

THE METALLICITY AND INTERNAL STRUCTURE OF THE LYMAN-ALPHA FOREST CLOUDS

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ABSTRACT

Using very high S/N, high spectral resolution data obtained with the HIRES spectrograph on the Keck 10 m telescope, we show that roughly half of Lyman-alpha forest clouds with $N_{\text{H I}} \geq 3 \times 10^{14} \text{ cm}^{-2}$ have measurable C IV lines with $N_{\text{C IV}} > 10^{12} \text{ cm}^{-2}$. We find the ratio of the median column density of C IV to the median $N_{\text{H I}}$ to be 2×10^{-3} , roughly corresponding to a metallicity of 10^{-2} solar. This is shown to be comparable to that of a sample of Lyman-limit system clouds with $N_{\text{H I}} \sim 3 \times 10^{17} \text{ cm}^{-2}$ and to the mean value in lower column density samples. The kinematic structure of the C IV lines shows that the Ly α clouds are blended complexes of cloudlets individually having $T \approx 35,000$ – $70,000$ K and velocity dispersions of $\sim 18 \text{ km s}^{-1}$; these complexes require a gravitational confinement mechanism.

1. INTRODUCTION

The rich spectrum of Lyman-alpha absorption lines in quasars (generally known as the Lyman forest) was first noted by Lynds (1971) and studied in detail by Sargent *et al.* (1980). Because of its ubiquity and spatial correlation properties, it is usual to assume that the forest is a distributed intergalactic population rather than being associated with large galaxies. Given this, it becomes extremely interesting to determine whether the forest is chemically primordial or has some weak metallicity.

Experimentally determining the metallicity of weak members of the Lyman-alpha forest has been a very difficult problem until now because of the limited sensitivity of spectroscopic observations. Some clouds have been found to have associated metal lines (Meyer & York 1987), but this has left open the question of whether the cloud population is bimodal, with a small population of weak metal line clouds contaminating a much larger population of primordial forest clouds. Stacking of metal absorption line spectra corresponding to many Ly α lines has been used to try to obtain a mean metallicity (Norris *et al.* 1983), but with mixed results: Lu (1991) reported a definite detection of $\langle N_{\text{C IV}}/N_{\text{H I}} \rangle = 6 \times 10^{-4}$ for cloud populations with $N_{\text{H I}} = 5 \times 10^{15} \text{ cm}^{-2}$; at lower $N_{\text{H I}}$, Tytler & Fan (1994) found only an upper limit of 10^{-2} . However, even with a positive detection obtained by stacking, the problem of contamination by a trace population of relatively metal-rich objects remains.

With much higher S/N, higher resolution ($R = 36,000$) spectra available from the HIRES spectrograph on the Keck 10 m telescope, it becomes possible to treat this problem in a much less ambiguous way by measuring the metal column densities of individual clouds. Here we use such data to show that roughly half of a population of Ly α forest clouds with $N_{\text{H I}} \geq 3 \times 10^{14} \text{ cm}^{-2}$ has associated metal features with $N_{\text{C IV}} \geq 10^{12} \text{ cm}^{-2}$, and that, correspondingly the Ly α forest, at least at these column densities, is not truly primordial,

but has undergone some level of chemical enrichment. We also show that the metallicities are comparable to those in $N_{\text{H I}} \sim 10^{17} \text{ cm}^{-2}$ Lyman-limit system (LLS) clouds and to the mean value in a sample with $\langle N_{\text{H I}} \rangle = 2 \times 10^{14} \text{ cm}^{-2}$.

2. OBSERVATIONS

As part of a program to measure (D/H) ratios in high- z absorption systems, a number of bright ($V < 18$) $z \sim 3$ quasars with partial Lyman-limit edges (optical depth $\tau < 3.5$) have been observed with the HIRES spectrograph (Vogt *et al.* 1994) on the Keck 10 m telescope. A more complete description is given in Songaila (1995). Each observation consists of a 3–6 h exposure covering the wavelength range 3600–6000 Å at a resolution R of 36,000. The wavelength coverage is complete at shorter wavelengths ($\lambda \leq 5000$ Å), but has small interorder gaps at longer wavelengths.

Three of these spectra (toward the quasars 0014+813, 0302-003, and 0636+680) are well suited to a study of the metallicity in modest column-density ($N_{\text{H I}} \sim 10^{14} \text{ cm}^{-2}$) Ly α forest lines: they have good S/N (≥ 50 per resolution element) and they have considerable redshift intervals where both the Ly α line and the corresponding C IV ($\lambda\lambda 1548, 1550$ Å) doublet are observed. (A typical spectrum is shown in Fig. 1: we show the spectrum longward of the quasar Ly α emission and compare this with the region of the spectrum where Ly α would correspond to C IV, shifted so that the Ly α line lies under the corresponding C IV 1548 line.) We have therefore used these quasars to analyze whether the Ly α forest lines have corresponding metal lines by searching a sample of forest lines satisfying $N_{\text{H I}} \geq 3 \times 10^{14} \text{ cm}^{-2}$ to find what fraction of the individual objects have metal absorption.

3. C IV/H I RATIOS

In order to select a uniform $N_{\text{H I}} \geq 3 \times 10^{14} \text{ cm}^{-2}$ sample and to avoid the blending problems intrinsic to an equivalent width selection, we have chosen our sample of higher column density Ly α lines based on the residual flux $r_\nu \equiv \exp(-\tau_\nu)$ in the base of the line. The line list was chosen

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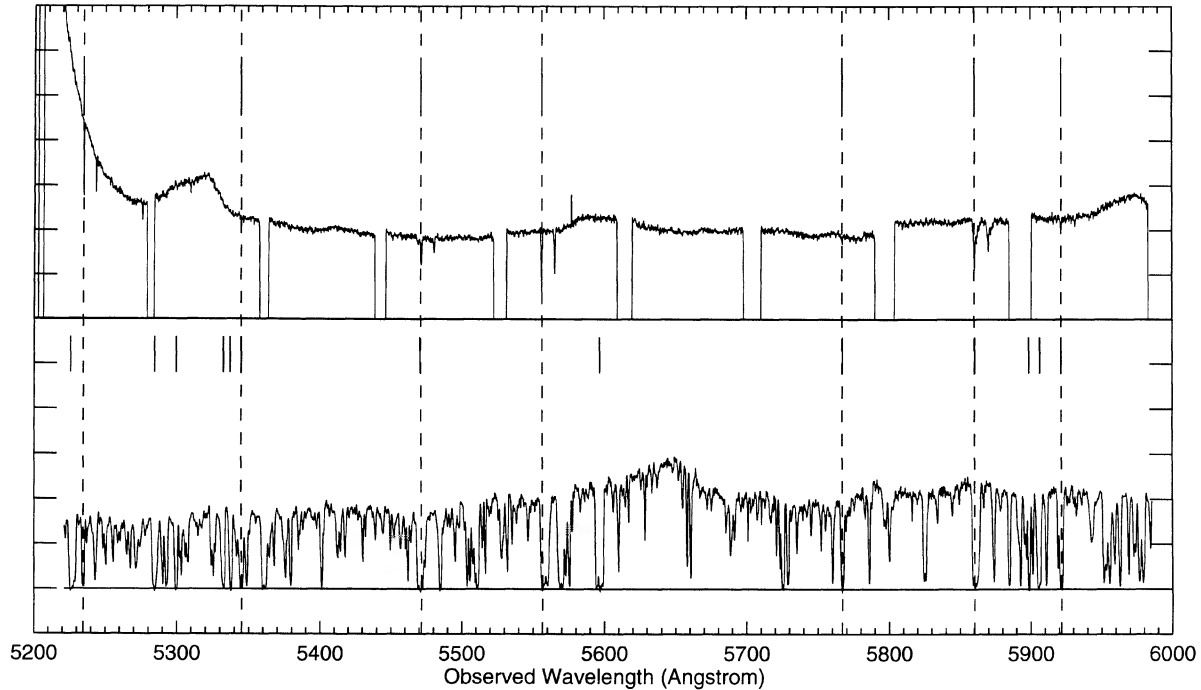


FIG. 1. A sample HIRES spectrum of Q0302-003 showing the spectrum longward of the quasar Ly α emission in the top panel. The x axis is labeled with the observed wavelength scale corresponding to this spectrum. The bottom panel shows the corresponding Ly α forest region shifted so that Ly α features should lie below their corresponding C IV 1548 features. The vertical tick marks in the lower panel indicate Ly α forest systems selected according to low residual flux at base of the line ($r_v < 0.025$) as described in Sec. 3 of the text. This roughly corresponds to systems with $N_{\text{H I}} \gtrsim 3 \times 10^{14} \text{ cm}^{-2}$. The C IV doublets of Tables 1a and 1b are shown in the top panel with dashed vertical lines drawn to indicate the corresponding Ly α features. It can be seen that roughly half of the Ly α forest lines selected by the r_v criterion have corresponding detections in C IV absorption, and we estimate that the corresponding sensitivity limit on the C IV detection is $N_{\text{C IV}} \gtrsim 10^{12} \text{ cm}^{-2}$. For a very small subset of the Ly α forest lines identified with this selection criterion, the corresponding C IV doublet falls in the interorder gaps that are present at long wavelengths. The properties of the identified C IV systems for the quasars Q0014+813, Q0302-003, and Q0636+680 are summarized in Tables 1(a) and 1(b), with column density, linewidth, and velocity information obtained from the Voigt profile fitting.

from objects with $r_v < 0.025$ at wavelengths where the corresponding C IV lies within the observed spectrum longward of the quasar Ly α emission. The wavelength of the line was taken to be the mean of the wavelengths where the r_v criterion is satisfied. The sample is given in Table 1 and illustrated for Q0302-003 in Fig. 1. (Note that the quoted redshifts correspond to the observed wavelength, and have not been corrected to the local standard of rest.) The r_v selection corresponds to

$$N_{\text{H I}} \gtrsim 3 \times 10^{14} \left(\frac{b}{34 \text{ km s}^{-1}} \right) \text{ cm}^{-2}, \quad (1)$$

where $b = 34 \text{ km s}^{-1}$ is the mean Ly α forest line b value (Carswell *et al.* 1991). Since $n(N)dN \sim N^{-1-\beta} dN$ with $\beta \sim 0.7$ (Carswell *et al.* 1991), the median $N_{\text{H I}}$ of the clouds is 2^β times the minimum value or $5 \times 10^{14} \text{ cm}^{-2}$; for an adopted maximum column density of 10^{17} cm^{-2} , the mean column density, which is more poorly defined, is around $4 \times 10^{15} \text{ cm}^{-2}$.

For each line we searched for the corresponding C IV doublet, and, if present, its profile was fitted with Voigt profiles to obtain column densities in C IV, velocities, and b values for distinguishable components. The C IV lines are unsaturated (see Figs. 1 and 2), and lie in the linear portion of the curve of growth, so column densities and b values should be accurate. Table 1 lists the column densities, v and b , and an

atlas of the Ly α lines with detected C IV doublets is shown in Fig. 2. Most lines are well fit by one or two C IV velocity components, but some systems with high C IV column density are much more complex. Clouds that were not detected at the sensitivity limit of $\sim 10^{12} \text{ cm}^{-2}$ for C IV are indicated by null entries, and we have noted instances where the C IV 1548 lies between orders or is contaminated by other lines. The latter systems are excluded from the subsequent discussion. We also exclude the Lyman-limit systems in the observed range, since the quasars were chosen for observation because of the presence of these systems. This leaves 31 lines in Table 1, where C IV could have been detected, and in 15 of these systems the C IV is in fact found; thus, roughly half of the Ly α lines with $N_{\text{H I}} \gtrsim 3 \times 10^{14} \text{ cm}^{-2}$ are detectable in C IV with our current sensitivity. (If we exclude those systems where the C IV line is not detected in both members of the doublet, 12 of the 31 Ly α lines are detected.) The median C IV column density is then very roughly 10^{12} cm^{-2} , implying a median (C IV/H I) ratio of 2×10^{-3} . The mean column density is $1.3 \times 10^{13} \text{ cm}^{-2}$, corresponding to a mean (C IV/H I) of 3×10^{-3} . (If the single system with $N_{\text{C IV}} = 1.7 \times 10^{14} \text{ cm}^{-2}$ is excluded, this drops to 1.5×10^{-3} , and if the systems with $N_{\text{H I}} \gtrsim 5 \times 10^{13} \text{ cm}^{-2}$ are excluded, to 0.6×10^{-4} .) Thus, the mean ratio is roughly consistent with the median ratio.

To determine the mean (C IV/H I) ratio at lower $N_{\text{H I}}$, we

TABLE 1(a). C IV in r_v -selected forest clouds.

Quasar	z	N_{CIV} (cm^{-2})	v (km s^{-1})	b (km s^{-1})	Quasar	z	N_{CIV} (cm^{-2})	v (km s^{-1})	b (km s^{-1})
0014 + 813	2.4730	4(12)	31	20	0302 - 003	2.7252	5(12)	-1	16
		5(12)	67	10		2.7853	4(12)	-56	11
		9(12)	-9	8		2(12)	-27	6	
	2.4922	1.5(13)	13	9		2.6(13)	2	30	
		1(12)	121	9		7(12)	10	7	
		<contam.>				3(12)	39	8	
	2.5252	<contam.>				1.4(13)	75	23	
	2.5431	—	—	5(12)		111	12		
	2.6185	2(12)*	-25	7		3(12)	145	9	
	2.6445	—	—	—		3(12)	178	11	
	2.6743	—	—	—					
	2.7174	1(12)	-11	13		2.8101	<off>	—	—
		5(12)	31	11	2.8150	—	—	—	
		2.7713	—	—	2.8248	1.0(13)	3	29	
		2.7819	<contam.>			0636 + 680	2.3100	2.0(13)	-3
	2.7968 ^b	5(12)*	-33	17	4.8(13)		9	16	
		9(12)	9	8	—		—	—	—
2.8213		<contam.>			2.3888		—	—	—
2.8376		1(12)	13	4	2.4307		—	—	—
2.8438	—	—	—	2.4734	1.4(13)		-153	7	
2.9083	4(12)	-77	10	—	5(12)		-119	10	
2.9222	—	—	—	—	2(12)		-96	5	
0302 - 003	2.3753	—	—	—	—		3(12)	-83	7
		—	—	—	—		9(12)	-65	29
		—	—	—	—	1.8(13)	0	9	
	2.4134	4(12)*	-31	10	—	1.0(13)	31	16	
	2.4233	2(12):	29	10	—	9.5(13)	68	14	
	2.4445	—	—	—	—	7(12)	121	16	
	2.4475	—	—	—	2.5496	—	—	—	
	2.4525	4(12)	7	13		2.5915	—	—	—
	2.5337 ^b	6(12)	-72	31		2.5955	—	—	—
		1(12)	-31	7	2.6792	2(12):*	5	7	
		1.4(13)	36	16	2.6808	—	<off>	—	—
		1.3(13)	61	16	—	—	—	—	—
	2.6150	—	—	—					

*based on single member of doublet, less certain entries marked with (-)

^bLyman-limit system

TABLE 1(b). Additional C IV lines.

Quasar	z	N_{CIV} (cm^{-2})	v (km s^{-1})	b (km s^{-1})
0302 - 003	2.3811	1.6(13)	6	12
	2.5890	5(13)	-3	17
	—	4(12)	32	6
0636 + 680	2.3238	6(12)	0	11
	—	3(12)	22	13
	2.5934	3(12)	4	15

Notes to TABLE 1b.

Systems not selected by r_v , but with $N_{CIV} > 3 \times 10^{13} \text{ cm}^{-2}$

have followed the stacking procedure. We selected Ly α clouds in the specified N_{HI} range by Voigt profile fitting (at $N_{HI} < 3 \times 10^{14} \text{ cm}^{-2}$ the Ly α forest clouds are not saturated, and profile fitting provides an accurate N_{HI}) and averaged all the C IV 1548 lines with $N_{CIV} < 10^{13} \text{ cm}^{-2}$ corresponding to these Ly α lines. The results are shown in Fig. 3, where we find $(C IV/H I) = 4 \times 10^{-4}$ for $N_{HI} \geq 3 \times 10^{14} \text{ cm}^{-2}$, when six systems with $N_{CIV} \geq 10^{13} \text{ cm}^{-2}$ are excluded, and $(C IV/H I) = 1.8 \times 10^{-3}$ for $N_{HI} = 10^{14} \rightarrow 3 \times 10^{14} \text{ cm}^{-2}$, when the one system with $N_{CIV} > 10^{13} \text{ cm}^{-2}$ is excluded. For lower N_{HI} we no longer have the sensitivity to detect C IV. $(C IV/H I) < 3 \times 10^{-3}$ (2σ) at $\langle N_{HI} \rangle = 7 \times 10^{13} \text{ cm}^{-2}$. Lu (1991) obtained a similar result with $(C IV/H I) = 6 \times 10^{-4}$ for clouds with $N_{HI} = 5 \times 10^{15} \text{ cm}^{-2}$, when the systems with stronger metal lines were excluded, while Tytler & Fan (1994) found an upper limit of 10^{-2} at lower N_{HI} .

A slightly different approach to the problem of determining the mean $(C IV/H I)$ ratio is to determine the distribution of C IV clouds as a function of column density and to compare this to the distribution of H I clouds. If the H I clouds are described by a power law $dn_H/dz = AN_{HI}^{-1-\beta} dN_{HI}$ and the C IV clouds are these same H I clouds convolved through a distribution of $(C IV/H I)$ ratios which is invariant as a function of N_{HI} , then the distribution of C IV should be $dn_C/dz = BN_{CIV}^{-1-\beta} dN_{CIV}$, where the mean $(C IV/H I) = (B/A)^{-1/\beta}$.

We have searched spectra of the three quasars for further C IV lines which satisfy $N_{CIV} > 3 \times 10^{12} \text{ cm}^{-2}$ but which were not in Table 1(a) (i.e., not identified with the systems selected according to residual flux in Ly α). Four additional systems were found which are given in Table 1(b). Combining Tables 1(a) and 1(b) we have a sample of 15 C IV clouds uniformly selected with $N_{CIV} > 3 \times 10^{12} \text{ cm}^{-2}$, where for these purposes we have considered each velocity complex as one entity with N_{CIV} equal to the total column density. A Kolmogorov fit (Fig. 4) to the distribution of column densities shows that it is consistent with a power law with a 90% confidence range of $\beta = 0.75 \pm 0.45$, which is indeed consistent with the N_{HI} power law (Tytler 1987; Sargent *et al.* 1989; Carswell *et al.* 1991). The total dz searched is 1.45 so that we find

$$\frac{dn_C}{dz} = 16 N_{C12}^{-1.75} dN_{C12} \quad (2)$$

at $\langle z \rangle = 2.6$, where N_{C12} is the C IV column density in units of 10^{12} cm^{-2} . From Hunstead *et al.* (1988) the total number of H I clouds between 10^{13} cm^{-2} and 10^{17} cm^{-2} is 270 per unit z at $z = 2.6$, which, with the same power law slope, gives

$$\frac{dn_H}{dz} = 1100 N_{H12}^{-1.75} dN_{H12}, \quad (3)$$

where N_{H12} is the H I column density in units of 10^{12} cm^{-2} . Combining Eqs. (2) and (3) we find a mean $(C IV/H I)$ ratio of 3.5×10^{-3} with a rough 1σ uncertainty of 10^{-3} . It is important to note that, because of the slope in the power law fit, mean values of both C IV and H I are weakly dominated by the highest column density systems so that trimming of high column density C IV systems is inappropriate in determining the means. In the following discussion we shall adopt a $(C IV/H I) = 3 \times 10^{-3}$ over the column density range $N_{HI} = 10^{14} \rightarrow 5 \times 10^{15} \text{ cm}^{-2}$ based on the internally homogeneous sample of Table 1.

4. CLOUD METALLICITY VERSUS COLUMN DENSITY

To determine a higher column density sample for comparison purposes, we have compiled a list (Table 2) of all Lyman-limit systems with measured τ (i.e., $\tau \leq 3.5$) in quasars with $V < 18$ in the lists of Sargent *et al.* (1989) and Lanzetta (1991). We exclude the system in 1159+123 which lies near the quasar and has anomalously high ionization and pressure. The remaining sample is homogeneous with well-defined $N_{HI} = \sim 3 \times 10^{17} \text{ cm}^{-2}$ and consists of the highest column density clouds where opacity effects are still minimal.

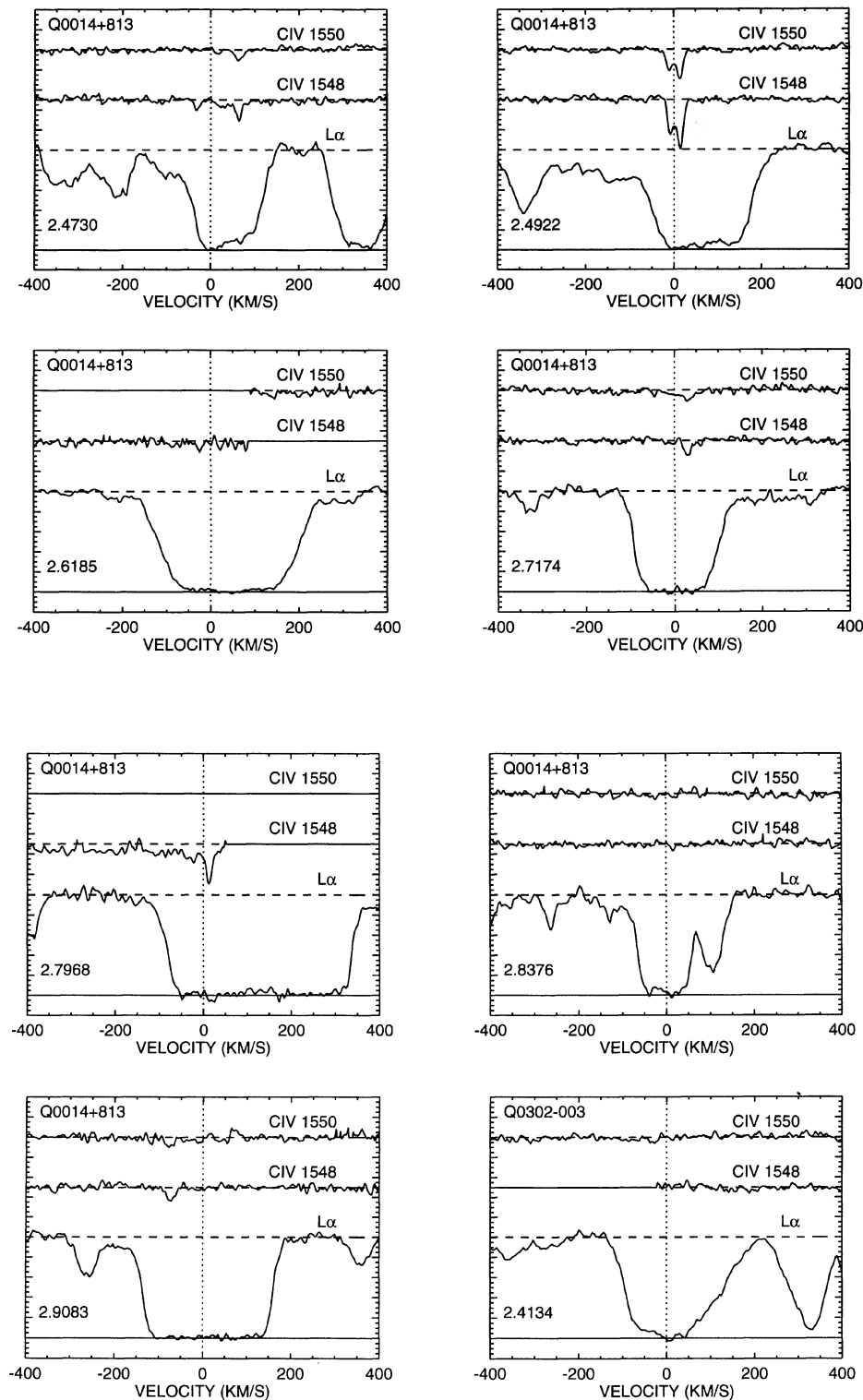


FIG. 2. An atlas of the detected C IV lines of Tables 1(a) and 1(b). Each plot shows the line profiles of the weaker C IV 1550 doublet line, the stronger C IV 1548 doublet line, and the Ly α line, plotted in velocity and normalized to the local continuum. Zero points for the C IV continua have been offset by 0.50 and 1.00 with respect to the Ly α continuum for clarity. For the stronger C IV features, it is possible to see quite a complex velocity structure in the doublet lines (see for instance the $z=2.4734$ system in Q0636+680), and it is evident that this complexity persists to lower column density systems, where sensitivity limits our ability to fit weak features.

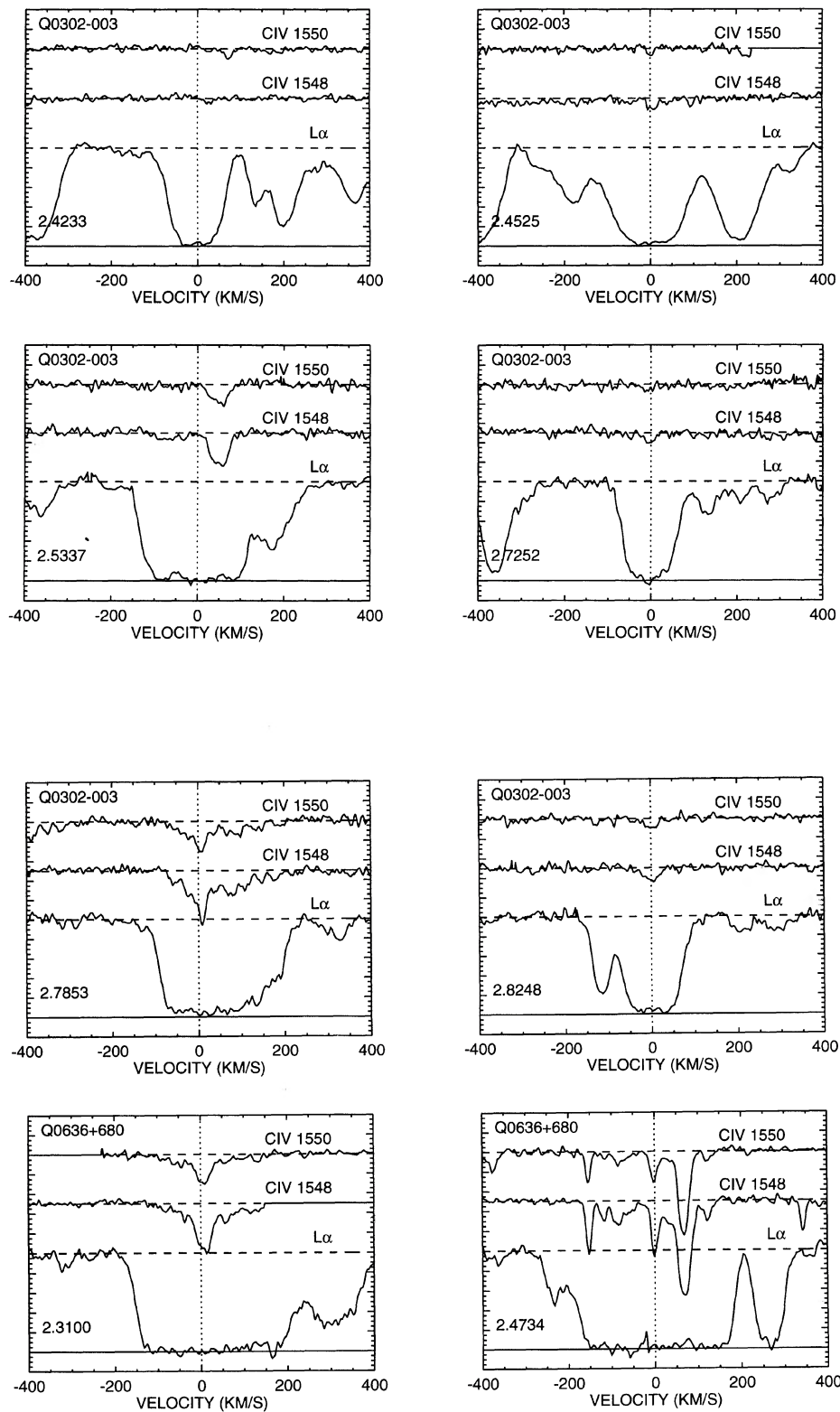


FIG. 2. (continued)

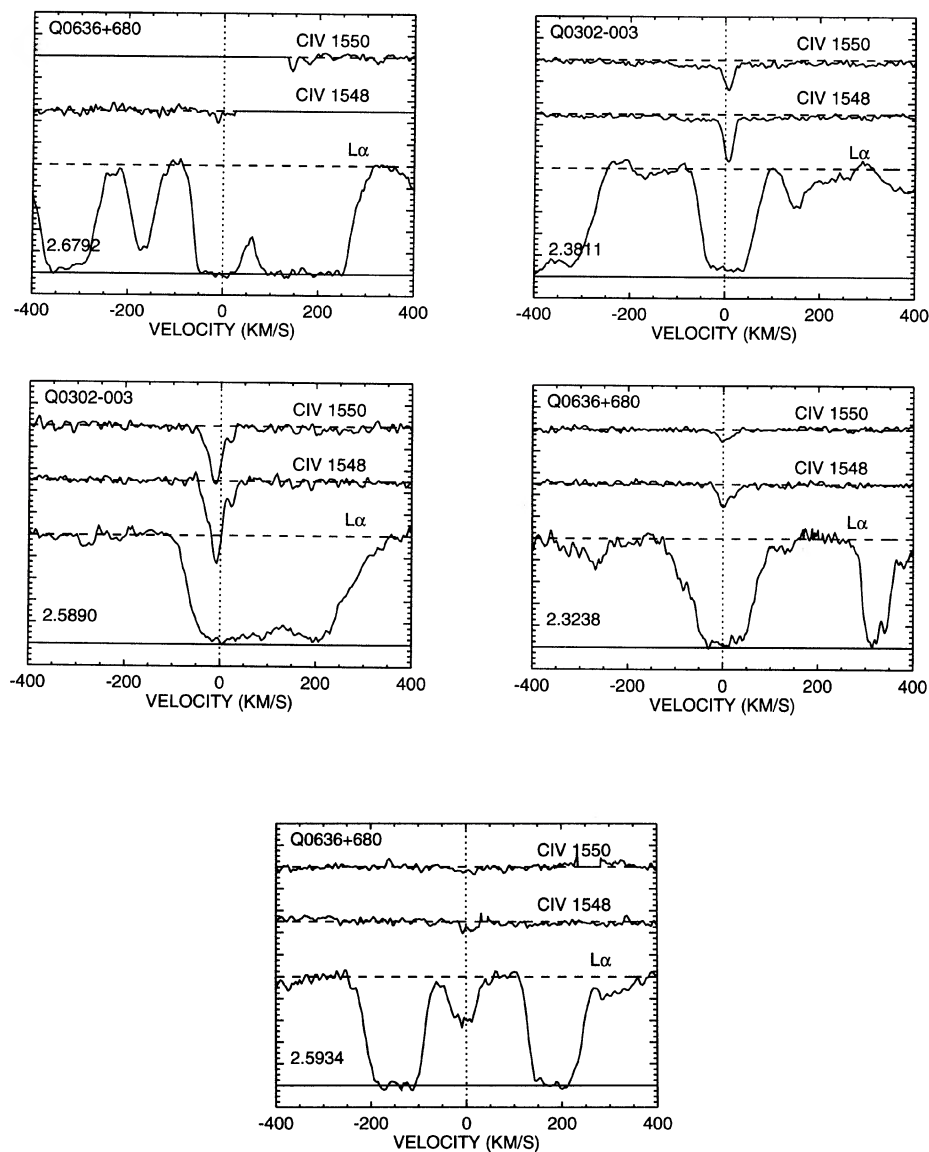


FIG. 2. (continued)

We have compiled the column densities of C IV, Si IV, C II, C II*, and N V, either from the present observations or from the literature.

The run of (C IV/H I) with $N_{\text{H I}}$ for both the weaker forest clouds of the previous section and the individual partial Lyman-limit system clouds is shown in Fig. 5. The Lyman-limit systems have a substantial scatter in (C IV/H I) with a median value of 1.3×10^{-4} which is lower than that in the lower- $N_{\text{H I}}$ clouds. The lower (C IV/H I) is partially a result of the optical depth in the LLS clouds. In Fig. 5, we have overplotted two standard photoionization models from Bergeron & Stasińska (1986) computed for ionization parameters,

$\Gamma = 2 \times 10^{-2}$ and 2×10^{-3} and metallicities of 10^{-2} solar. If simple photoionization models are applicable (but see the final section and Giroux *et al.* 1994), we would conclude that the lower density clouds have about eight times higher metallicity than the LLS clouds or (more probably) that Γ is higher in the low column density systems—again by about slightly less than an order of magnitude. The ionization balance in the Lyman-limit systems (Table 2) is consistent with Γ parameters lying between 10^{-3} and $10^{-2.5}$ with $N_{\text{C II}}$ generally comparable to $N_{\text{C IV}}$, and is consistent with their having metallicity $\sim 10^{-2}$ solar (cf. Steidel 1990). The lower column density systems do appear to be more highly ionized. A

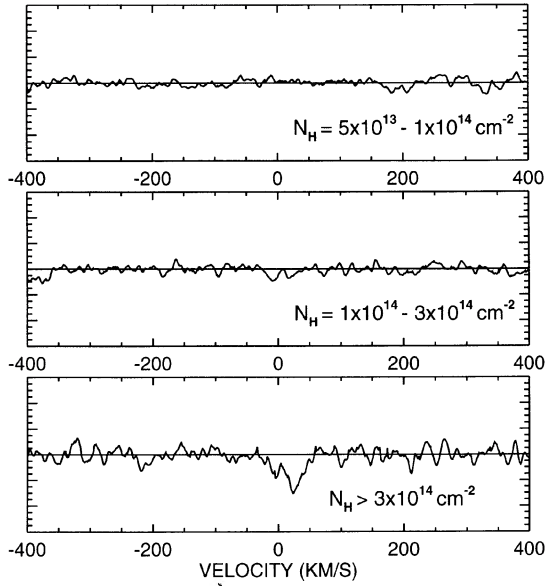


FIG. 3. Stacked C IV 1548 spectra corresponding to Ly α forest features in the density ranges $N_{\text{H I}} = 5 \times 10^{13} \rightarrow 10^{14} \text{ cm}^{-2}$, $N_{\text{H I}} = 10^{14} \rightarrow 3 \times 10^{14} \text{ cm}^{-2}$, and $N_{\text{H I}} > 3 \times 10^{14} \text{ cm}^{-2}$, where the Ly α lines have been selected by Voigt profile fitting of the Ly α forest. C IV systems with $N_{\text{C IV}} \geq 10^{13} \text{ cm}^{-2}$ have been excluded from the stacking. The bottom two plots yield a (C IV/H I) ratio of 4×10^{-4} for $N_{\text{H I}} \geq 3 \times 10^{14} \text{ cm}^{-2}$, with six systems excluded by the cutoff, whereas for $N_{\text{H I}} = 10^{14} \rightarrow 3 \times 10^{14} \text{ cm}^{-2}$ we find 1.8×10^{-3} with one system excluded. For systems with $5 \times 10^{13} \text{ cm}^{-2} < N_{\text{H I}} < 10^{14} \text{ cm}^{-2}$ (top panel), the sensitivity is insufficient to estimate $N_{\text{C IV}}$, even with stacking, with (C IV/H I) $\leq 3 \times 10^{-3}$ (2σ), assuming $b = 26 \text{ km s}^{-1}$. No systems were excluded by the upper limit cutoff in this case.

search for C II in the higher column density C IV systems gives C II < 0.1 C IV (Table 3), while a search for C II in higher- z forest clouds gives $(N_{\text{C II}}/N_{\text{H I}}) < 3 \times 10^{-4}$, consistent with the limit. The limits on C II and N V give $\Gamma = 10^{-2} - 10^{-1.5}$ in the low column density clouds, which

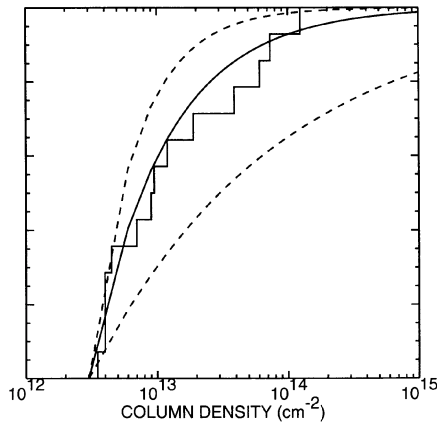


FIG. 4. Results of a Kolmogorov fit to a power-law distribution of cloud column densities in C IV. The solid line shows the best fit for a power-law index $\beta = 0.75$ to the observed cumulative distribution of C IV column densities, using the sample from Tables 1(a) and 1(b) ($N_{\text{C IV}} \geq 3 \times 10^{12} \text{ cm}^{-2}$). The 90% confidence limits to this fit ($\beta = 0.3$ and $\beta = 1.2$) are shown with bracketing dashed lines.

TABLE 2. Partial Lyman-limit systems.

Quasar	z_{em}	z_{LLS}	τ_{LLS}	$N(\text{C IV})$ (cm^{-2})	$N(\text{Si IV})$ (cm^{-2})	$N(\text{C II})$ (cm^{-2})	$N(\text{C II}^*)$ (cm^{-2})	$N(\text{N V})$ (cm^{-2})
0014 + 813	3.384	2.800	1.7	3(14); ^a	4.7(13)	1.9(14)	contam.	< 1(13)
		3.321	0.8	< 6(12) ^b	4(12)	8(12);	< 2(12)	< 1(13)
0256 - 000	3.374	3.090	2.1	4.0(13) ^c	1(13) ^c	$\leq 4(13)^c$	—	$\leq 1.5(14)^c$
0302 - 003	3.286	2.536	1.5	3.1(13)	4(12)	contam.	—	contam.
0636 + 680	3.174	2.903	3.5	1.7(14) ^c	1.4(14)	6.6(14)	< 1(12) ^d	contam.
0956 + 122	3.301	3.221	3.0	7.1(13) ^c	1.5(13)	2.5(12)	—	< 2(13)
1159 + 123	3.502	3.525	0.7	off	off	4.5(13)	1.8(13)	1.4(14)
2126 - 158	3.261	2.973	2.3	2.5(13) ^c	$\leq 6(12)^c$	2.5(13) ^c	—	< 1(14) ^e

^aSargent et al. 1989

^bChaffee et al. 1985

^cSteidel 1990

^d $n_e \leq 0.04 \text{ cm}^{-2}$

Notes to TABLE 2.

Column density measurements or upper limits of principal atomic features and optical depths for partial Lyman-limit systems taken from the literature or measured in this paper. The published sources used are noted. Uncertain values are indicated with a colon (:).

again would imply a typical metallicity around 10^{-2} solar.

We conclude that, in the photoionization model, the clouds are quite consistent with having a relatively invariant average metallicity of about 10^{-2} solar, but that the ionization parameter is higher by about a factor of 10 in the lower column density systems, implying that their internal space densities n are lower by this factor—presumably reflecting a lower-pressure environment. At least in some models, this may be reasonable for lower-mass objects. Interestingly this reduces the mass range of the clouds: since $x \equiv (N_{\text{H I}}/N_{\text{H}})$ scales as Γ^{-1} or n , the mass of a cloud is $M \sim N_{\text{H I}}^3/(x^3 n^2) \sim N_{\text{H I}}^3/n^5$ for spherical geometry, and we find that the clouds with $N_{\text{H I}} = 10^{17} \text{ cm}^{-2}$ are only roughly 10^4 times the mass of those with $N_{\text{H I}} = 10^{14} \text{ cm}^{-2}$.

5. CLOUD STRUCTURE AND KINEMATICS

It is clear from Fig. 2 that the individual forest clouds are not isolated objects but rather are colonies of smaller cloudlets blended in the Ly α line but often resolved in C IV. The partial Lyman-limit systems generally show many compo-

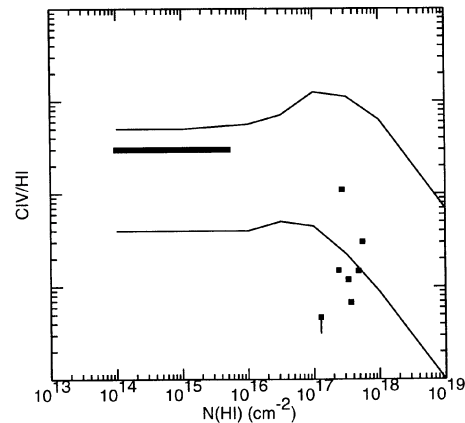


FIG. 5. Ratio of C IV/H I as a function of cloud column density, $N_{\text{H I}}$, for the combined distribution of Ly α forest clouds and Lyman-limit systems. The thick solid line shows our presently measured mean values for the forest clouds whereas the boxes show the individual values of the Lyman limit systems of Table 2. Also shown (solid lines) are two photoionization models from Bergeron & Stasińska (1986) computed for $\Gamma = 2 \times 10^{-2}$ (upper curve) and $\Gamma = 2 \times 10^{-3}$ (lower curve).

TABLE 3. Ionization balance in strong Ly α forest C IV lines.

Quasar	z	C IV (cm ⁻²)	Si II (cm ⁻²)	C II (cm ⁻²)	N V (cm ⁻²)
0014 + 813	2.4922	2.5(13)	< 1.0(12)	< 6(12)	< 1(12)
0302 - 003	2.3811	1.5(13)	< 1.0(12)	< 3(12)	< 4(12)
	2.5890	5.7(13)	< 2.0(12)	< 3(12)	< 5(12)
	2.7852	6.0(13)	< 2.0(12)	—	—
0636 + 680	2.3100	6.1(13)	—	—	< 7(12)
	2.3238	1.0(13)	—	—	< 7(12)

nents while the $N_{\text{H I}} \geq 3 \times 10^{14} \text{ cm}^{-2}$ forest systems show from 1 to 3 components, but this may be in the main a selection effect, and might suggest that we will see an increasing number of cloudlets as we lower the column density selection.

The median b value of the cloudlets in the C IV clouds is 10 km s^{-1} and the smallest well-defined b is around $7\text{--}8 \text{ km s}^{-1}$. If the clouds are purely thermally broadened then $T = 35,000 (b/7 \text{ km s}^{-1})^2 \text{ K}$, which is at the high end of the temperatures expected from photoionization. The cloudlets may of course be partially broadened by internal turbulence. The spread of the cloudlet velocity centroids relative to the (rather poorly determined) Ly α line centers can be measured from the stacked spectra of Fig. 3, giving $b_{\text{kin}} = 26 \text{ km s}^{-1}$. (Given the uncertainty in the placement of the Ly α centers, this value may be high but the velocity spread of C IV components within individual complexes suggests similar values.) If we again assume a mean b of 34 km s^{-1} for the Ly α lines, then this kinetic broadening and the thermal broadening are roughly equal and the hydrogen thermal b of 24 km s^{-1} corresponds to a temperature T of $32,000 \text{ K}$. There appears, therefore, to be at least a plausible description in which the individual cloudlets have a consistent temperature of just above $30,000 \text{ K}$, which can be produced by photoionization heating (e.g., Black 1981), and the $N_{\text{H I}} \sim 3 \times 10^{14} \text{ cm}^{-2}$ cloudlet complexes as a whole have line-of-sight velocity dispersions with $\langle \sigma_T \rangle = 18 \text{ km s}^{-1}$.

For a standard IGM radiation field the inferred density in the cloudlets is $\sim 10^{-2.5} \text{ cm}^{-3}$ for the LLS clouds (just consistent with the fine structure limits in Table 2) and $10^{-3.5} \text{ cm}^{-3}$ for the $N_{\text{H I}} > 3 \times 10^{14} \text{ cm}^{-2}$ clouds, giving dimensionless pressures ($2nT$) of 200 and 20 K cm^{-3} , respectively. To preserve the physical integrity of the cloudlets the cloud complexes must contain a confining material with $n \sim 10^{-5} \rightarrow 10^{-4} \times (T_{\text{hot}}/10^6 \text{ K})^{-1} \text{ cm}^{-3}$, where T_{hot} is the temperature of the confining material, or else have an equivalent ram pressure. A 10^{17} cm^{-2} cloud complex with a total hydrogen column density of 10^{19} cm^{-2} will have a line-of-sight size, L , of $10^{21.5} \text{ cm}$, while one with 10^{14} cm^{-2} , and a hydrogen column density of 10^{17} cm^{-2} will have a line-of-sight size of $10^{20.5} \text{ cm}$. (The transverse dimensions may of course be larger.) The breakup time for the smaller cloud complexes is then only $(L/\sigma_T) \sim 10^7 \text{ yr}$. This suggests in turn that the clouds must either be transient or else be gravitationally confined. In the latter case, the line-of-sight mass column density must be of order $(\sigma_T^2/GL) \sim 1000 \mathcal{M}_{\odot} \text{ pc}^{-2}$ or an equivalent proton column density of 10^{23} cm^{-2} . This is very suggestive of the disk of our own galaxy, and could even

imply that the Lyman clouds are in fact the outer relatively primordial regions of disk-like galaxies (Bahcall & Spitzer 1969). Alternatively, the confining material could be the CDM minihalos suggested by Rees (1986) or dwarf galaxies, as suggested by Fransson & Epstein (1982), or the clouds could be pancakes formed in the intergalactic medium (Cen *et al.* 1994).

6. DISCUSSION

We can summarize the conclusions very briefly. Over the column density range $N_{\text{H I}} = 10^{14} \rightarrow 5 \times 10^{17} \text{ cm}^{-2}$, Ly α clouds have a rather uniform metallicity of $\sim 10^{-2}$ solar; however, lower column density clouds have a lower internal space density and a higher ionization balance. The clouds have an internal phase structure and are complexes of cloudlets, which, for $N_{\text{H I}} \sim 10^{15} \text{ cm}^{-2}$, have internal temperatures of around $30,000 \text{ K}$ and line-of-sight velocity dispersions of very approximately 18 km s^{-1} . Confining the cloud complexes requires a substantial gravitational potential, implying that the cloud complexes are embedded either in galaxies or minidark halos. Alternatively, the cloud complexes could correspond to pancake formation in the intergalactic medium.

The most remarkable point is the invariance of the metallicity, since it would seem natural to suppose that the rate of star formation would be a function of the size of the complex, or at least of its internal density. It is possible (and perhaps probable) that the metallicity is a relict of an earlier star formation period in the history of the IGM as a whole. However, if the star formation is contemporaneous, it strongly suggests the presence of a governing mechanism: one very plausible mechanism is self-heating owing to star formation (Giroux *et al.* 1994 discuss this for Lyman-limit system clouds.) If each gram of metal production introduces a thermal energy of $\sim \text{few} \times 10^{17} \text{ erg}$ into the cloudlet, then we have a heating rate

$$H \sim \text{few} \times 10^{-27} t_9^{-1} Z_{-2} n \text{ erg s}^{-1}, \quad (4)$$

where t_9 is the time scale over which the star formation occurs in units of 10^9 yr and Z_{-2} is the cloudlet metallicity in units of 10^{-2} solar. By contrast the peak cooling rate in a hydrogen-helium plasma is $10^{-22} n^2 \text{ erg cm}^3 \text{ s}^{-1}$. Energy balance requires $Z_{-2} < 10 t_9 (n/10^{-3.5} \text{ cm}^{-3})$ and, particularly if the star formation is episodic, this can constrain the metallicity to the observed values, since clouds with higher metallicities would overheat and would no longer be observable. The presence of such heating may also account naturally for the internal phase structure in the clouds and could in turn produce a diffuse, $T \sim 10^5 \rightarrow 10^6 \text{ K}$, slightly metal-enriched intergalactic medium.

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