Elemental Abundance Measurements in Low-redshift Damped Lyman-α Absorbers

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Abstract

We present elemental abundance measurements for 9 damped Ly-α systems (DLAs) and 1 sub-DLA at 0.1 \( \lesssim z \lesssim 1.5 \) from recent observations with the Multiple Mirror Telescope. Most of these absorbers are found to be metal-poor, while 2 are found to have \( \approx 30 \text{--} 50\% \) solar metallicities. Combining our data with other data from the literature, we find that the systems with higher [Zn/H] also have stronger depletion as measured by [Cr/Zn] and [Fe/Zn]. The relationship between the metallicity and H I column density is also investigated. Together with our previous MMT survey (Khare et al. 2004) we have discovered 2 of the 4 known absorbers at \( z < 1.5 \) that lie above (although near) the “obscuration threshold”. This appears to be a result of selecting absorbers with strong metal lines in our sample. It would be interesting to find other similar systems by observing a larger sample and study how much such systems contribute to the cosmic budget of metals. Finally, an analysis of the \( N_{\text{HI}} \)-weighted mean metallicity vs. redshift for our sample combined with data from the literature supports previous conclusions that the \( N_{\text{HI}} \)-weighted mean global DLA metallicity rises slowly at best and falls short of solar levels by a factor of \( > 4 \) even at \( z = 0 \).

Key words: Quasars: absorption lines-ISM: abundances, dust, extinction

1 INTRODUCTION

Absorption line systems in QSO spectra provide a unique window into the high-redshift universe. These systems have been detected in the range \( 0 \lesssim z \lesssim 6 \), corresponding to \( \approx 90\% \) of the age of the universe. As the absorption line strengths depend primarily on the gas content, they are selected independent of the stellar luminosities of the galaxies. Thus in principle they may be expected to provide less biased probes of galaxies than objects used to study the high redshift universe through emission, which are biased toward brighter galaxies including actively star forming galaxies such as Lyman-break galaxies, active galaxy nuclei, and QSOs.

Damped Lyman-α Absorption systems (DLAs) with \( \log N_{\text{HI}} \geq 20.3 \) and sub-DLAs with \( 19.0 \leq \log N_{\text{HI}} < 20.3 \) seen in QSO spectra can be used as probes of the neutral gas content of the universe. DLAs and sub-DLAs are known to contain the majority of the neutral gas in the universe (e.g. Wolfe et al. 1995, Peroux et al. 2003). With such high neutral hydrogen column densities DLAs are believed to be closely linked to galaxies. DLAs may also be the neutral gas reservoirs used in star formation. Furthermore, DLAs and sub-DLAs provide detailed gas-phase abundances of a number of elements and can thus be used to test galactic chemical evolution models.

Several elements have been detected in DLAs including C, N, O, Mg, Si, S, Ca, Ti, Cr, Mn, Fe, Ni, and Zn. Zn is often used as a tracer of gas-phase metallicity as it is typically relatively undepleted in the Galactic ISM when the fraction of H in molecular form is low, which is the case for DLAs (Sembach et al. 1995). Zn tracks the abundance of Fe in Galactic stars (Mishenina et al. 2002), and the lines of Zn II \( \lambda\lambda \ 2026,2062 \) are fairly weak and unsaturated. Also, Zn II can be detected with ground-based observations over a wide range of redshifts (0.6 \( \lesssim z \lesssim 3.5 \)). Elemental abundances relative to Zn such as [Cr/Zn] or [Fe/Zn] can be used to estimate the dust content of the QSO absorber. Here and throughout the paper we adopt the standard notation \( [X/H] = \log (N_X/N_{\text{HI}}) - \log (X/\text{H}_\odot) \).

If DLAs do constitute a representative sample of galaxies, it would be expected that their global mean metallicity of these ob-
objects should rise to roughly solar values at low redshift. It is uncertain whether or not DLAs show this trend. The most recent evaluations of this by Kulkarni and Fall (2002), Prochaska et al. (2003b), and Kulkarni et al. (2005) show at best a weak evolution in the metallicity-redshift relation with slopes of $\sim 0.20 \pm 0.07$.

One proposed explanation of the lack of metal-rich DLAs in observed samples is that this population is being under-sampled due to dust obscuration (e.g.; Boisse et al. 1998; Pei & Fall 1993; Vladilo & Peroux 2005). Absorbers with higher metallicity may also contain more dust, making any background QSOs found that $N_{\text{HI}}$ is $\lesssim 1$ at a look-back time of the age of the universe. The paucity of Zn measurements at low $z$ is primarily because the Zn abundance is only marginally higher but within error limits of previous samples. However, the effects of dust may be expected to be stronger at low redshifts. The role of dust in DLAs is still unclear, and more investigation is needed. We discuss dust and reddening in our sample of absorbers in more detail in § 5.2.

Assuming a cosmology with $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$, $z < 1.5$ spans $\sim 70\%$ of the age of the universe. It is therefore critical to obtain more abundance measurements at low redshift. One reason for the uncertainty in the metallicity-redshift relation is the lack of abundance measurements in low-redshift absorbers. In fact $\sim 70\%$ of the existing Zn measurements are for $2 \leq z \lesssim 3.5$, which corresponds to only $\sim 10\%$ of the age of the universe. The paucity of Zn measurements at low $z$ is primarily because the Zn $\lambda 2026$, 2062 lines lie in the UV for $z < 0.6$, and deeply in the blue end of the spectrum for $0.6 \leq z \lesssim 1.3$, where most existing spectrographs are inefficient. In this paper we present new MMT observations toward 10 QSOs. The observations presented in this paper increases the size of the sample of absorbers at $z \lesssim 1.5$ by $\sim 40\%$.

In § 2 we describe our observations and our data reduction routines. § 3 describes the calculation of column densities. In § 4 we present notes on the individual objects. We present results from these measurements in § 5, and in § 6 we discuss our results and their implications.

## 2 OBSERVATIONS AND DATA REDUCTION

Our sample consists of 10 confirmed DLAs and sub-DLA absorbers at $0.2 \leq z \leq 1.5$, for which $N_{\text{HI}}$ is known from $HST$ spectra (Rao et al. 2005). Seven of these targets were observed in the Sloan Digital Sky Survey (SDSS), and most show the presence of strong Mg II or Fe II absorption features from SDSS spectra. Apparent magnitudes for these 7 QSOs are available from the SDSS Quasar Catalog III, Data release 3 (Abazajian et al. 2005).

The spectra presented here were obtained at the Multiple Mirror Telescope (MMT) during two separate epochs, 2004 May and 2005 February. Nearly 2.7 nights out of a total of 5 were lost due to poor weather. The Blue channel spectrograph was used with the 832 l mm$^{-1}$ grating in the first order, or the 1200 l mm$^{-1}$ grating in the second order, depending on the redshift of the absorber. A CuSO$_4$ blocking filter was used with the 832 l mm$^{-1}$ grating to block first order red light. The central wavelength for the 832 l mm$^{-1}$ grating was at 3670 Å and 3600 Å for the 2004 May and 2005 Feb epochs respectively. For the 1200 l mm$^{-1}$ grating the wavelength was centered at 4935 Å and 4770 Å during the 2004 May and 2005 Feb epochs respectively. In order to achieve the desired S/N while minimizing cosmic rays, multiple exposures of each target were taken with exposure times ranging from 1800 to 2700 s depending on the magnitude of the QSO. Each target observation was followed by a comparison spectrum from a He$^+$/Ne$^+$/Ar lamp for wavelength calibration. Quartz flat fields and bias frames were taken at both the beginning and end of the night. Table 1 lists the vacuum wavelengths and oscillator strengths used in identification of the features and subsequent analysis. Table 2 gives a summary of our observations.

Data reduction was carried out using standard IRAF routines. Images were bias subtracted, trimmed, and flat fielded using the task CCDPROC. These reduced 2-d spectra were then extracted and wavelength calibrated using the task DOSLIT. The wavelengths were converted to vacuum using the task CONINUUM. The solar abundances were adopted from Lodders et al. (2003).

Table 1. Atomic Data

| Species | $\lambda_{\text{rest}}$ Å | $f$ | References |
|---------|-----------------|----|-------------|
| Be II | 3130.4219 | 3.321E-1 | 1 |
| C IV | 1548.2040 | 1.899E-1 | 1 |
| Mg I | 1827.9351 | 2.420E-2 | 1 |
| Mg II | 2796.3543 | 6.155E-1 | 1 |
| Si II | 1808.0129 | 2.080E-3 | 1 |
| Si IV | 1393.7662 | 5.30E-1 | 1 |
| Ca II | 3933.6614 | 6.267E-1 | 1 |
| Ti II | 9190.6123 | 1.040E-1 | 1 |
| Cr II | 2056.2569 | 1.030E-1 | 1 |
| Mn II | 2576.8770 | 3.610E-1 | 1 |
| Fe II | 2260.7805 | 2.440E-3 | 4 |
| Zn II | 2026.1370 | 5.010E-1 | 1.6 |
| References | (1) Abazajian et al. 2005; (3) Wiesse et al. 1996; (4) Bergeson et al. 1996; (5) Bergeson et al. 1996; (6) Bergeson & Lawler 1993a |
3 ESTIMATION OF COLUMN DENSITIES

Column densities were estimated by fitting the observed absorption line profiles using the package FITS6P [Welty et al.[1991]], which has evolved from the code by Vidal-Madjar et al.[1977]. FITS6P iteratively minimizes the \( \chi^2 \) value between the data and a theoretical Voigt profile that is convolved with the instrumental profile. All lines were fit with a single component Voigt profile. If a multiplet was available such as Fe II \( \lambda \lambda 2344, 2374, 2382 \) the lines were fit simultaneously until convergence for a common \( N \), \( v \), and \( \sigma \). Equivalent width measurements were obtained with the package SPECP, also written by D.E. Welty. The 1σ equivalent width uncertainties were estimated using the photon noise uncertainties and the continuum uncertainties obtained by allowing the continuum to vary by \( \pm 10\% \). In all cases these uncertainties were dominated by the photon noise uncertainties.

The prescription of Khare et al.[2004] for fitting the Cr II and Zn II lines of was followed. Specifically, the Cr II \( \lambda \lambda 2056, 2066 \) lines were fit simultaneously to obtain \( N \), \( b_{eff} \), and \( v \). Equivalent width measurements were obtained with the package SPECP, also written by D.E. Welty. The 1σ equivalent width uncertainties were estimated using the photon noise uncertainties and the continuum uncertainties obtained by allowing the continuum to vary by \( \pm 10\% \). In all cases these uncertainties were dominated by the photon noise uncertainties.

The prescription of Khare et al.[2004] for fitting the Cr II and Zn II lines of was followed. Specifically, the Cr II \( \lambda \lambda 2056, 2066 \) lines were fit simultaneously to obtain \( N \), \( b_{eff} \), and \( v \). Then, the blended Cr II+Zn II \( \lambda 2062 \) line was fit starting with the values obtained from the previous fits, holding the Cr II component fixed. The Zn II \( \lambda 2026 \) line was then fit using the \( b_{eff} \) and \( v \) value from the Cr II \( \lambda \lambda 2056, 2062 \) fit while holding the Mg I component fixed. If the Cr II \( \lambda 2056 \) line could not be fit due to noise, we fit the Zn II \( \lambda 2026 \) line, holding the Mg I \( \lambda 2056 \) contribution fixed, then fit the Cr II + Zn II \( \lambda 2062 \) blend holding the Zn II component fixed. The Mg I column density was estimated by fitting the Mg I \( \lambda 2852 \) line from the SDSS spectra. York et al.[2006] showed that the Mg I \( \lambda 2852 \) line lies on the linear portion of the curve of growth for \( W_{rest}^{\lambda 2852} \sim 0.6 \) to 0.7. The Mg I \( \lambda 2852 \) line is often moderately saturated due to the line profile being composed of multiple components that could not be resolved at the resolution of our data.

4 DISCUSSION OF INDIVIDUAL OBJECTS

Table 2. Summary of Observations

| QSO        | \( g \) | \( z_{em} \) | \( z_{DLA} \) | \( \log N_{HI} \) | Grating Lines mm\(^{-1}\) | FWHM | Exposure Time | Epoch  |
|------------|--------|-------------|-------------|----------------|-----------------------|-----|--------------|--------|
| 0738+313   | 16.1   | 0.630       | 0.0912      | 21.18±0.06     | 832                   | 1.10| 3000         | 2005 Feb. |
| ...        | ...    | ...         | ...         | ...            | ...                   | ... | ...          | ...    |
| 0827+243   | 17.3   | 0.941       | 0.5247      | 20.30±0.05     | 832                   | 1.10| 3600         | 2005 Feb. |
| 1010+0003  | 18.3   | 1.398       | 1.2651      | 21.52±0.07     | 1200                  | 1.33| 3600         | 2005 Feb. |
| 1107+0003  | 18.7   | 1.741       | 0.9547      | 20.26±0.14     | 832                   | 1.10| 8100         | 2005 Feb. |
| 1137+3907  | 17.4   | 1.023       | 0.7190      | 21.10±0.10     | 832                   | 1.10| 5400         | 2004 May  |
| 1225+0035  | 18.9   | 1.226       | 0.7731      | 21.38±0.11     | 832                   | 1.10| 5400         | 2005 Feb. |
| 1501+0019  | 18.1   | 1.930       | 1.4832      | 20.85±0.13     | 1200                  | 1.33| 5400         | 2004 May  |
| 1712+5559  | 18.7   | 1.356       | 1.2095      | 20.72±0.05     | 1200                  | 1.33| 5400         | 2004 May  |
| 1715+4606  | 18.1   | 0.989       | 0.6511      | 20.44±0.13     | 832                   | 1.10| 5400         | 2004 May  |
| 1733+5533  | 18.1   | 1.074       | 0.9981      | 20.70±0.03     | 832                   | 1.10| 3600         | 2004 May  |
### Table 3. Equivalent Widths

| QSO         | $z_{abs}$ | Species | $\lambda_{rest}$ | $W_{rest}$ | QSO         | $z_{abs}$ | Species | $\lambda_{rest}$ | $W_{rest}$ |
|-------------|-----------|---------|------------------|-----------|-------------|-----------|---------|------------------|-----------|
| 0738+313    | 0.0912:A  | Ca II   | 3933             | 189±13    | 1.4832:A    | Mg I      | 2852    | 952±18           |
| $z_{em} = 0.630$ |          |         |                  |           |             |           |         |                  |           |
| 0.2210:B    | Ca II     | 3969    | 54±10            | 1901+0019 | Al III      | 1854      | 334±17  |
|             | Ca II     | 3933    | 63±10            |           | Al III      | 1862      | 216±18  |
|             | Ca II     | 3969    | 35±10            |           | Si II       | 1808      | 295±16  |
| Ti II       | 3383      | <14     |                  |           | Cr II       | 2056      | 105±16  |
| Ti II       | 3383      | <33     |                  |           | Zn II+Cr II | 2062      | 191±16  |
| 0.5247:B    | Mg I      | 2852    | 602±29           |           | 1.8510:B    | C IV      | 1548    | 154±18           |
|             | Mg II     | 2796    | 2416±27          |           | C IV        | 1550      | 116±18  |
|             | Mg II     | 2803    | 2316±28          |           | 1.9260:C    | C IV      | 1548    | 254±14           |
| Ti II       | 3383      | <30     |                  |           | C III       | 1550      | 154±14  |
| 1.2651:A    | Mg I      | 2852    | 404±18           |           | Al II       | 1670      | 88±11   |
| $z_{em} = 1.398$ |         |         |                  |           |             |           |         |                  |           |
| Al III      | 1854     | 104±21  | 1712+5559        | 1.1590:A  | Cr II       | 2056      | <33     |
| Al III      | 1862     | <46     | 1.356            |           | Cr II       | 2066      | <33     |
| Cr II       | 2056     | 91±19   |                  |           | Fe II       | 2344      | 415±30  |
| Cr II       | 2066     | 69±15   |                  |           | Fe II       | 2374      | 240±27  |
| Fe II       | 2249     | 144±26  |                  |           | Fe II       | 2382      | 592±32  |
| Fe II       | 2260     | 184±26  |                  |           | Zn II+Mg I  | 2026      | <33     |
| Fe II       | 2344     | 564±28  |                  |           | Zn II+Cr II | 2062      | <33     |
| Fe II       | 2374     | 543±35  | 1.2093:B         | Mg I      | 2852      | 367±18  |
| Fe II       | 2382     | 715±30  |                  |           | Cr II       | 2056      | <35     |
| Zn II+Mg I  | 2026     | 233±23  |                  |           | Cr II       | 2066      | <35     |
| Zn II+Cr II | 2062     | 181±22  |                  |           | Fe II       | 2344      | 973±33  |
| 1.741       | Mn II     | 2576    | <30               |           | Fe II       | 2374      | 723±31  |
| $z_{em} = 1.741$ |         |         |                  |           |             |           |         |                  |           |
| Mn II       | 2594     | <34     |                  |           | Fe II       | 2382      | 1168±35|
| Mn II       | 2606     | <20     |                  |           | Zn II+Mg I  | 2026      | <35     |
| Fe II       | 2344     | 139±36  |                  |           | Zn II+Cr II | 2062      | <35     |
| Fe II       | 2374     | <47     | 1715+4606        | GAL       | Ca II       | 3933      | 1556±46 |
| Fe II       | 2382     | 269±36  |                  |           | Ca II       | 3969      | 205±36  |
| Fe II       | 2586     | 185±25  | 0.6544:A         | Cr II     | 2056      | <165    |
| Fe II       | 2600     | 342±27  |                  |           | Cr II       | 2066      | <165    |
| 0.9547:B    | Ti II     | 1910    | <42               |           | Fe II       | 2344      | 1264±42 |
| Cr II       | 2056     | <42     |                  |           | Fe II       | 2374      | 851±40  |
| Cr II       | 2066     | <27     |                  |           | Fe II       | 2382      | 1556±46 |
| Zn II+Mg I  | 2026     | <27     |                  |           | Zn II+Mg I  | 2026      | <165    |
| Zn II+Cr II | 2062     | <27     |                  |           | Zn II+Cr II | 2062      | <165    |
| 1711:C      | Si IV     | 1393    | 618±36           | 1733+5533 | GAL        | Ca II     | 3933      | 482±36 |
| Si IV       | 1402     | 447±40  |                  |           | Ca II       | 3969      | 257±33  |
| 1.023       | GAL       | Ca II   | 3933             | 336±58    | Mg I        | 2852      | 362±18  |
| $z_{em} = 1.023$ |         |         |                  |           |             |           |         |                  |           |
| Ca II       | 3969     | 241±51  | 0.9984:A         | Al III    | 1854      | 179±31  |
| Cr II       | 2056     | <74     |                  |           | Al III      | 1862      | 100±27  |
| Cr II       | 2066     | <74     |                  |           | Si II       | 1808      | 178±30  |
| Fe II       | 2249     | 150±31  |                  |           | Ti II       | 1910      | <30     |
| Fe II       | 2260     | 291±34  |                  |           | Cr II       | 2056      | <35     |
| Fe II       | 2344     | 1768±67 |                  |           | Cr II       | 2066      | <29     |
| Fe II       | 2374     | 1300±37 |                  |           | Zn II+Mg I  | 2026      | <29     |
| Fe II       | 2382     | 2009±70 |                  |           | Zn II+Cr II | 2062      | <29     |
| Zn II+Mg I  | 2026     | 447±56  | 1.1496:B         | C IV      | 1548      | 453±55  |
| Zn II+Cr II | 2062     | 266±70  |                  |           | C IV        | 1550      | 341±51  |
| 1.226       | Mg I      | 2852    | 929±18           |           | Al II       | 1670      | <40     |
| $z_{em} = 1.226$ |         |         |                  |           |             |           |         |                  |           |
| Cr II       | 2056     | 259±81  |                  |           | Al III      | 1854      | <30     |
| Cr II       | 2066     | 177±76  |                  |           | Al III      | 1862      | <30     |
| Fe II       | 2249     | 339±73  |                  |           | Si II       | 1808      | <25     |
| Fe II       | 2260     | 372±80  |                  |           | Zn II+Mg I  | 2026      | <26     |
| Zn II+Cr II | 2062     | 181±91  |                  |           | Zn II+Cr II | 2062      | <26     |

- $^{a}$: From SDSS spectra.
- $^{b}$: Entries with GAL identifier are from lines originating in the Milky Way.
- $^{c}$: The Galactic Ca II λ 3933 line and Fe II λ 2383 line from the DLA at $z_{abs} = 0.6544$ are blended in the spectra.
Figure 1. Combined and normalized spectrum of Q0738+313. The expected positions of several lines of interest are marked above the continuum with their rest wavelength and species. The letters after the wavelengths refer to the different systems indicated at the top of the figure. An "X" signifies a defect in the CCD.
Figure 2. Same as Figure 1, but for Q0827+243.
Figure 3. Same as Figure 1, but for Q1010+0003.
Figure 4. Same as Figure 1, but for Q1107+0003.
Figure 5. Same as Figure 1, but for Q1137+3907.
Figure 6. Same as Figure 1, but for Q1225+0035.
Figure 7. Same as Figure 1, but for Q1501+0019.
Figure 8. Same as Figure 1, but for Q1712+5559.
Figure 9. Same as Figure 1, but for Q1715+4606.
Figure 10. Same as Figure 1, but for Q1733+5533.
Abundances in Low-redshift DLA systems

5 RESULTS AND DISCUSSION

5.1 Relative Abundances

The observed relative abundances of the elements are a combination of both the nucleosynthetic processes and of dust depletion. If dust is significantly present in DLAs, then refractory elements such as Cr, Mn, Fe, Co, and Ni should show substantial depletions. As already discussed in § 1, Zn is a relatively undepleted element due to its low condensation temperature. Ratios such as [Cr/Zn] and [Fe/Zn] are therefore a measure of dust depletion. Table 5 lists abundances of Cr, Fe, and Ti relative to Zn for the systems in our sample. Also given is the metallicity [Zn/H]. Although it is customary to estimate metallicity based on measurements of N_{ZnII}, it has been shown that [Zn/H] is not much affected by ionization (Vladilo et al. 2001).

No Ti II was found in any of the systems sampled. We determined [Ti/Zn] upper limits of -1.01 and -1.24 for the DLAs toward Q1010+0003 and Q1501+0019 respectively. The measured [Fe/Zn] in Q1010+0003 was also sub-solar (-0.69) also suggesting dust depletion. No Fe lines were sampled in the spectra of Q1501+0019, so [Fe/Zn] could not be measured.

Si is an α-capture element, and its abundance relative to Fe group elements can provide clues into the chemical evolution of DLAs. Disk stars in the Milky Way show a systematic decrease in [α/Fe] with increasing [Fe/H], which indicates an increase with time of Fe contributed to the ISM from type Ia supernovae, relative to type II supernovae (Edvardsson et al. 1993). Prochaska
true, then one would expect the most metal rich absorbers to be plotted. There is intrinsic scatter in the data, which is to be expected from the literature. Only detections, not limits have been plotted. Both figures 11 and 12 show a trend toward higher depletion with higher metallicity. Previous investigations have shown a similar anti-correlation between [Cr/Zn] or [Fe/Zn] and [Zn/H] although the vast majority of their data set has come from absorbers at $z \geq 1.5$ (Pettini et al. 1997; Prochaska & Wolfe 2002; Akerman et al. 2005). Our study increases the number of Zn measurements at $z < 1.0$ by $\sim 30\%$. A Spearman rank-order correlation test on this data set gives $R_S=0.428$, with a probability of obtaining such a value by chance of $P(R_S)=6.00 \times 10^{-3}$.

5.2 Dust Obscuration Bias

Several studies have tried to understand whether current DLA observations are affected by a dust obscuration bias. Recently, York et al. (2006) conducted a survey of 809 Mg II systems from the SDSS with $1.0 \leq z \leq 1.9$ and found that QSOs with an intervening absorber are at least three times more likely to have highly reddened spectra than QSOs without any absorption systems in their spectra. Furthermore, York et al. (2006) found a trend toward higher Zn II column densities but lower [Zn/H] and lower abundances of the first ions as the reddening E(B-V) increased. Significant red-
Table 5. Relative Abundances

| QSO          | \( z_{abs} \) | \([\text{Zn/H}]\) | \([\text{Cr/Zn}]\) | \([\text{Fe/Zn}]\) | \([\text{Ti/Zn}]\) | \([\text{Si/Zn}]\) |
|--------------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Q0738+313    | 0.0912      | \(<-1.14^a\)   | \(>-0.21^a\)   | \(>-0.48^a\)   | \(\cdots\)     | \(\cdots\)     |
| ...          | 0.2213      | \(<-0.7^a\)    | \(>-0.7^a\)    | \(\cdots\)     | \(\cdots\)     | \(\cdots\)     |
| Q0827+243    | 0.5247      | \(<-0.04^a\)   | \(<-0.3^a\)    | \(\cdots\)     | \(\cdots\)     | \(\cdots\)     |
| Q1010+0003   | 1.2651      | -1.19           | -0.46           | -0.54           | \(<-1.01\)     | \(\cdots\)     |
| Q1107+0003   | 0.9547      | \(<-0.72\)     | \(\cdots\)     | \(\cdots\)     | \(\cdots\)     | \(\cdots\)     |
| Q1137+3907   | 0.7190      | -0.30           | -0.67           | -0.82           | \(\cdots\)     | \(\cdots\)     |
| Q1225+0035   | 0.7731      | \(<-1.15\)     | \(>0.09\)      | \(>0.07\)      | \(\cdots\)     | \(\cdots\)     |
| Q1501+0019   | 1.4832      | -0.54           | -0.56           | \(\cdots\)     | \(<-1.24\)     | -0.28           |
| Q1712+5559   | 1.2093      | \(<-1.07\)     | \(\cdots\)     | \(<-0.51\)     | \(\cdots\)     | \(\cdots\)     |
| Q1715+4606   | 0.6511      | \(<-0.61\)     | \(\cdots\)     | \(<-0.78\)     | \(\cdots\)     | \(\cdots\)     |
| Q1733+5533   | 0.9981      | \(<-1.13\)     | \(\cdots\)     | \(\cdots\)     | \(\cdots\)     | \(>0.37\)      |

\(^a\): Abundance measurements from Kulkarni et al. (2005).

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Figure 11. \([\text{Cr/Zn}]\) vs. \([\text{Zn/H}]\) for our data as well as measurements from the literature. Only detections are plotted.

Figure 12. \([\text{Fe/Zn}]\) vs. \([\text{Zn/H}]\) for our data as well as from the literature. Only detections are plotted.

dening has also been seen in a sample of strong Ca II absorbers (Wild & Hewett 2005; Wild et al. 2006).

If dust obscuration effects are significant, highly reddened QSOs would be under-sampled due to their faintness. Boisse et al. (1998) pointed out that there is a deficit of systems with high \(N_{\text{HI}}\) and high \([\text{Zn/H}]\), and suggested that this may be caused by a dust obscuration bias (because such systems may also have high dust content and may obscure the background quasars more). They speculated that observations of fainter QSOs might reveal systems with high \(N_{\text{HI}}\) and high metallicity. Figure 13 shows a plot of \([\text{Zn/H}]\) vs. \(N_{\text{HI}}\) for DLAs from our sample as well as the literature (Akerman et al. 2005, Rao et al. 2005). Clearly, there is a deficit of systems that are seen with both low metallicity and low \(N_{\text{HI}}\). This could be attributed to observational limitations in detecting weak Zn II lines, although recent high resolution, high S/N observations still find a dearth of systems in this region. More interestingly though, there are few absorbers with high metallicity and high \(N_{\text{HI}}\), as noted by Boisse et al. (1998) and also by Akerman et al. (2005). This cannot be credited to observational limitations, because systems with similar metallicities have been detected at lower \(N_{\text{HI}}\), and seems to suggest that these types of systems are being under-sampled. Also, there is nothing unphysical about systems with high \(N_{\text{HI}}\) and high metallicity. It is thus surprising that only 3 points from the literature (of which 1 came from our previous sample in Khare et al. 2004) lie above the dashed line indicating the empirical “obscuration threshold” \(\log N_{\text{ZnII}} < 13.15\) suggested by Boisse et al. (1998).

Two of the systems at \(z < 1.5\) that lie above the “obscuration threshold” came from our samples (this paper and Khare et al. 2004), although it is still remarkable that all points in Fig. 13 lie fairly close to the threshold suggested by Boisse et al. (1998). Indeed, all but two of the points are consistent, within the errors, with being below the obscuration threshold. It should also be noted that the Boisse et al. threshold is not meant to be a hard limit, but an observationally determined boundary based on the much smaller sample available to Boisse et al. (1998). Indeed, hydrodynamical simulations by Cen et al. (2003) predict the existence of absorbers above this threshold. Thus, it may not be completely surprising that we are now finding some objects above the threshold.

We emphasize that the higher proportion of systems with \(N_{\text{ZnII}}\) close to the Boisse et al. threshold in our studies (this paper and Khare et al. 2004) is not due to errors in the column density estimations from the moderate resolution of the MMT spectrograph. Column densities derived from our observations of several systems with both the MMT and with the higher resolution (~ 5 \(\text{km s}^{-1}\)
Ultraviolet-Visual Echelle Spectrograph (UVES) on the Very Large Telescope (VLT) agree to within 0.1 dex \cite{Peroux2006}. A similar agreement was also found between column densities derived by Khare et al. (2004) from MMT spectra and those derived by Rao et al. (2005b) from Keck HIRES spectra. The reason for the higher proportion of metal-rich systems in our studies is that the targets in this paper and Khare et al. (2004) were chosen partially because of strong metal line absorption features seen in SDSS spectra. Thus, these systems may have been more likely to have higher Zn column densities. Indeed, composite SDSS quasar spectra indicate that systems with larger $W_{\text{rest}}$ of Mg II $\lambda 2796$ tend to have stronger Zn II lines \cite{Nestor2003,York2006}. One of our two systems has a large depletion consistent with the obscuration selection effect while the other system shows a moderate depletion, so it is not clear whether the small number of such systems found so far is caused by dust obscuration or small sample size especially at $z < 1.5$ where the effects of dust are expected to be the most pronounced \cite{Boissee1998}. It could also be the case that the most metal rich systems are truly rare.

Figures 14 and 15 show the dust content as measured by [Cr/Zn] and [Fe/Zn] respectively vs. $\log N_{\text{HI}}$ for these DLAs as well as those from the literature. As can be seen, there is very little trend in the data. It may appear surprising from Figs. 11-15 that there is no (anti)-correlation between [Cr/Zn] (or [Fe/Zn]) and $\log N_{\text{HI}}$ even though there is an (anti)-correlation between [Cr/Zn] (or [Fe/Zn]) and [Zn/H] and between [Zn/H] and $\log N_{\text{HI}}$. If one traces some of the extreme points in Figs. 11 or 12 and 13 that do show the correlation, one can see that the correlations in these two figures arise from different systems. For example, consider the 3 points A, B, and C with (Cr/Zn), [Zn/H], $\log N_{\text{HI}} \approx (-0.46, -1.19, 21.52); (-0.74, -0.30, 21.10);$ and (-0.54; -57; 20.85). Points such as A and B are responsible for the correlation in Fig 11. Points such as B and C are responsible for the correlation in Fig. 13. When one plots these points in Fig. 14, there is no strong correlation. (More generally, if data sets x,y and y,z show correlations, x and z do not necessarily show a correlation; whether or not they do depends on the distribution of the individual data values. See, for example, Casella & Berger 2002.)

5.3 Constraints on Metallicities and Potential Implications for Metallicity Evolution

The Zn abundances for our DLAs are listed in Table 5. In 4 of the systems at $0.6 < z < 1.5$ the abundances of Zn are about 100% solar or lower, while in 2 systems, the abundances are 50-50 % solar. We now briefly discuss the implications of our data for the metallicity evolution of DLAs. Our analysis is based on the statistical procedures outlined in Kulkarni & Fall (2002), and uses our data, the data compiled in Kulkarni et al. (2005), and other recent data from the literature \cite{Rao2005,Akerman2005}. We binned the combined sample of 109 DLAs in 6 redshift bins with 18 or 19 systems each and calculated the global $N_{\text{HI}}$-weighted metallicity in each bin. Figure 16 shows [Zn/H] vs. $z$ for the data in the literature as well as from this paper.

We constructed two samples for these 109 DLAs: a “maximum limits” sample where the Zn limits are treated as detections, and a “minimum limits” sample, where the Zn limits are treated as zeros. For an individual system these extreme cases cover the full range of possible values the Zn column densities can take in the case of the limits. The $N_{\text{HI}}$-weighted mean metallicity in the lowest redshift bin 0.1 < $z$ < 1.2 is $-0.78 \pm 0.11$ for the “maximum limits” sample and $-0.99 \pm 0.17$ for the “minimum limits” sample. The linear regression slope of the metallicity-redshift relation for the redshift range $0.1 < z < 3.9$ is $-0.18 \pm 0.07$ for the “maximum limits” sample, and $-0.25 \pm 0.10$ for the “minimum limits” sample. The corresponding estimates for the intercept of the metallicity-redshift relation are $-0.65 \pm 0.15$ for the “maximum limits” sample and $-0.63 \pm 0.21$ for the “minimum limits” sample. Thus our data support the conclusions of Khare et al. (2004) and Kulkarni et al. (2005) that the global mean metallicity of DLAs shows at best a slow evolution with redshift.

Fig. 13. [Zn/H] vs. $\log N_{\text{HI}}$ for our data as well as previous measurements from the literature. The dashed line indicates the empirical upper limit $N_{\text{ZnII}} < 13.15$ inferred from previous studies and suspected to be the “obscuration threshold”. Only detections are plotted.

6 CONCLUSIONS AND FUTURE WORK

The MMT observations presented here, together with our previous MMT and HST data have more than doubled the DLA Zn sample at $z < 1.5$ and more than tripled the sample at $z < 1$. Combining our data with data from the literature, we find that the systems with higher [Zn/H] also have stronger Cr depletion [Cr/Zn]. Analysis of the $N_{\text{HI}}$-weighted mean metallicity vs. redshift for our sample combined with previous data from the literature supports previous conclusions that the $N_{\text{HI}}$-weighted mean global DLA metallicity rises slowly at best and does not reach solar levels by $z = 0$.

Questions still remain pertaining to dust depletion and selection effects, and linked to this, the metallicity-redshift relationship of DLAs. Despite the large improvement from our surveys, DLA samples at $z < 1.5$ are still relatively small. Clearly, more observations of DLAs at $z < 1.5$ are needed for improved statistics in this vast epoch ($\sim 9$ Gyr). The large number of SDSS absorbers now available present a good opportunity for this purpose.

Two of our systems have higher $N_{\text{ZnII}}$ than the empirical upper limit ($N_{\text{ZnII}} < 13.15$) that has been attributed to dust obscuration in previous studies. The fairly high Zn abundances in these 2 DLAs suggests that metal-rich DLAs may be a rare class of objects, but can be found in a large enough sample. It would be interesting to confirm the metal-rich nature of these DLAs with higher resolution spectra in the future, and find similar other systems by observing a larger sample. If a large number of such systems are found, they may make a significant contribution to the cosmic budget of metals.
It has been suggested that the low metallicity found in DLAs is caused by metallicity gradients. On the basis of a small sample of objects Chen et al. (2005) reported a difference between emission line and absorption line metallicities. If metallicity gradients are present in DLAs, then metal poor DLAs may be more likely to be found because larger impact parameters are more probable. This may be because (a) they correspond to larger cross-sections and (b) they correspond to less dust. On the other hand, other studies (Schulte-Ladbeck et al. 2003; Bowen et al. 2005) have found no difference between emission and absorption line metallicities for other DLAs. Given that the metallicity gradients are not well established and fairly weak even in nearby spirals, it is not clear if metallicity gradients fully explain the low metallicities seen in DLAs.

So far, no DLA has been observed with a super-solar metallicity. The key to finding such systems may lie in observing faint, reddened QSOs. Vladilo & Péroux (2005) have estimated that dusty DLAs may contribute as much as 17% of the total metals. Δ(g - i) measurements are available from SDSS photometry for thousands of quasars with candidate DLAs and sub-DLAs. It would be interesting to obtain [Cr/Zn] and [Fe/Zn] for a large sample of such objects to study dust depletion patterns in quasar absorbers and to examine trends between quasar reddening and dust depletion.

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