

Understanding the Evolution of Galaxies Through the Eye of Highly Ionized Gas

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Abstract

In this study, we investigate highly ionized gas in galaxies in a total sample size of 120 damped Lyman α systems, in the redshift range of $1.747 < z < 4.224$. We analyze the column densities of C_{IV} , Si_{IV} , and H_I ; estimate column density of H_{II} ; and compute the column density ratios of C_{IV}/Si_{IV} and H_{II}/H . We find the average column density ratio of $C_{IV}/Si_{IV} \sim 3.40 \pm 2.06$ (including limits) which is very close to the average value of our Milky Way Galaxy $\sim 3.6 \pm 1.3$. It might suggest the processes that produce C_{IV} and Si_{IV} from the feedback of star formation in our present time, may be very similar to 9-11 billion years ago. On the other hand, we find column density ratio of ionized hydrogen H_{II}/H is greater than $\sim 15\%$ in these distant galaxies, whereas $H_{II}/H > \sim 3\%$ in our Milky Way Galaxy. This result might suggest that these galaxies have more highly ionized gas than our own Galaxy. We find the median for $N(C_{IV})$ is ~ 3 times greater than $N(Si_{IV})$ in these galaxies, whereas $N(C_{IV}) \sim 10-13$ times greater than $N(Si_{IV})$ in intergalactic medium. It suggests compare to Si_{IV} , there are less C_{IV} in these galaxies than in intergalactic medium. We find significant correlations (P Value $\leq .01$ i.e., CI $> 99\%$) between ΔV of galaxies and each of the metallicity, C_{IV} column density, Si_{IV} column density and $\Delta V(C_{IV})$; between metallicity and each of the column densities of C_{IV} , Si_{IV} and H_{II}/H (fraction of ionized hydrogen); between $\Delta V(C_{IV})$ and each of the column densities of C_{IV} and Si_{IV} . We do not find any correlation between metallicity and the column density ratio of C_{IV}/Si_{IV} . We find correlations of fraction of ionized hydrogen $[N(H_{II})/N(H)]$ with redshift and with $N(H_I)$. All these correlations give us the picture of our universe of 9 to 11 billion years back in time.

Introduction

Understanding the evolution of galaxies is often mysterious to us. We have passed 13.7 billion years since big bang. None the less, there are many questions unsolved, specially related to the evolution of our universe, from its baby form to today. Essentially, to understand galactic evolution we try to put together the puzzle, and to do so we look for signatures and clues around us. One such clue is the light, emitted from quasars (QSOs for short). Quasars are the active cores of very distant galaxies, ultraluminous, 10-1000 times of a large galaxy, and lie at great distances such as 10 billion light years. Thus this light provides us a great deal of information. As light travels through various clouds and highly ionized gas to reach earth, it gets absorbed by different ions because of the atomic transitions. As a result, spectral lines are produced i.e., a spectrum of intensity versus wavelength (also known as Kirchhoff's law for three types of spectra, 1859). Damped Lyman α systems¹ is one such spectrum out of other types of Lyman, Balmer, and Paschen series spectra. Each ion creates a unique signature in the spectral line. Therefore, analyzing the light spectrum reveals the properties of galaxies and clouds of our universe. Since quasars lie at great distances, many such emitted lights travel for billions of years to reach earth. Therefore, analyzing these absorption spectra, which in our study is damped Ly α systems, reveal secrets of our baby universe (Seeds 2006).

From the formation of stars through cold neutral medium in young galaxies (Howk et al. 2005) to our quest for indentifying new galaxies such as, dwarf galaxies & low surface-brightness galaxies (Calura, Matteucci & Vladilo 2003; Jimenez, Bowen & Matteuci 1999), damped Ly α systems has provided a great deal of information through its absorption lines spectrum (Wolfe et al. 2005). Though, damped Ly α system is defined by $\log N(\text{H i}) \geq 20.3$ (Wolfe 1986), yet the presence of high amount of neutral hydrogen over the ionized hydrogen is

¹ Or damped Ly α systems, or DLAs

often considered a fundamental difference between damped Ly α and other absorption systems (Wolfe et al. 2005). Various absorption lines (column density) at specific wavelength and specific redshift, provide us clues and signatures of different elements, their ionization states, metallicity, and other properties (Wolfe et al. 2005).

Meyer, Welty & York (1989) and Pettini, Boksenberg & Hunstead (1990) reported the measure of metallicity of damped Ly α systems, whereas, Savage & Sembach (1996) reported metallicity in Galaxy Interstellar Medium. Investigation conducted by Lehner et al. (2008) explored the properties of highly ionized gas in damped Ly α systems, to understand its relation with the feedback in babygalaxies, with other neutral gas and with kinematics.

Additionally, understanding the chemical evolution of galaxies is to understand the metal abundances in galaxies and its components. Metal abundances can also be determined by analyzing absorption spectrum of damped Ly α systems because it is associated with the natural gas reservoir for star formation at high redshift (Pettini 2004).

Damped Ly α systems also contributed in our understanding of various correlations and their implications in observational astronomy. Investigation by Fox et al. (2007) has shown the correlations between the metallicity versus C_{IV} column density as an evidence for galactic winds. On the other hand, correlation between velocity range in galaxies and metallicity suggested an underlying relation between galaxy mass and the metallicity (Ledoux et al. 2006).

In our study of highly ionized gas (i.e., C_{IV} & Si_{IV}), we confirm some of the reported correlations with bigger samples, find additional correlations with other components, and compare some of our calculated mean and median values of these galaxies with the Milky Way galaxy—habitat for life—and with the intergalactic medium. These findings will probably contribute to our quest of putting together the pieces of the puzzle to understand the evolution of galaxies.

Methods

In this investigation we have used a total sample of 120 damped Ly α systems, and various information related to these quasars ($1.747 < z < 4.224$). Profiles of these spectra give us information regarding the column densities of C_{IV}, Si_{IV}, H_I and associated errors; as well as metallicity, redshift, ΔV and $\Delta V(C_{IV})$. We obtained our first data set of 56 QSOs ($1.864 < z < 4.224$) from Prochaska et al. (2007). We only pulled out the samples (i.e., 56 QSOs) that had C_{IV} and Si_{IV} column density information out of over 200 QSOs. This sample set of 56 DLAs comes from the Keck telescopes² of Keck Observatory located in Hawaii. We added 63 DLAs from Fox et al. (2007) with our first sample set. This DLAs samples come from the telescope³ of Paranal Observatory located in Chile. We also added 1 DLAs from Lehner et al. (2008). We estimated column density of H_{II} (ionized hydrogen) using equation 3 and other reported values of Fox et al. (2007). We computed column densities C_{IV} / Si_{IV} and H_{II} / H. Finally we analyzed all these data and applied statistics in various sample combinations.

Results and Discussion

Our result shows the average column density ratio of $[C_{IV} / Si_{IV}] = 3.15 \pm 1.75$, in a sample size of 41 QSOs, $1.892 < z < 4.224$. When we include upper and lower limits in our calculation, we find $[N(C_{IV}) / N(Si_{IV})] = 3.40 \pm 2.06$, in a sample size of 52 QSOs, $1.747 < z < 4.224$. Our column density ratio is very close to the Milky Way Galaxy, 3.6 ± 1.3 (Sembach & Savage 1992). Sembach and Savage also reported that this fraction, C_{IV} / Si_{IV}, is remarkably constant throughout our Galaxy. Because our data comes from various distant galaxies, each having different properties, thus our result may suggest that this ratio is not only constant in our galaxy but throughout various galaxies of the universe (or at least within a very short range) at

² High Resolution Echelle Spectrometer (HIRES), and Echellette Spectrograph & Imager (ESI)

³ The Very Large Telescope/Ultraviolet-Visual Echelle Spectrograph (VTL/UVES)

different time frame. The significance of this result implies, the processes which produce C_{IV} and Si_{IV} from the feedback of star formation presently, may be very similar to the processes that took place 9-11 billion years ago.

We have found the average of the ionized hydrogen fraction $[H_{II}/H]$ is greater than $\sim 15\%$ in these distant galaxies, where as $[H_{II}/H]$ is greater than $\sim 3\%$ in our Milky Way galaxy (Howk 2006). This result suggests that these galaxies have more highly ionized gas than the Milky Way Galaxy—the home for human habitat.

We have also found the median for $\text{Log}_{10} N(C_{IV} / Si_{IV}) = 0.438$ in these galaxies. On the other hand, it is about 1.01-1.13 in the intergalactic medium (Boksenberg 2003) (*Fig. 10*). This implies, C_{IV} is ~ 3 times greater than Si_{IV} in these galaxies, where as C_{IV} is ~ 10 -13 times greater than Si_{IV} in intergalactic medium. In other words, compare to Si_{IV} there are less C_{IV} in these galaxies than intergalactic medium.

We have found various significant correlations (P Value $\leq .01$, i.e., Confidence Interval $> 99\%$) between different parameters associated with damped Ly α systems of these galaxies. In most case our P Value $\leq .001$, thus confidence interval $> 99.9\%$. We applied Pearson Product Moment and Spearman Rank Order correlation tests. Since we had measurements, upper limits, and lower limits in our data set, we calculated correlation coefficient⁴ (measure of the *strength* of the correlation) and P Value (to determine the *significance level* for the correlation) in all possible combinations, i.e., including limits as one case and excluding limits in other case. We treated 56 samples of Prochaska et al. (2007) separately as one case, and as other case, we added them with 63 samples of Fox et al. (2007) and 1 sample of Lehner et al. (2008), total of 120

⁴ *Correlation Coefficient* does not indicate whether a correlation is significant or not. It only indicates how strong or weak the correlation in a scale of 0-1 (1 being strongest). *P Value* is the measure that indicates whether the correlation is *significant* or not. It is possible that a weak correlation can be significant as a strong correlation can also be insignificant. Positive sign implies both variables tend to increase together. Negative sign implies one variable tends to decrease while the other increases.

samples. This bigger sample size increases the *reliability* and *generalizability* of our results (some of the correlations were reported before with a smaller sample size, such as Wolfe & Prochaska 1998). We tested correlations in various ways to increase the *degree of validity* of our result i.e., verifying the result in multiple approaches. Table 1 summarizes our result (correlation coefficient, P Value and sample size for all these scenarios are given).

⁵We find significant correlations between ΔV of galaxies and each of the metallicity, C_{IV} column density, Si_{IV} column density and $\Delta V(C_{\text{IV}})$; between metallicity and each of the column densities of C_{IV} , Si_{IV} and $\text{H}_{\text{II}} / \text{H}$ (fraction of ionized hydrogen); between $\Delta V(C_{\text{IV}})$ and each of the column densities of C_{IV} and Si_{IV} . We do not find any correlation between metallicity and the column density ratio of $C_{\text{IV}} / \text{Si}_{\text{IV}}$ (*Fig. 9*). We also find correlations between fraction of ionized hydrogen $[\text{N}(\text{H}_{\text{II}}) / \text{N}(\text{H})]$ with redshift and with $\text{N}(\text{H}_{\text{I}})$. See Table 1 for details.

$\Delta V(C_{\text{IV}})$ - ΔV relation shows that the velocity range in highly ionized gas is always greater than the velocity range in galaxies (*Fig. 2*).

Column density of neutral hydrogen versus fraction of ionized hydrogen correlation ($\text{Log}_{10}\text{N}(\text{H}_{\text{I}})$ vs. $\text{H}_{\text{II}} / \text{H}$) suggests, galaxies containing high amount of neutral hydrogen tend to have lower percent of ionized hydrogen (*Figs. 7 & 8*). On the other hand, galaxies that have lower amount of neutral hydrogen tend to have higher percent of ionized hydrogen as well as higher variability range. This result might also suggest that the processes which produce ionized hydrogen from neutral hydrogen may not maintain the same rate in these galaxies.

Correlation between the velocity range ΔV in galaxy versus the metallicity (*Fig. 1*) has been used to support the evidence of an underlying mass-metallicity relation in a galaxy (Ledoux et al. 2006; Wolfe & Prochaska 1998). Our result confirms this claim with a bigger sample size (100 QSOs). We see ΔV is also independently correlation with C_{IV} column density, Si_{IV} column

⁵ All the column densities are in Log_{10} scale. For details see Table 1

density (*Figs. 3 & 4*); and metallicity is independently correlated with column densities of C_{IV} and Si_{IV} (*Figs. 5 & 6*). All these correlations together might suggest that the galaxy-mass not only plays important role for metallicity but may also act as a determining factor for the amount of highly ionized gas, present in any galaxy. Thus galaxy mass may ultimately be the driving force for all various relations found in galaxies.

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Table

Table 1	Pearson Product Moment		Spearman Rank Order		Size	Sample Data	Source
	Correlation Coefficient	P Value	Correlation Coefficient	P Value	Number of Samples (QSO)	M=Measurements L=Limits	P = Prochaska et al. F = Fox et al. L = Lehner et al.
<i>Correlation</i>							
Metallicity vs. $\text{Log}_{10} N(\text{C}_{\text{IV}})$	0.608	0.000000853	0.631	0.000	55	M + L	P
	0.591	0.00000992	0.589	0.000	48	M	P
	0.648	1.748E-15	0.65	0.000	119	M + L	P + F + L
	0.536	8.670E-08	0.53	0.000	87	M	P + F + L
Metallicity vs. $\text{Log}_{10} N(\text{Si}_{\text{IV}})$	0.675	0.000000161	0.703	0.000	55	M + L	P
	0.623	0.00000804	0.651	0.000	43	M	P
Metallicity vs. $\text{Log}_{10} N(\text{H}_{\text{II}}/\text{H})$ est. from C_{IV}	-0.459	0.000426	-0.496	0.000	55	M + L	P
	-0.475	0.000647	-0.508	0.000	48	M	P
	-0.3	0.000929	-0.301	0.000	119	M + L	P + F + L
	-0.449	0.0000131	-0.46	0.000	87	M	P + F + L
Metallicity vs. $\text{Log}_{10} N(\text{H}_{\text{II}}/\text{H})$ est. from Si_{IV}	-0.47	0.000295	-0.504	0.000	55	M + L	P
	-0.451	0.0024	-0.461	0.00197	43	M	P
$\text{Log}_{10} N(\text{H}_{\text{I}})$ vs. $\text{Log}_{10} N(\text{H}_{\text{II}}/\text{H})$ est. from C_{IV}	-0.659	0.000000335	-0.645	0.000	56	M + L	P
	-0.732	3.320E-09	-0.71	0.000	48	M	P
	-0.635	7.106E-15	-0.629	0.000	120	M + L	P + F + L
	-0.735	3.526E-16	-0.714	0.000	88	M	P + F + L
$\text{Log}_{10} N(\text{H}_{\text{I}})$ vs. $\text{Log}_{10} N(\text{H}_{\text{II}}/\text{H})$ est. from Si_{IV}	-0.672	0.0000000146	-0.663	0.000	56	M + L	P
	-0.757	2.730E-09	-0.748	0.000	44	M	P
Redshift vs. $\text{Log}_{10} N(\text{H}_{\text{II}}/\text{H})$ est. from C_{IV}	0.382	0.00369	0.375	0.00457	56	M + L	P
	0.425	0.00258	0.396	0.00553	48	M	P
	0.197	0.0306	0.153	0.0946	120	M + L	P + F + L
	0.321	0.00228	0.284	0.00748	88	M	P + F + L
Redshift vs. $\text{Log}_{10} N(\text{H}_{\text{II}}/\text{H})$ est. from Si_{IV}	0.416	0.00141	0.406	0.00202	56	M + L	P
	0.486	0.000826	0.471	0.00134	44	M	P
ΔV vs. $\text{Log}_{10} N(\text{C}_{\text{IV}})$	0.472	0.00369	0.458	0.00525	36	M + L	P
	0.496	0.00535	0.408	0.02530	30	M	P
	0.493	0.000000191	0.49	0.000	100	M + L	P + F + L
	0.447	0.000106	0.346	0.00348	70	M	P + F + L
ΔV vs. $\text{Log}_{10} N(\text{Si}_{\text{IV}})$	0.434	0.00822	0.522	0.0012	36	M + L	P
	0.519	0.00659	0.601	0.00123	26	M	P
ΔV vs. Metallicity	0.535	0.00078	0.505	0.00178	36	M (no limits)	P
	0.525	2.02E-08	0.612	0.000	100	M + L	P + F + L
	0.477	0.0000334	0.466	0.000	69	M	P + F + L
$\Delta V(\text{C}_{\text{IV}})$ vs. $\text{Log}_{10} N(\text{C}_{\text{IV}})$	0.612	0.000537	0.652	0.000	28	M + L	P
	0.761	0.0000248	0.717	0.000	23	M	P
	0.498	0.000000507	0.577	0.000	91	M + L	P + F + L
	0.575	0.000000825	0.628	0.000	63	M	P + F + L
$\Delta V(\text{C}_{\text{IV}})$ vs. $\text{Log}_{10} N(\text{Si}_{\text{IV}})$	0.575	0.00137	0.549	0.00261	28	M + L	P
	0.615	0.00503	0.609	0.00568	19	M	P
$\Delta V(\text{C}_{\text{IV}})$ vs. ΔV	0.494	0.00759	0.462	0.0136	28	M (no limits)	P
	0.558	9.31E-09	0.404	0.000	91	M + L	P + F + L
	0.347	0.00529	0.379	0.00228	63	M	P + F + L
<i>No Correlation</i>							
Metallicity vs. $\text{Log}_{10} N(\text{C}_{\text{IV}} / \text{Si}_{\text{IV}})$	-0.198	0.168	-0.0485	0.737	50	M + L	P
	-0.158	0.324	-0.039	0.807	41	M	P
$\Delta V(\text{C}_{\text{IV}})$ vs. $\text{Log}_{10} N(\text{C}_{\text{IV}} / \text{Si}_{\text{IV}})$	0.151	0.481	0.154	0.468	24	M + L	P
	0.107	0.672	0.0568	0.818	18	M	P
				P	Measurement	Upper limit	Lower limit
P Value $\leq 0.001 \Rightarrow$ Confidence Interval $> 99.9\% \Rightarrow$ Significant Correlation				$\text{Log}_{10} N(\text{C}_{\text{IV}})$	86%	12%	2%
P Value $\leq 0.01 \Rightarrow$ Confidence Interval $> 99\% \Rightarrow$ Significant Correlation				$\text{Log}_{10} N(\text{Si}_{\text{IV}})$	79%	14%	7%
P Value $\leq 0.05 \Rightarrow$ Confidence Interval $> 95\% \Rightarrow$ Significant Correlation				$\text{Log}_{10}(\text{C}_{\text{IV}} / \text{Si}_{\text{IV}})$	80%	12%	8%
				P + F + L	Measurement	Upper limit	Lower limit
				$\text{Log}_{10} N(\text{C}_{\text{IV}})$	73%	26%	1%
				$\Delta V(\text{C}_{\text{IV}})$	75%	25%	
				Metallicity	99%	1%	

Figures

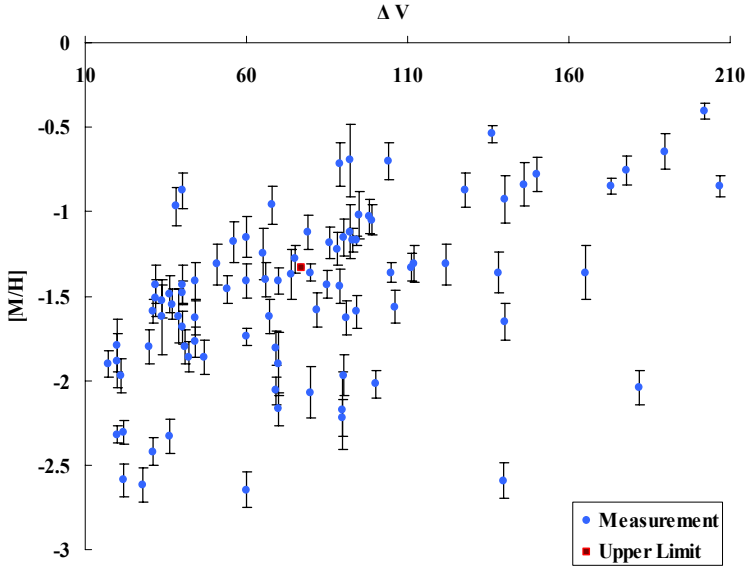


Fig. 1.—Plot of velocity range of galaxies versus corresponding metallicity. Sample size of 100 QSOs, with Pearson Correlation Coefficient = .525, Spearman Correlation Coefficient = .612, and P Value < .0001. Sample set P+F+L, including 1 limit point. For details, see table 1.

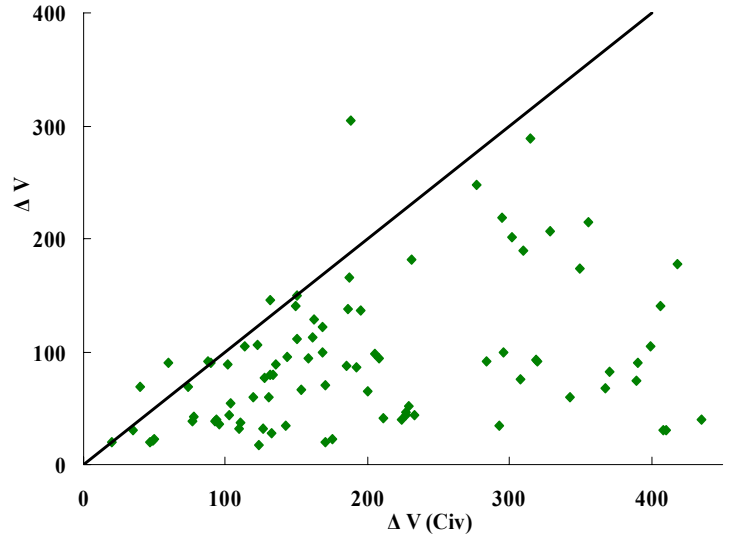


Fig. 2.—Plot of velocity range of galaxies versus velocity range of C_{IV} . Sample size of 91 QSOs, with Pearson Correlation Coefficient = .558, Spearman Correlation Coefficient = .404, and P Value < .0001. The straight line represents 1-1 ratio. Sample set P+F+L, including limit points. For details, see table 1.

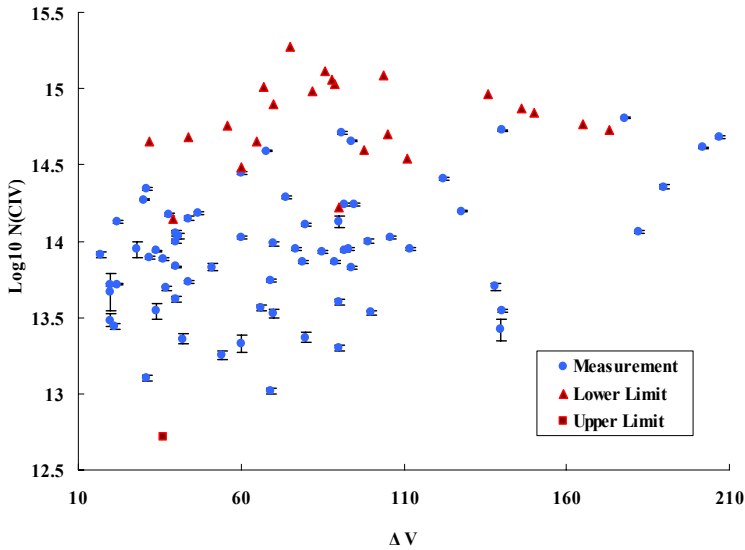


Fig. 3.—Plot of velocity range of galaxies versus column density of C_{IV} . Sample size of 100 QSOs (including limits), with Pearson Correlation Coefficient = .493, Spearman Correlation Coefficient = .49, and P Value < .0001. Sample set P+F+L. For details, see table 1.

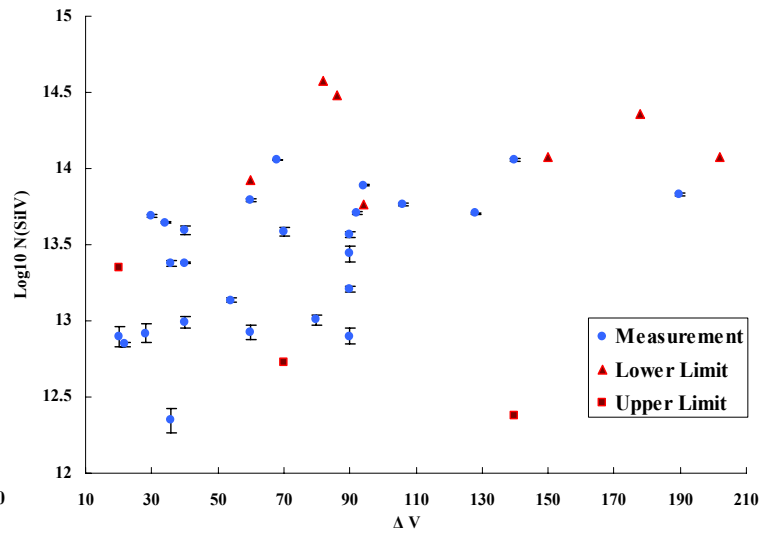


Fig. 4.—Plot of velocity range of galaxies versus column density of Si_{IV} . Sample size of 36 QSOs (including limits), with Pearson Correlation Coefficient = .434, Spearman Correlation Coefficient = .522, and P Value < .01. Sample set P. For details, see table 1.

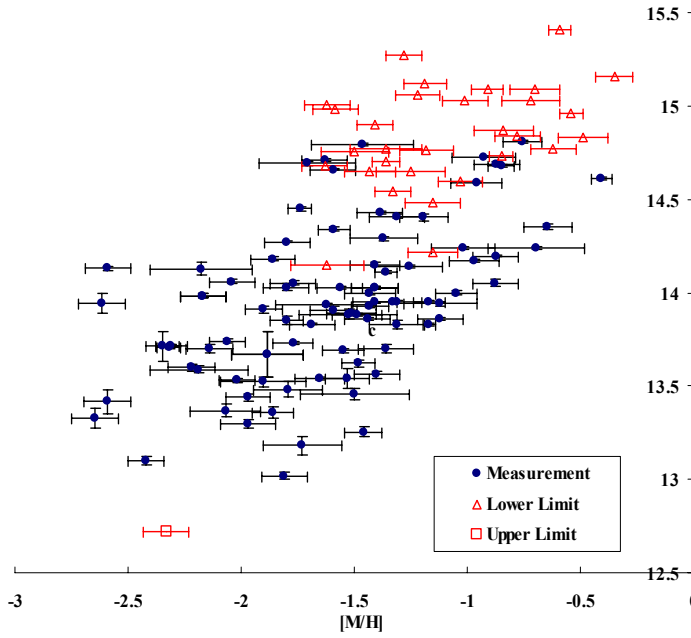


Fig. 5.—Plot of metallicity vs. column density of C_{IV} . Sample size of 119 QSOs (including limits), with Pearson Correlation Coefficient = .648, Spearman Correlation Coefficient = .65 and P Value < .0001. Sample set P+F+L. For details, see table 1.

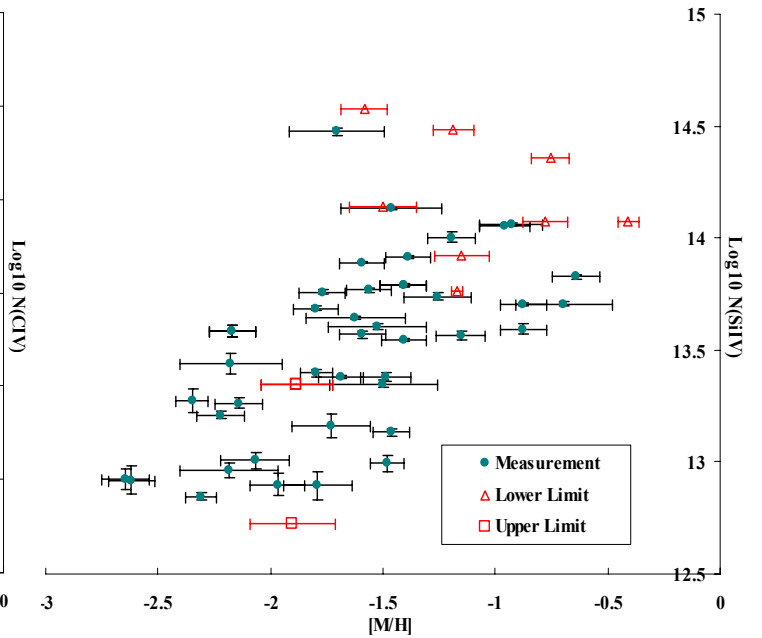


Fig. 6.—Plot of metallicity vs. column density of Si_{IV} . Sample size of 55 QSOs (including limits), with Pearson Correlation Coefficient = .675, Spearman Correlation Coefficient = .703 and P Value < .0001. Sample set P. For details, see table 1.

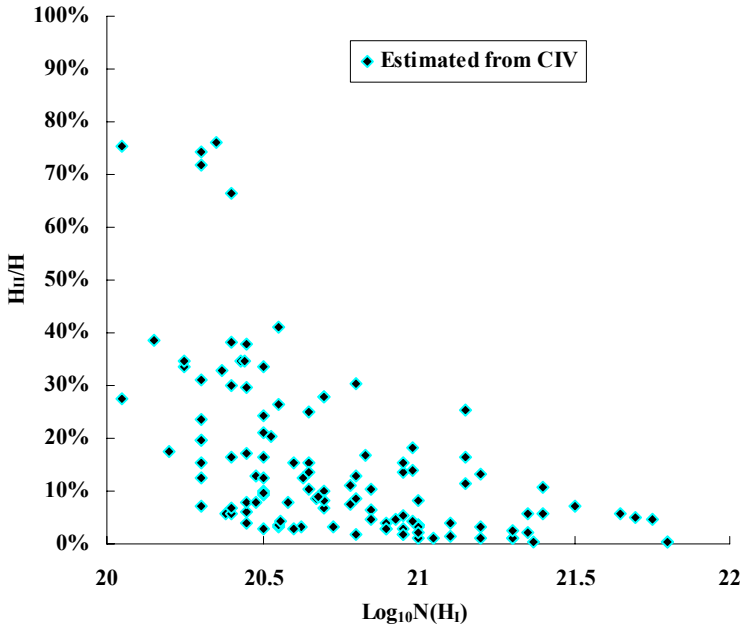


Fig. 7.—Plot of column density of neutral hydrogen vs. fraction of ionized hydrogen (*estimated from C_{IV}*). Sample size of 119 QSOs (including limits), with Pearson Correlation Coefficient = -0.536, Spearman Correlation Coefficient = -0.639, and P Value < .0001. Sample set P+F+L. For details, see table 1.

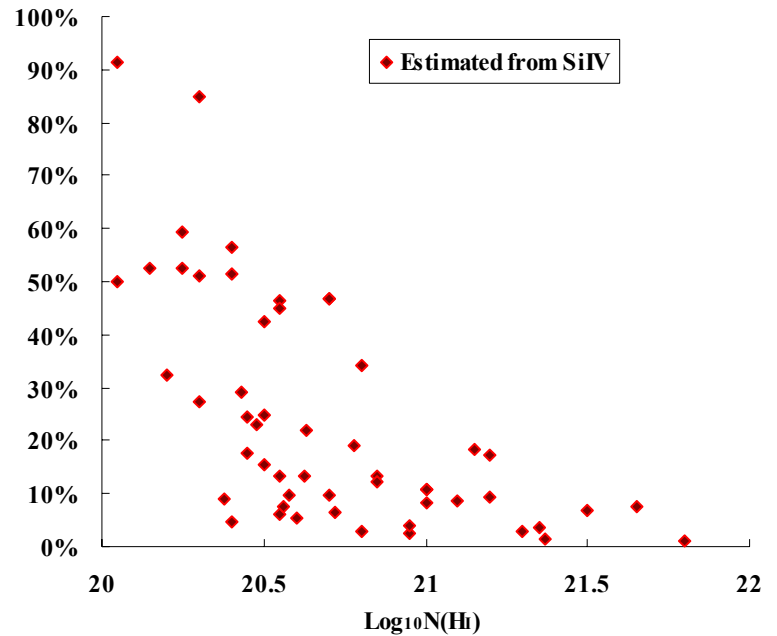


Fig. 8.—Plot of column density of neutral hydrogen vs. fraction of ionized hydrogen (*estimated from Si_{IV}*). Sample size of 53 QSOs (including limits), with Pearson Correlation Coefficient = -0.642, Spearman Correlation Coefficient = -0.704, and P Value < .0001. Sample set P. For details, see table 1.

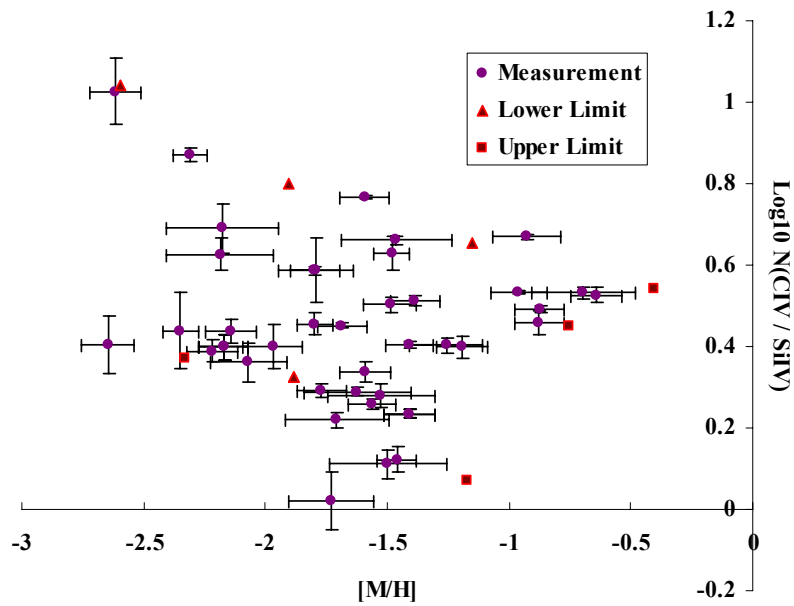


Fig. 9.—Plot of metallicity vs. column density ratio of C_{IV} / Si_{IV} . There is no correlation. Sample size of 51 QSOs, including limits. Sample set P. For details, see table 1.

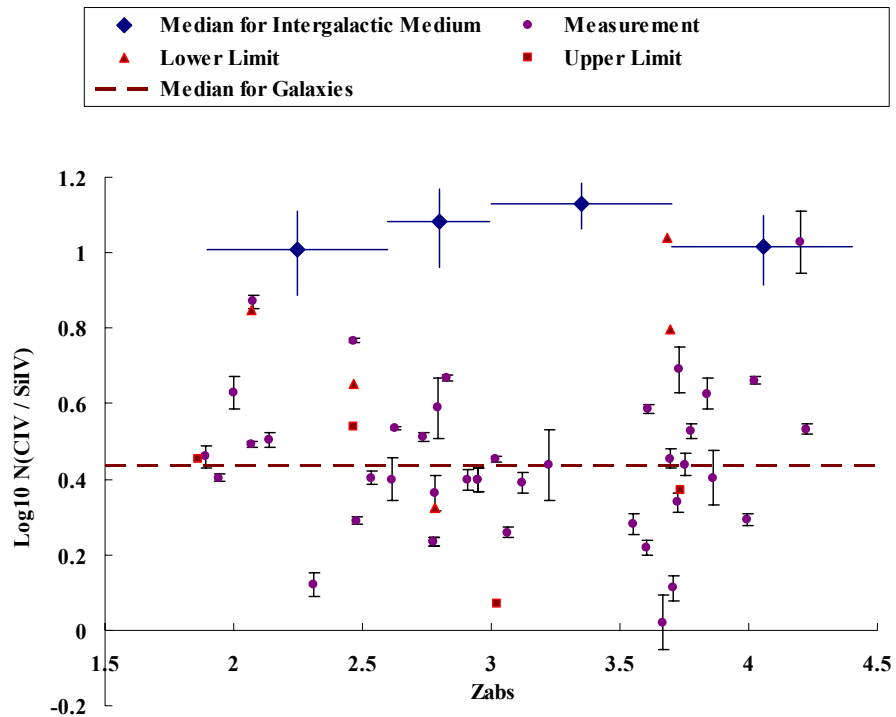


Fig. 10.—Plot of Redshift vs. column density ratio of C_{IV} / Si_{IV} . There is no correlation. The dotted line represents the *median* of C_{IV} / Si_{IV} , in these distant galaxies. On the other hand, the blue dots represent *median* of intergalactic medium (Boksenberg 2003). Sample size of 51 QSOs, including limits. Sample set P.