QSO ABSORPTION LINES: HEAVY ELEMENTS AND LYMAN-α CLOUDS

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ABSTRACT

The absorption lines in QSO spectra may be produced in material surrounding the QSO, in intergalactic clouds and in the interstellar gas of galaxies along the line of sight to the QSO. The intergalactic clouds produce weak Lyα absorption lines. The intervening galaxies produce absorption line systems with heavy element abundances and ionizations similar to the H I clouds in the halo of our galaxy. The material surrounding the QSO produces broad absorption troughs. Evidence suggests a continuity in spatial correlation and heavy element abundances for the Lyα clouds and intervening galaxies.

1. THE LYMAN-α CLOUDS

High redshift QSOs (those with $z > 1.7$) have many weak absorption lines that can be observed between the short wavelength atmospheric cutoff at 3100Å

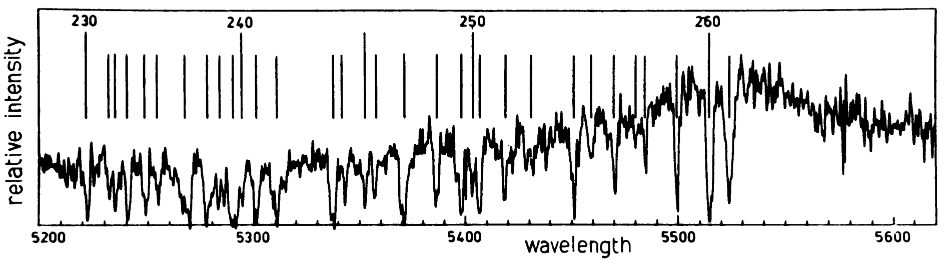

Figure 1. The spectrum of 1442+101 (OQ172) from 5200–5620Å (Peterson *et al.*, 1986). The Lyα emission line is at 5523Å. Almost all of the 261 absorption lines on the short wavelength side of the Lyα emission line are Lyα absorption lines at smaller redshifts, produced in intergalactic clouds along the line of sight to the QSO.

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and the redshifted Lyα emission line. Figure 1 shows a portion of the spectrum on the short wavelength side of the Lyα emission line of 1442+101 (OQ172) (Peterson *et al.*, 1986).

Counts of the number of Lyα lines per unit redshift interval, as a function of redshift are shown in Figure 2. The data are well represented by the solid line corresponding to

$$\frac{dN}{dz} = K(1+z)^{\gamma} \tag{1}$$

with $\gamma \approx 2$. The dotted line represents

$$\frac{dN}{dz} = \frac{K}{(1+z)\sqrt{z}} \tag{2}$$

corresponding to the number of uniformly distributed clouds along the line of sight assuming time invariant cloud properties in the chronometric cosmology (Segal 1983). The data are inconsistent with the chronometric theory. The dashed line represents the relation

$$\frac{dN}{dz} = \frac{c}{H_\circ}\sigma\rho_\circ\frac{(1+z)}{(1+2q_\circ z)^{\frac{1}{2}}} \tag{3}$$

corresponding to the number of uniformly distributed clouds along the line of sight assuming time invariant cloud properties in an expanding Universe with $q_\circ = 0.05$ (Peterson 1978). The difference between the observations and Equation 3 can be understood in terms of highly ionized H I clouds (Ostriker and Ikeuchi 1983, Atwood, Baldwin and Carswell 1985) which become progressively more ionized as the Universe expands.

2. THE HEAVY ELEMENT SYSTEMS

The heavy element absorption systems are associated with the gas in intervening galaxies. The observed heavy element lines are mostly ground state transitions of neutral and low ionization states of the more abundant elements. For example, the QSO 0528—250 (Morton *et al.* 1980) has two heavy element absorption systems with Lyα column densities of $n \approx 10^{21}$ cm^{-2}, and the prominent heavy element ions of C II, N I, O I, Si II, Al II, S II, Fe II, Si IV, and C IV. The column densities measured relative to H I and compared to solar abundances show that O I, N I, Si II, S II, and Fe II are down by a factor of 10, typical of H I clouds in the halo of our own galaxy (Savage and de Boer, 1981). The heavy element absorption line systems also exhibit velocity structure in the range 10–100 km s^{-1} (Boksenberg and Sargent, 1975, Sargent *et al.*, 1982).

3. HEAVY ELEMENTS IN LYMAN-α CLOUDS

In order to obtain a better understanding of the nature of the Lyα clouds, searches have been made for absorption lines of heavy elements in Lyα cloud spectra. As primeval matter was almost entirely hydrogen and helium, and the nucleosynthesis of heavy elements takes place in stars, the presence of heavy elements in the Lyα clouds would imply that the abundances of the clouds have been enriched by stellar material, and that the Lyα clouds are associated with galaxies.

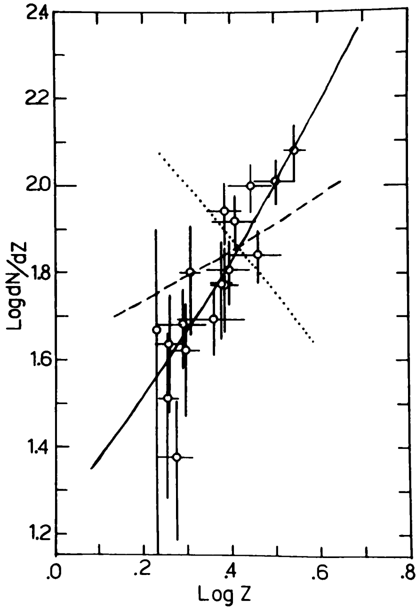

Figure 2. Counts, as a function of redshift, of the number of Lyα lines per redshift interval. The solid line is a power law fit to the data (Eq. 1). The dotted line is the relation expected from the chronometric theory (Eq. 2) for uniformly distributed clouds. The dashed line is the relation expected in an expanding Universe with uniformly distributed, non-evolving clouds (Eq. 3).

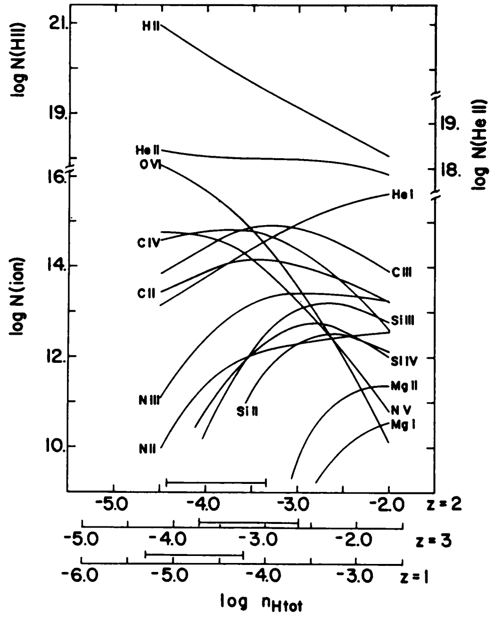

Figure 3. Column densities for dominant ions as a function of the total hydrogen density for a plane parallel slab with log N(H I) = 16.5 and [Z/H] = —1.7 (Chaffee *et al.*, 1986). Different epochs are labeled by redshift, and correspond to horizontal shifts in the density axis. The horizontal bars on each density axis show the the limits implied by the observed size constraints on the clouds at $z = 2$.

In order to be detectable in a Lyα cloud, an ion must have a column density greater than about 10^{14} cm^{-2}. In the sun, hydrogen is more abundant than the elements heavier than helium by about 10^6. Thus, in a Lyα cloud with solar abundances, a barely detectable heavy element ion, which was the dominant ionization state for that element, would be accompanied by a Lyα absorption line with a column density of 10^{20} cm^{-2} if the hydrogen was neutral. Low ionization absorption line systems such as these would be similar to those observed in 0528—250, and are associated with intervening galaxies.

For a typical Lyα cloud, the H I column density is about 10^{15} cm^{-2}. If heavy elements were present in these Lyα clouds with approximately solar abundances, they would be impossible to detect unless the Lyα clouds were very highly ionized. However, if the cloud was so ionized that only one part in 10^6 of the hydrogen was neutral, then the Lyα absorption line would be similar in strength to absorption lines produced by highly ionized species of the more abundant heavy elements. This is illustrated in Figure 3, where Chaffee *et al.* (1985) have plotted column densities for dominant ions as a function of the total hydrogen density as predicted by models where the Lyα clouds are photoionized by the background light from

QSOs, and the heavy element abundances, with respect to hydrogen, is $10^{-1.7}$ times the solar value ([Z/H] = —1.7). Note that the galactic stars with the lowest known abundances are CD−38°245 with [Fe/H] = —4.5 (Bessell and Norris, 1984) and G64–12 with [Fe/H] = —3.5 (Carney and Peterson, 1981). Heavy element absorption lines in Lyα clouds with abundances as low as [Z/H] = —3 would be practically undetectable.

Two approaches have been used to search for heavy elements in Lyα clouds. In the first, the ability to detect weak lines is enhanced forming a composite Lyα cloud spectrum by summing portions of QSO spectra in the rest frame of each Lyα cloud. In the second, a spectrum of a Lyα cloud with exceptionally high column density is examined for heavy element absorption lines.

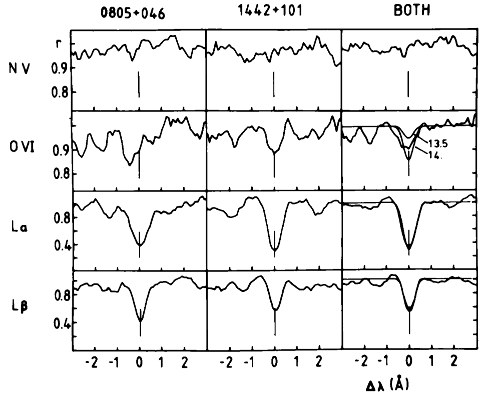

Figure 4. Composite spectra of the QSOs 0805+046 (left), 1442+101 (middle), and a weighted average of both objects (right) in the regions of N V, O VI, Lyα, and Lyβ (Norris *et al.*, 1982). The abscissa represents the distance from the folded line center. The composite spectra were produced by adding, in the rest frame, the spectra of 27 absorption redshift systems identified in the spectrum of 0805+046 by Chen *et al.* (1982) and 38 systems identified by Peterson *et al.* (1986) in the spectrum of 1442+101. Each redshift system consisted of a Lyα and Lyβ pair with the Lyα rest frame equivalent width greater than 1.0 Å. No evidence was found for N V. Theoretical profiles are fitted to the O VI, Lyα and Lyβ absorption lines.

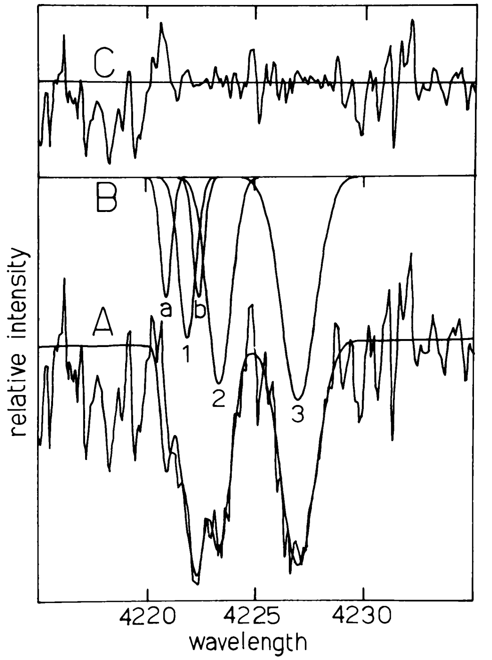

Figure 5. A portion of the spectrum of 0014+81 obtained by Chaffee *et al.* (1986). Panel A – The observed spectrum and computed spectrum. Panel B – The five Gaussian components of the computed spectrum. Components a and b are the C III lines predicted from a photoionization model assuming log N(H I) = 16.5 and [Z/H] = —2.7. Components 1, 2, and 3 are Lyα absorption lines. Panel C – Residuals for the observed and computed spectra.

Figure 4 shows portions of the resulting composite spectrum for the absorp-

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tion lines of N v, O vi, Lyα, and Lyβ that Norris, Hartwick, and Peterson (1983) obtained by summing the spectra of 27 Lyα clouds in front of 0805+046 and 38 in front of 1442+101. They detected O vi with 96 percent confidence (2.1σ) and found that the line profiles of the Lyα, Lyβ, and O vi lines were well represented by calculated profiles with a doppler parameter of $b = 30$ km s^{-1}, and column densities of of log N(H i) = 14.9, and log N(O vi) = 13.8. Limits on the column densities of C iv and N v were given as log N(C iv) ≤ 13.2, and log N(N v) ≤ 13.5. They concluded that their results were consistent with Lyα clouds, with Population II rather than primeval abundances, that were photoionized by the QSO background flux.

However, subsequent applications of this method have been unsuccessful in detecting heavy element absorption lines. Sargent and Boksenberg (1983) report finding no evidence for O vi, in an analysis of the spectrum of 1623+269, and Norris and Peterson (1986) failed to detect O vi in the Lyα clouds in front of 2000-330.

Using the second approach, Chaffee *et al.* (1985) examined a double Lyα absorption system in the QSO 0014+81 which had H i column densities of $N_a = 5 \times 10^{16}$ and $N_b = 2 \times 10^{16}$ cm^{-2}. They marginally (2.8σ) detected two features which could be Si iii (λ1206), and obtained an upper limit (5σ) for O vi of log N(O vi) ≤ 13.8. From their photoionization model they inferred that the heavy element to hydrogen ratio was $10^{-2.7}$ of the solar value.

However, in a following paper, Chaffee *et al.* (1986) discuss their ionization model, which predicts that if Si iii is detectable, C iii will be even stronger and must also be detectable (see Figure 3), and, on the basis of further observations, they conclude that the 3σ upper limit for C iii is log N(C iii) ≤ 12.9, five times less than predicted by their model from the strength of previously found Si iii lines.

In Figure 5A, I have re-plotted the spectrum obtained by Chaffee *et al.* (1986), and fitted the spectrum with the two predicted C iii lines (a and b) and with three arbitrary Lyα lines (1, 2, and 3). The individual fitted components are shown in Figure 5B, and the residual from the fit is shown in Figure 5C. It is the large positive residual at 4220.5Å that argues against the presence of line–a of C iii, and thereby invalidates the previous Si iii identification. Although a positive residual of similar amplitude also occurs at 4232Å, I estimate that there is only a 2 percent chance that line–a of C iii would be filled in by noise greater than or equal to the observed residual.

Sargent and Boksenberg (1983) report that in an analysis of a Lyα absorption system in the QSO 2126 − 158 which had an H i column density of $N = 2 \times 10^{17}$ cm^{-2}, possible O vi lines were found, setting an upper limit of log N(O vi) ≤ 14.4, and log N(O vi/H i) ≤ -2.9, which is less than log N(O vi/H i) $= -1.1$ found by Norris *et al.* (1983) for clouds with H i column densities of $N = 8 \times 10^{14}$ cm^{-2}.

Thus, the original reports of heavy elements in the Lyα clouds have not been satisfactorily confirmed by subsequent observations. On the other hand, the observations are not sufficient to exclude the presence of the lowest heavy element abundances found in the galaxy.

4. CONTINUITY OF LYMAN–α AND HEAVY ELEMENT SYSTEMS

Recent investigations indicate that there is continuity or overlap between the properties associated with Lyα clouds on the one hand and with heavy element systems on the other.

Tytler (1985) states that the H I column density distribution is a single power law from the weakest Lyα line up to the strongest heavy element system. Webb, Carswell and Irwin (1985) find that the Lyα absorbing clouds show velocity clustering on scales up to 150 km s^{-1}, which is similar to that for the heavy element systems. Bergeron and Boissé (1984) indicate that number of heavy element systems identified by C IV absorption lines increases with redshift as do the Lyα systems, and that the equivalent width distribution of the Lyα lines may overlap with the equivalent widths of Lyα systems inferred from the C IV lines.

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DISCUSSION

Segal : I am not at all clear what you mean by the chronometric prediction, - which I do not see how to make in any model-independent way for the complex systems you are studying. Aren't you making model-dependent assumptions without explicitly stating them - the origin of the absorbing clouds and the parametrization of the effect, in particular.

Peterson : The chronometric prediction that I have shown is that given by you, for the z dependence of non-evolving absorbing clouds that are uniformly distributed in 3-space.

Mallik : Is there any evidence for molecular Hydrogen absorption in these clouds ?

Peterson : There is no compelling evidence for molecular Hydrogen. It is more likely that the HI clouds are highly ionized.

Burbidge : Are there still many unidentified lines in these objects ?

Peterson : In the case of 0528-250, all of the lines are identified that lie on the long wavelength side of Lyα absorption line of the high redshift metal line system. On the short wavelength side of this Lyα line, the number of lines increases dramatically, and these are interpreted as Lyα lines produced by intergalactic Hydrogen clouds. There are also a few metal lines that can be identified in this wavelength region. Note that the emission redshift is very close to the redshift of the high redshift metal line system.

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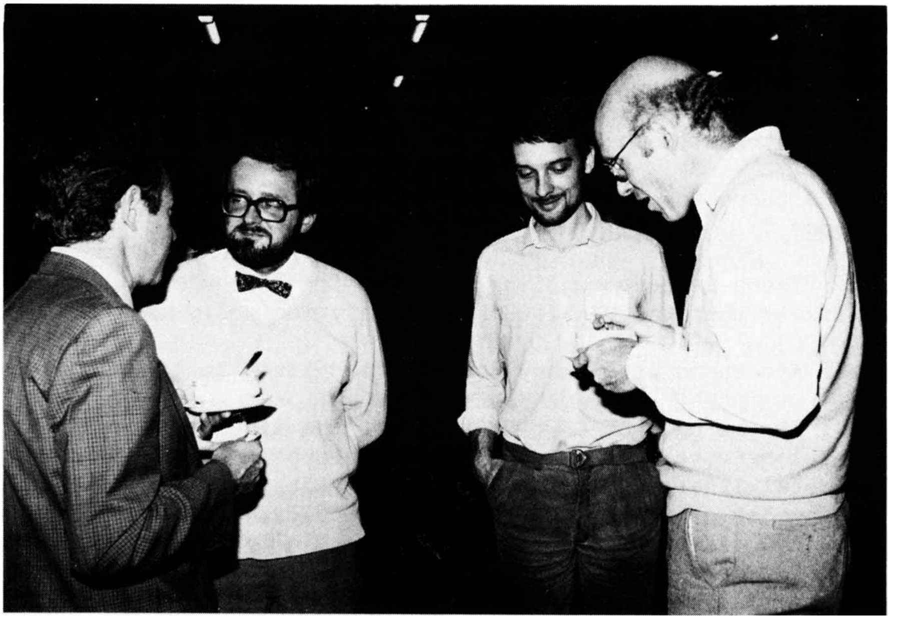

Claude Canizares (?), Bruce Peterson, John Peacock and Peter Shaver