UPPER LIMITS ON METALS IN QUASAR LYMAN-ALPHA FOREST CLOUDS: ABSENCE OF C IV LINES IN ECHELLE SPECTRA

DAVID TYTLER\textsuperscript{2, 3} and XIAO-MING FAN\textsuperscript{3, 4}

To Appear in the Astrophysical Journal Letters

Received: December 13, 1993
Accepted: January 13, 1994

\textsuperscript{1} Based on observations obtained at Lick Observatory, University of California.
\textsuperscript{2} Department of Physics, University of California, San Diego
\textsuperscript{3} Center for Astrophysics and Space Sciences, 0111, University of California, San Diego, La Jolla, CA 92093–0111. (tytler@cass155.ucsd.edu, fan@cass154.ucsd.edu)
\textsuperscript{4} Dept. of Astronomy, Columbia University, New York.
Recently Lu presented tentative evidence for C IV lines in QSO Lyα forest systems with strong lines. We have performed a similar search for C IV in our 10 km s$^{-1}$ echelle spectra of the bright QSO HS 1946+7658. We shifted the spectra to align the expected positions of the C IV lines in 65 Lyα systems, then added them. The resulting composite spectrum, equivalent to 390 hours of exposure time on the Lick 3-m telescope, has a signal-to-noise ratio of 80 per 0.025 Å in the rest frame of the absorbers. We do not see any C IV lines down to a 2σ limit of $W(1548) \leq 1.4$ mA, about one-fifth of the strength of the lines seen by Lu. The C IV lines which Lu saw must be restricted to rare Lyα systems with large H I column densities $\geq 10^{14}$ cm$^{-2}$, which are too rare to show C IV in our sample. More common Lyα systems with H I column densities $10^{13} - 10^{14}$ cm$^{-2}$ do not show C IV lines. If their ionization is H/H I $= 10^4$ then they have $[C/H] \leq -2.0$.

Subject Headings: galaxies: abundances – intergalactic medium – quasars: absorption lines
1. INTRODUCTION

Quasar Lyman-alpha (Lyα) forest absorption systems do not show metal lines in spectra with 1 Å resolution (e.g., Sargent et al. 1980; SYBT), but there has been much discussion of the possibility that they do contain metals (e.g., Tytler 1987; Verner, Tytler & Barthel 1994). Our recent discovery (Lanzetta et al. 1994) that at least 35 ± 10%, and likely 0.65 ± 0.18% of Lyα clouds at $z_{\text{abs}} \leq 1$ arise from the outer regions of luminous galaxies confirms our earlier proposition that Lyα forest systems are related to metal-line systems (the “one population” concept discussed by Tytler 1987), and makes us expect to find metals in at least some of these low-redshift systems.

We need three pieces of information to derive an observational limit on metal abundances: (1) a limit on the strength of the metal absorption lines, (2) a measurement of the $\text{H I}$ column density $N(\text{H I})$, and (3) an estimate of the level of ionization, which is used to calculate the abundance of the elements from the observed ions.

In this paper, we give improved upper limits on the strength of C IV lines in Lyα systems. There are two ways to obtain such limits: one is to observe the systems with the highest $N(\text{H I})$; the second is to form an average spectrum at the expected positions of the metal lines observed in many Lyα systems.

The first method relies on the fact that metals should be easier to detect in systems with the largest total column densities. Sargent & Boksenberg (1983) and Chaffee et al. (1985, 1986) found limits of $[\text{M/H}] \leq -3.5$ for two Lyα clouds with large $\text{H I}$ column densities of $10^{16} \leq N(\text{H I}) \leq 10^{17}$ cm$^{-2}$. There are two problems with this method: first, these Lyα clouds are very rare because their $N(\text{H I})$ is 300 times larger than those normally observed; second, we do not know if they actually have the largest total column densities because we do not know their ionizations.

We use the second method to look for metals in common Lyα clouds which have low $N(\text{H I})$. We shift spectra to align the expected positions of the metal lines, then we sum them to increase the SNR (signal-to-noise ratio). To shift a spectrum to the frame of a Lyα cloud at redshift $z_i$ we divide the observed wavelengths by $(1 + z_i)$, and we do this for each Lyα cloud which could have a metal line in the spectrum. This shift and sum technique was introduced by Norris, Hartwick & Peterson (1983), and was used by Lu (1991), who claimed a tentative detection of C IV at the 99.99% significance level. Here we use the same method on better data. Our echelle spectra yield more sensitive limits because: (1) the expected positions of the metal lines are more accurately located because we have higher resolution and more accurate wavelengths, (2) the continuum level is better determined, (3) we get more reliable identifications of weak lines in the C IV region, and (4) we know the $N(\text{H I})$ for each Lyα system in our sample. Echelle spectra do not always give better sensitivity, because this also depends on the SNR per Angstrom, the number of Lyα lines, and their $N(\text{H I})$ and ionization.
We consider only C IV because its doublet lines at 1548.20 and 1550.77 Å are likely to be the strongest metal lines at rest frame wavelengths greater than 1200 Å, where we have good data.

2. LIMITS ON THE STRENGTH OF C IV IN TYPICAL LYMAN-α SYSTEMS

We use spectra of only one QSO, HS1946+7658 (Hagen et al. 1992), which is the most luminous known QSO with $V = 15.85$ and $z_{em} = 3.051$. In August 1992 and June 1993, we obtained spectra with the Hamilton echelle spectrograph on the Lick 3-m telescope. These spectra have 10 km s$^{-1}$ resolution and cover 4220 – 7251 Å with inter-order gaps of 3.6 Å at the blue end and 42.6 Å at the red end. The SNR is one (per 0.1 Å pixel in the observed frame) at the blue end, 16 in the Ly$\alpha$ emission line, and 7 at the red end, but we also have complete wavelength coverage with intermediate resolution spectra in optical with high SNR, so our line identifications are unusually complete and accurate. Fan & Tytler (1994) discuss the properties of the Ly$\alpha$ forest clouds and the abundances of the metals in the damped Ly$\alpha$ system in this spectrum.

We rebinned all the spectra into new pixels with rest frame width $\Delta \lambda = 0.025$ Å, which is 4.8 km s$^{-1}$ at 1548 Å, close to the original mean pixel width of 0.026 Å. Fan & Tytler (1994) have already normalized the continuum of this spectrum, and for this project we replace all absorption lines that they listed in the C IV region with noisy continuum with the same SNR as the adjacent continuum.

For the shift and sum method, we need high SNR for both the Ly$\alpha$ and the C IV lines, so we consider systems with $z_{abs} = 2.471 – 3.051$ that have Ly$\alpha$ lines at 4220 – 4925 Å and C IV lines at 5374 – 6282 Å and where the spectra have SNR=10–14 per 0.10 Å pixel (observed frame) from 6 hours of exposure time. We shift the spectra of 65 Ly$\alpha$ systems to align the expected positions of the C IV lines, then we add the spectra. Because of the inter-order gaps, the number of spectral segments included in the composite depends on the wavelength. We have a maximum of 65 at C IV $\lambda$1548, 58 at C IV $\lambda$1550, 38 at the blue end, and 27 at the red end of the spectrum which we show in Figure 1. The resulting composite spectrum has an effective exposure time of 390 hours on the 3-meter telescope.

Figure 1 shows two composite spectra. The first, in panel (a), is an unweighted average with SNR=80 per 4.8 km s$^{-1}$. The second, in panel (b), is weighted by $N$(H I) with SNR=50. The C IV lines should extend over at least five pixels because the original spectra had a FWHM of two pixels. Panels (c) and (d) in Figure 1 show the rest frame equivalent width for lines that are five pixels wide. There are no significant C IV absorption lines. The rest frame equivalent width for the 1548 line, which should be twice as strong as the 1550 line, is $W_r = 1.4$ mÅ in the unweighted and 2.6 mÅ in the weighted composites. When we use log $N$(H I) as an alternative weight, the result is nearly identical to the unweighted composite in panel (a) because all Ly$\alpha$ lines have very similar log $N$(H I).
The C IV lines could be stronger than the $W_r$ values shown in panels (c) and (d) because noise can reduce as well as increase $W_r$. The statistical limits on $W_r$ depend on the SNR per pixel and the number of pixels which the lines are expected to cover ($M_L$). The $U\sigma$ limit is

$$W_{r,max} = \frac{U(M_c^2/M_c + M_L)^{0.5}}{(SNR^2 + U^2)^{0.5}}\Delta \lambda \ (\text{Å}),$$  

(1)

where $M_c$ is the number of pixels used to determine the continuum level. When the continuum is well-determined so that $M_c \gg M_L$ and the lines are weak so that $SNR \gg U$, this reduces to

$$W_{r,max} \simeq \frac{UM_c^{0.5}}{SNR} \Delta \lambda \ (\text{Å}),$$  

(2)

which is appropriate for our data. We use $U = 2$ because we know where to expect the lines, and $M_L = 5$, which gives $2\sigma$ limits of 1.4 mÅ for the unweighted and 2.2 mÅ for the weighted composites. There are small dips at the positions of the 1548 Å lines in both composites, but neither exceeds the $2\sigma$ level. The actual limits may be slightly higher because we have ignored the small increase in SNR which accompanies the smoothing which happens when data are rebinned, but this should be minimal because we kept a roughly constant pixel size (we did not oversample).

3. WHY DO OUR RESULTS DIFFER FROM LU’S?

Why did Lu (1991) see C IV 1548 lines that are five times stronger than our $2\sigma$ upper limit? He measured $W_r$ values of 2.4, 7.1, 7.2, 9.2, 11.1, 6.1, 9.5 and 14.1 mÅ in his eight composite spectra, which were all subsamples for Ly$\alpha$ lines of increasing strengths, and he used thorough simulations to show that most of these lines are statistically significant. For example, the 1548 line with $W_r = 7.1$ mÅ in his sample with $W_r(1216) \geq 0.4$ Å is significant at the 99.99% level because no similar lines were seen in 10,000 simulations. We accept that his lines are real and conclude that he saw them because his sample includes strong Ly$\alpha$ lines, some of which have weak C IV lines. We do not see C IV lines because our sample does not have any strong Ly$\alpha$ lines and is comprised of common Ly$\alpha$ clouds that do not have C IV lines with $W_r \geq 1.4$ mÅ.

Lu’s sample is larger but shallower than ours. We have 65 Ly$\alpha$ lines from one QSO, but Lu used up to 324 lines from 14 QSOs. Our sample has mean $N$(H I)$=1.0 \times 10^{14}$ cm$^{-2}$ for 1548 and $0.95 \times 10^{14}$ cm$^{-2}$ for 1550, but his subsamples have means of at least $2 \times 10^{15}$ cm$^{-2}$, with large uncertainties. Our means are 25 times lower because we detect much weaker Ly$\alpha$ lines, and because we do not have enough coverage to see the rare systems with large $N$(H I). Redshift is not a factor because our mean $z_{abs} = 2.79$ is similar to his (2.4 – 2.6).
Lu’s sample is more likely to contain Lyα clouds with weak C IV because: (1) most systems with strong Lyα lines have C IV (Tytler 1987), (2) Meyer & York (1987) showed that some Lyα systems have C IV lines which are too weak to be seen in the individual spectra used by Lu (e.g. three of the four systems seen by Meyer & York in Q2126-158 were not identified by Sargent, Boksenberg & Steidel 1988), and (3) we have identified and removed C IV lines which are as weak as those seen by Meyer & York. Lu recognized that his 1548 line could have resulted from 10 – 20 out of 100 – 200 Lyα clouds with $W_r(1548) \approx 84$ mÅ each, but since his composite spectrum remained similar as he raised $W_r(1216)$ above 0.4 Å, he suggested that all Lyα lines with $W_r(1216) \geq 0.4$ Å have about the same $W_r(1548)$. This $W_r(1216) \geq 0.4$ Å corresponds to $N(H I) \geq 10^{14}$ cm$^{-2}$ for all $b \leq 70$ km s$^{-1}$, and only 15 of our 65 Lyα systems have such high $N(H I)$, so our result is compatible with his.

4. METAL ABUNDANCES OF THE Lyα CLOUDS

Our limit of $W_r \leq 1.4$ mÅ for a typical C IV 1548 line corresponds to

$$N(C IV) \leq 3.5 \times 10^{11} \frac{W_r}{1.4 \text{ mÅ}} \text{ (cm}^{-2})$$

(3)

because the line will be on the linear part of the curve of growth. The corresponding abundance limit depends on the unknown level of ionization. If we follow SYBT, Chaffee et al. (1986), and Lu (1991), and if we assume that the clouds are highly ionized with $H/H_I=10^4$ and $C/C IV=5$, then our typical Lyα clouds with $N(H I)=4 \times 10^{13}$ cm$^{-2}$ would have $C/H \leq 4.4 \times 10^{-6}$, which corresponds to $[C/H] \leq -2.0$ since solar $C/H = 4.7 \times 10^{-4}$. This cloud would be 16.7 kpc thick if it had constant density and it was ionized by the Bechtold et al (1987) ”medium” spectrum of ionizing radiation, normalized to a flux of $10^{-21}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ at 912 Å at $z_{abs}=2.7$. If all our Lyα clouds have similar ionization and C/H, we should use the mean $N(H I)$ instead of the typical value, which gives $[C/H] \leq -2.4$. We can then use the composite spectrum weighted by $N(H I)$, which gives $[C/H] \leq -2.2$.

Lu obtained lower abundances of $[C/H] \sim -3.2$ because his sample had clouds with larger $N(H I)$, which he assumed had larger total column densities. We do not know the ionization or total column density of any individual Lyα system in our sample, nor do we know if the total column densities are the highest at low, intermediate, or high $N(H I)$. We think that it is unlikely that the clouds all have the same gas density and ionization because this would imply too large a range in size (Sherwin 1984), so we do not expect a simple one-to-one correspondence between $N(H I)$ and total column density, but rather a large range of ionization at a given $N(H I)$. Then if some high $N(H I)$ systems have high ionizations, they will have the largest total column densities, and the absence of metals in their spectra
will give the best abundance limits of any individual system. But we do not believe that all systems with high $N$(H I) give the best individual abundance limits.

Although we have shown that common Ly$\alpha$ clouds do not have C IV lines of the strength seen by Lu, they could still have abundances similar to the $[C/H] \simeq -3.2$ which he found for clouds with high $N$(H I), and they could have abundances similar to those in the outer halo, which might be expected if Ly$\alpha$ clouds at high redshift are associated with galaxies, as are most at $z \leq 1$ (Lanzetta et al. 1994).

We will obtain much better abundance limits in the coming year for several reasons. HST spectra will distinguish high from low ionization, although they will not give a quantitative measure of the ionization. SYBT predicted that high-ionization Ly$\alpha$ clouds should have He II lines that are stronger than H I, but no detectable He I, whereas low-ionization gas could show both He I and He II (see Fig. 3 of Chaffee et al. 1986). Reimers & Vogel (1993) report that new HST spectra should have the sensitivity to detect He I in low-ionization clouds. However, two other expected new measurements will not give the ionization. HST spectra of He II $\lambda$304 will not give the ionization because He II has the same electronic structure as H I, so He II/H I remains constant over a wide range of ionization and is a measure of the ratio of the flux at the two ionization edges, not of the ionization. Also, the potential detection of H$\alpha$ emission from Ly$\alpha$ clouds will not give the ionization because the flux depends on the product of $N$(H I) and the flux of ionizing photons, not on the density or ionization (Hogan & Weymann 1987; Williams & Schommer 1994).

The first few spectra from the HIRES echelle on the Keck telescope show that we should get SNR=120 per 0.1 Å at 5000 – 7000 Å on a $V = 15.87$ QSO in six hours. This SNR is ten times better than that of the data used here – 100 times more photons – because Keck is ten times larger and because QSO spectra from the Hamilton echelle on the Lick 3-m are degraded by dark current and readout noise. Keck will be able to detect $[C/H]$ ten times lower than the limits of $-2.0$ to $-2.4$ which we obtained here.

We will also target Ly$\alpha$ clouds with larger $N$(H I) and look at more QSOs, and we will use HST and Keck to search for metal lines in the rest-frame far UV. Chaffee et al. (1986) showed that C III $\lambda$997 should be stronger than C IV in low-ionization systems, while O VI $\lambda\lambda$ 1031, 1037 should be stronger at high ionization. Verner, Tytler & Barthel (1994) point out that Ne VIII $\lambda\lambda$ 770, 780 and Mg X $\lambda\lambda$609, 625 will be strong in very highly ionized gas.

We thank Limin Lu for detailed comments, Art Wolfe for showing us how he uses the spectrum of equivalent widths, and Abe Oren for keeping the computers going. FXM and DT were supported in part by NASA grant NAGW-2119 and by GO-3801.01-91A and GO-5492 from the Space Telescope Science Institute, which is operated by AURA, Inc. under NASA contract NAS5-26555.
REFERENCES

Bechtold, J., Weymann, R. J., Zou, L., & Malkan, M. A. 1987, ApJ, 281, 76
Chaffee, Jr., F. H., Foltz, C. B., Bechtold, J., Weymann, R. J. 1986, ApJ, 301, 116
Chaffee, Jr., F. H., Foltz, C. B., Röser, H.-J., Weymann, R. J., Latham, D. W. 1985, ApJ, 292, 362
Fan, X.-M., & Tytler, D. 1994, submitted to ApJ.
Hagen, H.-J., Cordis, L., Engels, D., Groote, D., Haug, U., Heber, U., Köhler, Th., Wisotzki, L., & Reimers, D. 1992, A&A, 253, L5
Hogan, C. J., & Weymann, R. J. 1987, MNRAS, 225, 1p
Lanzetta, K. M., Bowen, D. V., Tytler, D. & Webb, J. K. 1994 submitted to ApJ.
Lu, L. 1991, ApJ, 379, 99
Meyer, D. M. & York, D.G. 1987, ApJ, 315, L5
Norris, J., Hartwick, F. D. A., & Peterson, B. A. 1983, ApJ, 273, 450
Reimers, & Vogel, S. 1993, AApL, 276, L13
Tytler, D. 1987, ApJ, 321, 49
Sherman, R. D. 1984, ApJ, 284, 457
Sargent, W. L. W., Young, P. J., Boksenberg, A., & Tytler, D. 1980, ApJS, 42, 41 (SYBT)
Sargent, W. L. W., & Boksenberg, A. 1983, in Quasars and Gravitational Lenses, 24th Liegè International Colloquium, p.518
Sargent, W. L. W., Boksenberg, A. & Steidel, C. C. 1988, ApJS, 68, 539
Verner, D. A., Tytler, D., & Barthel, P. 1994, submitted to ApJL
Williams, T. B. & Schommer, R. A. 1993, ApJL, 419, L53
FIGURE CAPTIONS

Fig. 1 Composite spectra at the expected positions of the C IV absorption lines in Lyα systems. The expected wavelengths of the C IV doublet lines are shown by the two vertical lines in each panel. The number of spectral segments included in the composite spectra depends on the wavelength: 65 at C IV $\lambda$1548, 58 at C IV $\lambda$1550, 38 at the blue end, and 27 at the red end. In the top panel (a) the spectra are unweighted and the SNR=80. In panel (b) the spectra are weighted by $N$(H I) and the SNR=50. The pixel size in these spectra is 0.025 Å in the rest frame, or 4.8 km s$^{-1}$. The individual spectra have FWHM of about two pixels, so the C IV lines should be at least five pixels wide in the composite spectra. The two lower panels show the rest frame equivalent width for lines which are five pixels wide. Panel (c) applies to spectrum (a) and panel (d) to spectrum (b). Absorption lines are negative excursions in the spectra that are defined to have positive equivalent widths.

Fig. 2 Histogram of the H I column densities of the 65 Lyα systems used in the composite spectrum. The bins are $10^{13}$ cm$^{-2}$ wide, the range is $0.85 \times 10^{13} - 0.95 \times 10^{15}$, and the mean is $1.0 \times 10^{14}$ cm$^{-2}$. 
