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Unconedensed Matter in the Universe: Optical Evidence from Quasar Absorption Lines [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1980 **296**, 399-405
doi: 10.1098/rsta.1980.0184

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Phil. Trans. R. Soc. Lond. A **296**, 399–405 (1980) [399]
Printed in Great Britain

Uncondensed matter in the Universe: optical evidence from quasar absorption lines

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The properties of the clouds producing Ly α absorption and C IV absorption in the spectra of quasars are reviewed. The C IV-producing clouds may be classified into three groups representing ejection, clouds moving in a cluster containing the quasar itself, and intervening material at cosmological distances. The incidence of the latter type imply effective radii for luminous galaxies of order 100 kpc, and a present-epoch mean free path of *ca.* 10 Gpc. No decisive evidence yet exists about whether most of the Ly α producing clouds arise in truly primordial hydrogen clouds as opposed to metal-enriched material associated with galaxies. In the latter interpretation, the line density is such that the mean free paths are 100 times smaller and the effective galaxy radii 10 times larger than for C IV.

At about the time that the first quasars with large red shifts were discovered, it was realized by a number of people, notably Gunn & Peterson (1965) that the presence or absence of absorption in quasar spectra contained valuable information concerning the intergalactic medium. Unfortunately, the importance of the test was quickly overshadowed by the controversy over whether or not the quasar emission line red shifts were actually cosmological. This controversy now seems to have nearly run its course, especially in the light of the recent comprehensive work by Stockton (1978) on the association of quasars with small red shifts with small groups of galaxies.

In the remainder of this contribution we shall therefore assume the cosmological nature of the red shifts and ask what, if anything, absorption by gas clouds between ourselves and the quasars can tell us about uncondensed gas in the Universe.

Uncondensed neutral hydrogen

The simplest form of the test for intergalactic neutral hydrogen simply assumes that the gas is distributed uniformly along the line of sight between us and the quasar, and has no appreciable random velocity of its own. Photons emitted to the blue of the Ly α line in the continuum of a quasar would then be scattered out of the beam, forming a smooth absorption trough from Ly α towards the blue.

The effective optical depth at an epoch corresponding to some red shift z is then:†

$$\tau = [n_{\mathrm{H}}(z)\, cH_0^{-1}]\,\frac{\pi e^2}{mc}\,\frac{f}{\nu_0}\,(1+z)^{-\frac{3}{2}}. \tag{1}$$

In practice, this test is complicated by the fact that the continuum of most individual quasars with large red shifts are cut up by numerous absorption *lines* at shorter wavelengths than Ly α.

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† We use $H_0 = 50$ km s^{-1} Mpc^{-1} and a $q_0 = \frac{1}{2}$ cosmological model for illustrative purposes.

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It seems safe to say, however, that out to $z \approx 3$ there is no systematic universal depression of the continuum by more than about $\tau = 0.2$. This implies that $n_{\mathrm{H}} \lesssim 2 \times 10^{-11}\ \mathrm{cm}^{-3}$ at that epoch. The sensitivity of this test can best be illustrated by noting that this value is about 1.5×10^{-7} times that which would be expected at that epoch if all the material in the universe were uncondensed neutral hydrogen. I stress again that there is no evidence for a general depression of the continuum shortward of Ly α commending at any red shift so far observed.

One or both of the following seem the most likely ways of accounting for this stringent limit on the amount of neutral uncondensed gas:

(*a*) The gas was very highly ionized because it was very hot and/or because it was subjected to high intensity u.v. radiation, possibly from the earliest forming quasars (see, for example, Aarons & McCray 1970; Bergeron & Salpeter (1970)).

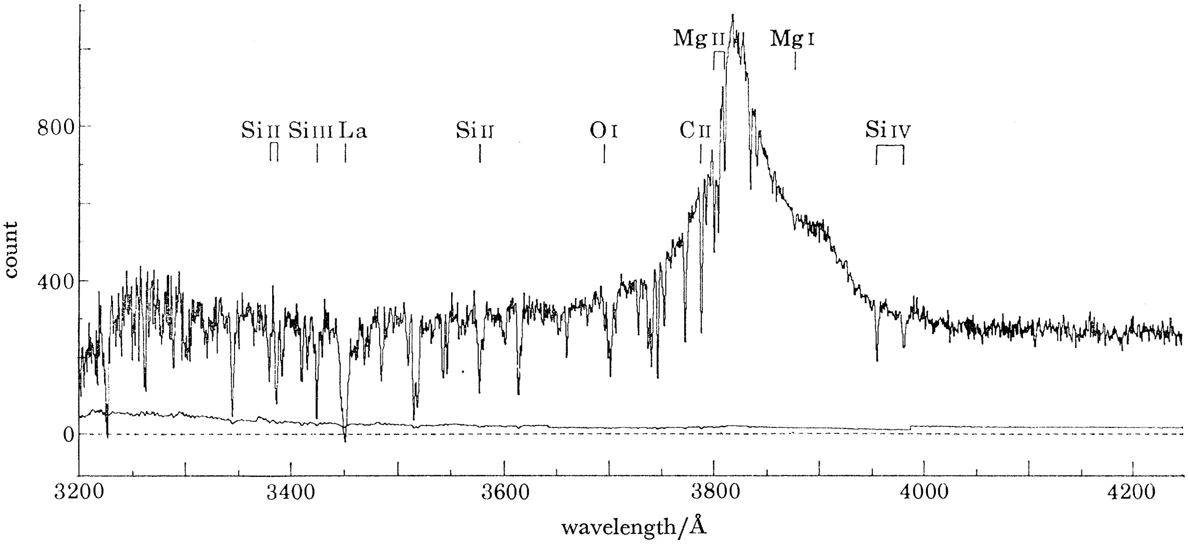

FIGURE 1. Spectrum of the quasar Q 1101 – 264 at a resolution of about 2 Å. The promient emission line is Ly α. Note the much higher density of lines blueward of the Ly α emission peak compared with redward of it. At very high resolution, about two-thirds of the lines cannot be identified with any common metal transitions and are presumably Ly α lines. (Figure courtesy of R. F. Carswell).

(*b*) The gas at early epochs ($2.0 \lesssim z \lesssim 3.5$) became strongly condensed and 'lumpy.'

There is no direct evidence bearing on the first possibility as far as quasar absorption lines are concerned. Concerning the second possibility, there is a striking tendency in quasars with $z \gtrsim 2.0$ for the density of absorption lines to increase markedly as one goes from longward of Ly α to shortward of Ly α (figure 1). This was first noted by Lynds (1971) who ascribed most of this excess to numerous separate absorption systems of Ly α (and, where observable, Ly β, γ, etc.).

Can we ascribe these 'Ly α forests' to 'primordial' hydrogen (i.e. material in which nucleosynthesis in stars or supermassive protostars has not yet occurred) that is condensing, possibly in the process of forming galaxies?

Several authors have considered this possibility. One can show that when there are no evolutionary effects, i.e. when condensation is complete or when there is no further change in the ionization of the gas, that the incidence of clouds of gas (assumed to be of constant proper cross section) $N(z)\,\mathrm{d}z$ varies between $(1+z)\,\mathrm{d}z$ for $q_0 = 0$ and $(1+z)^{\frac{1}{2}}\,\mathrm{d}z$ for $q_0 = \frac{1}{2}$. Recently,

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Peterson (1978) considered a small sample of high red shift objects of varying z and noted that the density of the Ly α forest seemed to increase considerably more rapidly with z than predicted by these simple cosmologies. He suggested that one interpretation of this result might be that one is observing hydrogen in the process of condensing over the epoch from $2 \lesssim z \lesssim 3.5$.

There is no compelling argument that this is the correct interpretation. First, there is still no conclusive resolution of the long-standing controversy over whether the bulk of the lines represent matter ejected by the quasar or intervening matter.

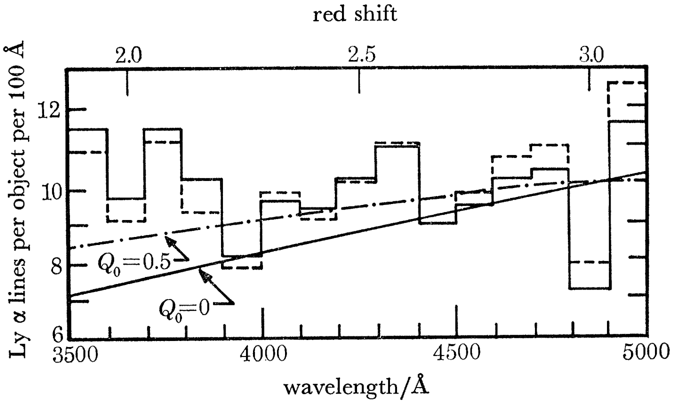

Figure 2. Density of absorption lines at wavelengths shorter than the Ly α emission peak based upon data from six quasars with large red shifts. The actual numbers of lines in each object have been normalized to the overall mean density to allow for slight differences in the quality of the data. The dotted histogram has been corrected to allow for the maximum probable contribution of the higher Lyman lines. The curves labelled $Q_0 = 0.0$ and 0.5 correspond to the distribution expected from two simple cosmological models. (Figure based on data made available by Dr R. F. Carswell and Dr G. Coleman.)

Secondly, there is no positive evidence yet for absorption systems that are truly 'pure hydrogen' – that is, a situation in which metal abundances are distinctly lower than in metal-poor clusters in our own galaxy. Such a system would require that the ratio $C:H < 3 \times 10^{-4} \times 0.1 \lesssim 3 \times 10^{-6}$. Consider what is required to confirm that such a system exists. With moderate resolution on a high red shift quasar of moderate brightness, it is reasonable to set a limit of *ca.* 0.2 Å† in the observer's frame on the equivalent width of a line like C IV λ1548. For an unsaturated line, this implies a column density of $N(\text{C IV}) \lesssim 10^{13}$. This in turn implies that to establish the existence of 'pure hydrogen' systems we must find systems with no detectable C IV or C II lines, but with column densities of $N(\text{H}) \gtrsim 3 \times 10^{18}$. Such column densities imply exceedingly strong Lyman lines, and, in fact, a system with strong Lyman continuum absorption, i.e. τ (Ly cont.) > 20. Absorption systems with noticeable Lyman continuum absorption certainly exist (Osmer 1979; Smith & Carswell 1979) but no quasars, when observed with a high resolution, have as yet demonstrated a lack of any metal lines associated with systems having column densities this large. Indeed, there are certainly systems that have metals in roughly normal abundances at $z \approx 3$ (i.e. at about 10–20% of the current age of the Universe), although there are some indications (Smith *et al.* 1979) that systems at this epoch may have only 10% of the solar metal:hydrogen ratio.

More recent work has not confirmed Peterson's (1978) result that the density of lines shortward of Ly α increases much more rapidly than $(1+z)$. In fact, figure 2, based upon data

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† 1 Å = 10^{-10} m = 10^{-1} nm.

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obtained by Coleman (1978), Coleman & Strittmatter (1979) and R. F. Carswell (personal communication) suggests that, if anything, the reverse is true. It shows that the density of lines at shorter wavelength than Ly α is practically constant with wavelength, and the interpretation in terms of intervening material requires a relative increase in the density and/or cross section of the hydrogen in intervening clouds at recent epochs over the predicted values for even $q_0 = \frac{1}{2}$.

The fact that the density of lines does not increase as rapidly with z as suggested by Peterson is also confirmed in work by Young & Sargent and their collaborators who also reached the following important conclusions:†

(*a*) There are no significant variations from one quasar to another in the number of Ly α lines. Lack of such variation is clearly required if this material is intervening.

(*b*) There is a lack of correlation ('clumping') of the Ly α red shifts on the scale and magnitude expected if the absorping material were concentrated in clusters of galaxies, which suggests that the material is quite uniformly distributed, perhaps embedded in a hot medium.

UNCONDENSED METAL-CONTAINING GAS

We now consider the question of the origin of the metal absorption lines in quasars and what the implications are for the existence of intra-cluster gas or gas in extended halos about galaxies. This question has been recently considered by Weymann *et al.* (1979) in connection with a homogeneous survey of a sample of quasars at moderate red shifts studied at intermediate resolution. The fact that moderate red shifts were used means, as a practical matter, that one is dealing with absorption caused mostly by the triply ionized carbon ion and in some cases by singly ionized magnesium. So, in this sample we are clearly dealing with metal-containing clouds. The advantage of such a sample is that the systems are usually rather simple and easy to identify because there are so few lines. We pay a heavy price for this, because the number of systems is so small that the statistical uncertainties are very large.

In any event, the results of this survey suggest that the quasar lines can be classified into three main groups. The basis for this classification comes from studying the relative frequency of red shifts as a function of $(z_{\mathrm{em}} - z_{\mathrm{abs}})$ or, if we interpret $z_{\mathrm{em}} - z_{\mathrm{abs}}$ as an ejection velocity, the distribution as a function of ejection velocity. This distribution is shown in figure 3. The most striking feature is the large peak around $V = 0$. Note that there are objects in the peak on both sides of $V = 0$ distributed roughly symmetrically about it out to a distance of order 3000 km/s. A guassian curve having the observed dispersion has been drawn in. We interpret these systems as being due to gas (either gas in galaxies or intra-cluster gas) which is moving in a cluster in which the quasar also happens to be. When this dispersion is corrected for the fairly large error involved in the emission line and when we further divide that dispersion by $\sqrt{2}$ (as we should in our interpretation to obtain the true dispersion of individual objects) we obtain about 750 km/s. This is reasonable for a cluster of galaxies, though so far the evidence suggests that quasars are found in small groups with a smaller dispersion (Stockton 1978).

The second main feature of the velocity histogram is a large tail extending to positive (outward) velocities of perhaps 15000–18000 km/s. This tail cannot be explained on the basis of either 'intrinsic cluster' or 'intervening galaxy' systems since the latter should not give rise to this tail and we must therefore ascribe such systems to ejection. There is some independent

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† I am indebted to Dr J. Gunn for providing a short account of this unpublished work.

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evidence that ejection is frequently encountered in the régime 0–18000 km/s. There are a number of objects with very broad, high ionization absorption 'troughs' of which PHL 5200 is the prototype. There are now about 15 objects known that can be put into this category. Figure 4 shows an example of an object of this class, no. 275 in the Michigan Curtis Schmidt Survey (MacAlpine *et al.* 1977).

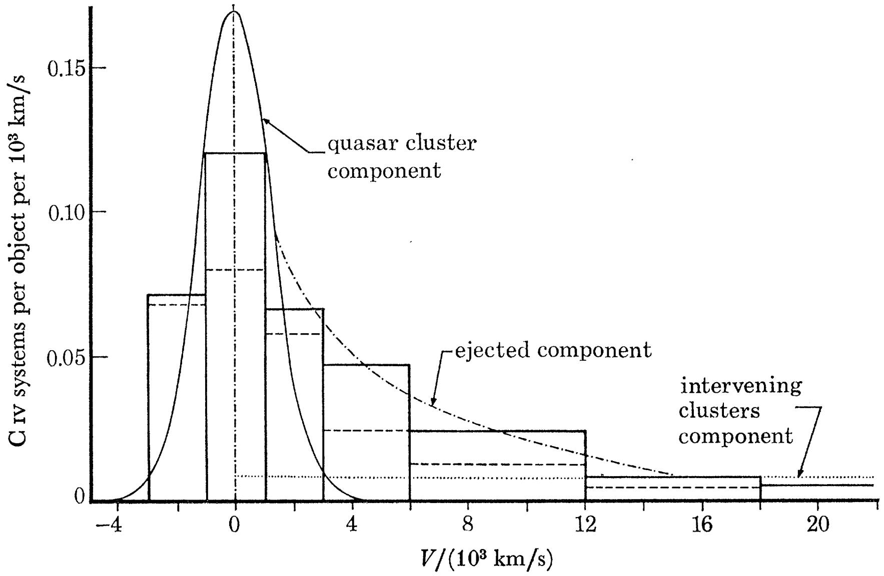

FIGURE 3. A histogram showing the observed distribution of C IV systems in a sample of intermediate redshift as a function of the velocity of the absorption system relative to the quasar. Most of the systems occur near the emission red shift, and the distribution has a tail extending from the peak out to velocities of order 12000–18000 km/s. Smooth curves have been drawn through the three separate components of the distribution corresponding to the three different proposed origins of the system. Histograms: ——, full sample; · · ·, predicted number of systems from intervening clusters; – – –, 1303 + 308, 1556 + 335 deleted.

The majority of the absorption systems with apparent velocity of ejection greater than about 15000–20000 km/s we interpret as intervening material. We may derive from the data a typical (present-epoch) mean free path between interception of such clouds: the result is *ca.* $1–2 \times 10^4$ Mpc for C IV. We may then also interpret the incidence of such highly displaced absorption components in terms of the required effective cross sections of galaxies. If we assume that the size of the galaxy halo producing such lines increases with luminosity as the observed optical size, then halo radii of order 100 kpc for luminous spirals are required. (Details are found in Weymann *et al.* (1979).) I stress that there is no compelling evidence for assuming that such material really is found in extended halos of galaxies as opposed, for example, to truly intra-cluster or even intergalactic matter. I also stress that these typical radii refer only to the incidence of C IV and Mg II lines at our level of detection (*ca.* 0.6 Å) and not to the Ly α lines.

As mentioned above, there is no evidence yet that the numerous Ly α absorption lines in quasars with large red shifts really represent primordial material with no metal enhancement. Therefore, it is worth inquiring whether a consistent and plausible set of parameters can be found which account for both the Ly α lines and the C IV lines and which relate the 'intrinsic cluster' properties with the 'intervening cluster' properties.

The quality of the data upon which figure 2 is based is roughly comparable with the C IV and Mg II survey described above. When the data of figure 2 are plotted in terms of ejection velocity,

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there is no obvious counterpart to the 'ejection tail' of figure 1. This may be due to the fact that the Ly α ejection component is simply swamped by the intervening component or it may be that the ejected components have such high ionization that Ly α tends to be relatively weak. The Ly α line density is so high that an effective bright galaxy radius of order 1 Mpc is required. The corresponding present-epoch mean free path between hydrogen absorption systems is only *ca.* 100 Mpc. At high red shifts the mean free path between clouds is only a few megaparsecs, and the average separation in velocity is only a few hundred kilometres per second. Thus, clumping in velocity on this scale may be obliterated.

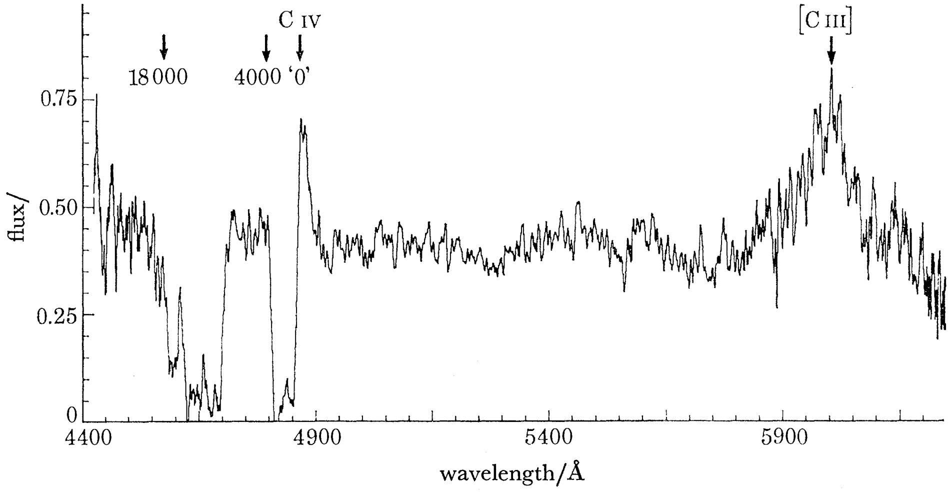

FIGURE 4. Spectrum of the quasar MCS 275 showing two broad displaced absorption troughs interpreted as ejection of material at velocities up to *ca.* 18000 km/s. Old systems of this type may be responsible for the excess tail in the distribution of figure 3.

When we try to relate the properties of the C IV-producing '*intrinsic*' cluster clouds with the properties of the C IV and Ly α clouds ascribed to '*intervening*' clusters we encounter the following difficulty: when the line of sight from the quasar passes through a hypothetical intervening cluster and produces at least one Ly α absorption line, the chances are, from the data above, only about 1 % that this intervening cluster will produce a C IV line. However, the incidence of C IV absorption found near the emission line red shift – that is, that ascribed to the 'intrinsic cluster' – is found empirically to be quite high, of the order of 50 %. The two most likely explanations for the large discrepancy between the 1 % and 50 % figure are, in my opinion:

(i) The quasar occupies a preferred position near the centre of its cluster, and there is a strong concentration of galaxies (whose halos produce the C IV) towards the centre of the cluster. This would explain the high incidence of C IV in the 'intrinsic cluster' as apposed to the much lower incidence in the intervening clusters.

(ii) The notion of the Ly α being associated with clusters is erroneous, and there is no basis, therefore, for the 1 % interception figure used above. This is consistent with the result of Young *et al.* alluded to above.

I wish to thank Professor M. Rees and his colleagues at the Institute for Astronomy for their hospitality during the meeting especially Dr R. F. Carswell for numerous discussions and suggestions. I am also grateful to Dr Carswell and Dr G. Coleman for permission to use unpublished data in preparing figure 2.

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Discussion

A. W. Wolfendale, F.R.S. (*Physics Department*, *University of Durham*, *U.K.*). I should like to know what information is available on the question of the chemical composition of the gas close to quasars. An important point is the considerable modification of the composition by gamma rays from the active part of the quasar.

Recent measurements with the Cos-B gamma ray detector (Swanenburg *et al.* 1978 *Nature, Lond.* **275**, 298) indicate that the gamma ray luminosity of the quasar 3C 273 is *ca.* 2×10^{46} erg s^{-1} (2×10^{39} W) in the energy range 50–500 meV. Calculations by Wdowczyk and myself show that gas nuclei within 10^{17} cm of the gamma ray source would be fragmented within about 10^4 years. For greater distances and shorter times fragmentation would not be complete, of course, but significant modification of the chemical composition would be expected (e.g. production of Li, Be, B). A detailed examination of the composition, by way of spectral studies, would therefore be useful.