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Cosmological implications of the redshift distribution of QSO absorption systems

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Summary. We have used the observational data on QSO absorption redshifts, as compiled by Perry, Burbidge and Burbidge (1978) (hereafter PB^2), Drew (1978) and Weyman *et al.* (1979) (hereafter W^2PT), to study various selection effects likely to affect the distribution of absorption redshifts and, then, to determine the probable number distribution of absorbers per redshift interval of 0.1, as a function of z. The distribution obtained, assuming all the observed absorption to be intervening, is found to be statistically incompatible with the redshift distribution of galaxies with constant cross-section for any Friedman cosmology with zero cosmological constant and $q_0 \geqslant 0$. Therefore, in order to eliminate the absorption systems which are plausibly intrinsic, we have applied the criterion suggested by W^2PT and by the analysis of the distribution of absorption systems as a function of the relative velocity between the emitting and the absorbing gas, for the PB^2 data set; to wit, we have analysed the distributions obtained by assuming that those systems with relative velocity greater than $0.02c$, $0.02c$ but $\neq 0.1c$ to $0.11c$ and $0.06c$ respectively, or those systems without O VI and N V lines, are produced by the intervening galaxies. All the four criteria provide acceptable fits with the predictions of Friedman models for $q_0 \simeq 0$ and galactic halo radii, $r_g \simeq 85\sqrt{H_{75}}$ kpc, where H_{75} is the Hubble constant in units of 75 km s^{-1} Mpc^{-1}. The quality of the match between the theory and observations improved significantly when allowance was made for evolution of either galactic cross-section or number density as $(1+z)^n$. All the four criteria for the separation of the two types of systems now provide excellent fits with Friedman models for $q_0 \simeq 0, n \simeq 1$ and $r_g \simeq 50\sqrt{H_{75}}$ kpc.

1 Introduction

Statistical studies of the distribution and multiplicity of QSO absorption line redshifts have, so far, been designed to determine whether the absorption arises in gas intrinsic to the QSO

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(in, for example, shells or clouds ejected from the QSO) or whether it arises in intervening matter condensed into galactic coronae or haloes or intergalactic clouds (Bahcall & Peebles 1969; Burbidge, O'Dell, Roberts and Smith 1977, hereafter BORS; W^2 PT). Recent observational and theoretical analysis favour the view that although a significant fraction of the narrow line absorption systems (containing lines of heavy elements) are intrinsic, the majority of the systems are probably intervening (Boksenberg 1978; Dyson, Falle & Perry 1979; PB^2; W^2 PT). Unfortunately, no definitive observational criteria for the separation of the intrinsic and intervening systems has yet been established. W^2 PT have proposed a three-component model to account for the distribution of the narrow-line absorption systems. In this model those absorption systems whose velocity relative to the QSO (calculated from the relative redshifts of the absorption and emission line systems) is less than *c*. 3000 $\mathrm{km\,s^{-1}}$, are produced in gas in galaxies within a cluster, of which the QSO is a member; those systems whose relative velocity is greater than *c*. 18 000 $\mathrm{km\,s^{-1}}$, arise in intervening matter. The systems whose velocity relative to the QSO lies between *c*. 3000 and 18 000 $\mathrm{km\,s^{-1}}$ are, according to this model, most probably due to material ejected from the QSO.

In this paper we shall no longer address the question whether or not the absorption can be, or is likely to be, mainly intervening, and shall rather assume that a significant fraction of the observed systems are in fact due to intervening matter. These absorption systems then provide, in principle, a unique source of information on the structure and evolution of the gaseous component of galaxies at redshifts significantly greater than those to which galaxies can be observed in their own light. We shall address ourselves here to the question 'What cosmological information can be obtained from the observational data on QSO absorption line redshifts?'

This paper is organized as follows: Section 2 discusses the method of analysis of the observed absorption-line systems, so as to determine the spatial distribution and size of the intervening absorbers as a function of redshift. The data used in our analysis (PB^2; W^2 PT; Drew 1978) and the selection effects affecting our analysis are discussed in Section 3. In Section 4 we give the normalized distributions of numbers of absorption-line systems as a function of velocity relative to the emitting gas and or redshift, for the data discussed in Section 3. The results of statistical analysis of these distributions for several different criteria for the separation of intrinsic and intervening systems is presented in Section 4. We discuss our results in Section 5.

2 Method

Absorption due to intervening matter may be produced in, for example, either galactic discs, coronae or haloes or in intergalactic clouds; it may be produced in all such objects. We consider, initially, a single, homogeneous population whose mean number density per unit comoving volume at z is $n(z)$. The mean effective cross-section of any member of the class is $\sigma(z)=\pi r^2(z)$, where $r(z)$ is the 'effective radius' of the object, defined such that any line of sight passing within $r(z)$ produces an observable absorption line (W^2 PT; BORS). Clearly, $r(z)$ is a function not only of the physical properties of the object, but depends also on the experiment, since the minimum ionic column density required to produce a detectable absorption line depends on the spectral resolution. We discuss these observational effects on $r(z)$ in the next section. The number of (heavy element) absorption line systems with redshift between z and $z+dz$ which is expected in the spectrum of any single QSO (with $z_{\mathrm{em}} > z+dz$) due to this population of intervening objects is

$$Y(z,dz)=n(z)\,\sigma(z)\,dl(z,dz), \tag{2.1}$$

where $dl(z, dz)$ is the path length corresponding to dz at z. If we assume that the Universe is well represented by a Friedman model with $\Lambda = 0$,

$$dl(z,dz) = \frac{c}{H_0} \frac{dz}{(1+z)^2 \sqrt{1+2q_0 z}}, \tag{2.2}$$

where H_0, q_0 have their usual meaning. Then

$$Y_{\mathrm{Fr}}(z,dz) = A(z)\,[(1+z)^2 \sqrt{1+2q_0 z}]^{-1}\,dz \tag{2.3}$$

where

$$A(z) = \frac{c}{H_0}\, n(z)\, \sigma(z). \tag{2.4}$$

For the case that several different populations of absorbers contribute, and that these are not distinguished spectroscopically, we have that

$$Y_{\mathrm{Fr}} = [\sum_i A_i(z)]\;[(1+z)^2 \sqrt{1+2q_0 z}]^{-1}\,dz. \tag{2.5}$$

It is important to note here than *observational determination of* Y(z, dz) *determines only* A(z) *and* q_0. Independent astrophysical information is needed if one is to extract $r(z)$ or $n(z)$ from $A(z)$. First, it must be assumed that the absorbers are indeed galactic coronae or haloes before independent determinations of galactic number density may be used to extract $r(z)$ from $A(z)$. Secondly, H_0 must be known. In the case of a single population of absorbers

$$r_0 = \left[\frac{1}{\pi}\frac{A_0}{c}\frac{75}{n_0(75)}\right]^{1/2} \left(\frac{75}{H_0}\right). \tag{2.6}$$

Thus, radii deduced from the same data (the same A_0) may differ by factors as large as 4 or more depending on the choice of n_0 and H_0 (*cf.* W²PT) (note that we have written $n_0 = n_0(H_0 = 75)\,(H_0/75)^3$, and use the subscript 0 for present epoch values.

Ideally, the observational determination of $Y(z, dz)$ should be based on a statistically complete sample of QSOs observed over the same – very wide – spectral range with identical detection probability for all z_{abs}. In practice, because of the large range in intrinsic brightness of the sources, the relatively small number of bright QSOs with $z \gtrsim 3$, and the inherent increase in detectability of high redshift systems because $\Delta\lambda_{\mathrm{obs}} = \Delta\lambda_{\mathrm{rest}}\,(1+z)$ such samples are not yet available. Those data which are available, of necessity, cover a wide range of emission line redshift and spectral coverage. Effects due to non-uniform resolution will be discussed in the next section. Here we define $Y_{\mathrm{obs}}\,(z, dz)$ accounting for variations in z_{em} and spectral coverage only (W²PT).

Since it is here assumed that the observed absorption may arise in intrinsic as well as intervening material the criterion for elimination of the intrinsic systems must be clearly stated and applied before $Y_{\mathrm{obs}}(z, dz)$ can be determined and analysed statistically to determine $A(z)$ and q_0. At present the only such criteria that can be generally applied is that of the relative velocity, since that is the only physical parameter which can be observationally determined for every absorption system. Other physical criteria, such as the number density (obtained from the appearance or absence of fine-structure lines), ionization state or column density cannot be applied because the necessary information exists for only a very small subset of all systems. We apply several different criteria (discussed in the next section) for separating the two types of systems and try to distinguish between them by testing the hypothesis that those absorption line systems which satisfy stated criteria arise in intervening objects randomly distributed in a space-time described by H_0, q_0, with a mean effective mean free path, $l(z)$, given by $(c/H_0)A^{-1}(z)$.

In any redshift bin of width dz at z

$$Y_{obs}(z, dz) = N_{abs}(z, dz)/N_Q(z, dz) \tag{2.7}$$

where $N_{abs}(z, dz)$ is the actual number of absorption line systems observed with redshift between z and $z+dz$ which satisfy the criterion for being intervening and $N_Q(z, dz)$ is the number of QSOs in the sample in whose observed spectra such an absorption line system could in principle have been observed (W^2 PT). For example, let us consider the criterion that all systems with relative velocity $v_{rel} = \beta c$ (where β is, as usual, given by $[(1+z_e)^2-(1+z_a)^2]/[(1+z_e)^2+(1+z_a)^2]$) greater than $\beta_c c$ are intervening and further that the detection of the C IV doublet at 1550 Å is required in order that the identification of a redshift system be acceptable. A particular QSO is then counted in $N_Q(z, dz)$ only if

$$\lambda_{min} < \lambda_{CIV}(1+z)$$

$$\lambda_{max} > \lambda_{CIV}(1+z+dz)$$

and

$$z+dz < [1-\beta_c)/(1+\beta_c)]^{1/2}(1+z_e)-1 \tag{2.8}$$

where λ_{min} and λ_{max} are the short and long wavelength limits of the spectral coverage, for that QSO.

Statistical comparison between $Y_{obs}(z, dz)$ and $Y_{Fr}(z, dz)$ can then yield $A(Z)$ and q_0.

3 Data set and selection effects

We have primarily used the data on QSO absorption redshifts compiled by PB^2 for the analysis presented in this paper despite its apparent inhomogeneity. We have done so because it is at present the only compilation of data covering a broad enough range in redshift to allow examination of the data for evolutionary effects. We have therefore made a careful examination of this data set to understand the effects of the inhomogeneities on our conclusions. As discussed below these are in no way as serious as may be thought at first glance. As controls, we have compared the results based on the PB^2 data with those obtained using the data compiled by W^2 PT and by Drew (1978). W^2 PT's data are the most homogeneous set available in the literature: all spectra were obtained at the same telescope with the same instrumentation resulting in a well-defined and uniform resolution. In addition uniform criteria of redshift identification has been applied. However, the survey covers only a limited range in redshift. Thus in the redshift range where the two data sets overlap they may be compared, as below, to provide a control on our conclusions based on the PB^2 data. Drew (1978) has meticulously applied a uniform procedure to identify absorption systems, to a subset of PB^2. Although the data set is smaller than either PB^2 or W^2 PT it does cover a wide redshift range and is thus also useful as a control.

Non-uniform spectral resolution is, in principle, the most serious flaw in the PB^2 data when one wishes to use that data for statistical purposes. Observations with high resolution tend to pick up weak lines which would have remained unidentified were the observations made with low resolution. Also, the absorption lines often reveal a complex structure at high resolution (Boksenberg 1978) which remains undetected at low resolution; often they split into many closely spaced multiple components. Since we are testing the intervening hypothesis, and since systems separated by less than about 500 km s^{-1} would, under this hypothesis, probably belong to the same object, we shall follow the procedure adopted by Drew (1978) and count all systems within 500 km s^{-1} as one.

It has often been claimed that because of the higher resolution used to study high redshift (z_{em}) QSOs, preferentially more absorption line systems are found at high redshift. This is only partially true, since many such high resolution spectra extend far enough to be able to pick up moderate to low z absorption. Even in a constant resolution survey, there is a systematic bias, however, due to the increased *effective* resolution because $\Delta\lambda_{obs} = \Delta\lambda_{rest}(1+z)$ (Boksenberg private communcation). The extent to which this effect will actually distort the results (even in the ideal case of a uniform resolution survey) depends strongly on the extent to which the statistics are based on marginally detectable absorption line systems. Since in fact a large percentage of the observed systems are very strong and are considerably stronger than the limits of detection this systematic effect can only be considered to result in a weakly increasing probability of detection with z. We may then write that $p(z) \sim p_0(1+z)^m$ where $m < 1$, and where p_0 is the probability of detection associated with the mean spectral resolution of the observation. The actual value of m can only be determined in a particular experiment when a well-formulated equivalent width criteria for identification is established; in that case $p_0 = p_0(W)$. The establishment of such criteria is now under study. Note that $p(z)$ is implicitly included in the definition of $\sigma(z)$.

In seeking to establish the effect on $Y_{obs}(z, dz)$ of the inhomogeneity of the resolutions, R, used in the PB^2 data, it is imperative to bear in mind that the distribution of $R(z_e)$ as a function of z_e is of no consequence. We must examine $R_{eff}(z, dz)$, the effective resolution over the redshift bin at z. In Fig. 1(a) we display the relative numbers of spectra in each bin (z, dz) which were obtained with very high ($\leqslant 2$ Å), high (2–5 Å), moderate (6–10 Å) or low resolution (general survey) respectively. In Fig. 1(b) a similar plot is given for those spectra where, instead of resolution, information on dispersion has been given. In all cases, the observed spectrum is considered to 'cover' the bin (z, dz) if either of the doublets Mg II (2796, 2803) or C IV (1548, 1551) were accessible. It is immediately obvious that the regions $z < 1.8$, and $z > 2.2$ have quite uniform resolution coverage, and that for $z < 2.0$ the coverage in dispersion is also uniform. As an approximate measure of the effect of slight variation in resolution and dispersion, we shall now define an effective mean resolution and dispersion. Since the probability of detection is inversely proportional to the resolution (measured in Å) or to the dispersion (in Å mm^{-1}) we have defined, in each redshift bin (z, dz),

$$\frac{1}{R_{eff}} \equiv \frac{1}{N'_Q(z, dz)} \sum_{i=1}^{N'_Q} \frac{1}{R_i}$$

$$\frac{1}{d_{eff}} \equiv \frac{1}{N''_Q(z, dz)} \sum_{i=1}^{N''_Q} \frac{1}{d_i}, \qquad (3.1)$$

where $N'_Q(z, dz)$ and $N''_Q(z, dz)$ are the number of QSOs in whose spectra absorption in the bin (z, dz) could have been detected, which have published spectral resolution or dispersion information respectively as given by PB^2. R_i and d_i are the resolution and dispersion used to observe the ith QSO. In Fig. 1(c) and (d), R_{eff} and d_{eff} are given as functions of z. (In cases where several spectra of the same object are reported in the same range of λ, the highest resolution spectra are taken for computation of R_{eff} and d_{eff}.) As is obvious from Fig. 1, the effective resolution and dispersion are remarkably constant in z, up to $z \sim 1.9$. Between

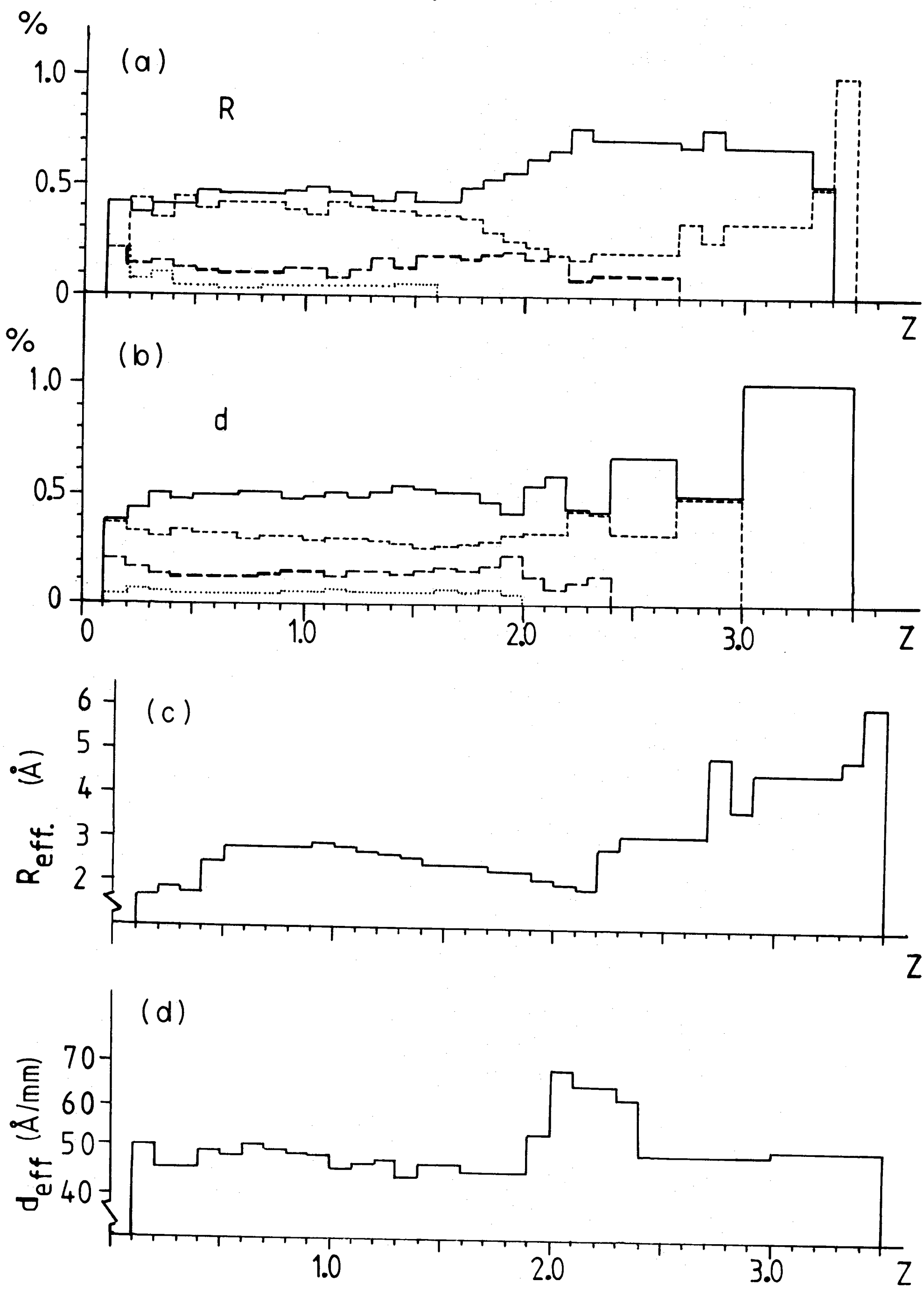

Figure 1. (a) Relative number of spectra in the PB[2] data set with very high (⩽2 Å, — —), high (2–5 Å, ———), moderate (6–10 Å, – – –) and low (⩾10 Å, ...) resolution as a function of redshift. (b) Relative number of spectra in the PB[2] data set with very high (< 30 Å mm^{-1}, — —), high (30–65 Å mm^{-1}, ———), moderate (65–100 Å mm^{-1}, – – –) and low (> 100 Å mm^{-1}, ...) dispersion as a function of redshift. (c) Effective resolution, R_{eff} (Å), as a function of redshift. (d) Effective dispersion d_{eff} (Å mm^{-1}) as a function of redshift.

$z = 1.9$ and 2.3 the effective resolution improves, whereas the effective dispersion deteriorates, so that the net probability of observation remains roughly the same as that for $z < 1.9$. For $z > 2.3$ the effective detection probability (as a function of the effective resolution) decreases somewhat. However, the decrease will be partially compensated for due to the increasing detection probability due to the $(1+z)^m$ effect discussed above. Therefore, we conclude that the effective resolution/dispersion is remarkably uniform over the whole range in z for the PB^2 data. The W^2PT survey has a uniform resolution of 2.5 Å which is only somewhat better than that of our data set, $\langle R_{\rm eff}\rangle \simeq 3$. Since, as discussed below, in the redshift range where the two surveys overlap, and where N_Q is large enough for statistical comparison ($1.1 < z < 1.9$), results from the two data sets agree, we conclude that for the purpose of the statistical analysis presented here, variations in $R(z)$ are insignificant.

Another potentially significant inhomogeneity in the PB^2 data is that which is due to differences in the criteria used by different observers to identify absorption systems. This effect could only be removed by a complete re-analysis of all the observations, using a single criterion of identification. However, since all analyses are presumed to be internally self-consistent, and since each observation spans a wide range of z, such inhomogeneities will average out in precisely the same manner as did the inhomogeneity in R and d. As a check on this assumption we have used Drew's (1978) data. Since she has applied a stricter criterion for acceptance of absorption systems, values of $N_{\rm abs}(z, dz)/N_Q(z, dz)$ for her data set are systematically slightly lower than those for PB^2 data set. However, they show the same basic z dependence. We shall discuss this point again in the next section after presenting the results, but again we conclude that this inhomogeneity is not signficantly affecting our general results.

There is another class of selection effect which arises due to the ease or difficulty of observing absorption lines at particular redshifts. There are primarily two such effects. The abrupt entry of important lines, such as C IV, L_α or Mg II into the observing window at particular values of z will increase the absolute value of $N_{\rm abs}(z, dz)$, (Basu 1979; Roeder 1971). However, there will be a simultaneous increase in $N_Q(z, dz)$. Since the essential lines for identification are in practice the doublets Mg II and C IV and L_α the entry of additional lines such as O VI or Si IV is not so crucial as to significantly change $Y(z, dz)$. This is of course in contrast to the situation for emission lines. This effect will therefore not affect our results. As has been pointed out by Roeder & Dyer (1972) (in connection with emission lines) there are a discrete set of redshifts at which one or more of the main absorption lines required for identification can be blanketed by night sky lines, leading to an underestimate of $N_{\rm abs}(z, dz)$. We have carefully repeated their analysis, for a complete set of night sky and QSO absorption lines. Over small ranges of dz the blanketing can in principle be important, but since the night sky lines are rather narrow, and since we use $dz = \Delta z = 0.1$, equivalent to $\Delta\lambda \simeq 150$ Å, the fraction of our bins which can be affected is of the order of only several per cent. It is therefore surprising and perplexing that several of the most prominent dips in the $Y(z, dz)$ curve turn out to be in bins affected by such night sky blanketing. We, however, do not believe that the dips can be caused by this night sky effect.

There are two individual QSOs in the data of PB^2 which require individual mention here. In 1548+114B, Burbidge *et al.* (1977) identify five absorption systems, all with $z \sim 1.6$. They identify six neighbouring lines as five pairs of line-locked C IV doublets. If their identification is correct, these systems must be presumed to be intrinsic and should not be included in our analysis. However, since there is an alternative identification assigning three of the lines of other redshift systems in the object, leaving only one pair of C IV doublets with a spacing of less than 500 km s^{-1}, we have chosen a somewhat cautious route and counted only one system at $z \sim 1.6$ as real for our analysis. In the case of PKS 0237 − 23 we have included only the following redshifts in our analysis: $z = 2.2013$, 2.1758, 1.955, 1.67, 1.65, 1.59, 1.56, 1.55, 1.51 and 1.36 (Boksenberg 1980, private communication).

4 Results

In what follows, we shall understand the data set of PB^2 to be their redshift list, modified as discussed in the last section; i.e. all systems separated by less than 500 $km\,s^{-1}$ are counted as one system, and further the systems in 1548+114B and PKS 0237−23 are as discussed above. In Fig. 2(a) and (b) we plot the normalized number distribution, $Y_{obs}(z, \Delta z)$, and the absolute number distribution, $N_{abs}(z, \Delta z)$ respectively for the entire data set of PB^2, for a bin size of $\Delta z = 0.1$. In Fig. 2(a), the number of QSOs in whose spectra absorption in the bin $(z, \Delta z)$ could have been observed, $N_Q(z, \Delta z)$, is shown below the bin on the

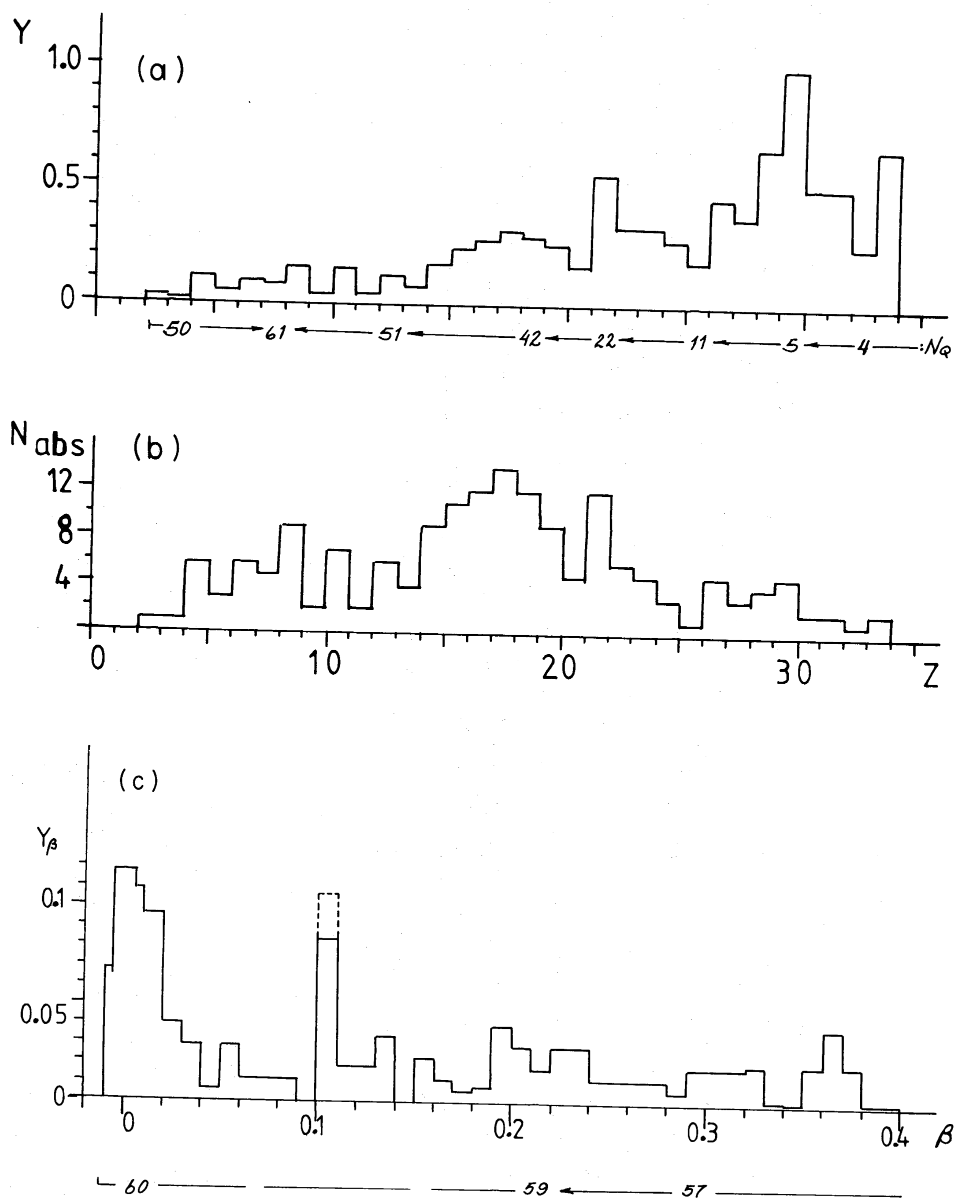

Figure 2. (a) Normalized number distribution of all observed absorption systems in the PB^2 data set as a function of redshift. (b) Absolute number distribution of all observed absorption systems in the PB^2 data set as a function of redshift. (c) Normalized number distribution of all observed absorption systems in the PB^2 data set as a function of relative velocity between the emitting and absorbing gas. (d) Normalized number distribution of absorption systems with $\beta > 0.02$ in the PB^2 data set as a function of redshift. (e) Normalized number distribution of absorption systems with $\beta > 0.02$ but $\neq 0.1-0.11$ in the PB^2 data set as a function of redshift. (f) Normalized number distribution of absorption systems with $\beta > 0.06$ in the PB^2 data set as a function of redshift. (g) Normalized number distribution of low ionization absorption systems (those not showing lines of O VI or N V) in the PB^2 data set as a function of redshift.

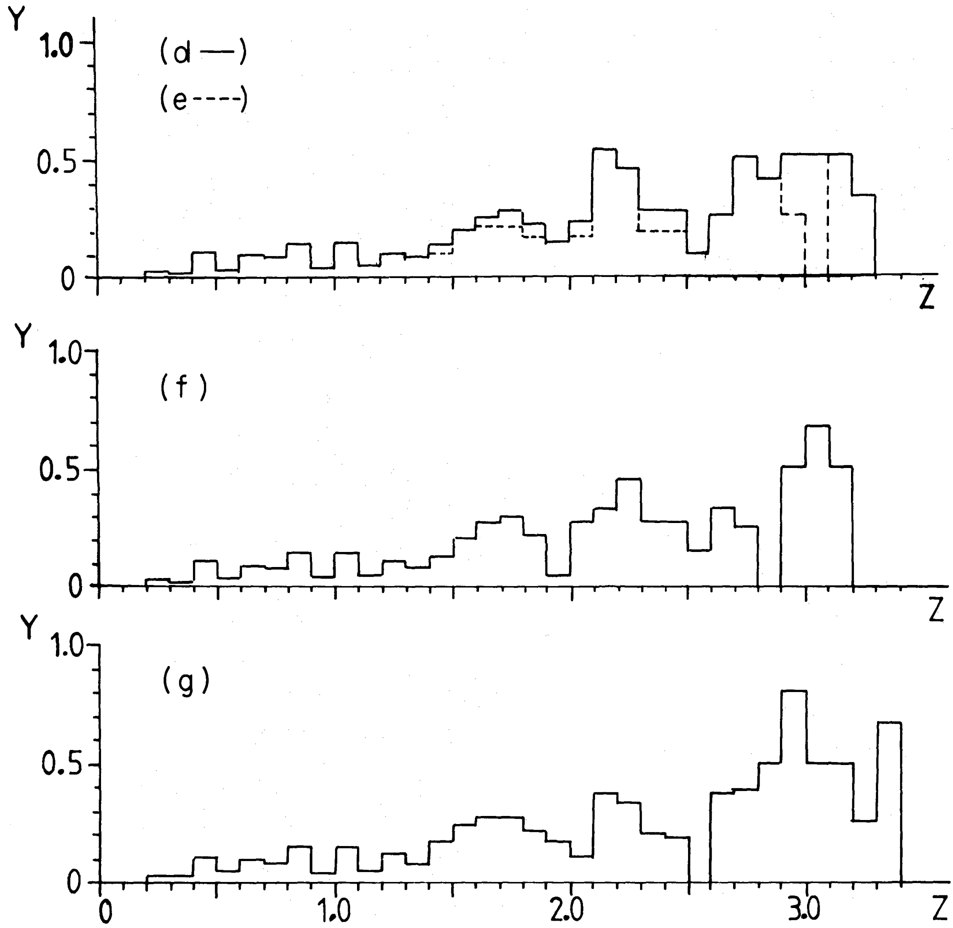

Figure 2 – *continued*

x-axis. The difference in the shape of the two distributions is very significant. It is particularly striking that in the normalized data none of the 'magic number' peaks are evident, and that there is a relatively steady increase in the incidence of absorption with increasing z. We have performed a χ^2 analysis for the significance of the peaks and dips in the curve and find that none are significant at the 3σ level.

In Fig. 2(c) we have plotted the normalized velocity distribution for the total data set of PB^2 defined as

$$Y_{obs}(\beta, \Delta\beta) = N_{abs}(\beta, \Delta\beta)/N_Q(\beta, \Delta\beta) \times (0.0033/\Delta\beta) \quad (4.1)$$

where all symbols have the same meaning as those of Sections 2 and 3, with β replacing z. Here we have chosen $\Delta\beta = 0.0033$ and 0.01. Fig. 2(c) can be compared with Fig. 1 of W^2PT. The peak near $\beta = 0$ is common to both data sets. Our data appears to indicate a drop off of the intrinsic systems at about $\beta \sim 0.02$ rather than 0.06 as in W^2PT.

The plot from $\beta = 0.02$–0.8 can be fitted with a straight line ($Y = 0.023$, $\chi^2 = 27.7$, $P = 0.9$), as is expected if these systems are intervening. However, the peak at $\beta = 0.1$ is significant at the 3σ level. If this peak is removed then the straight line fit for $\beta = 0.02$–0.8 ($\beta \neq 0.10$–0.11) is ($Y = 0.019$, $\chi^2 = 16.7$, $P = 0.99$) and the peak at 0.1–0.11 is significant at the 3.7σ level. We thus confirm Drew's results. No such peak is found by W^2PT. However, in the entire $\beta > 0.06$ range they find only 11 systems, so that no comparable statistical analysis to that discussed here is possible. We wish to emphasize that the peak is not a result of the five 'line-locked' systems in 1548+114B, since they have been treated as one system here. If

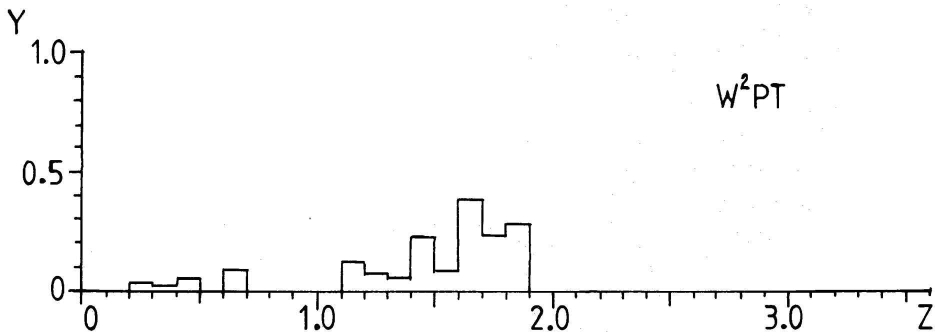

Figure 3. Normalized number distribution of all absorption systems in W^2 PT data set as a function of redshift.

we assume the peak is real and is due to intrinsic systems, then we should include all the five separate systems, and the peak would be enhanced, as is shown by the dotted line in the figure.

In Figs 3 and 4 the normalized z distribution $Y_{\text{obs}}(z, dz)$ for the data of W^2 PT and Drew are given. χ^2 analysis indicates that the PB^2 data and that of W^2 PT (in the range $1.1 < z < 1.9$) are drawn randomly from the same data base, confirming our conclusion that the inhomogeneity of the data in the PB^2 collection does not affect our results. Because of the small numbers in the W^2 PT data, and because of this agreement with the PB^2 data in the overlap region we shall not discuss the W^2 PT data any further.

4.1 CRITERIA FOR SEPARATION OF INTERVENING AND INTRINSIC SYSTEMS

Since all analyses of the velocity structure of the absorption (Drew; W^2 PT; our analysis of PB^2) show a statistically significant peak around $\beta = 0$ it is reasonable, on purely statistical grounds, to exclude low velocity systems from consideration when studying intervening absorption. In addition, it has been shown theoretically by Dyson, Falle & Perry (1980) and Falle, Perry & Dyson (1981) that narrow-line absorption systems can be formed in the outer regions of a QSO atmosphere through the action of a wind which sweeps ambient material into a shell headed by a shock wave. In the cases studied by these authors typical velocities are $\beta \sim 0.01$. In addition there is a rapidly growing collection of observations of QSOs which have broad line absorption indicative of continuous outflow (Boksenberg *et al.* 1978; Clowes *et al.* 1979). Many such systems extend up to 18 000 km s^{-1}, and it has been suggested (W^2 PT) that these systems may break up into line condensations. W^2 PT took such evidence of the possibility of outflow up to such high velocities as support for their hypothesis that the intrinsic component of the narrow-line systems extends to $\beta \sim 0.06$.

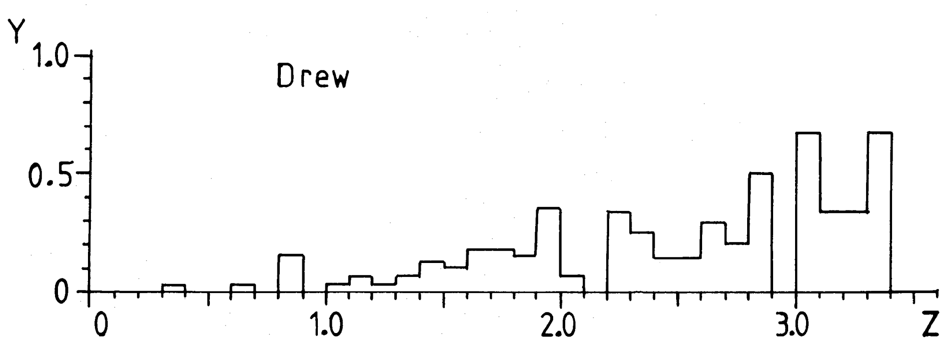

Figure 4. Normalized number distribution of all absorption systems in Drew's data set as a function of redshift.

Separation of the narrow-line systems into an intrinsic and an intervening component on the basis of a velocity discrimination thus appears to be a reasonable first step to sorting out the problem. While we expect such a criteria to be useful in a statistical sense, it is clearly not applicable in an individual case, particularly at values of β in the neighbourhood of 0.01 where we expect both types of absorption to be occurring. It will ultimately be necessary to develop physical criteria of separation, such as total ionic column density, state of excitation or local number density. The development of such criteria requires both more detailed predictions of theoretical models and much more extensive data.

In an attempt to develop a physical criterion for separation of the absorption line systems, we have examined the ionization state of all the systems listed in PB^2. We find that whereas only 15 per cent of the low ionization systems (i.e. those with lines of C II, Si II, Mg II or Fe II, but not O VI or N V) have $\beta < 0.06$, 75 per cent of the high ionization systems have $\beta < 0.06$. A similar effect is also noted by W^2PT. This would be consistent with a model where the intrinsic systems are physically close enough to the QSO to be highly ionized by the radiation field of the QSO. It is also consistent with the expectation of the shell model, where the cool shell is preceded by shock heated and ionized material. Unfortunately, these criteria are difficult to test since for many of the QSOs the spectral coverage was insufficient for observation of the lines of O VI or N V. In fact for $z < 1.5$ UV observations are necessary to observe these lines.

Since we do not believe that adequate support for any particular choice of cut-off in β has yet been developed, we shall test all the following hypotheses statistically:

(i) All absorption is intervening.

(ii) All absorption with relative velocity $v = \beta c > 0.02\,c$ is intervening.

(iii) All the absorption with relative velocity $> 0.02\,c$ is intervening, except for those systems with $\beta = 0.10$–0.11.

(iv) All the absorption with relative velocity $> 0.06\,c$ is intervening.

(v) All low ionization systems (those which do not show lines of O VI or N V) are intervening.

The histograms showing $Y_{\text{obs}}(z, \Delta z)$ as a function of z for the intervenings systems as per the above criteria (ii)–(v) are shown in Figs 2(d)–(g) respectively.

4.2 DETERMINATION OF $A(z)$ AND q_0

4.2.1 *The case that the absorbers do not evolve*

If it is assumed that the absorbers – whether galactic haloes or coronae or intergalactic clouds – have been formed prior to the epoch of observation (i.e. prior to $z \simeq 3.5$) and retain their identity thereafter, then $n(z) = n_0(1+z)^3$. If furthermore it is assumed (as is usually done) that there is no significant radial evolution of the absorber and that $p(z) = p_0$, then $\sigma(z) = \sigma_0$. Equation (2.3) then becomes

$$Y_{\text{Fr}}(z, dz) = \frac{c}{H_0} n_0 \sigma_0 (1+z)(1+2q_0 z)^{-1/2}\, dz. \tag{4.2}$$

Therefore

$$A_0 = \frac{c}{H_0} n_0 \sigma_0 = \frac{Y_{\text{obs}}(z, \Delta z)}{(1+z)\,\Delta z}(1+2q_0 z)^{1/2} = a_{\text{obs}}(z, \Delta z). \tag{4.3}$$

The assumption of constant cross-section and constant proper density thus requires that there be a value of q_0 which makes the r.h.s. of equation (4.3) constant, independent of z.

For the PB^2 data we have determined the best fit values of q_0 and A_0 for cases (i)–(v) of Section 4.1, by minimization of χ^2, defined as

$$\chi^2 = \sum_{i=1}^{N} \frac{[Y_{\text{obs}}(z_i, \Delta z) - Y_{\text{Fr}}(z_i, \Delta z)]^2}{\sigma_{z_i}}, \tag{4.4}$$

where

$$\sigma_{z_i} = [Y_{\text{Fr}}(z_i, \Delta z)/N_{\text{Q}}(z_i, \Delta z)]^{-1/2}. \tag{4.5}$$

We have also determined the values of q_0 and A_0 for Drew's data for case (i). We have considered the range $0.02 \leqslant A_0 \leqslant 5$, $0 \leqslant q_0 \leqslant 1$. The results are summarized in Table 1. There, in addition to the optimum values of q_0 and A_0, we list the minimum χ^2, the number of degrees of freedom, ν, and the probability that the observed data is drawn from the parent distribution given by the theory (equation 4.2).

The first, and most important, conclusion to be drawn from the results summarized in Table 1, is that (assuming constant detection probability) the assumption that all the absorption arises in intervening objects of constant cross-section is incompatible with any Friedman cosmology with zero cosmological constant and $q_0 \geqslant 0$. All the other cases give acceptable fits. The most acceptable fit for constant cross-section occurs if it is assumed that the low velocity systems ($\beta \leqslant 0.02$) and those in the 'magic' peak at $\beta = 0.1$–0.11 are intrinsic, and that the remainder are intervening. In Fig. 5(a) we plot $a_{\text{obs}}(z, \Delta z)$ for this case (having set $q_0 = 0$ in equation 4.3) and show the line $A_0 = 0.63$. A_0 lies considerably above the data near the origin, and below the data at large z. This suggests that a Friedman model with provision for evolution in galactic size or number density – either or both of these quantities having been larger at earlier epochs than they are at present – would give a better representation of the observations.

4.2.2 *z-Dependent absorption probability*

Since no theoretical models for the radial evolution of the absorbers exist – and since it is not yet clear exactly what interpretation of the data on intervening absorption is correct – we have chosen to represent the z dependence of A by the simple power-law

$$A(z) = A_0 (1+z)^{3+n}. \tag{4.6}$$

We have repeated the analysis of the previous section, using (4.6) in (2.3) and minimized χ^2 with respect to q_0, A_0 and n. Our results are given in Table 2. There is a dramatic increase in the statistical probability that the theory adequately represents the data and a drop in the present epoch value of A_0 by factors of 2–2.4, with only a moderate evolutionary factor of

Table 1. χ^2 minimization results for the case of non-evolving absorbers.

Case no.*	A_0	q_0	χ^2	ν	P	r_1^*(kpc)	r_2^*(kpc)
(i)	0.84	0	53.2	32	0.01	71	109
(ii)	0.71	0	39.7	31	0.14	66	100
(iii)	0.63	0	37.6	31	0.20	62	94
(iv)	0.67	0	36.1	30	0.16	64	97
(v)	0.73	0	41.6	32	0.12	67	102
(vi)	0.54	0	44.9	32	0.05	57	87

* As described in the text, case (vi) refers to Drew's complete data set.

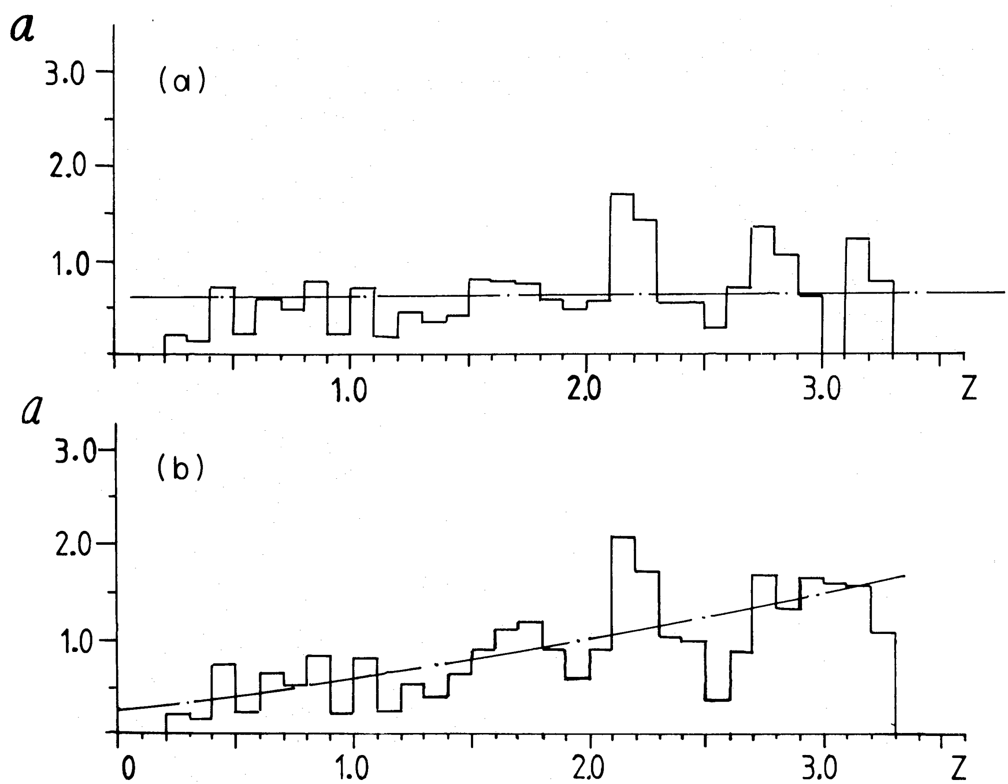

Figure 5. (a) $a_{\rm obs}(z, \Delta z)$ for $q_0=0$ and $\Delta z=0.1$, for absorption systems with $\beta>0.02$ but $\neq 0.1$–0.11 in the PB² data set as a function of redshfit and the best fit straight line for the case of non-evolving absorbers. (b) $a_{\rm obs}(z, \Delta z)$ for $q_0=0.105$ and $\Delta z=0.1$ for absorption systems with $\beta>0.02$ in the PB² data set as a function of redshift and the curve $y=A_0(1+z)^n$ for $A_0=0.26$ and $n=1.23$ for the case of evolving absorbers.

$n=0.9$–1.4 required. The optimum values of q_0 now range from $q_0=0\rightarrow 0.28$, all of which are in accord with determinations based on present conventional cosmological methods. Somewhat surprisingly, in view of the sharpness of the $\beta=0.1$ peak, and its apparent significance in the case of non-evolving cross-sections, we now find that the assumption that only the low velocity systems are intrinsic gives a better agreement with the data than the assumption that both the low velocity and the $\beta=0.1$ systems are intrinsic. This is mainly due to the fact that the data set used here is rather small and the statistical fluctuations are therefore quite large. Not much importance can therefore be attached to the small differences in values of χ^2 and P for cases (i)–(v) in Table 2. For the PB² data it is thus difficult to argue, on the basis of the results presented here, for a clear superiority of one of the models (i)–(v) although a marginal preference does appear to lie with (ii). What does emerge from this analysis, however, is the necessity of having a z-dependent A. In Fig. 5 we plot $a_{\rm obs}(z, \Delta z)$ for case (ii) (having set $q_0=0.105$ in equation 4.3) and show the curve $y=A_0(1+z)^n$ for values of A_0 and n for this case as given in Table 2.

Table 2. χ^2 minimization results for the case of absorbers evolving as $\sigma(z)=\sigma_0(1+z)^n$.

Case no.	A_0	q_0	n	χ^2	ν	P	r_1^*(kpc)	r_2^*(kpc)
(i)	0.25	0.1	1.4	29.9	31	0.54	39	59
(ii)	0.26	0.105	1.23	26.2	30	0.65	40	61
(iii)	0.3	0.015	0.87	29.3	30	0.51	43	65
(iv)	0.28	0.25	1.29	26.5	29	0.58	41	63
(v)	0.3	0.28	1.29	29.3	31	0.56	43	65
(vi)	0.25	0	0.86	32.8	31	0.3	39	59

Table 3. χ^2 minimization results for the case of absorber evolving as $\sigma(z) = \sigma_0 (1+z)^n$, assuming $q_0 = 0$.

Case no.	A_0	η	χ^2	ν	P	r_1^*(kpc)	r_2^*(kpc)
(i)	0.26	1.21	29.9	32	0.59	40	61
(ii)	0.27	1.03	26.2	31	0.72	41	62
(iii)	0.3	0.84	29.3	31	0.56	43	65
(iv)	0.3	0.93	26.6	30	0.65	43	65
(v)	0.31	0.91	29.3	32	0.6	43	66
(vi)	0.25	0.86	32.8	32	0.4	39	59

Our results are rather insensitive to q_0. If we set $q_0 = 0$ and optimize for A_0 and n then we obtain the results presented in Table 3.

Both because of the discontinuity in the effective resolution for $z \geqslant 2.6$, and because N_Q is smaller than 10 for $z \geqslant 2.5$, we have repeated all of the statistical tests for the absorption systems in the range $0 \leqslant z \leqslant 2.5$. The values of q_0, A_0 and n change by less than 10 per cent in all cases.

Note that our results for Drew's data set are not significantly different from those for the PB^2 data. We thus feel justified in assuming that whereas improved resolution and homogeneity of the data will certainly improve the ability to discriminate between various separation criteria, the basic conclusions will remain unchanged.

4.3 DETERMINATION OF GALACTIC SIZES

We shall now assume that the intervening absorption is due to galactic haloes or coronae. As discussed in Section 2, the determination of galactic coronal radii from A_0 requires an independent knowledge of the number density of the galaxies. The observational value of the number density has been discussed by BORS and W^{2}PT, and depends on the choice of ϕ^*, the normalization factor in the luminosity function of galaxies (Schecter 1976).

$$\phi(L)\, dL = \phi^*(L/L^*)^{-5/4} \exp(-L/L^*)\, d(L/L^*). \tag{4.7}$$

Here L^* is the luminosity corresponding to $M_B^* = 20.6$. The values of ϕ^* used by BORS and W^{2}PT differ by a factor of 3.2. There is also a small differences in the radius–luminosity relation used by the two groups of authors. However, this has only a negligible effect on the results. For convenience we shall therefore use the analytical relation as used by BORS. We thus have

$$\sigma_0 \eta_0 = \sigma^* \phi^* \Gamma(7/12) \tag{4.8}$$

where σ^* is the cross-section of the galaxy with $M_B^* = 20.6$ and $\Gamma(7/12)$ is the gamma function. Using (2.6) we can thus write

$$r^* = \left[\frac{A_0 75}{c\phi_{75}^* \pi \Gamma(7/12)}\right]^{1/2} \frac{75}{H_0} \tag{4.9}$$

$$= 78(119) A_0^{1/2} \left[\frac{75}{H_0}\right] \left[\frac{1.7(0.75) \times 10^{-2}}{\phi_{75}^*}\right]^{1/2} \left[\frac{f}{0.5}\right]^{-1/2} \text{kpc} \tag{4.10}$$

Here ϕ_{75}^* (Mpc^{-3}) is the value of ϕ^* for $H_0 = 75$ km s^{-1} Mpc^{-1} and f is the fraction of galaxies capable of producing absorption lines in the spectra of QSOs. The numerical coefficient and its alternate value, given in brackets, are obtained using $\phi_{75}^* = 1.7 \times 10^{-2}$ and 0.73×10^{-2} Mpc^{-3}

as given by BORS and W^2 PT respectively and taking $f=0.5$. The values of r^* (r_1^* and r_2^*) for these two choices of ϕ^* are included in Tables 1–3. The galactic halo radii for the case of non-evolving cross-sections are probably too large compared to the observed values (BORS). For the case of evolving cross-section, however, the halo radii have reduced considerably and may not be inconsisent with observations (Boksenberg 1978).

5 Discussion

We have shown that inclusion of the redshift dependence of the effective mean free path $l=[n(z)\,\sigma(z)]^{-1}$ between absorbers producing narrow-line absorption systems in the spectra of QSOs helps to remove one of the primary objections to the interpretation that the majority of such systems arise in intervening objects. That objection has always been the large cross-sections deduced for such objects, in particular the large extent of the heavy element enriched haloes of galaxies which have been proposed. (For detailed discussions of the arguments we refer the reader to the recent comprehensive discussions in BORS, PB^2 and W^2 PT). We find that the effective, present epoch, cross-sections are reduced by a factor of ~ 3 in comparison to those required if no redshift dependence is allowed for. Thus, instead of heavy element-enriched haloes of roughly 60–100 kpc radial extent (depending on the choice of H_0 and the present epoch number density) we find a required size of only 40–60 kpc.

Furthermore, the method proposed here for analysis of the absorption line data promises to be a quite useful method for the determination of q_0 because of its applicability out to redshifts of ~ 3.5, far beyond the inherent limitations of the Hubble diagram (at about $z=0.8$). Both the redshift dependence of the frequency of absorption (discussed here) and of the magnitude of galactic images (Hubble law) depend on the convolution of the space–time metric with the physical size of the object. As discussed above, the frequency of absorption depends on the product of the metric distance, $dl(z)$, with the square of the effective radius for absorption, $r(z)$. The Hubble law, on the other hand, depends on the quotient $r_0(z)/a(z)$, (Ellis & Perry 1979), where $r_0(z)$ is the 'observer area distance' to the galaxy whose effective radius for radiation is $a(z)$. Since $r_0(z)$ and $dl(z)$ are well defined for any Robertson–Walker metric, knowledge of the relationship of $a(z)$ and $r(z)$ would make these two methods of observational cosmology complementary, and would permit the determination of q_0 and H_0 without detailed knowledge of the z dependence of the radius. For the presently available data analysed here we find that the most likely value of q_0 is close to 0.

We have attempted a statistical separation of the systems into those which are intrinsic to the QSO and those which arise in intervening objects, but have only been marginally successful. Separation on the basis of relative velocity between the emitting and the absorbing gas appears to provide the only viable method at present. However, the marginal improvement in the statistical significance of the results which results from the elimination of the low relative velocity systems cannot yet be considered conclusive evidence in favour of any particular separation criteria. Physical criteria, such as local number density or degree of ionization of the systems, cannot yet be applied because the observational data are not extensive enough.

In conclusion, the method presented here appears to be a powerful method for obtaining cosmological information and could be used very effectively to study the evolution of galactic coronae and to obtain q_0 when a more extensive and uniform data set becomes available. It is most important to obtain data with wavelength coverage adequate to permit separation of the systems on the basis of the degree of ionization. The recent observations from the *IUE* may eventually provide the required data.

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