QSO ABSORPTION LINES

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ABSTRACT

The evidence for the evolution of the intergalactic clouds that produce the Lyman-alpha absorption lines in the spectra of QSOs is reviewed. The recent detection of OVI in clouds that produce both Lyman-alpha and Lyman-beta absorption lines is discussed. The identification of molecular hydrogen in the spectrum of 1442+101 (OQ172) is not confirmed by high resolution spectra.

1. INTRODUCTION

The absorption lines seen in the spectra of QSOs are produced by gas clouds along the line of sight to the QSO. There are three major sites for these absorbing clouds: 1) near the QSO, 2) the interstellar medium of intervening galaxies, and 3) intergalactic space. The absorbing material associated with the QSO forms large absorption troughs on the short wavelength side of the emission lines. These absorption troughs are deepest nearest the emission line, and decrease in optical depth at shorter wavelengths (which correspond to the larger ejected velocities). In many cases, the smooth absorption troughs break up into discrete absorption line systems (Clowes et al. 1979, Wright et al. 1979, Turnshek et al. 1980). The absorption line systems produced by the interstellar medium in intervening galaxies are similar to the absorbtion line systems seen in satellite ultraviolet spectra of stars in our own galaxy. The column densities measured relative to HI and compared to solar show that OI, NI, SiII, SII, and FeII are down by a factor of 10, typical of HI clouds in the halo of our own galaxy (Morton et al. 1980, Savage et al. 1981). The intergalactic clouds produce narrow absorption lines that are due to Lyman-alpha. Recent work on the absorption lines produced in the intergalactic clouds is described in the next two sections.

For a comprehensive review of QSO absorption lines, see Weymann, Carswell and Smith (1981) and references therein.

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2. THE EVOLUTION OF THE LYMAN-ALPHA CLOUDS

Consider the distribution of the Lyman-alpha absorption lines that would be produced by intergalactic clouds with invariant cross-sections, and with a uniform space distribution. The number of clouds in a unit redshift interval is given as a function of redshift by Equation 1.

$$dN/dz = \frac{c}{H_o} \sigma \rho_o \frac{(1 + z)}{(1 + 2q_o z)^{\frac{1}{2}}} \qquad (1)$$

Here sigma is the cloud cross-section, rho is the number of clouds per unit volume at the present epoch, H and q are the Hubble constant and the deceleration parameter at the present epoch, c is the speed of light, and z is the redshift (lambda, the cosmological constant, is taken to be zero.)

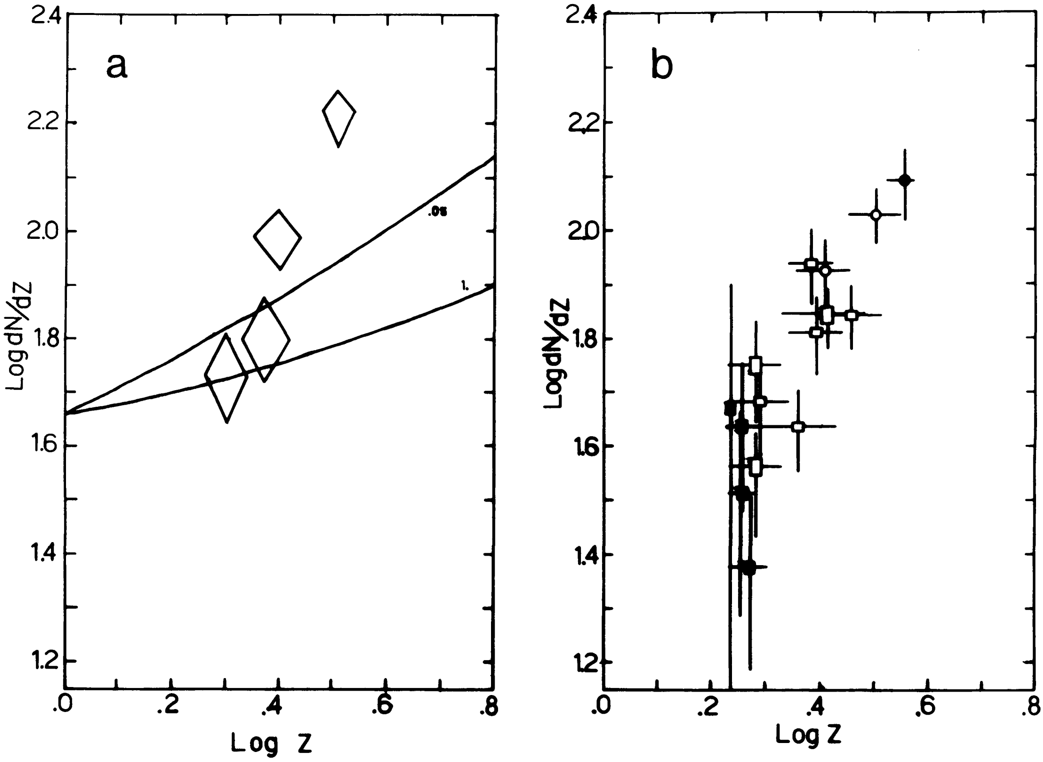

Figure 1. Line density (the number of absorption lines in a unit redshift interval) vs. redshift on log-log scales. The horizontal extent of the symbols indicates the redshift interval. The vertical extent of the symbols indicates the r.m.s. error ($N \pm N^{\frac{1}{2}}$) where N is the number of observed lines in the interval. Panel a shows the first evidence for the evolution of the intergalactic clouds (Peterson 1978). The diamonds are from counts of absorption lines in the four QSO's 1442+101, 0805+046, 0329-255, 1448-232. The curved lines represent the expected relation between line density (given by Equation 1) and redshift for non-elvolving clouds and $q_o = 0.05$ and $q_o = 1.0$ Panel b shows the current evidence. The line counts include unidentified lines with rest frame equivalent widths greater than 0.32. The data are from (●) 2000-330 Peterson (1982); (○) 1442+101, 0805+046 Peterson, Chen, Morton, Wright, Jauncey (1982), Chen, Morton, Peterson, Wright, Jauncey (1982); (□) 0453-423, 2126-158, 0002-422, 1225+317, 0100+130 Sargent, Young, Boksenberg, Tytler (1980); (▯) 0420-388, 0122-380, 1104-264 Smith (1978), Carswell, Whelan, Smith, Boksenberg, Tytler (1982); (▮) 1115+080, 0119-046, 0002+051 Young, Sargent, Boksenberg (1982). The data on which the counts for 2000-330 were made were supplied by Hunstead, Murdoch, Blades, and Pettini.

The first evidence for evolution of the intergalactic clouds came from counts of absorption lines in the spectra of four QSOs at various redshifts (Peterson 1978). These counts are shown in Fig. 1a along with two lines which represent the relation between the number of clouds in a redshift interval and the redshift of the interval for $q = 1.0$ and for $q = 0.05$ as given by Equation 1 for non-evolving clouds. On the basis of the data in Fig. 1a., Peterson suggested that the rapid increase in the number of absorption lines with redshift could be understood in terms of a progressive ionization of the intergalactic medium that started with the turn on of QSOs at z of about 4, or in terms of a change in cloud cross-section produced by collapse, perhaps to form galaxies. These conclusions and the significance of this newly discovered effect were disputed by Sargent et al. (1980) who studied five QSOs at various redshifts. They state

> "We have found that the overall Lyman-alpha absorption line density is statistically the same in all five QSOs. This is in sharp contrast to Petersons (1978) conclusion that in four QSOs the line density increases systematically by a factor of 3 with redshift over the range Z(em)=2.21 to Z(em)=3.53."

However, inspection of the data given by Sargent et al. in their Table 9 reveals that their data is in better agreement with the rapidly increasing line density discovered by Peterson. Using their Table 9 data only, a least squares fit gives

$$dN/dz = K(1 + z)^{\gamma}, \quad \gamma = 1.6 \pm 1.3.$$

The current status regarding the significance of the evidence for evolution of the intergalactic clouds is shown in Fig. 1b. Using all the data shown in Fig. 1b, gamma = 2.2 with an RMS error of 0.4. The data are given for the number of lines with rest frame equivalent widths greater than 0.32, and are taken from the work of several groups, as indicated. With this data, the relation between the number of lines per unit redshift interval and redshift as given by Equation 1 for non-evolving clouds is excluded at the 3.5 sigma level for the most favorable case of $q = 0.05$. Larger values of q are excluded with greater significance.

Thus the current evidence supports Petersons original conclusion that the increase in the numbers of lines seen in the spectra of high redshift QSOs is more rapid than allowed by the cloud model with no evolution of the cloud properties. It may be that the clouds evaporate or increase their ionization as the Universe expands, or that the clouds are self-gravitating and collapse after a time.

3. ABUNDANCES IN THE LYMAN-ALPHA/BETA CLOUDS

For most of the intergalactic Lyman-alpha clouds, the column density is too low for any other lines to be seen. In some cases, the

Lyman-alpha column density approaches logN(HI) = 15, and the Lyman-beta line can be identified, but at this neutral hydrogen column density, no lines of heavier ions are strong enough to be observed in a single redshift system. In order to increase the detecability of other lines, Norris et al. (1982) added the rest frame spectra of 65 clouds that produced both Lyman-alpha and Lyman-beta lines in the spectra of the two QSOs 0805+046 (Chen et al. 1982) and 1442+101 (Peterson et al. 1982). Norris et al. were able to detect OVI and measure a column density of logN(OVI) = 13.8 in the Lyman-alpha/beta clouds with logN(HI) = 14.9. Upper limits of 13.2 for logN(CIV) and 13.5 for logN(NV) were obtained. Fig.2 shows the composite rest frame spectra of each QSO, and for both QSOs added together. In Fig. 2, the two components in the NV doublet and in the OVI doublet have been added together. The curves in the panel on the right in Fig. 2 are calculated line profiles for logN(HI) = 14.9 and for logN(OVI) = 13.5 and 14.0 with b = 30 km/s and a Gaussian instrumental profile of 0.5 A FWHM.

No detection of NV was claimed. The significance of the OVI detection was tested by generating sets of random redshifts and requiring that the equivalent widths of both components of the OVI doublet in the composite spectrum obtained from the random redshift sets be greater than or equal to that observed. This occurred 2.7% of the time for 0805+046, 0.6% of the time for 1442+101, and 0.4% of the time for both QSOs added together.

The oxygen to hydrogen abundance ratio was calculated by assuming that the clouds were ionized by the integrated QSO background flux. With a cloud temperature of 40000K and a volume density of log n(H) = -3 to -4, the following (log) abundances (relative to solar) were obtained: O/H = -1.8 to -1.9, C/H less than -1.1, N/H less than -0.8. For a wide range of cloud model parameters, no values for an abundance less than values found in halo objects in our galaxy are deduced.

The abundance of the clouds is similar to the heavy element enrichment found in isolated extragalactic HII regions and in Population II material in our galaxy. Thus the clouds are not primeval, and it may be necessary to consider a pre-galactic enrichment process (e.g. see Peebles and Dicke 1968).

4. MOLECULAR HYDROGEN ABSORPTION IN QSO SPECTRA?

Molecular hydrogen absorption lines are produced in the ultraviolet spectra of galactic stars by the interstellar medium in our galaxy (Morton 1975, Morton and Dinerstein 1976). Molecular hydrogen absorption lines have been identified in the spectra of various QSOs (Carlson 1974, Aaronson et al. 1974, Varshalovich and Levshakov 1982 and references therein). In the particular case of 1442+101, Levshakov and Varshalovich (1979) have identified molecular hydrogen with two redshift systems at z = 2.651 and 3.092 using a spectrum obtained by Baldwin et al. (1974). Peterson et al. (1982) have obtained a spectrum of 1442+101 at higher resolution, and it has been examined for

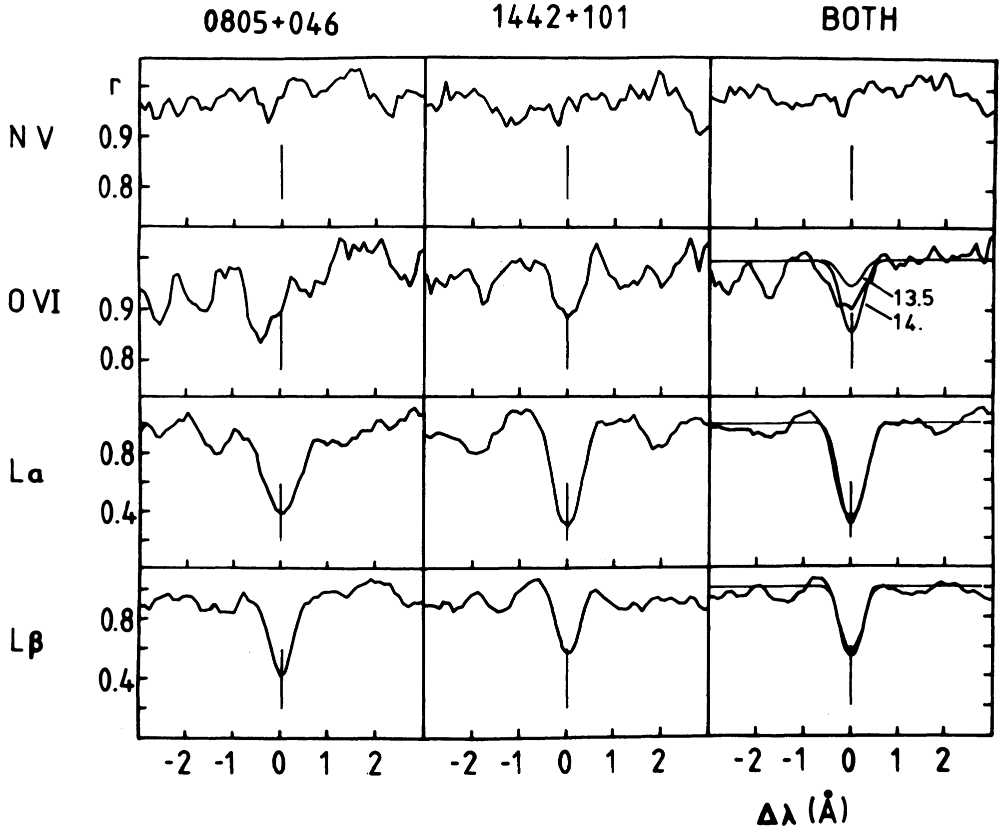

Figure 2. Composite spectra of the QSO's 0805+046 and 1442+101 in the regions of NV OVI Lα and Lβ (Norris et al. 1982). The abcissa represents the distance from the line center. The composite spectra were produced by adding (in the rest frame) the spectra of 27 absorption redshift systems identified in the spectrum of 0805+046 by Chen et al. (1982) and 38 systems identified by Peterson et al. (1982) in the spectrum of 1442+101 with Lα/Lβ pairs that have rest frame equivalent widths greater than 1.0 A.

redshift systems containing the strongest interstellar lines seen in the spectra of zeta-Oph (Morton 1975) and zeta-Pup (Morton 1978) (plus CIV, NV, OVI, and SiIV) and for redshift systems containing the lines of molecular hydrogen at various temperatures. Fig. 3 shows the result of cross-correlating the ion lines (upper panel) and the molecular hydrogen lines (lower panel) with the high resolution spectrum of 1442+101. The two redshift systems identified by Peterson et al. at z = 2.0701 and 2.5631 are seen in the ion line cross-correlation. There is no significant ion line cross-correlation amplitude for the two redshift systems of Levshakov and Varshalovich, and no significant molecular hydrogen cross-correlation amplitude at their redshifts or at any other redshift for molecular hydrogen in the temperature range 3K to 2000K. A detailed comparison of the QSO spectrum with the spectrum of molecular hydrogen at the redshifts of Levshakov and Varshalovich shows that at least one of the three strongest lines is missing.

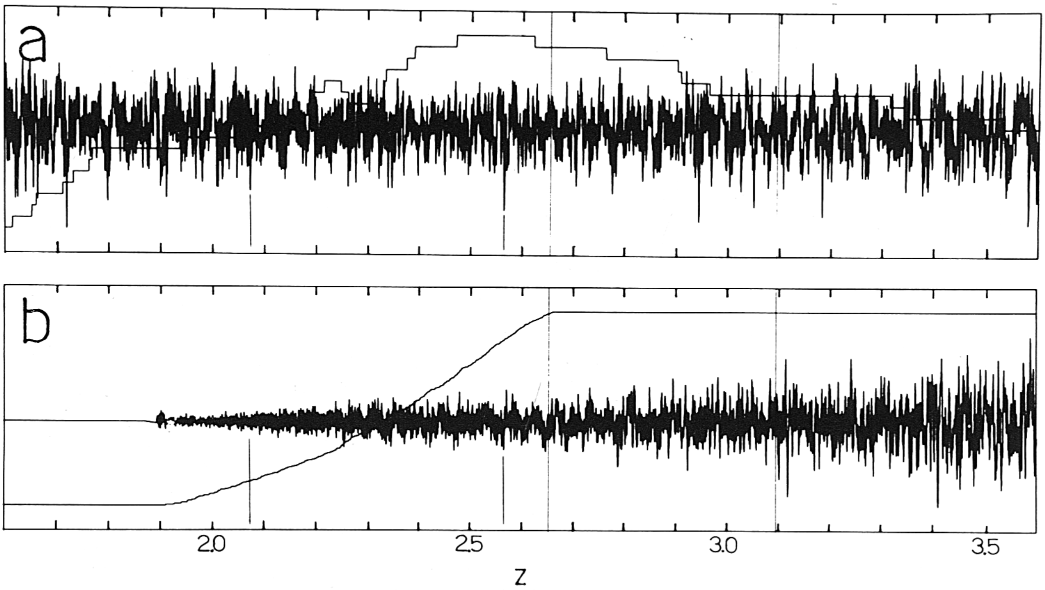

Figure 3. Cross-correlation amplitude per line (together with the number of lines used in the cross-correlation) vs. redshift. The locally averaged cross-correlation amplitude has been subtracted. Panel a shows the cross-correlation of atomic ions [C IV N V O VI Si IV plus the ions with the largest column densities through the interstellar medium of our galaxy in the direction of ζOph (Morton 1975) and ζPup (Morton 1978) all given equal weights] with the spectrum of 1442+101 obtained by Peterson et al. (1982). Panel b shows the cross-correlation of the lines of H_2 [weighted according to their absorption strengths at 1000° as calculated from the molecular data given by Morton & Dinerstein (1976)] with the spectrum of 1442+101 obtained by Peterson et al. (1982). The atomic ion absorption line systems at $z = 2.0701$ and $z = 2.5631$ found by Peterson et al. (1982) and the redshifts of the H_2 and atomic ion absorption line systems at $z = 2.651$ and $z = 3.092$ identified by Levshakov & Varshalovich (1979) in the spectrum of 1442+101 obtained by Baldwin et al. (1974) are marked in both panels.

Thus with increased resolution, there is no significant evidence for molecular hydrogen in the spectrum of 1442+101.

5. SUMMARY

The intergalactic clouds which produce Lyman-alpha absorption lines in QSO spectra evolve as the Universe expands, in the sense that there were more absorption lines produced at earlier epochs. The clouds may become more ionized and evaporate with time, or they may be gravitationally bound and collapsing.

These clouds are not primeval, but have undergone enrichment similar to Population II objects in the galaxy.

The identification of molecular hydrogen absorption lines in the spectrum of 1442+101 is not confirmed by high resolution spectra.

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Discussion

Boksenberg: I have two comments: 1) I do not accept that the statement concerning evolution of the hydrogen clouds made by Sargent, Young, Boksenberg and Tyler is controversial as you have stated. Our full study showed that a non-evolving population was consistent within the carefully derived errors of our result. In this, we accounted for the equivalent width spectrum including blending effects and imposed a cutoff in the rest frame equivalent in deriving the number density as a function of redshift for all six objects. You did not do this for your data in your earlier note. Subsequently, with more data on a broader redshift baseline, Young, Sargent and Boksenberg did show positive evolution in the number density of the Lyman α clouds, with a hint of a break in number density at redshift near 2. More data we now have seem to confirm this, but they have not yet been fully processed.

2) The systems of large column density in H I you have picked to look for the "Lyman α" systems and heavy element systems merge: the heavy element systems more commonly have high column density, while the "Lyman α" systems more commonly have low.

Peterson: I disagree with your suggestion that I should not have seen in 1978 what you have only just seen in 1982.

M. Burbidge: There is an alternative hypothesis for the origin of the narrow Lα absorptions; that is, they really belong to the QSOs and do not arise in unconnected intergalactic clouds. Pointers in this direction are that the numbers and strengths of Lα absorptions in the same wavelength band (say 3300 - 3600 Å) appear to depend on the emission-line redshifts and luminosities of the objects. In looking at that wavelength band in QSOs with z_{em} between 1.9 and about 3, one should be sampling the same redshift range of intergalactic gas and the Lα should be randomly distributed, independent of z_{em} or luminosity of the QSO. However, one finds QSOs at the low end of the 1.9 - 3 range of z_{em} which have really few and relatively weak Lα narrow absorptions.

Peterson: If one considers the same wavelength region in the observer's frame, then as the redshift of the QSO increases, the absorption lines seen in this observing window first consist of Ly-alpha, then Ly-beta and Ly-alpha, then Ly-gamma, Ly-beta, and Ly-alpha, so that as the redshift of the QSO increases, absorption lines higher in the Lyman series, which are produced by the more distant absorbing clouds, are seen along with the Ly-alpha absorption lines produced by the nearby clouds. This produces the correlation between the number of absorption lines in a fixed wavelength interval in the observer's frame and the QSO redshift.

If one considers the same wavelength region in the emitter's frame, say the region between the Ly-alpha and the Ly-beta emission lines as I have done here, then there should be no change in the number of absorption lines as a function of the QSO redshift if the absorption lines are associated with the QSO. The observed increase, in the number of absorption lines in this interval as a function of the QSO redshift, is evidence that the absorption lines are not associated with the QSO but with intergalactic clouds.

Boksenberg: 1) I have observed two QSOs of similar redshifts, but one having more than ten times the luminosity of the other and I have found no difference in H I line density.

2) If the H I absorption redshifts are interpreted in terms of velocities of ejection from the QSOs: a) the number of densities of clouds is uniformly distributed in "ejection velocity"; b) the number density is statistically the same in all objects measured in a consistent way; c) there is no correlation between line strength and "ejection velocity."

3) I believe it inherently unlikely that an ejection theory can be constructed to account for these observations, but no difficulty arises when we interpret the systems as being cosmologically distributed intervening material not associated with the QSOs.

Wolfe: I question your estimate of the oxygen abundance for two reasons: First, in order to know the total column density of hydrogen, you have to know the fractional ionization which is likely to be quite high. The latter depends on the cloud density and the mean intensity of ionizing radiation, both of which are uncertain by many orders of magnitude. Second the O VI column density you quote should be treated as a lower limit. The reason is that the absorption profile is likely to break up into narrow components which would be undetectable at the resolution you used. These narrow components may contain most of the oxygen, yet they would contribute little to the equivalent widths. So I believe that the O/H ratio which you quoted has little meaning.

Peterson: Of course, the oxygen-to-hydrogen abundance ratio is model dependent, but it varies within a range restricted by limits that can be placed upon the model parameters. The table below illustrates the sensitivity of the abundance ratio to the cloud density, the spectral index of the ionizing continuum, and the intensity of the ionizing continuum.

Sensitivity of [O/H] to the Ionizing QSO Background Flux

$$I_\nu = 10^{-21} I_{\nu-21}(\nu/\nu_0)^{-\alpha}$$

		α	0	1	2
		T	60000	40000	30000
$I_{\nu-21}$	log n			[O/H]	
0.1	-3.6 to -4.6		-1.2 to -0.9	-1.4 to -1.9	-0.2 to -2.2
1	-3.0 to -4.0		-1.0 to -0.9	-1.8 to -1.9	-1.4 to -2.7
10	-2.4 to -3.4		-0.9	-1.9	-2.2 to -2.9

The cold, high density clouds associated with 21-cm and Mg II absorption line systems have low velocity dispersions which result in narrow, saturated absorption lines that cannot be resolved optically. I agree that abundance determinations for these clouds suffer from the problems that you mention. However, the O VI clouds discussed here are hot clouds that have thermal velocity dispersions which correspond to our observed line profiles. Therefore, our O VI column density measurement does not suffer from the saturation and blending effects that you mention and is more reliable than you believe.