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New Evidence from the Lyman-Alpha Forest concerning the Formation of Galaxies

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New evidence from the Lyman-alpha forest concerning the formation of galaxies

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A new type of survey for galaxies with $z > 2$ will be described. The idea is to search for the spectroscopic imprint that the H I disc of a foreground galaxy leaves on radiation emitted by a background QSO; namely, a Lyman-α absorption line broadened by radiation damping. A continuing survey has revealed the presence of 15 damped Lα lines with redshifts between 1.8 and 2.8 in the spectra of 68 QSOs. In comparison, no more than three discs with the properties of nearby galaxies should have been detected. Furthermore, the mean column density of the 15 absorbers, $\langle N(\text{H I})\rangle = 1.4\times 10^{21}\ \text{cm}^{-2}$, is much larger than expected for the outskirts of H I discs.

Both statistical and physical evidence has accumulated which suggests that the damped Lα systems are a distinct population of absorbers with properties reminiscent of H I discs. First, the Lyman-α absorption lines detected in the survey follow a frequency distribution of equivalent width that cannot be due to previously detected cloud populations. At large equivalent widths, where the damped Lα lines occur, a new population of absorbers must exist. This damped population is therefore unrelated to clouds that are known to differ physically from galaxy discs. Secondly, detailed studies of the damped population reveal many of the properties shared by the H I discs of galaxies. For example, (*a*) the absorption spectra due to ions of abundant elements are dominated by low ions such as C^+, Si^+ and Fe^+, instead of C^{3+} and Si^{3+}, which are usually seen and (*b*) the recent detection of 21 cm absorption at $z = 2.04$ in one of the damped systems shows that the H I is cold and that it has a low level of turbulence ($\sigma \approx 10\ \text{km s}^{-1}$). Another piece of evidence connecting the damped population with discs is that the cosmological mass density of the absorbers is characterized by a density parameter, $\Omega \approx 3\times 10^{-3}/h$. This is comparable to the Ω due to luminous baryons. We suggest that this agreement is not coincidental, but rather reflects the fact that we have detected the progenitors of the baryon content of nearby galaxies.

The discovery of the damped population has a number of implications for theories of galaxy formation. First, if the damped absorbers are identified with the normal population of galaxies, the H I discs at $z > 2$ have radii $R \approx 3\,R_{\text{Ho}}$ (Holmberg). Because their redshift distribution is consistent with formation at $z > 2.8$, the production of large H I discs from the collapse of protogalaxies must occur more rapidly (within less than 3 Ga) than predicted in many theories. Secondly, the collapse to discs of present size must occur in the galactic plane rather than from the halo.

1. Introduction

The aim of this paper is to present evidence for a new and distinct population of baryons with redshift values of between two and three. The new population is notable for its mass density which exceeds the sum total of all the baryonic matter previously known at these redshifts.

Moreover, the baryon content per unit comoving volume approximately equals that of luminous matter in nearby galaxies. Indeed, a typical member of the new population bears a striking resemblance to a gaseous galactic disc.

In what follows it is argued that we have in fact detected disc galaxies at an early stage of evolution. The arguments are based on (*a*) statistical evidence for a distinct population of objects and (*b*) physical evidence which shows that, in addition to the comoving mass density, the kinematics, ionic composition and thermal state of the gas comprising the new population are similar to that of nearby galactic discs. On the other hand, there are systematic differences. We find that the early discs must be greater both in size and in H I content than their nearby counterparts, *if* there is a one-to-one correspondence between the membership of each group. Thus our interpretation implies a revision of the standard picture of galactic evolution, where the gaseous protogalaxy collapses directly into the current-size disc (Eggen *et al.* 1962). Rather, we suggest that disc formation is a two-stage affair in which the protogalaxy first collapses into a giant protodisc, followed by a radial contraction in the plane to the present-day object. We also find that the early discs are not very metal poor.

The disc-like objects were discovered in a recent survey for Lα absorption in the spectra of 68 QSOs (see Wolfe *et al.* 1986*a*). We carried out a low resolution ($\Delta\lambda = 10$ Å†) search for Lα lines broadened by radiation damping, because they are spectroscopic imprints of an opaque layer of H I with column densities expected for a galactic disc, i.e. $N(\mathrm{H\,I}) > 10^{20}\ \mathrm{cm^{-2}}$. The damped lines are valuable signatures of discs because they are predicted to be much stronger than the weak Lα lines that typify the spectrum blueward of Lα emission, i.e. the Lα forest (see Sargent *et al.* 1980; hereafter S.Y.B.T.). In §2 we describe the survey and its principal result, a list of features that are candidates for damped Lα absorption. We also summarize the results of accurate follow-up observations (described in §4), which confirmed 15 candidates as damped Lα absorbers. Section 3 presents statistical evidence that the damped absorbers are a distinct population. In §4 we discuss the observational evidence that (*a*) Lα is in fact damped and (*b*) the damped systems resemble galactic discs. The implications for galaxy formation are discussed in §5.

2. The Lick survey

In the first step of our survey we acquired low-resolution spectra of a large number of high-redshift QSOs with the 3 m telescope of Lick Observatory. The resolution, $\Delta\lambda = 10$ Å, was chosen to match the observed width, not less than about 20 Å, predicted for Lα absorption lines arising in disc galaxies. The linewidths exceed the Doppler width, *ca.* 0.1 Å, corresponding to $\sigma \approx 10\ \mathrm{km\,s^{-1}}$, the velocity dispersion observed in H I discs (Lewis 1984), because the dominant broadening mechanism in these very opaque layers of H I is radiation damping. In this case the rest-frame equivalent width of Lα is given by

$$W = 7.3\,[N(\mathrm{H\,I})/10^{20}\ \mathrm{cm^{-2}}]^{\frac{1}{2}}\ \text{Å}. \tag{1}$$

To estimate W we assume a simplified distribution of H I in which $N(\mathrm{H\,I}) > 2\times10^{20}\ \mathrm{cm^{-2}}$ at radii in the interval $R = [0, 1.5\ R_{\mathrm{Ho}}]$ (Bosma 1981), and $N(\mathrm{H\,I}) \approx 0$ at $R > 1.5\ R_{\mathrm{Ho}}$, where R_{Ho} is the Holmberg radius (Briggs *et al.* 1980). As a result foreground H I discs create Lα lines with $W > 10$ Å. Because the observed equivalent width of a line that forms at redshift z is

† 1 Å = 10^{-1} nm = 10^{-10} m.

$E = (1+z)\,W$, and because the atmospheric cutoff at 3200 Å limits the minimum Lα redshift to $z > 1.6$, one finds that $E > 27$ Å. This corresponds to a FWHM of the Lα profile that exceeds 18 Å.

The QSO sample consisted of 68 objects brighter than $V = 18.5$ mag with emission redshifts $z_{em} > 2.25$. A large number of QSOs was necessary because the interception probability predicted for disc galaxies with radius $R = 1.5\,R_{Ho}$ is small. To compute the number of discs encountered by a line of sight we adopt the standard assumptions of constant comoving density and cross section, a Schecter (1976) form for the galaxy luminosity function, and the Holmberg relation between radius and luminosity (cf. Wolfe *et al.* 1986*a*). The result is that the number of discs per unit redshift interval is

$$\mathrm{d}N_{disc}/\mathrm{d}z = K(1+z)\,(1+2q_0 z)^{-\frac{1}{2}},$$
$$K = 2\times 10^{-2}. \tag{2}$$

Thus the lines of sight to 100 objects would intercept between four and nine discs in the interval $z = [1.6, 3]$ for cosmologies with q_0 between 0.5 and 0.0. The actual number of intercepted discs will be considerably lower than this because the number of known QSOs with $z_{em} > 3$ is small, and because the minimum redshift for detecting Lα is often greater than 1.6. Nevertheless, discs should still outnumber other populations of clouds with $W > 10$ Å. The remaining sample criteria, i.e. for V and z_{em}, were compromises between the need for a statistically meaningful sample on the one hand, and the need for high signal:noise ratio and large interception probabilities on the other.

Figure 1 shows examples of the acquired spectra. In each case the solid smooth line is the model continuum that was fit to data blueward of Lα emission, and the dotted line is the 1σ error array (see Wolfe *et al.* 1986*a* for details). Most of the absorption features are unresolved with widths set by the instrumental resolution. The majority of these are unidentified, as we have completed detailed follow-up spectroscopy for only a few objects (see §5). Following S.Y.B.T. we assume that features blueward of Lα emission are Lα.

The spectrum in figure 1 (*a*) typifies data of high quality. The average equivalent width, $\langle E\rangle$, of the detected features is *ca.* 8 Å, which is about $5\langle E\rangle$ for lines detected at high resolution (S.Y.B.T.). Most of the latter are unidentified and are designated as Lα-only lines, i.e. Lα lines arising in clouds apparently devoid of heavy elements. At the low resolution of our survey the stronger Lα-metal lines, i.e. Lα associated with CIV doublets (S.Y.B.T.), should dominate. But in any case, there is no evidence for damped 'Lα disc' absorption. Figure 1 (*b*) shows a high-quality spectrum with three candidates for damped absorption at $\lambda = 3821$, 4268 and 4614 Å. Whereas the first two features have not been studied further, follow-up spectroscopy shows that the last feature is damped Lα. Finally, figure 1 (*c*) shows a noisier spectrum with damping candidates at $\lambda = 3559$ and 3742 Å. High-resolution observations by Robertson *et al.* (1983) show that both are damped Lα.

The principal results of the Lick survey are the list of significant absorption features (i.e. $E > 4\sigma_E$) found in all 68 QSOs, and the subset considered to be candidates for 'Lα discs'. The latter consist of all significant features with $W > 5$ Å; we relaxed the original threshold on W to account for possible measurement errors in equivalent width. In all there are 47 disc candidates. We have determined whether or not 26 of these are damped Lα. From accurate data that we acquired and data published by other groups we find that 15 of the 26 are damped

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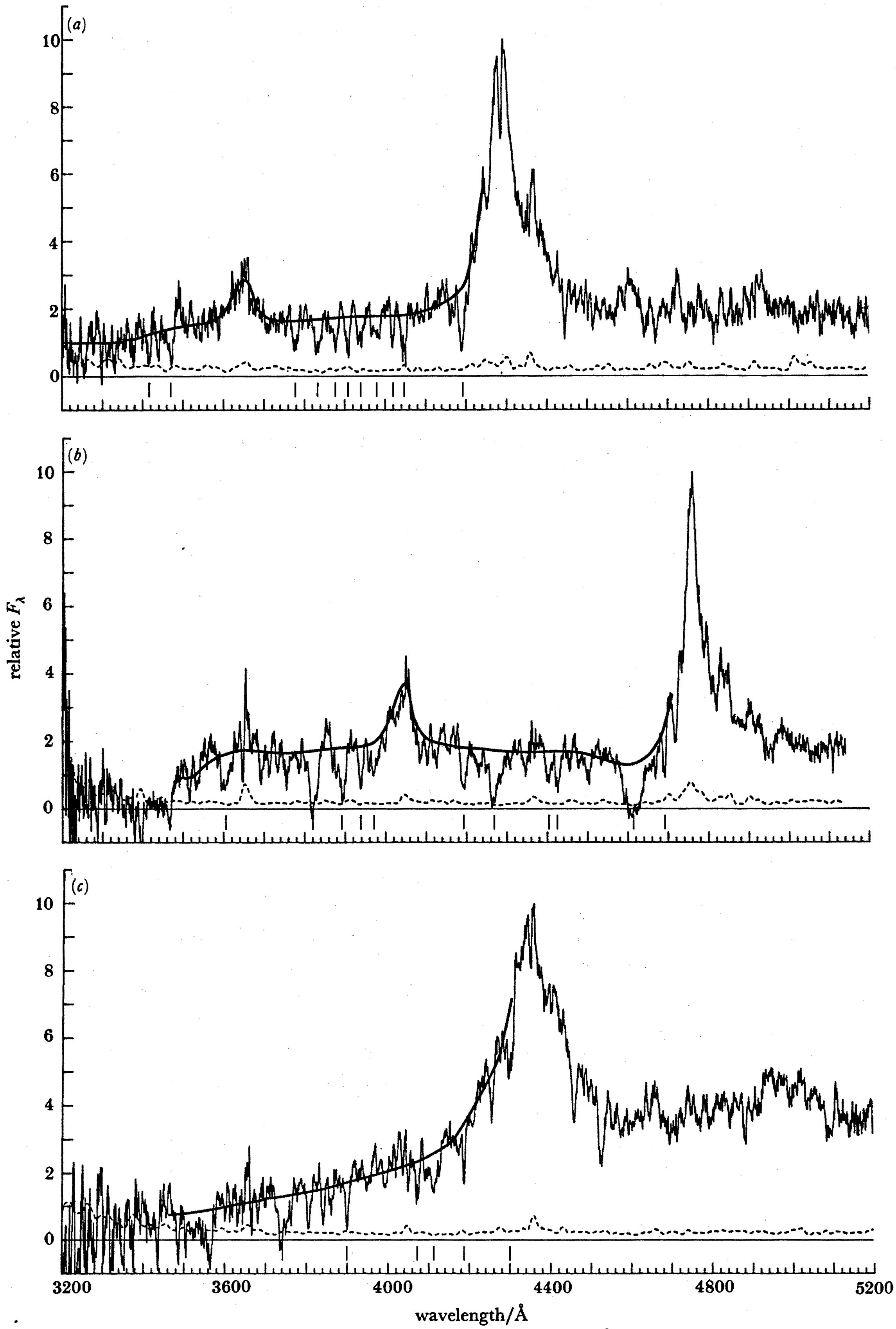

FIGURE 1. (a) Lick spectrum of Q0933+733. The spectral resolution is 10 Å or 8 pixels. The relative flux, F_λ, has units erg cm^{-2} s^{-1} Å^{-1}†. The dashed curve is the 1 σ error array and the solid curve is the continuum fit to the spectrum. Absorption features blueward of Lα emission are marked (see Wolfe *et al.* 1986*a*). (b) Lick spectrum of Q1337+113 (see Wolfe *et al* 1986*a*). (c) Lick spectrum of Q2206−199N (see Wolfe *et al.* 1986*a*).

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Lα. The remaining 11 features consist of 1 Lβ transition and 10 features that split up into narrow multicomponents spanning velocity intervals exceeding *ca.* 1000 km s^{-1}. The histogram in figure 2 indicates that the incidence of damped absorbers increases with *increasing* W until they dominate at $W > 10$ Å. In contrast, the incidence of multicomponent absorbers increases with *decreasing* W down to the 5 Å threshold.

These results are interesting for two reasons. First, the number of discs predicted to intercept our sample of QSOs is no more than three (see §4). Second, figure 2 gives the first hint that the distribution of equivalent widths for strong features is comprised of two (or more) populations that are statistically distinct.

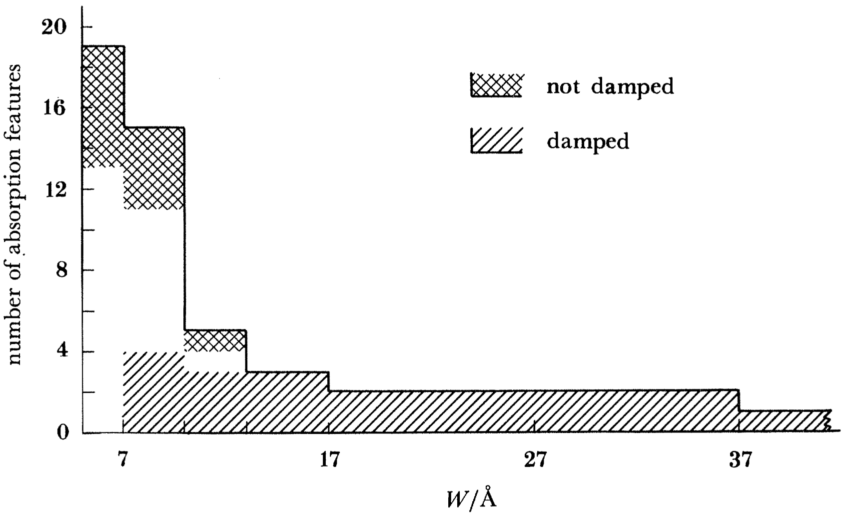

FIGURE 2. Histogram of 47 absorption features that are candidates for 'Lα discs'. Damped and non-damped features are indicated (see Wolfe *et al.* 1986*a*).

3. THE FREQUENCY DISTRIBUTION OF EQUIVALENT WIDTH AT $W > 2$ Å

In order to learn more about the damped systems, let us check whether they belong to cloud populations discovered previously, or whether they form a distinct population of their own. The detailed study of S.Y.B.T. showed that in the interval $W = 0.32$–2.5 Å the Lα-only and Lα-metal clouds are drawn from statistically distinct parent populations. The two populations are distinguished by differences in the frequency distribution of equivalent width, the two-point correlation function along the line-of-sight, and redshift dependence of $\mathrm{d}N/\mathrm{d}z$. The damped systems exhibit some of the same ions detected in the Lα-metal clouds. Moreover, the Lα-metal absorbers also occur more frequently than normal galactic discs (cf. Wolfe 1986). Thus it is entirely possible that the damped absorbers merely extend the Lα-metal population to large equivalent widths.

S.Y.B.T. defined an equivalent-width distribution $n(W,z)$, where $n(W,z)\,\mathrm{d}W\mathrm{d}z$ is the expected number of Lα lines with rest-frame equivalent widths in the interval $(W, W+\mathrm{d}W)$ and in the redshift interval $(z, z+\mathrm{d}z)$. From their high-resolution ($\Delta\lambda < 0.8$ Å) study of six QSOs, S.Y.B.T. found that within the range $W = 0.32\ \text{Å} \leqslant W \leqslant 2.5$ Å, n can be represented by the sum of two exponentials, i.e.

$$n(W,z) = \sum_i \frac{N_i(z)}{W_i} \exp\left(-\frac{W}{W_i}\right), \quad i = (\alpha\mathrm{o}, \alpha\mathrm{m}), \tag{3}$$

where the indices αo and αm denote Lα only and Lα metal, and $dN = N_i(z)\,dz$ is the total number of lines in the interval $(z, z+dz)$. The distributions are distinguished by a sharp decline with W for the Lα-only clouds ($W_{\alpha o} = 0.22$ Å) and a mild decline for the Lα-metal clouds ($W_{\alpha m} = 1.05$ Å). S.Y.B.T. could not determine the form of $n(W, z)$ at $W > 2.5$ Å because the redshift path covered by six QSO spectra does not adequately sample the infrequent strong lines. With a redshift path some 20 times longer our survey is ideal for determining $n(W, z)$ out to large equivalent widths.

The data base for this task, the sample of 476 absorption features presented by Wolfe *et al.* (1986*a*), cannot be used as it stands. Because of the wide range in signal:noise ratio of the Lick spectra, lines of a given equivalent width will not be uniformly sampled. Moreover, the shape of the empirical $n(W, z)$ will be affected by line blending caused by instrumental resolution. In Wolfe *et al.* (1986*b*), Monte Carlo simulations are used to correct the original line list for incompleteness. The resulting equivalent-width distribution is shown in figure 3. By comparing it with an extrapolation of (3) we see that the Lα-metal metal distribution appears to give an adequate fit to the data for 2 Å ⩽ W ⩽ 7 Å, but falls off too steeply at $W > 7$ Å.

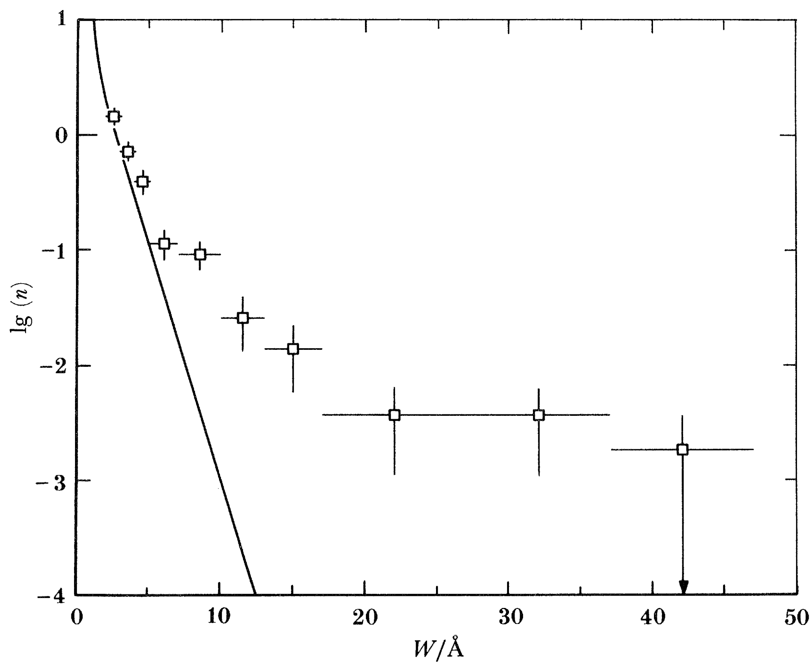

FIGURE 3. Frequency distribution of equivalent width of Lα absorption features found in Lick survey. Ordinate is the logarithm of distribution function and abscissa is rest-frame equivalent width. Sample of 122 features has been corrected for completeness. Solid curve is extrapolation of S.Y.B.T. distribution (see Wolfe *et al.* 1986*b*).

To check whether the observed flattening in $n(W)$ is an artifact of line blending, Wolfe *et al.* (1986*b*) simulated a series of synthetic surveys in which Lα lines were drawn from the parent populations in (3) and injected along 68 lines-of-sight with the same redshift paths as the actual spectra. The 'spectra' were smoothed, given noise characteristics of the real data, and subjected to the same algorithms used to construct the original line list. As before, the resulting line list was corrected for incompleteness. In every case a random distribution was used to select the Lα equivalent widths of both populations and the redshifts of the Lα-only clouds. The two-point correlation function discussed by S.Y.B.T. was used to select redshifts for the Lα-metal clouds. The resulting frequency distributions fall off sharply with W. As a result, the observed flattening cannot be due to line blending alone.

There are two straightforward explanations for the shape of the equivalent width distributions. Either lines throughout the entire range of equivalent widths in figure 3 are drawn from a single parent population (presumably a power law $n(W) \propto W^{-2.4}$), or they are drawn from the Lα-metal population in the interval $2\ \text{Å} \leqslant W \leqslant 7\ \text{Å}$ and from another population at larger equivalent widths. If all the equivalent widths in figure 3 were drawn from the same parent population, they would form an ordered sequence in the *same* physical variable throughout the entire range in W. However, the evidence in §4 indicates otherwise. Whereas the features within $2\ \text{Å} \leqslant W \lessapprox 7\ \text{Å}$ form a continuous sequence of increasing velocity width, the features with $W > 10\ \text{Å}$ are all damped lines which form a sequence of increasing $N(\text{H I})$. In other words, there is strong evidence for two separate sequences or populations. When the damped lines are separated from the remaining features, one finds that the damped lines form a flat frequency distribution ($W_{\text{damp}} \approx 10\ \text{Å}$) which probably peaks at $W \approx 10\ \text{Å}$. To explain the shape of the distribution of the remaining features we drew clouds from a Lα-metal population in which the redshifts were correlated over $\Delta V = 2000\ \text{km s}^{-1}$. In this picture, line blending between correlated clouds is responsible for the excess of features at $W = 5\ \text{Å} \lesssim W \lesssim 13\ \text{Å}$. This is tentative evidence for a galaxian two-point correlation function at large redshifts (Peebles 1980; S.Y.B.T.).

4. Physical evidence for galaxy discs

In order to deduce the physical properties of the damped population we have acquired high-resolution optical spectra (cf. Turnshek *et al.* 1986) and, when possible, accurate radio spectra (cf. Wolfe *et al.* 1985) of the background QSOs. The data indicate that the properties of the damped population are not described by the same distributions of physical parameters as other cloud populations. Rather, the properties of the damped absorbers appear to form separate sequences of their own. Moreover, these properties have much in common with the gaseous discs of nearby galaxies.

Figure 4 shows a MMT spectrum of Q1347+112, a QSO with a damped absorption spectrum at $z_a = 2.4705$. What sets this absorption system apart from the average Lα-metal system is (*a*) the dominance of Lα in comparison to the heavy-element lines, (*b*) the fact that Lα is well fit by a Voigt damping profile and (*c*) the appearance of prominent low-ionization stages in the heavy-element absorption spectrum. By contrast, in the Lα-metal systems the Lα line is Doppler broadened and is not much stronger than the high-ion lines that dominate the heavy-element absorption (cf. S.Y.B.T.). Although high ions such as C^{3+} and Si^{3+} are sometimes present in the damped systems, as they are in this case, they are not stronger in absorption than low ions such as C^{+}, Si^{+}, O^{0}, and Fe^{+}. In all these respects the damped spectra resemble absorption spectra of the H I disc of the Galaxy (cf. Morton 1975).

Voigt damping profiles have been fitted to all 15 'Lα disc' absorption features. The goodness of fit ranges from 'excellent', as in the high signal:noise ratio data of figure 4, to 'reasonable' for some of the noisier spectra (cf. Wolfe *et al.* 1985). Of course one could also reproduce the broad 'Lα disc' absorption trough with many narrow features created by low-$N(\text{H I})$ clouds that are strategically distributed across a velocity interval of *ca.* 1000 km s^{-1}. The problem with

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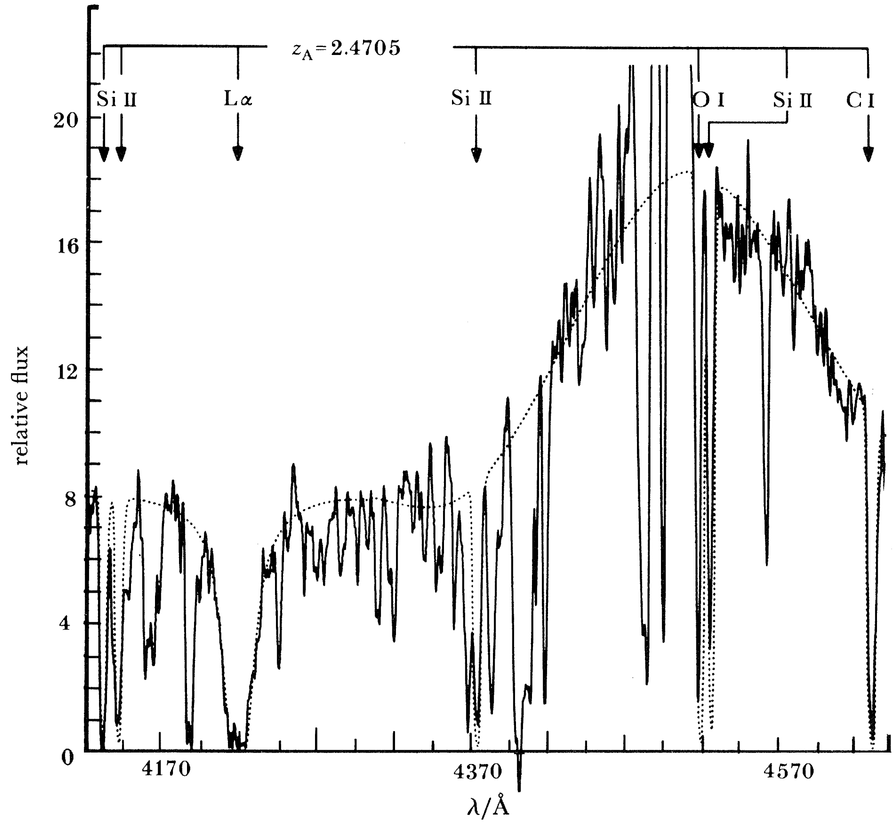

FIGURE 4. MMT spectrum of Q1347+112. Spectral resolution is 2 Å or 2 pixels. Relative flux has units erg cm^{-2} s^{-1} $Å^{-1}$. Dotted line is continuum fit with absorption lines expected at 'Lα disc' redshift, $z_a = 2.4705$. Identifications are noted (see Turnshek *et al.* 1986).

this idea is that the low-ion transitions and, in one case, the 21 cm line arise at single redshifts which predict Lα to be at the centre of the trough. The Voigt fits lead to determinations of N(H I) that range from 1×10^{20} to 8×10^{21} cm^{-2}, with a mean $\langle N(\text{H I})\rangle = 1.4 \times 10^{21}$ cm^{-2}: the typical error in N(H I) is *ca.* 50% and is mainly due to uncertainty in the continuum level. It is important to emphasize that these H I column densities are independent of velocity dispersion, and, owing to the large Lyman-limit optical depth ($\tau_{LL} \sim 6 \times 10^3$), represent the total H column density of the absorber. The column densities are significantly higher than those inferred for the Lα-metal systems (Weymann *et al.* 1981). Rather, they are similar to the N(H I) deduced for lower z_a systems detected in 21 cm absorption (cf. Wolfe 1980). Moreover, the $\langle N(\text{H I})\rangle$ is at least 10 times the threshold column density expected at the outskirts of nearby H I discs.

In principle it is also possible to deduce column densities for the heavy ions detected in absorption. This is not straightforward in practice because most of the observed lines are saturated and therefore the equivalent widths lie on the flat portion of the curve of growth where determination of column densities is highly uncertain. On the other hand, the pattern of equivalent widths reveals the total extent of velocity broadening in the absorption-line gas, and shows that it is characterized by velocity dispersions in the range 10 km $s^{-1} \lesssim \sigma \lesssim 60$ km s^{-1}. Previous studies of 'Lα discs' with 21 cm absorption indicated that in order to reconcile the wide range of σ encompassed by the heavy-element lines with the low σ characterizing the 21 cm line, 'Lα discs' must include a quiescent velocity component ($\sigma \approx 10$ km s^{-1}) containing most of the gas and a turbulent component that varies both in σ ($\approx$20–60 km s^{-1}) and in relative gas content (Briggs & Wolfe 1983; Briggs *et al.* 1985). Thus it is necessary to extract the quiescent component if the aim is to make realistic abundance determinations. This requires very high resolution ($\Delta\lambda < 0.2$ Å) spectra, or a redshift system in which the turbulent component is absent. Although spectra with very high resolution have not been obtained, the weak low-ion lines and absence of CIV absorption in the 'Lα disc' in Q1337+113 are indicators of a pure quiescent system with $\sigma < 15$ km s^{-1}. This 'Lα disc' is ideal for abundance determinations, because the H I column density, N(H I) $= 7.9 \times 10^{20}$ cm^{-2}, is accurately known. Moreover, the absence of the high ions, C^{3+} and Si^{3+}, indicate that the observed C^+ and Si^+ are the dominant stages of ionization in C and Si. Unfortunately, all the Si II lines detected so far are saturated. As a result, although the abundances predicted by the best-fit curve of growth (i.e. $\sigma = 8$ km s^{-1}) are O/H $= -1.0$, C/H $= -0.14$, Si/H $= -1.8$, and Fe/H $= -1.2$, the data do not exclude 0.01 times the solar abundance for each of the metals in this $z_a = 2.8$ absorber.

The frequent occurrence of 21 cm absorption in the damped Lα absorbers is further evidence that they differ from other populations of clouds in the Lα forest. Whereas a search for 21 cm absorption in 18 redshift systems with Mg II absorption resulted in two detections (Briggs & Wolfe 1983), a similar search of four redshift systems with damped Lα ended in three detections. In each case the 21 cm lines were fitted with Gaussians having velocity dispersions $\sigma < 15$ km s^{-1} (cf. Wolfe 1980); hence the concept of the quiescent component. In addition to experiencing a low level of turbulence the H I gas in 'Lα discs' is relatively cold. The spin temperatures, T_s, deduced from combining the optical and radio data are less than 10^3 K. Unless the gas density is exceedingly low, these limits also apply to the kinetic temperature, T_k. Consequently in comparison to the 'hot', $T_k \sim 10^4$ K, and turbulent ($\sigma \approx$ 10–400 km s^{-1}), gas characterizing the Lα-metal population, the H I in the 'Lα disc' appears to be cold and quiescent.

At the same time the 21 cm data provide strong support for the disc hypothesis. First, 21 cm absorption is a generic feature of the H I disc of the Galaxy. Comparison between the line profiles detected at intermediate galactic latitudes (Dickey *et al.* 1979) and those detected in 'Lα discs' (Wolfe *et al.* 1985) reveal a close similarity. Second, the low velocity dispersion of the quiescent component is comparable to the $\sigma \approx 10$ km s^{-1} velocity dispersion detected throughout the H I discs of face-on spiral galaxies (Lewis 1984; Van der Kruit & Shostak 1984). Third, the limits derived for T_s in 'Lα discs' are in the range of spin temperatures deduced for H I clouds in the Galaxy. Fourth, the detailed 21 cm line profile measured in the $z_a = 2.04$ 'Lα disc' in PKS 0458−02 provides additional information about conditions in one of these absorption systems. Wolfe *et al.* (1985) show that the two narrow ($\sigma \approx 5$ km s^{-1}) absorption features are unlikely to arise in single pressure confined clouds. Instead, it is probable that each feature arises in a concentration of H I (a spiral arm?) comprising many clouds that move with virial motions in the gravitational field provided by all the gas. The *ca.* 15 km s^{-1} separation between the velocity centroids of the features could arise from differential rotation of the absorbing disc. These speculations will be put to test by forthcoming VLBI observations which will place limits on the transverse size of the absorbing H I (Briggs *et al.* 1986).

The final physical property to be discussed is cosmological mass density. By combining the mean column density of any population of absorbers with their incidence along the redshift path of the defining survey it is possible to obtain a mass density averaged over our past light cone (see S.Y.B.T.). The usual assumption of constant comoving density leads to an estimate of the cosmological density parameter, Ω_{damp}, which is given by

$$\Omega_{damp} = \frac{\mu m_H \langle N(\mathrm{H\,I})\rangle \sum_{j=1}^{68} (N_{disc})_j}{(c/H_0)\,\rho_{crit} \sum_{i=1}^{68} C_i(q_0, z_{min}, z_{max})}. \tag{4}$$

In the last equation μ is the mean molecular mass of the gas, ρ_{crit} is the critical density, and the C_i are functions of the minimum and maximum redshift for which Lα can be detected along the line of sight to the ith QSO. The important point is that Ω_{damp} is independent of assumptions about absorber size. Rather it depends on q_0 and h $(=H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ in the following way:

$$\Omega_{damp} = \begin{cases} 3\times10^{-3}/h, & q_0 = 0.5 \\ 1.5\times10^{-3}/h, & q_0 = 0.025. \end{cases} \tag{5}$$

Comparison with Ω determined for the other populations of clouds in the Lα forest (S.Y.B.T.) shows that Ω_{damp} is larger by at least a factor of 10. In fact Ω_{damp} is comparable to recent estimates of Ω_{lum}, the mass density of luminous matter in galaxies. From the mass:light ratios given by Faber (1982) and a luminosity density of galaxies given by $L_B \approx (2\times10^8 h)\, L_\odot/\mathrm{Mpc}^3$ one finds that $\Omega_{lum} = 1.5\times10^{-3}$ for spirals and 4×10^{-3} for all galaxies. The rough agreement between Ω_{lum} and Ω_{damp} may of course be a coincidence. On the other hand, in my opinion it indicates that we have detected the baryon content of galaxies at a time just after the dissipational collapse of the protogalaxy, when most of the baryons were located in the interstellar medium of the disc.

The foregoing arguments are summarized in table 1. The difference between the Lα-metal and the Lα-damped population is evident. At the same time, with the exception of size and possibly dust content, the resemblance between the damped absorbers and galaxy discs is also evident. The radii were derived by assuming a one-to-one relation between nearby galaxies

TABLE 1. PHYSICAL PROPERTIES

		population	
property	Lα metal	nearby discs	Lα damped
W_*/Å[a]	≈1 Å	—	≈10 Å
N(H I)/cm^{-2}[b]	10^{16}–10^{19}	≈10^{21}	≈10^{21}
H^0/H	≪1	≈1	≈1
$\sigma_{\mathrm{H\,I}}$/km s^{-1}	≈10–400	≈10	≈10
21 cm[c]	infrequent	generic	frequent
T_k/K	≈10^4 K	50–10^3 K	<10^3 K
$C^+:C^{+3}$	≪1	≫1	≫1
R/R_{H0}[d]	5–6	≈1	3–4
Ω	<10^{-4}	2×10^{-3}	$3\times10^{-3}/h$
Z	>0.1 $Z_\odot$	≈$Z_\odot$	> 0.01 $Z_\odot$
D/G[e]	?	$Z_\odot$	?

[a] e-Folding equivalent width $|n(W)/(\mathrm{d}n/\mathrm{d}W)|$ of the frequency distribution of equivalent width, $n(W)$.
[b] H I column densities corresponding to $R < R_{H0}$ for nearby discs, and to the outskirts of the damped Lα systems.
[c] Incidence of 21 cm absorption.
[d] Cross-sectional radius in units of Holmberg radius.
[e] Dust:gas ratio.

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and members of either population of absorber. More specifically, the 14 damped systems with $N(\text{H I}) \geqslant 2\times10^{20}$ cm^{-2} were compared with the 1.9–3.2 discs predicted for (i) $q_0 = 0.5$–0.025, (ii) the redshift path of the Lick survey, and (iii) for $R = 1.5\ R_{\text{Ho}}$, corresponding to the average radius of disc galaxies at the limiting column density, $N(\text{H I}) = 2\times10^{20}$ cm^{-2} (Bosma 1981). The radii required for galaxy halos to explain the Lα-metal systems are taken from Wolfe (1986). Estimates of Z, the gas-phase metal abundance, are taken from Weymann *et al.* (1981) for the Lα-metal clouds, Spitzer & Jenkins (1975) for galaxy discs, and our determination of the metallicity of the damped absorber in Q1337+113 for the damped population. Although the dust content of the absorption-line gas has not been discussed, it is included in table 1 because of its importance in discriminating between alternate scenarios of galactic evolution.

The most straightforward interpretation of the data is that the damped population is comprised of giant disc-like objects which are the progenitors of current galactic discs. While observational programmes are being planned to test this hypothesis, independent evidence which already exists tends to support it. For example, the large size of the discs depends critically on the conclusion that the high detection rate of damped Lα systems in our sample reflects a mean free path that is shorter than predicted by the 'standard' model. However, a standard mean free path would be compatible with the data if gravitational lensing by foreground galaxies enhanced the surface density of background QSOs (in a magnitude-limited sample), thereby causing a high detection rate of discs. The discovery of a pair of damped Lα systems along two lines of sight argues against such an enhancement. Comparison between the probabilities for detecting two foreground discs and for detecting one foreground disc shows that the ratio depends only on the *actual* mean free path. If this equalled the standard value, the probability of detecting two damped Lα pairs would be negligible, contrary to observation. Secondly, figure 5 compares the observed frequency distribution of $N(\text{H I})$ with that expected

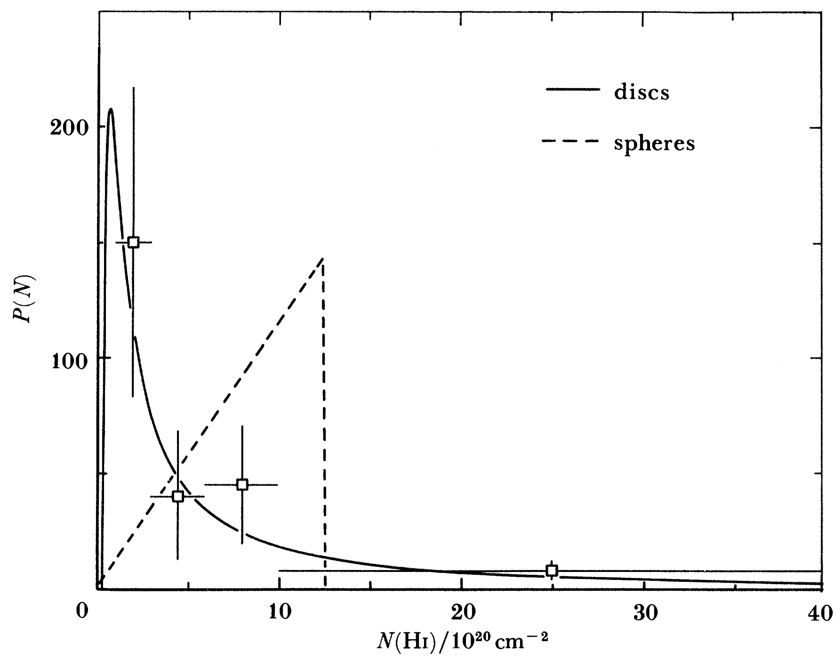

FIGURE 5. Frequency distribution of H I column densities deduced for 'Lα discs'. Solid curve is theoretical prediction for randomly oriented exponential disc with central column density $N_c = 6\times10^{21}$ cm^{-2} and cutoff column density $N_{co} = 4\times10^{19}$ cm^{-2}. Dashed curve is prediction for random lines of sight through uniform spheres with $N_c = 1.25\times10^{21}$ cm^{-2} (see Wolfe *et al.* 1986*b*).

for random lines of sight that penetrate a population of identical exponential discs that are randomly oriented, and a population of identical uniform spheres. The disc distribution is compatible with the data, whereas the distribution of spheres is not. This argues against models in which the damped Lα originates in small self-gravitating clouds (Silk & Norman 1981). Future observations of the diameters of the damped absorbers should further help to discriminate between these and other models.

5. Implications for galaxy formation

The interpretation of the damped Lα population discussed in §4 implies a revision in the current view of how the protogalaxy collapsed. If at early times the baryon content of spiral galaxies was mainly in the form of giant gaseous discs, then these discs must be an intermediate stage of galactic evolution, one that occurs after the halo stars formed but before development of the present disc. The new picture differs from the standard one (Eggen *et al.* 1962) in that the immediate progenitor of the present disc would itself be a disc rather than a gaseous protogalaxy. Therefore the formation of the present disc would occur in two stages: collapse of the protogalaxy to a giant disc and then its contraction in the plane to its current size.

The first stage of the collapse brings to mind scenarios in which a gaseous protogalaxy undergoes dissipative collapse in the spherically symmetric gravitational field of a dark, non-dissipative halo (cf. Efstathiou & Jones 1980). Because the required radius of the resulting disc is *ca.* $3R_{\mathrm{Ho}}$, the sizes of the initial protogalaxies would be scaled-up versions of current models. The tidal torque theory (Peebles 1969) predicts that the gas would collapse to a centrifugally supported disc, provided that the initial radius is *ca.* 10 times the disc radius, the baryon mass is *ca.* 10% of the total mass, etc. (cf. Efstathiou & Jones 1980). The subsequent contraction of the disc would have to proceed quasistatically through the outward transport of angular momentum. This might be driven by torques arising from turbulent viscosity (Lynden-Bell & Pringle 1974) or by other interactions (cf. Lacey & Fall 1985). In every case the time scale for contraction would not be less than *ca.* 10^{10} a. On the other hand, collapse to a disc by factors considerably less than 10 would occur if the halo gravitational field were non-spherical. Jones & Wyse (1983) show how this leads to the production of discs that are out of centrifugal equilibrium. The contraction to the present centrifugally supported disc therefore occurs on a dynamic time scale of *ca.* 10^9 a. One can decide between these possibilities by conducting a survey for 'Lα discs' with $z_{\mathrm{a}} \approx 0.5$–$1.5$. In the case of dynamic contraction, the disc radii in this redshift interval would equal *ca.* R_{Ho}, whereas $R \approx 3R_{\mathrm{Ho}}$ for the slower quasistatic contraction. As a result, the number of low-z_{a} discs detected in the case of quasistatic contraction should be about 10 times the number detected for dynamic contraction. The presence of huge H I envelopes which surround some nearby spirals (Briggs 1983) provides tentative support for quasistatic contraction.

Finally, the redshift distribution of the damped Lα absorbers implies that the epoch of disc formation occurs before the time corresponding to $z_{\mathrm{a}} = 2.8$, the largest absorption redshift in the sample. This follows from Monte Carlo calculations in which 15 redshifts were (*a*) randomly selected from a parent distribution obtained with the assumption of constant cross-section and constant comoving density and (*b*) placed along the same redshift paths as the 68 QSOs in the survey. Every simulation produced a distribution that was compatible with the observed one. Therefore there is no evidence for epoch-dependent effects, such as disc formation, at $z_{\mathrm{a}} < 2.8$, i.e. $t_a \gtrsim 3 \times 10^9$ a. This argues against models in which the disc grows slowly outward, on a time scale of *ca.* 10^{10} a (cf. Larson 1976; Gunn 1982). Moreover, it implies that there should be no observable gap between the age distribution of stars in the halo and stars in the disc. Whether this is consistent with the apparent gap observed in the Galaxy (Mihalas & Binney 1981) is unclear at present.

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