PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Distribution and Composition of Intergalactic Clouds at Large Red-Shifts [and Discussion]

W. L. W. Sargent, W. H. McCrea and M. J. Rees

Phil. Trans. R. Soc. Lond. A 1982 **307**, 87-96
doi: 10.1098/rsta.1982.0103

Phil. Trans. R. Soc. Lond. A **307**, 87–96 (1982)
Printed in Great Britain

The distribution and composition of intergalactic clouds at large red-shifts

By W. L. W. Sargent, F.R.S.
Palomar Observatory, California Institute of Technology, Pasadena, California 91125, *U.S.A.*

Most of the sharp absorption lines in the spectra of quasars of high red-shift are single Lyman-α lines. The stronger ones have associated Lyman-β or Lyman-γ lines but not lines of heavy elements. Recent statistical studies have shown that the density of Lyman-α absorption lines is statistically the same in all quasars and that the lines are randomly distributed, with no tendency to cluster. It is now thought that the single Lyman-α absorption lines are produced by primordial, intergalactic clouds. Studies now in progress are aimed at giving limits on the heavy-element composition of the clouds, as well as a value for the deuterium abundance of primordial gas.

1. Introduction

It is now generally recognized that there are at least three distinct kinds of absorption red-shift systems in the spectra of quasars. These are as follows.

(1) *The 'trough' systems.* A small minority of quasars (about 3%) show very broad absorption lines on the blue side of the corresponding emission lines. Lines of very high states of ionization such as C IV, Si IV, N V and O VI are always found in addition to Lyman-α absorption. The abnormally high ionization state suggests immediately that the material responsible for the absorption is close to the quasar. The profiles of the lines resembled those observed in the spectra of novae after maximum light and in the P Cygni stars. Both novae and P Cygni stars are experiencing mass outflow.

(2) *The 'heavy-element' systems.* These are sharp lines due to H and the heavier elements, which can be shown to arise in a tenuous gas of near-solar composition. Interpreted in terms of relative velocity the observed values of $z_{em} - z_{abs}$ yield velocities ranging from infall to the quasar at a few thousand kilometres per second to outflow speeds of up to $0.8c$.

(3) *The Lyman-α systems.* All quasars so far observed with red-shifts large enough to bring the Lyman-α emission line into the observable spectral region ($z_{em} \geqslant 1.7$) show an enhanced density of sharp absorption lines on the blue side of the Lyman-α emission compared with the red side. It has been established that most of these are Lyman-α absorption lines; in some cases there are accompanying Lyman-β and Lyman-γ lines but no lines of heavier elements (Lynds 1971; Young *et al.* 1979).

It is generally accepted that the trough systems represent material ejected from the quasar at speeds up to $0.2c$ and with a spread in velocity as large as $0.15c$. (For a summary of statistical evidence on the distribution of $z_{abs} - z_{em}$ for these systems, see Young *et al.* 1982*a*).) On the other hand, the nature of the matter responsible for the 'heavy-element' systems and the 'Lyman-α' systems has been more controversial. For some years the possibility has been entertained that the 'heavy-element' systems are produced by ejected material. (See, for example, Perry *et al.* (1978) for a summary of their viewpoint.) However, the weight of the evidence has gradually turned against the ejection hypothesis over the past few years and towards the view that the lines are produced by galaxies.

The main reason for believing that the 'heavy-element' systems are primarily produced by cosmologically distributed galaxies lying between the quasar and the observer are as follows.

(1) The distribution of the number of red shifts per quasar is Poissonian (Young *et al.* 1982*a*), as it must be for intervening objects (Bahcall & Peebles 1969).

(2) The distribution of $z_{\mathrm{em}}-z_{\mathrm{abs}}$ is flat and shows no measurable tendency to cluster around $z_{\mathrm{em}}-z_{\mathrm{abs}}=0$, as would be expected if the absorbing material has been ejected from the quasar (Young *et al.* 1982*a*).

(3) The example of the Ca II H and K absorption lines produced by the galaxy NGC 3067 in the spectrum of the nearby quasar 3C 232 shows directly that galaxies contain absorbing gas out to radii much greater than their apparent optical diameters (Boksenberg & Sargent 1978).

(4) The absence of detectable Lyman-α emission halos around quasars leads to severe energy and momentum difficulties if the absorbing material has been ejected from the quasars (Goldreich & Sargent 1976; Sargent & Boroson 1979).

(5) The ultraviolet spectrum of 3C 273, observed with the IUE satellite (Ulrich *et al.* 1980), shows only absorption lines due to our own Galaxy, as would be expected for such a nearby quasar.

(6) Ultraviolet spectra of bright stars in the Magellanic Clouds, also obtained with IUE, have shown that the halo of our own Galaxy produces absorption lines that are remarkably similar to the sharp 'heavy-element' systems observed in quasar spectra (Savage & de Boer 1981; Savage & Jeske 1981).

Taken as a whole, these different lines of evidence provide overwhelming support for the intervening hypothesis to explain the 'heavy-element' absorption systems. However, it is generally conceded that the frequency of absorption systems is only compatible with galaxies as the absorbing objects if a typical galaxy has a much larger effective cross section than the optical Holmberg radius. For example, a recent discussion of a homogeneous body of spectra of 33 quasars by Young *et al.* (1982*a*) shows that a galaxy of luminosity $L_* = 3\times10^{10}L_\odot$ (Schechter 1976) must have an effective radius $R_* = 44\,(H_0/100)$ kpc. Observations of quasars near galaxies on the plane of the sky, such as the observation of 3C 232 referred to above, are capable of directly testing this requirement.

Recent work on the single Lyman-α absorption lines has suggested that they too are produced by intervening objects rather than by material ejected from the quasars. However, the single Lyman-α red shifts are much more common that the 'heavy-element' systems: partly as a consequence Sargent *et al.* (1980) were led to suggest that the Lyman-α lines are produced in intergalactic clouds. In the rest of this paper I shall review the evidence for this hypothesis, including a brief summary of recent work on the composition of the Lyman-α clouds. I shall show that the available evidence points strongly to the idea that the Lyman-α lines are produced in primordial intergalactic clouds and that future studies of their properties should lead to information on the state of the intergalactic medium at red shifts z_{em} in the range $1.7 < z < 3.5$ and to new insights into element production in the Big Bang.

2. Statistics and clustering of Lyman-α absorption lines

(*a*) *Statistics*

If the Lyman-α lines are produced by cosmologically distributed galaxies or intergalactic clouds, then there are two clear predictions regarding the distribution of lines. First, we must observe statistically the same number of lines in any red-shift interval z^1_{abs} to z^2_{abs} in the spectrum of any quasar having $z_{\text{em}} \geqslant z^1_{\text{abs}}$ (assuming that $z^1_{\text{abs}} > z^2_{\text{abs}}$). This prediction is independent of how the objects responsible for producing the absorption lines are distributed in red shift. In particular, it is independent of the detailed geometry of the Universe and also independent of the way in which the absorbing objects evolve in cosmic time. The second prediction is that the number of lines observed in any given red-shift interval $z^1_{\text{abs}} - z^2_{\text{abs}}$ should obey a Poisson distribution.

These two conditions were first stated explicitly in connection with the 'heavy-element' red shifts in Bahcall & Peebles (1969). They were first tested on a homogeneous body of observations of the Lyman-α absorption lines by Sargent *et al.* (1980). Observed spectra of high quality are required because the number of lines increases exponentially with decreasing line strength (Sargent *et al.* 1980); consequently, in counting lines for statistical purposes it is necessary to adopt a minimum line strength that is accurately the same in all objects of a given sample. It is convenient to deal with the quantity $N(z)$, the number of absorption lines per unit red-shift range whose equivalent widths W_0 in the rest frame ($W_0 = W_{\text{obs}}(1+z)^{-1}$) exceed some well defined limit W_0^{lim}. It is easy to show that for a population of absorbing objects whose properties do not evolve in cosmic time

$$N(z) = N_0(1+z)\,(1+2q_0 z)^{-\frac{1}{2}}. \tag{1}$$

If the absorbers have a space density $\Phi(z)$ and cross section πR^2, then

$$N(z) = (c/H_0)\,\pi R^2 \Phi(z)\,(1+z)^{-2}\,(1+2q_0 z)^{-\frac{1}{2}}, \tag{2}$$

where H_0 is the value of the Hubble constant at the present epoch. If the absorbing clouds evolve in cosmic time then N_0 is itself a function of red shift $N_0(z)$. In this case, both the number of clouds per co-moving volume and the effective cross section πR^2 could be functions of red shift.

A detailed study of the spectra of six quasars with red shifts in the range $2.20 < z_{\text{em}} < 3.3$ by Sargent *et al.* (1980) enabled the distribution of Lyman-α lines to be studied in the range $1.7 < z_{\text{abs}} < 3.3$. Regarding the overall distribution of the lines it was found that there was (i) no significant variation in $N(z)$ among the different objects; (ii) no significant variation of $N(z)$ with red shift; (iii) no significant variation of the distribution of rest equivalent width W_0 among the objects; (iv) no systematic difference in the properties of the absorption lines in the wing of the Lyman-α emission line compared with those in the continuum.

Subsequent work has confirmed most of these conclusions. The typical quasar with a red-shift in the range $z_{\text{em}} = 2$–3 has a mean line density $\bar{N}(z) = 58 \pm 4$ for $W_0 \geqslant 0.32$ Å†, with a distribution about that mean consistent with Poisson statistics. One modification of the conclusions listed above is provided by evidence that the line density is in fact a function of red shift. If we suppose that such a red-shift dependence may be represented by an equation of the form

$$N(z) = \text{const}\,(1+z)^{\gamma}, \tag{3a}$$

then it is easy to show from (1) that

$$\gamma = (1+q_0 z - q_0)/(1+2q_0 z), \tag{3b}$$

so that $\gamma = 1$ for $q_0 = 0$ and $\gamma = \frac{1}{2}$ for $q_0 = \frac{1}{2}$. A recent study of an enlarged sample of 10 quasars by Young *et al.* (1982*b*) shows a significant slope on a plot of lg $N(z)$ against lg $(1+z)$. A straight-line fit yields $\gamma = 1.81 \pm 0.48$. This implies that for any reasonable cosmological model the

† 1 Å = 10^{-10} m = 10^{-1} nm.

Lyman-α clouds evolve in cosmic time in the sense that there were more or larger absorbers per co-moving volume at higher red shifts. This result is not unexpected; however, it must be confirmed by more data before it can be regarded as firmly established.

As stated earlier, a critical test of the idea that the Lyman-α absorption lines are due to cosmologically distributed objects is provided by the requirement that quasars with small red-shifts (with $z_{\mathrm{em}} < 2$, say) and with large red-shifts (with $z_{\mathrm{em}} > 2$, say) should have the same line density in the observable range $1.7 < z_{\mathrm{abs}} < 2.0$ in common. The test is complicated by the fact that the Lyman-α lines with $2.2 < z_{\mathrm{abs}} < 2.6$ will have the corresponding Lyman-β lines falling among the Lyman-α's in the range $1.7 < z_{\mathrm{abs}} < 2.0$. Consequently, high-quality observations must be used to subtract the Lyman-β lines in preparing the Lyman-α samples. Recent work on the quasar Q1623+269 with $z_{\mathrm{em}} = 2.52$ has shown that its Lyman-α density is the same as those found in quasars with smaller red-shifts once the Lyman-β's have been subtracted (Sargent *et al.* 1982).

(*b*) *Clustering*

If the Lyman-α clouds are clustered in space then they also should be clustered in red shift. A convenient way to test for clustering is then to use the two-point correlation function, whose properties have been explored for relatively nearby ($z < 0.2$) galaxies by Peebles and his associates. Extensive work has shown that, given a galaxy G_1, the probability of finding a second galaxy G_2 at a distance r and in volume $\mathrm{d}V$ is

$$\mathrm{d}P = \mathrm{d}V\Phi_0\{1+\xi(r)\}, \tag{4}$$

where Φ_0 is the local space density of galaxies. The first term in (4), $\mathrm{d}P \propto \mathrm{d}V\Phi_0$, corresponds to a randomly distributed population of objects. The second term represents the tendency of the objects to cluster if $\xi(r)$ is positive. If two objects at red shifts z_1 and z_2, respectively, have no peculiar motions, then it is convenient to obtain their separation by taking the difference in their co-moving distances from the observer

$$s_0 = S_0(z_1) - S_0(z_2), \tag{5}$$

as measured at the present cosmic epoch. Full expressions for calculating the distances S_0 for any value of q_0 may be found in Sargent *et al.* (1980). As an example, if $q_0 = \frac{1}{2}$ then

$$S_0(z, \tfrac{1}{2}) = 2(c/H_0)\,\{1-(1+z)^{\frac{1}{2}}\}, \tag{6}$$

where c/H_0 is the Hubble radius at the present epoch. At any earlier epoch, when the cosmological scale factor is a,

$$S(z) = S_0(z)\,(a/a_0) = S_0(z)/(1+z), \tag{7}$$

with a corresponding change in the separation s_0.

The work of Sargent *et al.* (1980) yielded the surprising result that the distribution of line separations in their sample of six quasars was random on all observed scales from 0.0 to 0.07 Hubble radii. No clustering could be detected on any scale. In particular, the degree of clustering (which would show up as an excess of small separations s_0 in the correlation function) was shown to be incompatible with a naïve extrapolation of the currently observed $\xi(r)$ for galaxies back to larger red shifts. In fact, the local empirically determined $\xi(r)$ has a power-law form

$$\xi(r) = (r/r_{\mathrm{c}})^{-1.8}; \quad r_{\mathrm{c}} = (5/H_0)\ \mathrm{Mpc}, \tag{8}$$

which means that there is no preferred scale-length for galaxy clustering in the Universe. The simplest possible estimate of the evolution of the correlation function in cosmic time is obtained by supposing that the power-law form given by (8) is retained for small separations and that $r_c(z)$ is a decreasing function of z as the 'Poissonian background' of field galaxy separations rises as the scale factor a decreases. The space density of galaxies then increases according to the relation

$$\Phi(z) = \Phi(1+z)^3, \tag{9}$$

and it is easy to see that r_c must decrease according to the relation

$$r_c(z) = r_c(1+z)^{-\frac{5}{3}}. \tag{10}$$

A recent study of the distribution of Lyman-α absorption line separations in two quasars, Q1623+269 ($z_{em} = 2.52$) and Q1623+268 ($z_{em} = 2.61$) has enabled Sargent *et al.* (1982) to place a severe limit on the value of r_c for the Lyman-α clouds at $z \approx 2.5$. It is shown in their paper that if the clustering indeed remains self-similar as it evolves then the excess of small separations due to clustering is given by

$$\frac{N_{excess}}{N(z)} = 2(1+z)^2\,(1+2q_0 z)^{\frac{1}{2}}\,I(2-\alpha)\left(\frac{H_0 l}{c}\right)\left(\frac{r_c(z)}{l}\right)^{\alpha}, \tag{11}$$

where
$$I(x) = \int_0^{\frac{1}{2}\pi} (\sec\theta)^x\,\mathrm{d}\theta.$$

Here $\alpha = 1.8$ is the exponent in the power-law form of $\xi(r)$ and l is the spectral resolution of the observations, which effectively limits the degree to which clustering on small scales can be sampled. Sargent *et al.* (1982) showed that the observations of the two quasars imply that the cloud–cloud correlation function must be such that

$$r_e^{cc}(z = 2.5) \leqslant 0.2\,\mathrm{Mpc} \tag{12}$$

rather than the value $r_c(z = 2.5) = 1.07$ Mpc predicted for galaxies by (8) and (10). (These comparisons are made with $H_0 = 60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = \frac{1}{2}$.)

The quasars Q1623+268 and Q1623+269 were observed because they are separated by only $\theta = 172''$ on the plane of the sky. This angular separation corresponds to a linear separation

$$l = \frac{c\theta}{H_0}\left\{\frac{Z(q_0, z)}{(1+z)}\right\}, \tag{13}$$

where
$$Z(q_0, z) = [q_0 z + (q_0 - 1)\{(1+2q_0 z)^{\frac{1}{2}} - 1\}]/q_0^2(1+z) \tag{14}$$

and where the separation l was measured at the epoch z. For the two quasars under discussion the separation is

$$\left.\begin{aligned} l &= 1.92(60/H_0)\,\mathrm{Mpc} \quad (z = 2.5;\ q_0 = 0),\\ l &= 0.86(60/H_0)\,\mathrm{Mpc} \quad (z = 2.5;\ q_0 = 1),\end{aligned}\right\} \tag{15}$$

which is comparable with, but not smaller than, the value of r_c ($z = 2.5$) = 1.07 Mpc inferred for the galaxy–galaxy clustering earlier. A cross-correlation analysis shows that the distribution of line separations between all lines in Q1623+268 and all lines in Q1623+269 is, like the autocorrelation, flat on all observed scales. This means, in particular, that there is no observable tendency for lines to fall at the same observed wavelengths in the two quasars. Consequently, the Lyman-α clouds must have a size $D \leqslant l = 1.92$ Mpc ($q_0 = 0$), thus eliminating the possibility suggested by Oort (1981) that the Lyman-α lines arise in generally distributed gas in superclusters of galaxies. Superclusters at the present epoch have their longest dimension of order 30 Mpc. Since, as we have seen, Q1623+268 and Q1625+269 have $l \approx$ 1–2 Mpc while r_c ($z = 2.5$) $\approx$ 1 Mpc, these two quasars are a little too far apart to set an interesting limit on r_c^{cc};

for this purpose the spectral resolution of the observations is such that a better limit is obtained from the autocorrelation analysis.

It appears therefore that the Lyman-α clouds, with $r_0^{\mathrm{cc}}(z = 2.5) \leqslant 0.2\,\mathrm{Mpc}$, cluster less strongly than galaxies are expected to do if the correlation function $\xi(r)$ evolves in a self-similar manner. This would imply that the clouds are not distributed like the galaxies; Sargent *et al.* (1980) inferred that the clouds '...must be an intergalactic population which is not associated with galaxies'.

Dekel (1982) has recently explored a scenario for cluster formation in which galaxies form before superclusters collapse to form the 'pancakes' in which galaxies now appear to be distributed. (For excellent reviews of the properties of superclusters, the reader is referred to the articles by Oort (1981, 1983).) This 'dissipationless' collapse is to be contrasted with the view, proposed initially by Sunyaev & Zel'dovich (1972), that galaxies form *after* the dissipative collapse of gaseous pancakes. A necessary consequence of Dekel's suggestion is that superclusters collapsed to their present flattened elongated forms at relatively recent epochs, say $z \leqslant 0.5$. On this hypothesis galaxies were much less clustered at $z \approx 2$ than they are now. Moreover, since on Dekel's picture the power in $\xi(r)$ at small separations comes mainly from the smallest dimensions of the pancakes, the correlation function evolves in a manner that is far from being self-similar. Dekel (1982) has carried out numerical simulations of the evolution of superclusters in which the galaxies were already formed before they started to collapse. He has also calculated the correlation function in red shift that would be measured in the range $z = 1.7$–2.5 by an observer at $z = 0$ who sees along the line of sight a number of superclusters oriented at random angles to the line of sight, with a range of dynamical collapse times and random range of distances from the centre. The result of these calculations is that it is possible to have a completely flat correlation function in the range $z = 1.7$–2.5 provided that the superclusters collapsed at recent epochs; the *local* correlation function (i.e. that at $z = 0$) is compatible with that observed by Peebles and his coworkers.

In summary, the observed flatness of the correlation function of the Lyman-α clouds is incompatible with the expected distribution of the clouds at $z \approx 2$ if they cluster in the way that galaxies are expected to cluster in a hierarchial clustering scenario. On the other hand, the clouds could be clustered in the same way as the galaxies if Dekel's late dissipationless collapse picture is correct. Clearly, the next stage in this investigation would be to compare the correlation function of the 'heavy-element' red-shift systems (which are thought to be produced in the extended halos of galaxies) with that of the Lyman-α clouds. This is a difficult observational task because the number density of the single Lyman-α lines is about 50 times greater than that of the 'heavy-element' lines. It is well known that the correlation function of the 'heavy-element' lines shows a sharp peak for separations less than about $150\,\mathrm{km\,s^{-1}}$ (Boksenberg & Sargent 1975), quite different from the behaviour of the single Lyman-α lines. The difference is shown clearly in figure 5 of the paper by Sargent *et al.* (1980); however, the excess of small splittings in the 'heavy-element' systems has been attributed to the motions of discrete clouds in the galaxy halos rather than to galaxy clustering (Bahcall 1975). Recent work on the distribution of C IV doublets in a sample of 33 quasars by Young *et al.* (1982*a*) shows some signs of an excess of separations for $\Delta v \leqslant 2000\,\mathrm{km\,s^{-1}}$, a relative velocity too high to be explained by relative motions of halo clouds. Further work is proceeding on much larger samples of quasars to confirm this effect, which, if real, would show directly that the Lyman-α clouds and the objects responsible for producing the 'heavy-element' red shifts are clustered differently.

3. The physical state and composition of the clouds

It was shown by Sargent *et al.* (1980) that the typical single Lyman-α absorption line had no associated Lyman-β line above the detection limit of the spectra and that this implied that the typical line was unsaturated. The neutral hydrogen column density, $N_{\mathrm{H\,I}}$, corresponding to a line of rest equivalent width W_0, is then given by

$$N_{\mathrm{H\,I}} = 1.8 \times 10^{14}\,(W_0/1\,\text{Å})\ \mathrm{cm}^{-2}, \tag{16}$$

so that a typical line with $W_0 = 0.5$ Å corresponds to a column density $N_{\mathrm{H\,I}} \approx 10^{14}\,\mathrm{cm}^{-2}$.

If the clouds are supported by pressure and not by rotation or turbulence, then they must obey the Jeans limit and have a diameter D such that

$$D < 2.5 \times 10^{22} (T_{\mathrm{c}}/10^4)^{\frac{1}{2}}\,(10^{-3}/n^{\mathrm{c}}_{\mathrm{H}})^{\frac{1}{2}}\ \mathrm{cm}, \tag{17}$$

where T_{c} is the cloud temperature and $n^{\mathrm{c}}_{\mathrm{H}}$ is the total hydrogen density (neutral plus ionized). (The possibility that the clouds are gravitationally bound was rejected on the grounds that this would lead to an implausibly high contribution of the clouds to the cosmological density parameter Ω.)

A larger, but more definite, size limit is obtained from the observation that the lines are generally unresolved, with widths (f.w.h.m.) less than *ca.* 1 Å at λ4000. This corresponds to a velocity spread of no more than 75 km s^{-1} and so demands that

$$D < 6.5 \times 10^{23}\,(W_0/H_0)\,(1+4.9q_0)^{-\frac{1}{2}}\ \mathrm{cm}, \tag{18}$$

from considerations of the Hubble flow.

A lower limit to the size of the clouds may be obtained from the observation that the stronger Lyman-α absorption lines reach zero intensity, both in the continuum and also when seen projected against the blue wings of the Lyman-α emission line. From this we can deduce that clouds must be larger than the diameter of the emission-line region

$$D \geqslant 3 \times 10^{20}\ \mathrm{cm} \tag{19}$$

if it is supposed that the clouds are more or less spherical.

As Sargent *et al.* (1980) argued, the Lyman-α clouds are most probably ionized by the metagalactic ionization flux from quasars in general. It was estimated by Sargent *et al.* (1979) that the radiative flux below the Lyman limit is

$$I_{\nu_{\mathrm{c}}} \approx 10^{-21} (\nu/\nu_{\mathrm{c}})^{-1}\ \mathrm{erg\,s^{-1}\,Hz^{-1}\,cm^{-2}},\dagger \tag{20}$$

where ν_{c} is the frequency of the Lyman limit. The ionization state of hydrogen is then given by

$$\frac{n^{\mathrm{c}}_{\mathrm{H\,II}}}{n^{\mathrm{c}}_{\mathrm{H\,I}}} = 7.7 \times 10^3 \left(\frac{T_{\mathrm{c}}}{10^4}\right)^{\frac{3}{4}} \left(\frac{n^{\mathrm{c}}_{\mathrm{e}}}{10^{-3}}\right)^{-1} \left(\frac{I_{\nu_{\mathrm{c}}}}{10^{-21}}\right) + 4.0 \times 10^4 \left(\frac{T_{\mathrm{c}}}{10^4}\right)^{\frac{5}{4}} \exp\left\{-15.8 \left(\frac{T_{\mathrm{c}}}{10^4}\right)^{-1}\right\}. \tag{21}$$

The value of T_{c} will depend on the heavy-element composition of the clouds, which controls the cooling rate after photoionization. If we suppose for the moment that the absence of detectable lines of heavy elements indeed reflects a low abundance, then the cooling will be predominantly through the hydrogen recombination lines, leading to $T_{\mathrm{c}} \approx 3 \times 10^4$ K. Moreover, combining the typical neutral hydrogen column density given by (16) with the size limits given by (17),

$$n^{\mathrm{c}}_{\mathrm{H\,I}} \leqslant 3 \times 10^{-6}\ \mathrm{cm}^{-3}. \tag{22}$$

---

† 1 erg = 10^{-7} J.

It is then clear from (21) that the Lyman-α clouds must be highly ionized, with $n^{\mathrm{c}}_{\mathrm{H\,II}}/n^{\mathrm{c}}_{\mathrm{H\,I}} \approx 10^4$. Thus the typical total hydrogen column density is

$$N_{\mathrm{H}} = N_{\mathrm{H}} D = 10^{18}\,\mathrm{cm}^{-2}. \tag{23}$$

The limits on the cloud diameter D given by (17) and (19) then lead to density limits:

$$1.2 \times 10^{-4} < n^{\mathrm{c}}_{\mathrm{H}} < 4.2 \times 10^{-3}\,\mathrm{cm}^{-3}. \tag{24}$$

It should be emphasized that these density limits are fairly insensitive to the exact shape of the clouds, since it can easily be seen that their state of ionization would be the same even if they were in the form of thin sheets. The critical assumption is that the clouds are, in fact, ionized by the metagalactic quasar radiation field.

The relative state of ionization of the various elements is controlled, for a power-law source of ionizing photons, by the parameter

$$\Upsilon = n_{\mathrm{H}}/n_{\gamma}, \tag{25}$$

where n_{γ} is the density of ionizing photons beyond the Lyman limit. The metagalactic value of n_{γ} has been estimated by Sargent *et al.* (1979), who found it to be fairly insensitive to red shift:

$$n_{\gamma}(z = 2.5) = 3 \times 10^{5}\,\mathrm{cm}^{-3}; \quad n_{\gamma}(z = 1.0) = 2 \times 10^{-5}\,\mathrm{cm}^{-3}. \tag{26}$$

Thus we may estimate that the Lyman-α clouds have an ionization parameter in the range

$$\left.\begin{aligned} 4 &< T < 1.4 \times 10^{2} \\ \text{or} \qquad 0.6 &< \lg \Upsilon < 2.15. \end{aligned}\right\} \tag{27}$$

The relative strengths of lines of various abundant elements when ionized by a power-law ionizing flux have been calculated as a function of Υ by McKee *et al.* (1973). Reference to their figure 1 shows that, in the range of Υ given by (27), C IV and Si IV are much more abundant than the lower stages of ionization of the elements. Moreover, within this range the ratio of H I to C IV and Si IV is practically independent of Υ. Specifically, the diagram shows that if the carbon abundance has the 'cosmic' value then the C IV/H I ratio should only vary in the range

$$4.0 < \frac{n_{\mathrm{H\,I}}}{n_{\mathrm{C\,IV}}} < 4.8,$$

with the quoted range for Υ.

In summary, I have shown that if the Lyman-α clouds are indeed photoionized then their state of ionization is such that we need only set a limit on the strength of the C IV absorption lines relative to the Lyman-α lines to deduce the heavy element content of the cloud material: we do not have to concern ourselves with the lower states of ionization of carbon because they are expected to have negligible strengths under the inferred range of physical conditions in the clouds.

High-quality spectra of Q1623 + 269, the brighter of the two quasars referred to in §2, have been used by Sargent *et al.* (1982) to set a limit on the C/H abundance ratio in the Lyman-α clouds by setting a limit on the strength of the corresponding C IV λλ1548, 1550 doublets. It was found that the most sensitive procedure is to add up portions of spectrum in which C IV doublets would be expected, the portions each being corrected to the rest wavelength obtained from the corresponding Lyman-α line before the addition is made. In this manner it was shown that the strength of the C IV λ1548 line corresponding to a typical Lyman-α line does not exceed

$W_0(\lambda 1548) = 0.003$ Å. It is then found that $N_{\mathrm{C_{IV}}}/N_{\mathrm{H_I}} \leqslant 0.01$, a factor of 30 below the value expected if the Lyman-α clouds have a normal C/H ratio and are photoionized. We thus have preliminary evidence that the clouds have a low abundance of heavy elements – as would be expected if they are, in fact, primordial intergalactic clouds.

4. Conclusions and prospects

In broad terms there is now very strong evidence that the Lyman-α absorption clouds are intergalactic objects. If, as seems likely, they are photoionized, they have a low heavy-element composition. The lack of clustering revealed by their correlation function may or may not be compatible with the clustering of galaxies at $z \approx 2.5$ since, as we have seen, the evolution of the galactic correlation function in cosmic time is poorly understood theoretically and there is no directly relevant observational evidence. It is therefore clearly important to try to determine the galactic correlation function by using the heavy-element red shifts as outlined in §2*b*. This must be done for red-shift separations in the range 300–2000 km s^{-1}, where motions of clouds within galaxies must be unimportant. In fact, such an approach offers the only way of directly investigating the clustering of galaxies at large red shifts ($z \approx 2.5$), which can currently be envisaged.

An equally important prospect is to try to use the Lyman-α clouds to determine the composition of primordial matter. At this point, absorption spectroscopy of the clouds does not seem a promising way of determining the primordial He/H abundance ratio because they are thought to be highly ionized. Consequently, although the ultraviolet resonance lines of $\mathrm{He^0}$ and $\mathrm{He^+}$, at λ584 and λ304 respectively, are red-shifted at $z \approx 2.5$ into the wavelength range observable from spacecraft, there seems to be no conceivable way of determining the ionization correction for $\mathrm{He^{2+}}$ without resort to theoretical considerations, which in our present state of knowledge would be very doubtful. (This state of affairs is to be contrasted with that involved in emission spectroscopy where the proportion of $\mathrm{He^{2+}}$ and $\mathrm{He^+}$ can be directly inferred from the observed recombination lines in $\mathrm{He^+}$ and $\mathrm{He^0}$, respectively, but where the correction for $\mathrm{He^0}$ is doubtful.)

The Lyman-α clouds offer better prospects for the determination of the D/H ratio, which, as both Pagel and Schramm describe in this symposium, is poorly known despite the fact that it is more sensitive than the He/H ratio to the physical conditions prevailing in the Big Bang. The D_α line lies only 0.33 Å shortward of the Lyman-α line. However, this separation is increased by a factor of $1+z$ and can be resolved by currently available detectors in the spectra of the brighter quasars. Moreover, as Boksenberg, Lambert & Vidal-Madjar have shown in unpublished calculations, the probability of detecting the expected weak D_α line can be optimized by choosing saturated Lyman-α lines, which are near the intersection of the logarithmic and damping portions of the curve of growth – so that the Lyman-α lines have a high column density but are not yet too broad. Boksenberg and his colleagues have thus estimated that it should be possible to detect D_α in the Lyman-α clouds if the D/H ratio is in the expected range $10^{-4} > \mathrm{D/H} > 10^{-5}$. However, it is clear that the approach must involve statistics in order to avoid the possibility of a second, weak Lyman-α line falling at the expected wavelength of a particular D_α line.

I thank my colleagues A. Boksenberg, F.R.S., A. Dekel and J. Fillmore for discussions and inspiration. Most of the work described here was begun in collaboration with the late Peter Young. I thank the National Science Foundation for support under contract no. AST 80-22279.

REFERENCES

Bahcall, J. N. 1975 *Astrophys. J. Lett.* **200**, L1.
Bahcall, J. N. & Peebles, P. J. E. 1969 *Astrophys. J. Lett.* **156**, L7.
Boksenberg, A. & Sargent, W. L. W. 1975 *Astrophys. J.* **198**, 31.
Boksenberg, A. & Sargent, W. L. W. 1978 *Astrophys. J.* **220**, 42.
Dekel, A. 1982 *Astrophys. J. Lett.* (In the press.)
Goldreich, P. & Sargent, W. L. W. 1976 *Comment. Astr. Astrophys.* **6**, 133.
Lynds, C. R. 1971 *Astrophys. J. Lett.* **164**, L73.
McKee, C. F., Tartar, B. C. & Weisheit, J. C. 1973 *Astrophys. Lett.* **13**, 13.
Oort, J. H. 1981 *Astron. Astrophys.* **94**, 359.
Oort, J. H. 1983 *A. Rev. Astr. Astrophys.* **21**. (In the press.)
Perry, J. J., Burbidge, E. M. & Burbidge, G. R. 1978 *Publs A.S.P.* **90**, 337.
Sargent, W. L. W., Boksenberg, A., Fillmore, J. & Young, P. J. 1982 *Astrophys. J.* (In preparation.)
Sargent, W. L. W. & Boroson, T. A. 1979 *Astrophys. J.* **228**, 712.
Sargent, W. L. W., Young, P. J., Boksenberg, A., Carswell, R. F. & Whelan, J. A. J. 1979 *Astrophys. J.* **230**, 49.
Sargent, W. L. W., Young, P. J., Boksenberg, A. & Tytler, D. 1980 *Astrophys. J. Suppl.* **42**, 41.
Sargent, W. L. W., Young, P. J. & Schneider, D. P. 1982 *Astrophys. J.* **256**. (In the press.)
Savage, B. D. & de Boer, K. S. 1981 *Astrophys. J.* **243**, 460.
Savage, B. D. & Jeske, A. 1981 *Astrophys. J.* **244**, 768.
Schechter, P. 1976 *Astrophys. J.* **203**, 297.
Sunyaev, R. A. & Zel'dovich, Ya. B. 1972 *Astron. Astrophys.* **20**, 189.
Ulrich, M. H., Boksenberg, A., Bromage, G., Carswell, R., Elvius, A., Gabriel, A., Gondhalekar, P. M., Lind, J., Lindegren, L., Longair, M. S., Penston, M. V., Perryman, M. A. C., Pettini, M., Perola, G. C., Rees, M., Sciama, D., Snijders, M. A. J., Tanzi, E., Tarenghi, M. & Wilson, R. 1980 *Mon. Not. R. astr. Soc.* **192**, 561.
Young, P. J., Sargent, W. L. W. & Boksenberg, A. 1982*a* *Astrophys. J. Suppl.* **48**, 455
Young, P. J., Sargent, W. L. W. & Boksenberg, A. 1982*b* *Astrophys. J.* **252**, 10.
Young, P. J., Sargent, W. L. W., Boksenberg, A., Carswell, R. F. & Whelan, J. A. J. 1979 *Astrophys. J.* **229**, 891.

Discussion

W. H. McCrea, F.R.S. (*Astronomy Centre, University of Sussex, U.K.*). Does Professor Sargent consider that clouds of material, having the density and extent that he infers, could hold together in intergalactic space – either in isolation or as envelopes of galaxies – and survive to the epoch when they would produce the effects described?

W. L. W. Sargent. In our paper (Sargent *et al.* 1980) we deduced the properties of the clouds precisely from the condition that they should be in pressure equilibrium with a hot intergalactic medium. One of the important constraints was the condition that the clouds should be able to survive the 'ablation' by the hot exterior gas. The clouds must have been formed close to the epoch of observation ($z \approx 3$) and, since the supposed confining medium has expanded with the Universe, they would not have survived to the present epoch if our ideas are correct. Obviously, observations with Space Telescope will be of enormous interest in this last connection.

M. J. Rees, F.R.S. (*Institute of Astronomy, Cambridge, U.K.*). How firmly can Professor Sargent really conclude that the material causing the 'Lyman only' absorption systems is deficient in heavy elements? If the clouds were somewhat denser and less highly ionized than he has assumed (and sheet-like in structure), then the hydrogen lines could be much stronger than others even for 'solar' abundances.

W. L. W. Sargent. I believe that the properties of the clouds are sufficiently well tied down to exclude the possibility that Professor Rees mentions. However, it would be very important to obtain a direct estimate of the cloud size from observations of quasars close together on the plane of the sky – as would be provided, for example, by a gravitationally lensed quasars of suitable red shift.