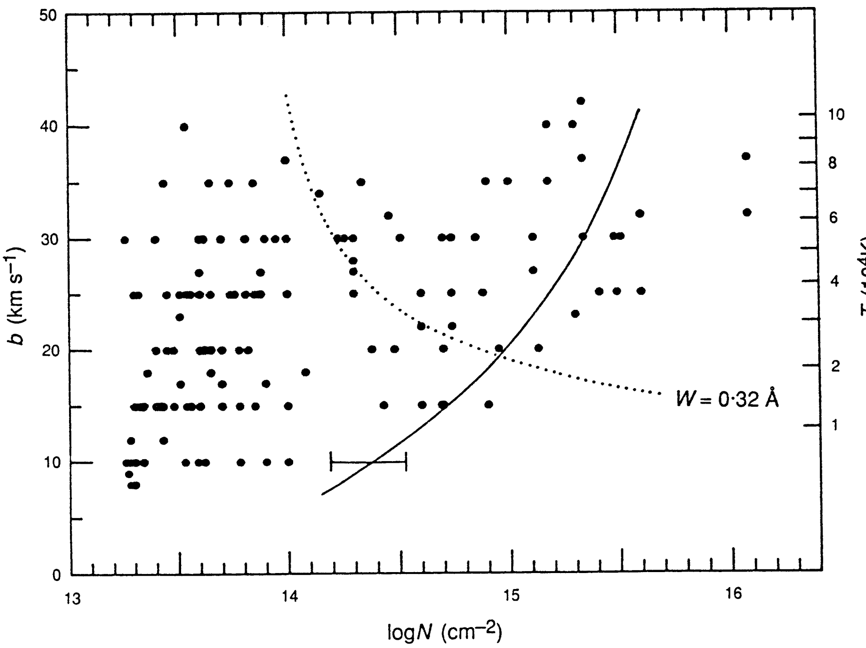

Fig. 5. Plot of b versus log$N$ for Lyα lines in 2000–330 with $z_{abs} = 3.43 - 3.78$; the average instrumental b value was 20 km s^{-1}. The solid curve is obtained from (7) by assuming redshift evolution in N according to (6), with $\eta = 10$; the 'error bar' corresponds to the range in z_{abs} for 2000–330. The dotted curve is the locus for an absorption line with equivalent width $W_0 = 0.32$ Å *(adapted from Hunstead et al. 1987).*

(b) Re-evaluation of the Earlier Data

In trying to elucidate the process of Lyα line evolution, it is helpful at this stage to review the earlier HPBM data for Lyα forest lines at $<z>= 3.65$ in 2000–330. These data were obtained at lower resolution than the recent AAT échelle data (typically 30 km s^{-1} FWHM), but this is partly compensated (at least for the stronger lines) by good coverage of the higher-order Lyman lines.

If we assume that the fitted curve in Fig. 4 defines the b:N relation at $<z>= 2.38$, we can test whether column densities do in fact evolve according to the simple power law of (6), assuming that clouds with different b values evolve at similar rates.* In Fig. 5, we show the data from HPBM together with the curve from Fig. 4 redshifted to $<z>= 3.65$, assuming $\eta = 10$; the horizontal bar indicates the range in log$N$ corresponding to the redshift span of the 2000–330 sample. Also shown in Fig. 5 is a curve of constant equivalent width, $W_0 = 0.32$ Å. We can draw several tentative conclusions from this figure:

(i) The redshift-evolved form of (7) appears to provide a reasonable fit to the high-N but not to the low-N clouds. Even the high-N points show a wide scatter about the curve, but this may plausibly be attributed

* In the context of line density evolution, we note that all of the lines in the 2206–199N sample plotted in Fig. 4 have equivalent widths $W_0 < 0.3$ Å, whereas the lower-resolution studies used to establish the evolution (see §2) are based on samples with $W_0 > 0.32$ Å.

to line blending which is a serious problem in the rich spectrum of 2000–330 at 30 $\mathrm{km\,s^{-1}}$ resolution. In particular, the dearth of low-b high-N clouds, already noted by HPBM, fits well the evolution of the $b:N$ relation from $<z>=2.38$ to 3.65.

(ii) There is no doubt of the existence of clouds with $\log N < 14$ at $<z>=3.65$, but these clouds do not appear to show an obvious trend between b and N. A trend could, of course, be washed out by line blending. An alternative possibility is that the high density of lines with $\log N < 14$ may indicate a *separate* population of Lyα clouds which is quite distinct from the high-N clouds; a possible break in the column density distribution near $\log N \sim 14-14.5$ was in fact noted by HPBM and Hunstead (1988). It is important to point out, furthermore, that if *all* clouds evolve according to (6) we would not be able to detect this low-N population in our data for 2206–199N, since our limit of $\log N = 12.75$ in 2206–199N corresponds to $\log N \sim 14.15$ at $<z>=3.65$. While there is suggestive evidence in the AAT échelle data for many weak lines which appear to cause a significant depression of the continuum, the reality of these lines awaits confirmation from higher S/N observations.

(iii) If our interpretation of Fig. 5 is correct, we predict that in samples selected according to a lower cut-off *either* in equivalent width *or* in column density, there should be a tendency for the mean b to decrease with increasing z. Examination of existing data for 1101–264 (z = 2.14, Carswell *et al.* 1984), 0420–388 (z = 3.12, Atwood *et al.* 1985) and 2000–330 (z = 3.78, HPBM) suggests that such a trend may indeed be present, but this question is best addressed by extending the high-resolution observations to a higher redshift QSO.

(iv) Finally, we believe that the HPBM b values are reliable for lines with $\log N \geq 15$ and *if* the evolution is simply in N, we would be surprised to find Lyα clouds at lower z with $b > 45-50$ $\mathrm{km\,s^{-1}}$, since such lines are rare at $<z>=3.65$.

(c) Confinement of the Lyα Clouds

The true nature of the Lyα clouds and the mechanism for their confinement remain a puzzle. A constraint in all models is that the IGM must be very highly ionised in order to explain the absence of a Gunn-Peterson effect (Steidel and Sargent 1987). In the widely-promoted 'pressure-confined' model (e.g. SYBT, Ostriker and Ikeuchi 1983, Ikeuchi and Ostriker 1986, Baron *et al.* 1989 and references therein), the Lyα clouds have galactic dimensions (~10 kpc) and are highly ionised by the metagalactic UV flux due to QSOs and other active objects. The clouds, with density $n \simeq 10^{-4}$ $\mathrm{cm^{-3}}$, temperature $T \simeq 3\times10^4$ K and neutral fraction $\sim10^{-5}$, are in pressure balance with a hot, tenuous IGM with $n \simeq 10^{-5}$ $\mathrm{cm^{-3}}$ and $T \simeq 3\times10^5$ K. There is no *direct* evidence for such a hot IGM, and the temperature could be as low as 10^4 K if photoionisation rather than collisions were responsible for keeping the gas highly ionised (Rees 1988).

Other models suggest that the Lyα clouds may be related to dwarf galaxies (Fransson and Epstein 1982), could be self-gravitating (Black 1981) or could be gravitationally confined by cold dark matter (Rees 1986, 1988). Hogan (1987) suggests that the clouds may be formed by protogalactic shocks and therefore be at significantly higher pressures, leading to smaller sizes, higher densities and much larger neutral fractions than in the pressure-confined models.

It is not our intention here to examine these models in detail but it is useful to explore the direct consequences of our new data for 2206–199N. Black (1981) has calculated the ionisation and thermal equilibrium for a low-density gas of H and He. In this model, temperatures as low as 5000 K can be reached only at very high gas densities ($n > 0.2$ cm^{-3}), where the gas is mainly neutral. Black's model does not extend to this density regime but here we adopt $n > 0.2$ cm^{-3} as a working value. For $N(\mathrm{H\ I}) = 10^{13}$ cm^{-2}, the linear size becomes $D < 2 \times 10^{-5}$ pc, far smaller than the QSO's broad emission line region! Therefore, in order to cover the broad line region, the clouds need to be markedly non-spherical, possibly in the form of dense sheets (Hogan 1987) or very thin spheroids (Barcons and Fabian 1987).

A possible clue to the confinement of the Lyα clouds comes from the empirical relationship between b and N given by (7). If we assume that $n(\mathrm{H\ I})$ is constant from cloud to cloud, then $N \propto D$ and (7) becomes

$$D \propto b^{2.1 \pm 0.3}, \tag{8}$$

which is strikingly similar to the well-known relation, $D \propto \sigma^2$. The so-called $\sigma : D$ relation applies to pressure-supported stellar systems ranging from elliptical galaxies to giant H II regions (Terlevich and Melnick 1981), in which the velocity dispersion arises from motions in the gravitational potential of the gas-star system. If the analogy with Lyα clouds is correct, we can use the velocity dispersions to estimate cloud masses directly. From the data for giant H II regions compiled by Terlevich and Melnick, the virial mass estimates for systems with b values in the range $10 - 30$ km s^{-1} are $10^5 - 10^7 M_\odot$. For the apparent upper-limit b value of ~ 45 km s^{-1}, the corresponding mass is $\sim 2 \times 10^8 M_\odot$, comparable with H II galaxies and dwarf irregulars. As the H I mass itself is only a very small fraction of this, we must assume that most of the mass exists as stars, ionised gas or possibly as cold dark matter.

We emphasise, however, that the above interpretation is highly speculative and leaves a number of questions unanswered. In particular, it is difficult to imagine how a correlation between b and $N(\mathrm{H\ I})$ as tight as that observed could arise if the contribution of the gas to the gravitational potential is negligible.

5. Conclusions

The number density $d\mathcal{N}/dz$ of Lyα forest clouds evolves steeply with redshift, implying that the equivalent width of individual clouds must decrease with time and eventually fall below the sample limit. The composite $\mathcal{N}(W,z)$ distribution leads to the prediction of a steep dependence of the H I column density N on z. The physical mechanism responsible for this evolution is not yet understood.

New AAT échelle spectra of the QSO 2206–199N at a resolution of 6.5 km s^{-1} have shown that Lyα forest clouds typically have low velocity dispersions, confirming tentative indications from earlier work. Furthermore, we have established a clear correlation between b and N for Lyα lines in the range $z_{abs} = 2.103 - 2.587$; such a trend suggests that the velocity dispersions arise predominantly from turbulent rather than thermal motions. If this interpretation is correct, then *all* clouds could be at temperatures as low as 5000 K and be mainly neutral.

These results pose fundamental constraints on the physical conditions in the absorbers and, in particular, lead to severe difficulties for the conventional view of the Lyα forest lines as arising in tenuous, highly-ionised clouds in pressure equilibrium with a confining IGM. Rather, the low temperatures inferred may be indicative of dense and highly-flattened structures. Furthermore, the empirical relation found between b and N is reminiscent of the well-known $\sigma : D$ relation, raising the possibility that the Lyα clouds may be gravitationally bound systems. However, as the inferred mass of H I is trivially small, this picture requires additional mass $\sim 10^{5-8} M_{\odot}$ in the form of stars, ionised gas or cold dark matter to provide the bulk of the gravitational potential.

Earlier data at lower spectral resolution appear to be consistent with the $b : N$ trend discovered here, after allowance for simple redshift evolution of column density. It is obvious, however, that high-quality échelle data are needed for QSOs spanning a range of redshifts in order to obtain a full picture of the evolution of individual Lyα clouds.

Acknowledgment

RWH acknowledges support for this program from the Australian Research Council.

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Manuscript received 2 January, accepted 13 February 1990