

THE ROLE OF SUB-DAMPED $\text{Ly}\alpha$ ABSORBERS IN THE COSMIC EVOLUTION OF METALS

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ABSTRACT

Observations of low mean metallicity of damped $\text{Ly}\alpha$ (DLA) quasar absorbers at all redshifts studied appear to contradict the predictions for the global mean interstellar metallicity in galaxies from cosmic chemical evolution models. On the other hand, a number of metal-rich sub-DLA systems have been identified recently, and the fraction of metal-rich sub-DLAs appears to be considerably larger than that of metal-rich DLAs, especially at $z < 1.5$. In view of this, here we investigate the evolution of metallicity in sub-DLAs. We find that the mean Zn metallicity of the observed sub-DLAs may be higher than that of the observed DLAs, especially at low redshifts, reaching a near-solar level at $z \lesssim 1$. This trend does not appear to be an artifact of sample selection, the use of Zn, the use of $N_{\text{H I}}$ weighting, or observational sensitivity. While a bias against very low metallicity could be present in the sub-DLA sample in some situations, this cannot explain the difference between the DLA and sub-DLA metallicities at low z . The primary reason for the difference between the DLAs and sub-DLAs appears to be the dearth of metal-rich DLAs. We estimate the sub-DLA contribution to the total metal budget using measures of their metallicity and comoving gas density. These calculations suggest that at $z \lesssim 1$, the contribution of sub-DLAs to the total metal budget may be several times that of DLAs. At higher redshifts also, there are indications that the sub-DLAs may contribute significantly to the cosmic metal budget.

Subject headings: ISM: abundances — quasars: absorption lines

Online material: machine-readable table

1. INTRODUCTION

As the cycle of stellar birth and death progresses in galaxies, the interstellar gas is expected to become increasingly metal-rich. A fundamental prediction of most chemical evolution models is that the mass-weighted mean interstellar metallicity of galaxies should rise from a low value at $z > 2$ to a near-solar value at $z = 0$ (e.g., Pei et al. 1999; Somerville et al. 2001; Cora et al. 2003). Indeed, the mass-weighted mean metallicity of local galaxies is close to solar (e.g., Kulkarni & Fall 2002; Fukugita & Peebles 2004). How was this present level of metallicity reached? A direct way to study this enrichment history is through the absorption lines superposed by galaxies on the spectra of background quasars, in particular the DLAs (defined to have neutral hydrogen column densities $\log N_{\text{H I}} \geq 20.3$) and the sub-DLAs (defined to have $19.0 \leq \log N_{\text{H I}} < 20.3$; Péroux et al. 2003). These absorbers contain sufficient neutral gas mass to account for a significant fraction of the visible stellar mass in present-day galaxies (e.g., Storrie-Lombardi & Wolfe 2000; Péroux et al. 2003, 2005; Prochaska et al. 2005). Indeed, hydrodynamic simulations naturally produce DLAs from cool gas accumulating at centers of cold dark matter (CDM) halos and predict DLAs to be closely associated with star-forming regions (e.g., Haehnelt et al. 2000; Cen et al. 2003; Nagamine et al. 2004).

Previous studies of element abundances in high- $N_{\text{H I}}$ quasar absorbers have focused primarily on DLAs, especially those at high redshift (e.g., Prochaska et al. 2003b). Recently, we have

started to expand the low- z DLA Zn data and tripled the $z < 1.5$ sample so far (Khare et al. 2004; Kulkarni et al. 2005; Meiring et al. 2006, 2007; Péroux et al. 2006b). These studies find that the DLA mean metallicity stays substantially subsolar even at low redshifts and increases relatively slowly (see also Prochaska et al. 2003b). Furthermore, based on deep emission-line imaging studies (e.g., Kulkarni et al. 2006 and references therein), the star formation rates (SFRs) of a large fraction of DLAs appear to fall far below the predictions from the cosmic star formation history (inferred from galaxy imaging surveys such as the Hubble Deep Field, e.g., Madau et al. 1998). A missing metals problem has also been noted in high- z DLAs from SFR estimates based on C II* absorption (Wolfe et al. 2003). These results could potentially present important challenges to our understanding of galaxy evolution.

Why do DLA data disagree with the mean metallicity in galaxies predicted from the global star formation history? Smoothed particle hydrodynamics (SPH) simulations (Nagamine et al. 2004) indicate that true DLA metallicities could be $\frac{1}{3}$ solar at $z = 2.5$ and higher at lower z . Has the DLA metal content been underestimated, or is there a larger quantity of metals in a hitherto unexplored absorber population? While dust selection or metallicity gradients can lead to a flat metallicity-redshift relation, the extent of these effects is still uncertain (e.g., Boissé et al. 1998; Vladilo & Péroux 2005; Ellison et al. 2005; Akerman et al. 2005; Chen et al. 2005; Zwaan et al. 2005). It has been suggested recently that dust obscuration is not significant and that metal-rich DLAs are inherently rare (Meiring et al. 2006; Khare et al. 2007, hereafter K07; Herbert-Fort et al. 2006). In view of this, it is important to explore other possible sites for the missing metals.

Over the past 2 years, we have been investigating the metallicities of sub-DLAs at $z < 1.5$ (Khare et al. 2004; Péroux et al. 2006a, 2006b; Meiring et al. 2007). These studies have led to the discovery of five solar or supersolar metallicity sub-DLAs at $0.7 < z < 1.5$. Before these studies began, only a single metal-rich sub-DLA was identified (Pettini et al. 2000). Indeed, five of

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TABLE 1
Zn MEASUREMENTS IN SUB-DLAs AND DLAs

Quasar	Reference	z_{abs}	[Zn/H]	$N_{\text{H I}}/10^{20}$ (cm^{-2})	$N_{\text{Zn II}}/10^{12}$ (cm^{-2})	[X/H] ^a	W_{2796} (\AA)	W_{2600} (\AA)
Sub-DLAs:								
0058+019	1	0.6125	0.13	1.20 ± 0.42	6.46 ± 1.61	...	1.63	1.27
1028–0100	2	0.6321	–0.04	0.79 ± 0.26	2.88 ± 1.31	...	1.58	1.14
1028–0100	2	0.7088	<0.06	1.02 ± 0.33	<4.71	...	1.21	0.89
1323–0021	3	0.7160	0.62	1.62 ± 0.78	26.80 ± 2.77	...	2.23	1.45
0134+0051	4	0.8420	<–0.36	0.85 ± 0.23	<1.48	...	1.17	0.86

NOTE.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

^a Abundances of S or Si, if available, are listed for sub-DLAs in cases with Zn upper limits.

REFERENCES.—(1) Pettini et al. 2000; (2) Khare et al. 2004; (3) Péroux et al. 2006a; (4) Péroux et al. 2006b; (5) Meiring et al. 2007; (6) Meiring et al. 2006; (7) Pettini et al. 1999; (8) Kulkarni et al. 1999; (9) Lu et al. 1996; (10) Dessauges-Zavadsky et al. 2003; (11) Ellison & Lopez 2001; (12) Pettini et al. 1994; (13) Ledoux et al. 2006; (14) Srianand & Petitjean 2001; (15) Lu et al. 1995; (16) Kulkarni et al. 2005; (17) Boissé et al. 1998; (18) de la Varga et al. 2000; (19) Meyer & York 1992; (20) Rao et al. 2005; (21) Meyer et al. 1995; (22) Lopez et al. 1999; (23) Pettini et al. 1997; (24) Prochaska et al. 2001; (25) Prochaska & Wolfe 1999; (26) Akerman et al. 2005; (27) Petitjean et al. 2000; (28) Prochaska & Wolfe 1998; (29) Centurión et al. 2003; (30) Lopez et al. 2002; (31) Ge et al. 2001; (32) Lopez & Ellison 2003; (33) Prochaska et al. 2003c; (34) Prochaska et al. 2002; (35) Prochaska et al. 2003a; (36) Péroux et al. 2002; (37) Molaro et al. 2000.

the nine sub-DLAs with Zn data at $z < 1$ and six of the 17 sub-DLAs at $z < 1.5$ have solar or supersolar metallicity. Despite the small number of measurements (caused by the focus on DLAs in the past), the large fraction of metal-rich sub-DLAs suggests that $\log N_{\text{H I}} \approx 20.0$ may be the optimum range for revealing metal-rich systems, since such $N_{\text{H I}}$ is high enough to have a significant metal column density and low enough to make dust attenuation less important (Lauroesch et al. 1996; Vladilo & Péroux 2005; Péroux et al. 2005, 2006a). To investigate this further, here we examine the evolution of the observed amount of metals in neutral gas in sub-DLAs and their contribution to the cosmic metal budget.

2. METALLICITY EVOLUTION OF DLAs AND SUB-DLAs

2.1. Observed Trends

We now compare the observed Zn metallicity evolution of DLAs and sub-DLAs. For several reasons, the nearly undepleted element Zn is the most robust metallicity indicator in DLAs. Zn tracks Fe closely, to within $\sim \pm 0.1$ dex, in Galactic halo and disk stars for $[\text{Fe}/\text{H}] \gtrsim -3$ (e.g., Cayrel et al. 2004; Chen et al. 2004). Furthermore, Zn II has two, often unsaturated, absorption lines at $\lambda\lambda 2026, 2062$ that, for low- z QSOs, are free of blending with the Ly α forest.⁷ We do not include [O/H] estimates based on X-ray absorption measurements because these may be systematically biased with respect to [Zn/H]. Finally, we do not include metallicity estimates based on emission lines detected from absorber galaxies (available only for a few DLAs) since these do not necessarily probe the metallicity of the absorbing gas.

Our samples contain 119 DLAs with $0.1 < z < 3.9$ and 30 sub-DLAs with $0.6 < z < 3.2$. (No Zn data exist for sub-DLAs with $z < 0.55$ because Zn II $\lambda\lambda 2026, 2062$ can be accessed at $z < 0.55$ only with space-based UV spectrographs, and the few existing UV measurements at $z < 0.55$ focused on DLAs rather than sub-DLAs.) The samples are based on our recent data (Khare et al.

2004; Kulkarni et al. 2005; Meiring et al. 2006, 2007; Péroux et al. 2006b) and data from the literature. Recently Prochaska et al. (2006) reported two metal-rich sub-DLAs at $z \approx 1.8$, but the use of these systems for studying the sub-DLA metallicity evolution could be debated since they were discovered in a study targeted specifically toward metal-rich systems, i.e., those with strong Zn lines detected in the SDSS (Sloan Digital Sky Survey) spectra. We therefore do not include the Prochaska et al. (2006) systems in our primary sample, but do discuss the effect of adding these two systems. For the same reason, we do not include the DLAs from Herbert-Fort et al. (2006), but discuss the effect of adding these DLAs later. Table 1 lists our primary sub-DLA sample (sample 1), together with the DLA sample. The DLA sample contains 68 detections and 51 limits, while the sub-DLA sample contains 13 detections and 17 limits. We find that 80% of the DLA Zn limits and 53% of the sub-DLA Zn limits are at $z > 1.5$.

Our analysis uses statistical techniques described in Kulkarni & Fall (2002). We divided the 119 DLAs into six redshift bins with 19 or 20 systems each and the 30 sub-DLAs into three redshift bins with 10 systems each. In each bin, we calculated the $N_{\text{H I}}$ -weighted mean metallicity, using the Kaplan-Meier estimator to account for the presence of Zn II upper limits. These calculations were done using the astronomical survival analysis software ASURV, revision 1.2 (Feigelson & Nelson 1985; Isobe & Feigelson 1990). Figure 1 shows the results. The circles denote DLAs, while the squares denote sub-DLAs (sample 1). The look-back times are estimated assuming the concordance cosmology $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In each bin, the data point is plotted at the median look-back time, with horizontal bars indicating the range of look-back times spanned by the systems in that bin. The vertical error bars denote the 1σ uncertainties in the $N_{\text{H I}}$ -weighted mean metallicity, including sampling as well as measurement uncertainties.

Clearly, the global mean metallicity of DLAs is substantially subsolar even at low z (-0.82 ± 0.15 in the bin $0.1 < z < 1.2$). Since the lowest redshift bin spans a large time interval, we also calculated the metallicity in two halves of this bin with 10 DLAs each and obtained nearly identical values (denoted by dashed circles in Fig. 1). On the other hand, the two lower z sub-DLA points appear higher than the DLA points. The $N_{\text{H I}}$ -weighted mean metallicity in the sub-DLA bin at $0.6 < z < 1.4$ is 0.05 ± 0.27 . A linear regression fit to the $N_{\text{H I}}$ -weighted mean metallicity versus

⁷ Some authors have advocated using S and Si. We prefer to use Zn alone to have homogeneous data without the complication of nucleosynthetic differences between different elements. Furthermore, Si can be considerably depleted in some cases (e.g., $[\text{Si}/\text{Zn}] = -0.9$ dex in the cold diffuse interstellar clouds). Finally, the only accessible lines of Si and S are often saturated and the S lines nearly always lie in the Ly α forest. Nevertheless, as discussed below, we have checked that using S and Si measurements in cases of Zn limits makes essentially no change to our results.

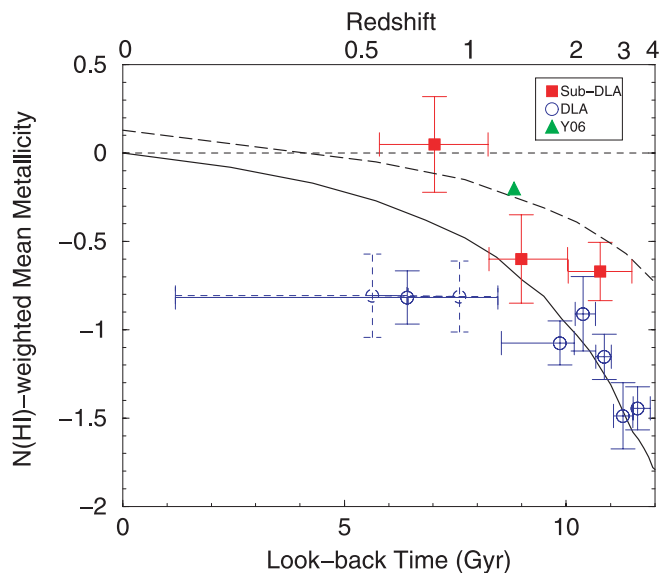


FIG. 1.—Logarithmic $N_{\text{H I}}$ -weighted mean Zn metallicity plotted vs. look-back time for DLAs and sub-DLAs. Dashed circles refer to the lowest time bin split into two bins with 10 DLAs each. The triangle denotes the formal lower limit to the average $[\text{Zn}/\text{H}]$ for a composite spectrum from 698 absorbers with average $\log N_{\text{H I}} \sim 20$ (sample 24) from York et al. (2006). The solid and long-dashed curves show, respectively, the mean metallicities in the chemical evolution models of Pei et al. (1999) and Somerville et al. (2001).

redshift data gives a slope of -0.25 ± 0.07 for DLAs (in agreement with Prochaska et al. 2003b and Kulkarni et al. 2005), and -0.36 ± 0.19 for sub-DLAs.

We next attempt to judge the dependence of our results on the sample definition, the use of Zn, and the use of $N_{\text{H I}}$ -weighted metallicities. We repeated our calculations for a number of changes in technique and assumptions. These results are summarized in Table 2. Concerning sample definitions, for example, we find that including the two metal-rich sub-DLAs reported by Prochaska et al. (2006) increases the metallicity in the middle redshift bin by 0.17 dex. We also find that the DLA results change very little if the DLAs from Herbert-Fort et al. (2006) are included: metallicities within 0.01–0.10 dex of those shown in Figure 1 for five of the bins, within 0.2 dex for the remaining bin at $2.6 < z < 3.1$, and the same linear regression slope (-0.25 ± 0.07). If $[\text{S}/\text{H}]$ or $[\text{Si}/\text{H}]$ are used, where available ($z > 1.8$ and $z > 1.3$, respectively), in cases of Zn limits, and solar S/Zn or Si/Zn ratios assumed, the two higher redshift sub-DLA points in Figure 1 change by ≤ 0.05 dex. (There was no change in the lowest redshift bin where S or Si data do not exist, and the relative number of Zn limits is anyway lower.) The resultant slope of the sub-DLA metallicity-redshift relation is virtually identical to that obtained

from Zn alone, i.e., -0.39 ± 0.19 . The sub-DLA trend suggested by Figure 1 is, therefore, not an artifact caused by the use of Zn. Finally, repeating our calculations using the unweighted mean metallicity also gives similar results.

It thus appears that the sub-DLA global mean metallicity may be higher than that of DLAs, reaching a near-solar value at low z , consistent with predictions for the global mean metallicity in galaxies from chemical evolution models (see the curves in Fig. 1). Of course, it should be remembered that not every sub-DLA is metal-rich, and that our result holds for the $N_{\text{H I}}$ -weighted mean metallicity. This result agrees with the conclusion of York et al. (2006) that the average $[\text{Zn}/\text{H}] \gtrsim -0.2$ for a composite spectrum made from 698 SDSS absorbers with average $\log N_{\text{H I}} \sim 20.0$. Furthermore, our result supports the conclusion of K07, based on observed correlations between $[\text{Zn}/\text{H}]$ and $N_{\text{H I}}$, and a detailed consideration of various selection effects involved therein, that sub-DLAs are more metal-rich than DLAs. Our result also supports a similar suggestion by Péroux et al. (2003) based on $[\text{Fe}/\text{H}]$.

It is important to note that the low- z sub-DLAs in our sample were not chosen a priori to have strong Zn lines. [In fact, none of the 10 SDSS sub-DLAs with $z < 1.5$ in our sample showed Zn detections in the low-resolution SDSS spectra. Three of these 10 SDSS systems show detections of other relatively weak lines ($\text{Si II } \lambda 1808$ or $\text{Fe II } \lambda 2249$) in the SDSS data, but interestingly, all of these systems have low metallicity $[\text{Zn}/\text{H}] < -0.8$.] The low- z sub-DLAs that we observed for Zn II were chosen based on a known H I column density from *HST* UV data, moderately strong Fe II $\lambda 2344$ lines in the SDSS spectra, and a reasonably bright background quasar (usually with $V \lesssim 19$ magnitude) with coordinates appropriate for the observing site and time. It is important to note that such systems are much more common than the “metal-strong” systems (with strong Zn II $\lambda 2026$ or Si II $\lambda 1808$ lines seen in SDSS spectra) used in the sample of Herbert-Fort et al. (2006). Furthermore, the samples in Figure 1 include data from the literature as well (50% of sub-DLAs and 43% of DLAs at $0.6 < z < 1.5$). Finally, the DLAs at $z \lesssim 0.5$ from Kulkarni et al. (2005) were selected regardless of the Fe II strengths, and most were still found to be metal-poor.

2.2. Some Potential Selection Effects

2.2.1. Does Mg II Selection Bias the Low- z Sub-DLA Sample toward Metal-rich Systems?

Most of the low- z sub-DLAs and DLAs for which we have obtained Zn measurements were discovered in the *HST* UV surveys of Mg II–selected systems ($W_{2796}^{\text{rest}} \geq 0.3 \text{ \AA}$; e.g., Rao et al. 2006). One might, therefore, wonder whether the Mg II–selected systems would tend to be more metal-rich simply because they are selected by the presence of strong Mg II lines. If a constant rest equivalent width threshold of Mg II $\lambda 2796$ implied a fixed

TABLE 2
BINNED SUB-DLA MEAN METALLICITIES FOR VARIOUS SAMPLES

Sample	Number of Systems	Elements Used	$N_{\text{H I}}$ -Weighted?	Redshift Ranges of 3 Bins ^a	Mean Metallicity in the 3 Bins
1 ^b	30	Zn	Yes	0.61–1.14, 1.15–1.87, 1.89–3.17	0.05 ± 0.27 , -0.60 ± 0.25 , -0.67 ± 0.16
2 ^c	32	Zn	Yes	0.61–1.15, 1.22–1.87, 1.89–3.17	0.02 ± 0.25 , -0.43 ± 0.27 , -0.78 ± 0.21
3 ^d	30	Zn, S, Si	Yes	0.61–1.14, 1.15–1.87, 1.89–3.17	0.05 ± 0.27 , -0.55 ± 0.23 , -0.70 ± 0.18
1 ^e	30	Zn	No	0.61–1.14, 1.15–1.87, 1.89–3.17	0.16 ± 0.19 , -0.67 ± 0.20 , -0.63 ± 0.15

^a In each case, the sample was divided into three redshift bins with a roughly equal number of systems.

^b Primary sample, Zn only.

^c Sample including Prochaska et al. (2006).

^d Primary sample, S or Si for Zn limits.

^e Primary sample with unweighted means.

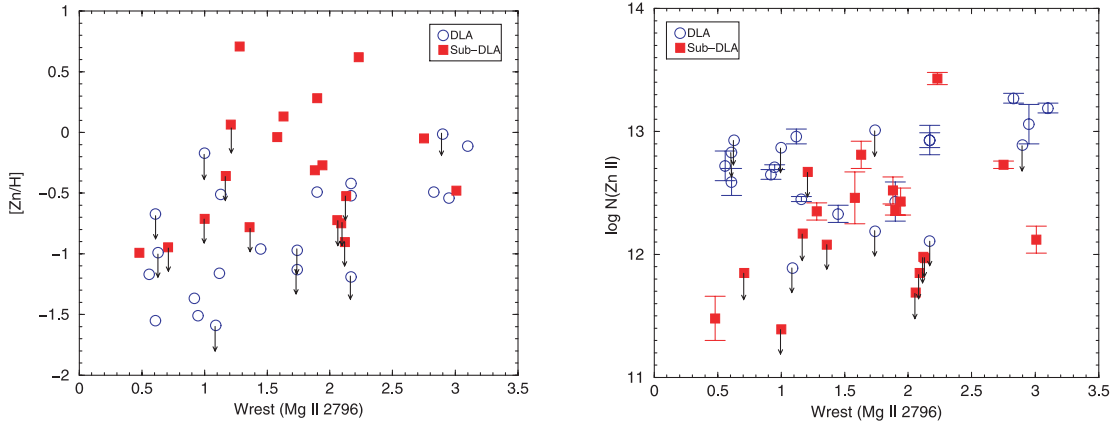


FIG. 2.—*Left:* $[Zn/H]$ vs. rest equivalent width of $Mg\ II\ \lambda 2796$ for sub-DLAs and DLAs at $z < 2$ from our sample for which both quantities are available. *Right:* $\log N_{Zn\ II}$ vs. W_{2796}^{rest} for the same set of sub-DLAs and DLAs. (See text for further details.)

threshold of $N_{Mg\ II}$, then one may think that systems with low $N_{H\ I}$ would be included only if they were more metal-rich, compared to systems with higher $N_{H\ I}$. However, there are several indications that this does not appear to be the reason for the higher metallicity we see in sub-DLAs compared to DLAs. First, Figures 5–7 of York et al. (2006), based on hundreds of SDSS $Mg\ II$ systems, show that strong W_{2796}^{rest} occur for all $E(B - V)$. This, together with the trend of decreasing metallicity with increasing $E(B - V)$ in the data of York et al. (2006) (e.g., their Table 7) implies that using systems with large W_{2796}^{rest} does not bias one toward selecting only metal-rich sub-DLAs. Second, the $Mg\ II\ \lambda 2796$ line is almost always highly saturated in DLAs and sub-DLAs. The systems with larger W_{2796}^{rest} have larger velocity spreads rather than larger $Mg\ II$ column densities. For example, the compilation of Ledoux et al. (2006) for DLAs/sub-DLAs based on VLT UVES spectra shows that the velocity spread of such systems is typically about $100\ km\ s^{-1}$, and is even $\geq 200\ km\ s^{-1}$ in some cases. In other words, selecting systems with larger W_{2796}^{rest} does not necessarily translate into selecting systems with larger $N_{Mg\ II}$. Finally, as seen in Table 1, the $N_{H\ I}$ values of the sub-DLAs in our samples are relatively large: 86% of the 30 systems in our primary sample have $\log N_{H\ I} > 19.7$ and 73% have $\log N_{H\ I} > 19.9$. The difference in abundance needed in order to exceed a given threshold of $N_{Mg\ II}$ is thus not substantial between our DLA and sub-DLA samples.

The left panel of Figure 2 plots $[Zn/H]$ versus W_{2796}^{rest} for DLAs and sub-DLAs at $z < 2$ for which both quantities are available. (We consider only $z < 2$ here because $Mg\ II\ \lambda 2796$ is not available for the $z > 2$ systems.) Systems with large W_{2796}^{rest} appear to show a wide range of $[Zn/H]$, and systems with high $[Zn/H]$ also show a range of W_{2796}^{rest} . In other words, $Mg\ II$ selection does not appear to bias the sub-DLA sample toward only solar or supersolar systems. Note that the fact that the sub-DLAs in the left panel of Figure 2 have $[Zn/H] \gtrsim -1$ merely states the observed difference between DLAs and sub-DLAs that we have mentioned all along in this paper. It does not necessarily indicate a metallicity bias in the sub-DLA sample.

To quantify the above considerations further, we now estimate what minimum $[Mg/H]$ can be covered by the low- z sub-DLAs in our sample where the lowest W_{2796}^{rest} is $0.48\ \text{\AA}$. We use $Mg\ II/H\ I$ to estimate $[Mg/H]$, given that (1) most photoionization calculations for sub-DLAs predict Mg/H to differ from $Mg\ II/H\ I$ by at most $0.1 - 0.2$ dex for the relevant range of ionization parameters (e.g., Dessauges-Zavadsky et al. 2003; Meiring et al. 2007); and (2) this also appears to be the case for diffuse interstellar clouds

within the Milky Way (e.g., Jenkins et al. 1986; Cartledge et al. 2006). If one assumes a linear curve of growth, then $W_{2796}^{rest} \geq 0.5\ \text{\AA}$ would correspond to $\log N_{Mg\ II} \geq 13.1$, i.e., $[Mg/H] \geq -2.2$ for $\log N_{H\ I} = 19.7$. Of course, it is not correct to assume a linear curve of growth for such strong $Mg\ II$ lines. To make more accurate estimates of the $[Mg/H]$ threshold of our low- z sub-DLA sample, we generated a range of synthetic $Mg\ II\ \lambda 2796$ Voigt profiles with $W_{2796}^{rest} = 0.5\ \text{\AA}$. We considered three types of component velocity structures: (1) To begin, we considered the simplest and most conservative case of only one component (extremely unlikely given the complex $Mg\ II\ \lambda 2796$ line profiles observed in existing high-resolution studies of DLAs/sub-DLAs). For a single component with an effective Doppler b parameter of $30\ km\ s^{-1}$, we get $W_{2796}^{rest} \geq 0.5\ \text{\AA}$ if $\log N_{Mg\ II} \geq 13.3$, i.e., $[Mg/H] \geq -2.0$ for $\log N_{H\ I} = 19.7$. For a single component with effective b of $20\ km\ s^{-1}$, we get $[Mg/H] \geq -1.7$ for $\log N_{H\ I} = 19.7$. (2) Next, we considered a more realistic, yet simple, case of multiple narrower components. For three components with equal $N_{Mg\ II}$ at velocities $v = -50, 0, 50\ km\ s^{-1}$ with $b = 10\ km\ s^{-1}$ each, one would need a total $\log N_{Mg\ II} \geq 13.3$, i.e., $[Mg/H] \geq -2.0$ for $\log N_{H\ I} = 19.7$, to have $W_{2796}^{rest} \geq 0.5\ \text{\AA}$. (3) Finally, we produced profiles with three to nine components with random relative $N_{Mg\ II}$, b , and v values. Each component was given a b value ranging from 5 to $30\ km\ s^{-1}$ chosen with a random number generator. The velocities of the components were taken to range from -100 to $100\ km\ s^{-1}$, again selected with a random number generator. Each component was given a starting column density distributed randomly in the range $9 < \log N_{Mg\ II} < 11$. Then, the column density of each component was increased by a small constant factor in successive iterations until the total EW of the profile was $0.5\ \text{\AA}$. Simulations were repeated for three to nine components. Finally, the simulations were repeated for velocity ranges of -200 to $200\ km\ s^{-1}$ and -50 to $50\ km\ s^{-1}$. For each case, 1000 profiles were generated as described above, and histograms of the total $Mg\ II$ column densities were examined. In these simulations, we obtained total median $\log N_{Mg\ II}$ in the range of $13.3 - 13.2$ (with the total $N_{Mg\ II}$ decreasing with increasing number of components). In other words, one can reach $[Mg/H] \geq -2.0$ for $W_{2796}^{rest} \geq 0.5\ \text{\AA}$ for $\log N_{H\ I} = 19.7$. Thus, for all velocity structures considered, the sub-DLA sample should include systems with $[Mg/H] \gtrsim -2$, not only those with $[Mg/H] > -1$.

Of course, systems with single narrow components would only be included in the $W_{2796}^{rest} \geq 0.5\ \text{\AA}$ sample for higher metallicities, but in general $Mg\ II\ \lambda 2796$ lines in DLAs/sub-DLAs are

not observed to show such narrow velocity structures. The $N_{\text{Mg II}}$ needed to reach higher W_{2796}^{rest} can be larger, but such systems usually also have larger velocity spreads than systems with lower W_{2796}^{rest} . For $W_{2796}^{\text{rest}} = 1 \text{ \AA}$, our simulations with five to nine components spread over -100 to 100 km s^{-1} or -200 to 200 km s^{-1} give $[\text{Mg}/\text{H}]$ in the range of -1.5 to -1.7 for $\log N_{\text{H I}} = 19.7$. For $W_{2796}^{\text{rest}} = 1.5 \text{ \AA}$, the simulations with five to nine components over the velocity range -100 to 100 km s^{-1} give $[\text{Mg}/\text{H}]$ of about -1.0 to -1.2 dex for $\log N_{\text{H I}} = 19.7$ or -1.3 to -1.5 dex for $\log N_{\text{H I}} = 20.0$ (64% of the sub-DLAs in our sample with $W_{2796}^{\text{rest}} > 1.5 \text{ \AA}$ have $\log N_{\text{H I}} > 20.0$). Even these values are almost an order of magnitude lower than the metallicities actually observed for most of these sub-DLAs. In any case, the sub-DLAs in our sample were not specifically chosen to have very large W_{2796}^{rest} . This is the reason we calculate the $[\text{Mg}/\text{H}]$ thresholds using the lowest W_{2796}^{rest} in our sample (0.48 \AA). We therefore believe that while a bias against very low metallicity could be present in some situations (e.g., narrow single components or very large W_{2796}^{rest}), this is not likely to explain the difference between DLAs and sub-DLAs in Figure 1. Indeed, as the left panel of Figure 2 shows, the higher W_{2796}^{rest} systems do not have systematically higher $[\text{Zn}/\text{H}]$, and vice versa. Furthermore, as we show in § 2.3, our results would not be affected much even if there were a bias against sub-DLAs with $[\text{Zn}/\text{H}] < -1$. We note, however, that systematic observations of a much larger sample of DLAs and sub-DLAs are essential to study the issue of selection effects more definitively.

2.2.2. Observational Sensitivity for Weak Zn II Lines

The right panel of Figure 2 plots $\log N_{\text{Zn II}}$ versus W_{2796}^{rest} for the systems from the left panel. The DLAs show a narrower range of $N_{\text{Zn II}}$ than the sub-DLAs. In fact, the DLAs and sub-DLAs with comparable W_{2796}^{rest} do not necessarily have similar $N_{\text{Zn II}}$. There are many $N_{\text{Zn II}}$ detections or upper limits for sub-DLAs that are actually below the DLA points at comparable W_{2796}^{rest} . Clearly, the sub-DLA measurements have adequate sensitivity to see low Zn II column densities. The metallicities of some of the sub-DLA systems, derived after the fact by dividing the $N_{\text{Zn II}}$ by $N_{\text{H I}}$, are high (see Fig. 2, left). The $N_{\text{H I}}$ values play no direct role in the detection of Zn II lines. Of course much stronger Zn II lines could have been detected as well, and would in fact have to be there if there were a significant number of solar- or supersolar-metallicity DLAs. However, such strong Zn II lines for DLAs are not seen. On the other hand, there are a small fraction of sub-DLAs that have $N_{\text{Zn II}}$ larger than those for many DLAs, and these are of course highly metal-rich systems. Thus, the larger fraction of metal-rich sub-DLAs does not appear to be a result of sampling similar $N_{\text{Zn II}}$ values at lower $N_{\text{H I}}$ values compared to the DLAs.

2.3. The Role of Metal-rich and Metal-poor Systems

It is interesting to compare the mean metallicities of the subsets of the DLA and sub-DLA samples after removing the systems with $[\text{Zn}/\text{H}] < -1$, since there cannot be a selection bias against the remaining systems.⁸ These subsamples consist of 50 DLAs and 27 sub-DLAs. Dividing these subsamples into three bins each, the $N_{\text{H I}}$ -weighted mean metallicity is -0.66 ± 0.15 in the lowest redshift DLA bin, while it is 0.08 ± 0.28 in the lowest redshift sub-DLA bin. While these numbers are certainly not representative of the overall observed DLA and sub-DLA populations (since by design they exclude the metal-poor systems), the DLA and sub-DLA means still seem to differ at a 2–3 σ level.

⁸ Of course, given the discussion above, the sub-DLA samples should be sensitive well below $[\text{Zn}/\text{H}] = -1$ dex.

Thus, the difference between DLA and sub-DLA metallicities at low z would not be affected much even if the sub-DLA samples were biased against systems with $[\text{Zn}/\text{H}] < -1$.

In principle, if there were a large number of metal-poor sub-DLAs with metallicity $\lesssim 1/100$ solar that could be missing from the Mg II–selected samples, then the “true” sub-DLA mean metallicity could be lower. To assess this possibility, we repeated the survival analysis calculations after adding a hypothetical metal-poor sub-DLA population with a typical $\log N_{\text{H I}} = 20$ in the lowest redshift bin (where the difference between DLA and sub-DLA mean metallicities is largest). We conclude that one would need to add 64 sub-DLAs with $[\text{Zn}/\text{H}] = -2.0$ (or 75 sub-DLAs with $[\text{Zn}/\text{H}] = -1.5$) in order to bring the $N_{\text{H I}}$ -weighted mean metallicity of the sub-DLAs down to the DLA level (-0.82 dex) in the lowest redshift bin. Such a large population of metal-poor sub-DLAs cannot be ruled out, but seems quite unlikely, given that there are currently only 10 sub-DLAs with Zn measurements in this redshift bin (of which six are solar or supersolar). Turning the argument around, if the fraction of metal-poor sub-DLAs were the same as the fraction of DLAs with $[\text{Zn}/\text{H}] < -1$, e.g., if there were 15 hypothetical sub-DLAs with a typical $[\text{Zn}/\text{H}] = -1.5$ in addition to the 10 observed sub-DLAs in the lowest redshift bin, then the $N_{\text{H I}}$ -weighted mean metallicity of the combined sample of 25 sub-DLAs would be -0.35 dex, not -0.82 dex as for DLAs. In other words, it would take a bimodal metallicity distribution very different from that for known DLAs to force the sub-DLA mean to equal the observed DLA mean. In fact, since the low- z DLAs are also discovered in the Mg II–selected *HST* surveys, in principle there could be a population of low- z DLAs with $[\text{Mg}/\text{H}] < -2.6$ undetected in current DLA surveys that could drive the DLA mean metallicity to even lower values. Thus the DLA and sub-DLA means could still remain different.

It appears that the primary reason for the difference between the observed DLAs and sub-DLAs in Figure 1 is not a bias against metal-poor sub-DLAs, but the dearth of metal-rich DLAs, for which there should be no difficulty in detecting the metal lines. Figure 1 shows that metal-rich systems can be found among the sub-DLAs, whereas they seem to be quite rare among the DLAs, despite much more extensive observations for the DLAs. Larger samples are needed, at any rate, to refine the differences between metal-rich sub-DLAs and metal-poor sub-DLAs and DLAs, and those larger samples can be searched for more subtle or different selection effects than those we can study here.

2.4. Other Considerations

We note that owing to the relatively small size of the sub-DLA sample, the mean metallicities for this sample are sensitive to the particular details of the metal-rich sub-DLAs discovered so far. The maximum effect on the mean metallicity in the lowest z bin comes from the sub-DLA with the highest $N_{\text{Zn II}}$ in our sample, i.e., the system at $z = 0.716$ toward SDSS J1323–0021 (Péroux et al. 2006a). We have adopted $\log N_{\text{H I}} = 20.21_{-0.18}^{+0.21}$ for this system since this gives the best fit to the Ly α absorption profile (Khare et al. 2004; Péroux et al. 2006a). Rao et al. (2006) reported $\log N_{\text{H I}} = 20.54 \pm 0.15$ for this system, while Prochaska et al. (2006) reported $\log N_{\text{H I}} = 20.3$. The value of Prochaska et al. is only stated to one decimal, without error bars, but is much closer to the value adopted here. In any case, if one were to take this system out of the sub-DLA sample, and put it instead in the DLA sample (adopting the Rao et al. 2006 value for its $N_{\text{H I}}$), then the sub-DLA mean metallicity in the lowest redshift bin would become -0.26 ± 0.16 . The corresponding value in the DLA sample would change only a little to -0.73 ± 0.15 . (The DLA sample is larger and is less affected by an individual system.) Thus, the

mean metallicity at low redshift would be still higher for the sub-DLA sample than for the DLA sample at the 3σ level, but the difference would be smaller.

Overall, we conclude that the higher mean sub-DLA metallicity does not appear to be an artifact of sample selection (on the basis of either Mg II or other metal lines), the use of Zn, or the use of $N_{\text{H I}}$ weighting, and does not arise from insufficient $N_{\text{Zn II}}$ sensitivity. However, it is necessary to verify our results with (1) much larger sub-DLA and DLA Zn samples, and (2) more accurate $N_{\text{H I}}$ measurements for DLAs as well as sub-DLAs with higher resolution and higher S/N observations of the Ly α profiles.

3. CONTRIBUTION OF SUB-DLAs TO THE COSMIC METAL BUDGET

Our knowledge of the cosmic metal budget is highly incomplete. Earlier estimates including contributions of high- z DLAs, Lyman break galaxies, and the Ly α forest suggested only $\sim 10\%$ of the amount of metals expected from the cosmic star formation history (e.g., Pettini 2004). Recent estimates also including submillimeter galaxies and star-forming galaxies at $z \sim 2$ yield $\sim 40\%$ – 50% of the expected comoving metal density ($\approx 4 \times 10^6 M_{\odot} \text{Mpc}^{-3}$; Ferrara et al. 2005; Bouché et al. 2005, 2006a; Pettini 2006). It has been suggested that dwarf galaxies contaminate the intergalactic medium with hot ionized gas (e.g., Tumlinson & Fang 2005), but the extent of this effect is not clear. Given the available observations, about half of the predicted quantity of metals appears to be unaccounted for.

In this context, it is interesting to quantify the contribution of the possibly metal-rich sub-DLAs to the metal budget. At low redshift it is difficult to estimate the sub-DLA contribution with the available data. The statistics for sub-DLAs and hence the comoving density of H I gas ($\Omega_{\text{H I}}$) in sub-DLAs are not yet known at $z < 1.7$. However, one could assume that the relative H I contributions of DLAs and sub-DLAs at low z are similar to those at high z . At $z \sim 2.5$, the comoving density of H I gas in DLAs and sub-DLAs is measured to be $\Omega_{\text{H I}} = 0.85 \times 10^{-3}$ and 0.18×10^{-3} , respectively (Péroux et al. 2005), i.e., a ratio $\Omega_{\text{H I}}^{\text{sub-DLA}}/\Omega_{\text{H I}}^{\text{DLA}} = 0.21$. Therefore, the comoving mass density of metals in sub-DLAs, in units of $\Omega(Z_{\odot})$ ($=\Omega_{\text{baryons}} \times Z_{\odot} = 5.5 \times 10^{-4}$; $Z_{\odot} = 0.0126$ by mass), is $\Omega_{\text{Z}}^{\text{sub-DLA}} = f \times 10^{0.0} \times Z_{\odot} \times \Omega_{\text{H I}}^{\text{sub-DLA}}/\Omega(Z_{\odot}) = f \times 22.9 \times \Omega_{\text{H I}}^{\text{sub-DLA}}$, where $f (>1)$ accounts for the ionized fraction of the gas. For sub-DLAs near the high $N_{\text{H I}}$ end, the ionized fraction is not important, but it may be important for sub-DLAs with low $N_{\text{H I}}$. The exact value of f will depend on detailed photoionization calculations as well as the $N_{\text{H I}}$ distribution of the sub-DLAs, but is likely to be in the range of 1–10. Thus, if the sub-DLA metallicity exceeds that of DLAs by a factor of about 7 at low z (Fig. 1), and the relative H I contributions of DLAs and sub-DLAs at low z are similar to those at high z , then the metal contribution of sub-DLAs will exceed that of DLAs by a factor of $f \times 1.5$ [since $\Omega_{\text{Z}}^{\text{DLA}} = 2.6 \times 10^{-3}$, in units of $\Omega(Z_{\odot})$]. This factor may be even higher if the relative H I contribution of sub-DLAs at low z is higher than that at high z (e.g., the factor will be $f \times 4.5$ if $\Omega_{\text{H I}}$ values of Prochaska et al. 2005 are used). These expectations will need to be confirmed with more data on sub-DLA $\Omega_{\text{H I}}$ and metallicity.

At high redshifts, the mean global metallicity of the sub-DLAs is $[\langle \text{Zn}/\text{H} \rangle] \approx -0.7$ (Fig. 1). Therefore, the comoving mass density of metals in sub-DLAs, in units of $\Omega(Z_{\odot})$, is $\Omega_{\text{Z}}^{\text{sub-DLA}} = f \times 10^{-0.7} \times Z_{\odot} \times 0.18 \times 10^{-3}/\Omega(Z_{\odot}) = f \times 8.2 \times 10^{-4}$. Thus, at high redshifts, sub-DLAs contribute at least 32% of what DLAs contribute to the metal census. The sub-DLA contribution could be higher depending on the value of f . Prochaska et al. (2005), based on their analysis of the SDSS Data Release 3, find a value

of $\Omega_{\text{H I}}$ for systems with $17.3 \leq \log N_{\text{H I}} \leq 20.3$ to be 0.57 times $\Omega_{\text{H I}}$ in DLAs, a large fraction coming from the sub-DLAs. Thus, the sub-DLA contribution to the metal budget may be higher than that estimated above. We note, however, that the conclusions of Prochaska et al. (2005) will need to be confirmed at high resolution, which is essential to obtain reliable $N_{\text{H I}}$ for sub-DLAs (Péroux et al. 2005). Taken together, the suggestions of high metallicities at $z \sim 2$ for a few sub-DLAs and our finding of an even larger effect at low redshifts are consistent with sub-DLAs being more significant contributors to the total metal abundance of gas in the universe than was previously realized.

4. SUMMARY AND DISCUSSION

While the sub-DLA samples are still small and not all the observed sub-DLAs are metal-rich, the fraction of observed metal-rich systems is larger for sub-DLAs than for DLAs. Our calculations suggest that the mean metallicity of the observed sub-DLAs is higher than that of the observed DLAs, reaching a near-solar level as expected in cosmic chemical evolution models. At $z < 1$, we find that the contribution of the observed sub-DLAs to the total metal budget may be several times higher than that of the observed DLAs. At higher z , the observed sub-DLAs may contribute $\geq 32\%$ of the DLA contribution to the total metal budget. Furthermore, the results of Prochaska et al. (2005) on the relative number of sub-DLAs and DLAs may triple the contribution of sub-DLAs compared to the results based on Péroux et al. (2005). In general, our results support and extend the suggestions by Péroux et al. (2006a), York et al. (2006), and Prochaska et al. (2006) that sub-DLAs may contribute significantly to the overall global metallicity.

One may wonder whether ionization effects are likely to be responsible for the difference we see between the global metallicities for the DLA and sub-DLA samples. We believe that this is not a significant effect for our samples. First, the $N_{\text{H I}}$ values of the sub-DLAs in our sample are relatively high (86% systems with $\log N_{\text{H I}} > 19.7$ and 73% with $\log N_{\text{H I}} > 19.9$ in our primary sample). Second, photoionization calculations presented in high-resolution studies of sub-DLAs (Dessauges-Zavadsky et al. 2003; Meiring et al. 2007) show that while sub-DLAs have some ionized gas, the ionization corrections in abundance estimates are not significant, and would increase $[\text{Zn}/\text{H}]$ if applied. Vladilo et al. (2001), Dessauges-Zavadsky et al. (2003), York et al. (2006), and Meiring et al. (2007) all suggest that there is no trend in $N_{\text{Al III}}/N_{\text{Al II}}$ versus $N_{\text{H I}}$ in sub-DLAs and that the ratio is smaller than 1. Therefore, using $N_{\text{Zn II}}/N_{\text{H I}}$ in sub-DLAs for a measure of $N_{\text{Zn}}/N_{\text{H}}$ does not introduce a systematic bias.

It is important to establish whether the observed DLA and sub-DLA samples reflect their true properties or differential dust selection effects. If dust obscuration is significant and depends primarily on the metal column density (e.g., Vladilo et al. 2006), then metal-rich DLAs may be more affected by dust selection than metal-rich sub-DLAs (Vladilo & Péroux 2005). Such an effect could make DLAs appear less metal-rich than sub-DLAs; but, this alone would not explain the large difference between DLAs and sub-DLAs seen in Figure 1, because so far there is no evidence for the necessary large number of high-extinction DLAs (K07). K07 use this result and the observed mass-metallicity relationship for galaxies (e.g., Tremonti et al. 2004; Savaglio et al. 2005; Erb et al. 2006) to conclude that sub-DLAs may arise in massive galaxies and DLAs in less massive galaxies, consistent with the relatively stronger evolution of metals in sub-DLAs compared to DLAs that we find here. That conclusion is also consistent with trends in gas dispersion with metallicity of quasar absorbers (Ledoux et al. 2006; Meiring et al. 2007). (But, see an

opposing opinion on this last point by Bouché et al. [2006b], using a less direct argument.)

The relatively smaller sample size for sub-DLAs compared to DLAs and the conflicting results on gas velocity dispersion just referred to emphasize the need for much larger samples of sub-DLAs and better velocity dispersion measurements for the absorbers at a range of redshifts, to confirm the results reached here. Large telescopes are essential to obtain adequate samples of excellent abundance and velocity dispersion measurements. The sub-DLA sample needs to be made at least as large as the DLA sample. It will also be important to obtain $N_{\text{H I}}$ and $[\text{Zn}/\text{H}]$ for absorbers toward UV-faint quasars, to confirm that there are not a large number of highly reddened quasars with foreground DLAs.

More extensive observations with the *HST* Cosmic Origins Spectrograph to measure H I at $z < 1.5$ and Zn II at $z < 0.55$, and with ground-based spectrographs to measure Zn II at $0.55 < z < 1.5$, will be very important to confirm the findings presented here.

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