QUASAR ABSORPTION LINES: EVOLUTION AND CLUSTERING

Wallace L.W. Sargent
Palomar Observatory, 105-24
California Institute of Technology
Pasadena Ca. 91125
U.S.A.

ABSTRACT. A large new sample of absorption redshifts derived from the C IV doublet in the spectra of 56 QSOs has been used to study the evolution and clustering tendencies of the heavy element absorbers (thought to be galaxies). The new data have been compared with more extensive existing data for the more common Lyman α forest lines (thought to be produced by intergalactic clouds). Little or no clustering is observed in the Lyman α forest lines; moreover, there is no evidence for voids in their distribution. Clustering has been detected in the heavy element redshifts on scales $\Delta v \geq 200$ km s^{-1} where relative motions of clouds *within* galaxies are unlikely to dominate. The degree of clustering inferred at $z \approx 2$ is of the order expected on the simplest model for the evolution of galaxy clustering in cosmic time. The recent discovery of similar concentrations of absorption features extending over $\Delta z \sim 0.2$ in the spectra of widely separated QSOs on the sky provides evidence for very large structures, probably filaments or sheets of galaxies, extending over 100 Mpc (co–moving). The Lyman α forest and heavy element redshifts evolve very differently. The Lyman lines show a rapid increase in density with increasing z, while the C IV doublets show a *decrease*. This result emphasizes that there are two discrete populations of absorbers. The decrease in C IV line density may be due to the effects of the onset of stellar nucleosynthesis in galaxies.

1. INTRODUCTION

Research over the last several years has shown that the majority of the sharp absorption lines found in the spectra of quasars are produced by cosmologically distributed, intervening objects. (For recent reviews see, for example, Sargent 1988 and references therein.) In brief, it is now generally accepted that the lines of the "Lyman α forest" on the blue side of the Lyman α emission line are probably produced by intergalactic clouds while the much less common "heavy element" redshift systems are produced by galaxies. The absorption lines have several applications to different cosmological questions (Sargent 1987). Here I shall concentrate on two questions of central importance to this Symposium — the evolution of the absorption line–density in cosmic time and the evolution of clustering in the Universe. The main reason for isolating these two topics is that a large body of new observations has become available during the last few weeks which add considerably to our knowledge of the evolution and clustering properties of the heavy element absorbers. Thus (by prior arrangement) I shall trespass on Dr. Bergeron's territory in talking about the heavy–element absorbers.

It is important to note that, with our present technical limitations, QSO absorption lines provide the only practical way with which to investigate the clustering and evolution of galaxies

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at redshifts beyond z = 2, and the only way to investigate the properties of intergalactic clouds.

2. RUSTLINGS IN THE FOREST

2.1. Prologue

There is not enough time in this talk to go into the question of the general properties and the nature of the absorbing objects. This will be done for the heavy element absorption systems by Dr. Bergeron. A recent summary of these aspects of the Lyman α forest was given by Sargent (1987). However, there are two recent developments which merit special emphasis.

2.2. One Population?

Tytler (1987a) has recently argued that the distribution of number of Lyman α absorption lines as a function of column density follows a single power law over the range $10^{12} \leq logN(H) \leq 10^{22}$ cm^{-2}. He points out that, since the lower end of this range is dominated by the lines in the Lyman α forest and the upper end is dominated by Lyman α's associated with heavy element redshift systems, it would be strange if the lines originated in two completely different kinds of object. Moreover, it is hard to understand why no break is observed at log N(H) $\sim 10^{17}$ cm^{-2} if, as is commonly supposed, the clouds which produce the low column density lines are highly ionized. Tytler then goes on to postulate that the clouds are neutral and, in consequence, very small – about 3 pc in diameter instead of being of galactic dimensions. Tytler's original claim has been disputed (Bechtold 1987, Wolfe 1988). Moreover, as we shall show, the Lyman α forest and heavy element lines differ in both their evolution and in their clustering properties. Thus, despite the remarkable nature of Tytler's observation, it appears that it is still reasonable to attribute the lines to two different sources.

2.3 The "inverse effect"

Recent developments on the behavior of the Lyman α forest in the vicinity of the Lyman α emission line have opened up new avenues to explore the UV radiation background and the properties of the general intergalactic medium at high redshifts. Carswell *et al.* (1984) pointed out that there is statistical evidence for a deficiency of absorption lines in the blue wing of the Lyman α emission line. They suggested that this effect was due to the influence of the QSO itself on the ionization of the Lyman α clouds in its immediate vicinity. Later, Murdoch *et al.* (1986) pointed out that, while in QSO spectra overall there is an obvious tendency for the density of Lyman α forest lines to increase with redshift, in an *individual* QSO spectrum there is a flat or even declining number density distribution with increasing redshift over the range in redshift between the Lyman α and Lyman β emission lines. This result, named the "inverse effect" by Murdoch *et al.* was shown to be due to a general statistical deficiency of Lyman α absorption lines close to the emission line, as Carswell *et al.* had suggested. Tytler (1987b) extended this result; however he showed that the onset of the deficiency in absorption lines sets in gradually longwards of the Lyman β emission line. Bajtlik, Duncan and Ostriker (1987) have quantified Carswell *et al.*'s original suggestion and have shown that Tytler's data may be fitted very well if it is assumed that close to the QSO the local radiation field dominates over the metagalactic QSO flux. They also point out that by observing the "inverse effect" in QSOs with a range in intrinsic luminosity it should be possible to determine the total UV ionizing flux due to all sources as a function of redshift. Since the QSO contribution is directly observable from the counts, it then becomes possible to estimate from the "proximity effect" (as Bajtlik *et al.* call it) the contribution to the metagalactic flux of ionizing radiation at high redshifts of lower luminosity sources such as star–forming galaxies and Seyfert nuclei which cannot be observed directly. Interestingly, Bajtlik *et al.* found, in a highly model–dependent calculation, a preliminary fit to the observations with a meta–galactic flux at z=2.5 of $I_\nu = 10^{-21}$ ergs s^{-1} cm^{-2} $ster^{-1}$, close to the value which has been estimated as close to the total contribution of QSOs alone. The success of Bajtlik *et al.*'s calculation probably enhances one's confidence that the Lyman α clouds are indeed highly ionized by the metagalactic UV flux as Sargent *et al.* (1980) proposed. It should be noted, however, that Tytler (1987b) does not believe that Bajtlik *et al.*'s explanation can account for all of the observed "inverse effect". At any rate, it is clear that detailed studies of the Lyman α forest offer a unique possibility to set constraints on the properties of the intergalactic medium and on the ionizing radiation field due to both QSOs and galaxies at high redshifts.

3. A NEW SURVEY OF C IV REDSHIFTS

The heavy element redshifts are about 60 times less common than the single Lyman α lines of the "forest" at redshifts around $z \approx 2.5$. In order to study the evolution and clustering of the heavy element redshifts, Boksenberg and the writer have devoted the last five years to the systematic accumalation of spectra of QSOs with redshifts in the range $1.8 \leq z_{em} \leq 3.6$ using the IPCS detector attached to the Double Spectrograph at the cassegrain focus of the Hale 5 meter telescope. The final survey (Sargent, Boksenberg and Steidel 1988) contains spectra of 56 QSOs brighter than 17.5 magn. The spectra have a uniform signal–to–noise ratio of 20:1 and have a resolution of 1.5Å (about 100 km s^{-1}). The wavelength coverage is 1250Å, extending from the C IV λ1549 emission line downwards; the spectra thus extend down as far as the Lyman α emission line only for the lower redshift objects. The typical range in redshift is $\Delta z \approx 0.6$. In some cases spectra having a resolution of 0.7Å were obtained and in some cases the coverage was extended to include the Lyman α forest region to the blue of the Lyman α emission line.

The spectra of QSOs on the long wavelength side of the Lyman α emission line are only sparsely populated with absorption lines. Accordingly, given spectra of sufficently quality, it is possible to identify essentially all of the lines with relative ease. We have produced a sample of redshifts from the survey spectra identified using only the C IV $\lambda\lambda$1548, 1550Å doublet. This procedure, of course, isolates a particular type of highly ionized absorption system.

The resulting sample contains 220 absorption redshifts, much the largest number produced in any single, homogeneous survey. A smaller sub–sample was also derived of 146 redshifts with rest equivalent widths $W_0 \geq 0.15$Å. This limit was chosen so that all of the 146 redshifts could have been discovered anywhere in any of the spectra. A further sub–sample was produced in which redshifts occuring in clumps in which the separations were less than 1000 km s^{-1} were treated as a single system. This sample is referred to as the "Poisson sample"and contains 113 redshifts. Evidence has recently accumulated that clumps of absorption redshifts are found near the emission redshift preferentially in radio–loud QSOs (Foltz *et al.* 1986; Barthel and Tytler 1987). There is *a priori* evidence that the redshifts in these clumps are sometimes associated with the QSO itself and, accordingly they should not be used for statistical purposes. Thus, for some purposes we have derived a third restricted sample in which absorption redshifts within 5000 km s^{-1} of the emission redshift are eliminated. This "restricted Poisson sample" contains 88 redshifts. Only the three restricted samples can be used with confidence to investigate evolutionary effects and clustering on large scales.

Both the total sample of C IV absorption redshifts and the statistically more more homogeneous sub–samples show no significant tendency to fall preferentially near the emission redshift— perhaps they are not dominated by radio–loud QSOs. The distribution of the number of absorption systems per QSO resembles the Poisson distribution that is expected for randomly distributed intervening absorbers (Bahcall and Peebles 1969); however, there are too many QSOs with 7 systems in the tail of the distribution. A statistical test shows that a Poisson distribution can be rejected with a high degree of confidence. As will appear in §6, the effect is probably due to the existence of very large scale features in the galaxy distribution.

4. EVOLUTION IN REDSHIFT

4.1 Theory

Because the Universe is expanding, the number of absorbers intercepted per unit redshift range

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along a given line of sight is expected to increase with redshift. If the cosmological constant $\Lambda = 0$, the expected behavior for absorbers of constant cross–section πr_0^2 and constant co–moving number density Φ_0 is:

$$\frac{dN}{dz} = N_0(1+z)(1+2q_0z)^{-1/2} \tag{1}$$

where the local value of N(z) is $N_0 = \pi r_0^2 \Phi_0 c/H_0$. If the absorbers evolve in cosmic time then $N_0 = N_0(z)$. It is convenient to compare the observed data with a power–law of the form $dN(z)/dz = const. \times (1+z)^\gamma$. It is easy to show that the general expression for the exponent γ is

$$\gamma = \left(\frac{1+q_0z-q_0}{1+2q_0z}\right) \tag{2}$$

Particular values are $\gamma = 1$ for $q_0 = 0$ and $\gamma = 1/2$ for $q_0 = 1/2$. This test could be used to determine q_0 if one had evidence that N_0 did not evolve in time for a particular class of absorbers. Otherwise the test has the same problems wih evolutionary corrections as the more familiar redshift–apparent magnitude and redshift–angular diameter tests. However, the density of absorbers test has, in principle, the advantage that it is maximally sensitive at z = 0 where there is the best chance of understanding evolutionary effects.

4.2 Evolution and the Lyman α forest

A glance at spectra of the Lyman α forest region of the spectra of a pair of QSOs with $z_{em} \sim 2$ and $z_{em} \sim 3$, respectively, shows immediately that there is perceptible evolution in the density of lines. This effect was noticed qualitatively by Peterson (1978) and is now well established despite detailed disagreements between different observers. Quantitatively, the most recent studies indicate a value for $\gamma \sim 2$; Murdoch *et al.* (1986) found $dN(z)/dz \sim (1+z)^{2.3\pm0.4}$ from a sample of 11 QSOs with redshifts in the range $1.5 \leq z_{em} \leq 3.78$. Thus, it is well established that $\gamma > 1$, the maximum value permitted with no evolution in the properties of the absorbing clouds. The rapid increase in the density of the Lyman α absorption lines at large redshifts is naturally explained in physical models in which the clouds are confined by the pressure of a general intergalactic medium which itself expands adiabatically with the Universe (Ostriker and Ikeuchi 1983). However, the mechanism for initially heating and ionizing the medium is still not understood (Shull 1988, Shapiro 1988).

4.3 Evolution of the heavy element redshifts

Since the absorption redshifts which contain lines of the heavy elements are much less common than the Lyman α cloud redshifts, it is much harder to obtain statistical samples large enough to study their evolution. Perhaps the best data have been assembled by Tytler (1986) for the "Lyman limit" redshift systems which are produced by objects with H I column densities greater than $\sim 10^{17}$ cm^{-2}. Such systems produce a pronouced discontinuity in the spectrum at the Lyman limit which can be easily detected even in spectra of low signal–to–noise ratio. This has enabled Lyman limit sytems to have been discovered with the IUE satellite down to redshifts of around $z_{abs} \sim 0.4$ while ground–based observations cover the range $2.8 \leq z_{abs} \leq 3.5$. Over this wide range in redshift the data are in reasonable accord with a $q_0 = 0$ model, but not in agreement with $q_0 = 1/2$. There is no evidence for evolution in the properties of the absorbing clouds because the mean column density of the systems does not vary sensibly with redshift (Tytler 1986). Data for a sample of Mg II systems show a very similar behavior to the Lyman limit systems (Tytler 1986). Meagre data on C IV absorbers show some, probably insignificant, evidence for evolution (Bergeron and Boissé 1985).

The extensive catalogue of C IV redshifts described in §3 covers the redshift range $1.4 \leq z_{abs} \leq 3.0$. Plots of the data in any of the three restricted, homogeneous "Poisson" samples shows a definite trend for the density of C IV absorption systems to *decrease* with increasing

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redshift. A maximum likelyhood fit to the most restricted set of 88 redshifts leads to the relation $N(z) \propto (1+z)^{-1.20\pm0.71}$, as compared with $N(z) \propto (1+z)$ for $q_0 = 0$ and $N(z) \propto (1+z)^{1/2}$ for $q_0 = 1/2$, respectively. If we construct a new homogeneous sample of C IV redshifts with $W_0 \geq 0.3$Å by combining the new data with the less extensive samples published by Young, Sargent and Boksenberg (1982) and by Foltz *et al.* (1986), we find $\gamma = -1.72 \pm 0.81$. Finally, if we use all 179 systems in our sample with values of $|z_{em} - z_{abs}|$ such that the corresponding $\Delta v \geq 5000$ km s^{-1}, we get $\gamma = -0.90 \pm 0.50$. Taken together, these results give strong evidence that the C IV absorbers are evolving in cosmic time. No evolution with $q_0 = 0$ is certainly excluded, while $q_0 = 1/2$ and no evolution of the absorbers is excluded at about the 3σ level.

The data only tell us that the product $\pi r_0^2 \Phi_0$ is a decreasing function of z. This could be naturally accounted for in two ways. The most likely explanation is that we are observing the effects of the initial enrichment in heavy elements of the interstellar gas in galaxies. This may be combined with a systematic change in the ionization state of the halo gas with time. These possibilities are both open to direct test through detailed observation of the physical state and composition of the absorbers using the absorption lines themselves. In any case, it is clear that the QSO absorption lines will in the future provide important constraints on early galactic evolution.

5. CLUSTERING

5.1. The correlation function in redshift

The observation of absorption lines along the line of sight to a particlar QSO only gives rudimentary information on the clustering tendency of the absorbers which must be gleaned from the degree to which the systems clump in redshift. In principle, more can be learned by studying the spectra of QSOs near to one another on the plane of the sky (Sargent, Young and Schneider 1982). However, in practice this approach is severely limited by the relatively low areal density of QSOs. In measuring the clustering from such one–dimensional information it is very convenient to make use of the two–point correlation function (Sargent *et al.* 1980). The 2–point correlation function measures the excess probability $\xi(r)$ due to clustering of finding an object at distance r from a given object. The correlation function for local galaxies has the power-law form $\xi(r) = (r/r_c)^{-1.77}$ (Peebles 1973) where $r_c = 5(H_0/100)^{-1}$ Mpc.

In evaluating the correlation function from the splittings between the absorption redshifts, we have to take into account that the positions of the absorbing objects are sampled at different stages in the expansion of the Universe as the light travels along its path to the observer. Therefore, it is convenient to use the differences in co–moving coordinate $S_0(q_0, z)$ between the pairs of absorbers (Sargent *et al.* 1980). For $q_0 = 1/2$ we have:

$$S_0(1/2, z) = 2c/H_0[1 - (1+z)^{-1/2}] \tag{3}$$

We then calculate the co–moving separation between a pair of absorbers with redshifts z_1 and z_2 from:

$$s_0 = |S_0(1/2, z_1) - S_0(1/2, z_2| \tag{4}$$

The unit of distance is the Hubble radius at the present epoch—or 6000 Mpc for $H_0 = 50$ km s^{-1} Mpc^{-1}. For small redshift differences $\Delta z = z_2 - z_1$ it is convenient to express splittings in terms of the velocity difference due to the Hubble flow:

$$v = c\Delta z/(1+z) = cs_0(1 + 2q_0 z)^{1/2} \tag{5}$$

where $z = (z_1 + z_2)/2$. This is the velocity which would be deduced by an observer on one absorber observing the redshift of a second absorber in the case where the redshift difference is small. A summary of the various measures of the correlation function in redshift and of their interpretations is given in Sargent *et al.* (1980).

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5.2. Clustering in the forest

It was shown by Boksenberg and Sargent (1975) that the heavy element redshifts in QSO spectra are strongly clustered on a scale of ~ 150 km s^{-1}. This was interpreted by Bahcall and Spitzer (1975) as being due to the motions of clouds within galactic halos. Sargent, Young, Boksenberg and Tytler (1980) then discovered from a study of the 2–point correlation function that the lines of the Lyman α forest are not perceptibly clustered. This result was quantified by Sargent, Young and Schneider (1982), who showed that the clustering length $r_c \leq 0.2$ Mpc at z = 2.5. On the simplest hierarchical clustering model (which is approximated in the currently popular "cold dark matter" scenario) the power law retains the same slope as clustering proceeds in the non-linear regime, while $r_c(z) = r_c(0)(1+z)^{-5/3}$. Thus the expected value at z= 2.5 is $r_c = 1.0(H_0/100)^{-1}$ Mpc, a factor of 5 higher than the observed limit.

Recent work by Webb, which has not been fully reported in the literature, indicates a small tendancy for small–scale clustering in the Lyman α forest lines at $z \sim 2$ but not at $z \sim 3.5$ (Webb 1988). It is very important to confirm and extend Webb's results because he may have observed the first feeble onset of clustering in a constituent of the Universe which appears to be much less clumped than the galaxies.

No departure has been found from a Poisson distribution on large scales (out to $\Delta v \approx 30000$ km s^{-1}) in the 2–point correlation function of the Lyman α clouds. Rees and Carswell (1987) have shown that voids of the kind found in the local galaxy distribution are not present in the Lyman α cloud distribution at redshifts $z \geq 2$. It should be possible with the *Hubble Space Telescope* to investigate the gaseous contents of nearby voids. An important observation will be to see if the Lyman α clouds inhabit the voids (providing they survive to the present epoch).

5.3. Clustering of heavy–element redshifts

The samples of C IV redshifts alluded to in §3 and §4 provide the best homogeneous data set yet obtained with which to study the clustering tendency of the heavy element redshifts. The 2–point correlation function obtained from the sample shows a generally flat (Poisson) distribution on large scales with a pronounced peak on velocity scales Δv in the range 100 to 500 km s^{-1}. (We are limited by the finite resolution of the spectra to spittings $\delta v \geq 100$ km s^{-1}. Quantitatively, we find 21 splittings for bins in the range $200 \leq \Delta v \leq 1000$ km s^{-1}, as compared with a total of 4 expected. Thus, the new C IV survey has revealed clustering of the heavy element redshifts on large velocity scales for the first time. However, could this excess be due to relative cloud motions in massive, luminous galaxies?

5.4. Expected contribution of cloud motions

We estimate the expected contribution of cloud motions within galaxies to the two–point correlation function as follows. Assume that the galaxian luminosity function may be represented by Schechter's (1977) expression:

$$\Phi(L)dL = \Phi_*(L_*)(L/L_*)^{-5/4}\exp[-L/L_*]dL \tag{6}$$

Next, assume that the effective cross–section for C IV absorption scales with luminosity like the Holmberg radius:

$$R(L) = R_*(L/L_*)^{5/12} \tag{7}$$

Finally, assume that typical cloud velocities within a galaxy scale like the Faber–Jackson (1976) or Fisher–Tully (1900) relations:

$$v(L) = v_*(L/L_*)^{1/4} \tag{8}$$

With these assumptions it is easy to calculate that galaxies with luminosity $L \leq L_*$ contribute 81% of the total absorption cross–section, while galaxies with $L \leq 3L_*$ contribute 98%.

However, the area–weighted mean velocity spread in a galaxy is given by:

$$\langle v\rangle = \frac{\int_0^\infty \Phi(L)L^{1/4}R^2 dL}{\int_0^\infty \Phi(L)R^2 dL} \tag{9}$$

This gives $\langle v\rangle = 0.65v_*$ where $v_* \approx 200$ km s^{-1} is the typical velocity spread in a galaxy of luminosity L_*. Therefore, with the above assumptions, we expect the mean velocity splitting for QSO absorption lines produced by motions in galaxies to be ~ 130 km s^{-1}. It is therefore unlikely that the observed C IV splittings which go up to 500 km s^{-1} are due to motions within galaxies; it is more likely that we are observing the tip of the galaxian two–point correlation function.

5.5. Correlations due to galaxy clustering.

Given the assumptions used to calculate the effect of motions within galaxies summarized in equations 6 to 8, it is found from equation 1 that the mean effective radius for absorption for an L_* galaxy is given in terms of the number density of absorption systems $N(z) \equiv dN/dz$ by the expression:

$$R_* = 59\left(\frac{100}{H_0}\right)\left[\frac{N(z)}{(1+z)}\right]^{1/2}(1+2q_0z)^{-1/4}\text{kpc} \tag{10}$$

If we adopt the assumptions summarized in §5.1 regarding the form of the local galaxian correlation function and its evolution in cosmic time, we find for the number of *correlated* galaxies along the line of sight:

$$n_c(R) = \int_0^R 4\pi s ds \int_0^\infty dl\Phi r_c^\alpha (s^2+l^2)^{-\alpha/2} - \int_0^R 4\pi s ds \int_0^{(D_{min}^2-s^2)^{1/2}} dl\Phi r_c^\alpha (s^2+l^2)^{-1/2} \tag{11}$$

Here s is the distance along the line of sight and l the distance perpendicular to the line of sight. The last term is added to prevent galaxies being closer than D_{min} to any fiducial galaxy. In order to exclude velocity splittings on scales $\Delta v \leq 200$ km s^{-1} which might be due to motions within galaxies we put D_{min} equal to the corresponding Hubble flow distance at a redshift z = 2, that is, $D_{min} = 6R$. On substituting we find that $n_c/N(z) = 0.06$. The mean number of splittings per unit redshift range in the "Poisson" sample (with $W_0 \geq 0.15$Å) is N(z) = 2.63. Thus the number of excess splittings over the mean Poisson level is $n_c = 0.06 \times 2.63 = 0.16$. With 90 absorption systems in the Poisson sample, we therefore expect $0.16 \times 90 \approx 14$ excess splittings, strikingly close to the observed value of 17. It thus appears that the pronounced peak in the two–point correlation function of the C IV doublets is produced by galaxy clustering which can therefore be studied at redshifts beyond where galaxies can be directly observed. For illustrative purposes we have compared these new data only with the predictions of the simplest possible scenario for the evolution of clustering. The data clearly warrent a more sophisticated approach. In this connection, it is interesting that Salmon and Hogan (1986) compared data for Lyman α and for C IV clustering which had been published by Sargent *et al.* (1980) with simulations of the expected distribution of absorption–line redshifts in Cold Dark Matter cosmologies. The then available data had revealed only the C IV clustering on scale of $\Delta v \leq 150$ km s^{-1} which could be due to motions *within* galaxies. However, interpreting these splittings as being due to the tip of the galaxian correlation function, Salmon and Hogan found two possible interpretions of the data:

1. The heavy–element absorption systems are associated with *galaxies* which are an *unbiased* sample of the mass–distribution in an $\Omega_0 = 0.2$ Universe. (If this is the case, some mechanism must be found in order to prevent the Lyman α clouds following the overall mass distribution. For example, as Ostriker (*private communication*) has emphasized, the pressure of

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the inter–galactic medium is likely to be higher in the vicinity of galaxy aggregates; certainly the X–ray observations show directly that the inter–galactic gas pressures in clusters like the Coma cluster are about five orders of magnitude higher than the pressures inferred for the Lyman α clouds.)

2. In a Universe with $\Omega_0 = 1$ the correlations expected at $z = 3$ are much smaller than those in an $\Omega_0 = 0.2$ Universe. The *Lyman α clouds* are then an *unbiased* sample of the mass distribution and the heavy element absorbers, like the galaxies, are *more strongly clustered* than the mass as a whole.

These simulations show the potential significance of the absorption–line clustering data for understanding the evolution of clustering. The new more extensive clustering data will be compared with the simulations in the near future.

6. EVIDENCE FOR LARGE STRUCTURES

In general, examples of *correlated* absorption between pairs of QSOs has been confined to cases where the separation on the sky is $\leq 1'$ (for a review see Shaver and Robertson 1984). An angle θ on the sky corresponds at redshift z to separation d given by the expression:

$$d = (c\theta/H_0)[Z(q_0, z)/(1+z)] \tag{12}$$

where

$$Z(q_0, z) = \frac{q_0 z + (q_o - 1)[(1 + 2q_0 z)^{1/2} - 1]}{q_0^2(1+z)} \tag{13}$$

We thus find that a separation of $1'$ corresponds to a linear separation of 0.4 Mpc for $q_0 = 0$ and 0.6 Mpc for $q_0 = 1/2$, respectively at $z = 2.5$. The corresponding values at $z = 2$ are almost identical. (The calculated linear dimension d obtains at the epoch pertaining to z; if the dimension is expanding with the Universe, the value at the present epoch will be increased by a factor of $1 + z$.)

In general, correlated absorption features have only been found in the spectra of QSOs separated by less than $1'$ on the plane of the sky (Shaver and Robertson 1983, Sargent 1987). In particular, the QSOs which are thought to be gravitationally lensed and in which the images are separated by a few arcseconds show common absorption features. (For a particularly important case see Foltz *et al.* 1984.) Thus, until recently, cases of common absorption had been limited to separations of order the largest dimensions associated with galactic halos. It therefore came as a surprise when Jakobsen *et al.* found an unusually high density of C IV absorption doublets in the spectra of two QSOs, Tol 1038-2712 ($z_{em} = 2.331$) and Tol 1037-2704 ($z_{em} = 2.193$) which were separated by $17'$ on the sky. According to Jakobsen *et al.*, and confirmed by Sargent and Steidel (1987), there are at least five absorption redshifts or clumps of redshifts in the range $1.85 \leq z_{abs} \leq 2.14$ in the spectra of both of these QSOs, a density unequaled in the C IV survey of 56 QSOs described in §3. Even more remarkably, two fainter QSOs in the same field, Q1038-2707 ($z_{em} = 1.937$) and Q1035-2737 ($z_{em} = 2.168$) also have strong absorption redshifts at $z_{abs} = 1.89$ and $z_{abs} = 2.13$, respectively. The picture which emerges is that there is a supercluster in this region of the sky, extending from $z \sim 1.85$ to $z \sim 2.14$. The corresponding co–moving size in the radial direction (assuming $q_0 = 1/2$) is ~ 100 Mpc. The projected extent of the supercluster on the plane of the sky is at least 5 Mpc by 15 Mpc. Further observations of the absorption spectra of other QSOs discovered by Bohuski and Weedman (1979) in this region of the sky are currently underway to more closely define the boundaries. Since the density of absorption features is so high in the spectra of QSOs thought to be on the far side of the supercluster, it is likely that we are observing along a filament of galaxies or along the plane of a sheet. The existence of such large, unsymmetrical structures would lead to a complication in the statistics of the expected number of absorbers per QSO, which would only be Poisonian for observed redshift intervals Δz which were large as compared with the sizes of the largest structures. Since the typical redshift range for the C IV survey of §3 is only $\Delta z \approx 0.6$, as compared with $\Delta z \approx 0.2$ for the hypothetical supercluster discussed above, the existence of the tail on the Poisson distribution of the number of absorbers per QSO then has a natural explanation.

Most importantly, however, the discovery by Jakobsen *et al.* opens up the possibility of using QSO absorption lines to investigate directly the details of the large–scale distribution of galaxies at high redshifts and early times.

7. SUMMARY

We have presented the following main results:

1. Little or no clustering is observed in the "Lyman α forest" lines. Also, there is no evidence for voids in their distribution.

2. Clustering in the heavy–element redshifts has been detected on a velocity scale where it is very unlikely to be due to the relative motions of clouds within galaxies.

3. This clustering is at a level roughly expected on the simplest hierarchical clustering model; comparison of the data with more sophisticated Cold Dark Matter clustering simulations will be carried out.

4. The existence of similar concentrations of absorption features in QSOs separated by several minutes of arc on the sky (corresponding to several Mpc at $z \approx 2$) provides evidence for *very large structures* extending over $\Delta z = 0.2$, or a co–moving size of 100 Mpc.

5. The *evolution in redshift* of the Lyman α forest and heavy–element absorbers are very different. There is preliminary evidence that the C IV line density is going down with increasing z. It is still to be determined whether this effect is due to a systematic change in the state of ionization of galaxy halos with redshift or whether it reflects the growth of the heavy element content of the interstellar gas with cosmic time as nucleosynthesis proceeds.

Nevertheless, while all these doubts remain, it is clear that the QSO absorption lines will eventually lead to important new constraints on the evolution of clustering in the Universe and on the evolution of the physical conditions in galaxies.

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