THE METAL-STRONG DAMPED Lyα SYSTEMS

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ABSTRACT

We have identified a metal-strong (logN(Zn\textsuperscript{+}) \textgtrsim 13.15 or logN(Si\textsuperscript{+}) \textgtrsim 15.95) DLA (MSDLA) population from an automated quasar (QSO) absorber search in the Sloan Digital Sky Survey Data Release 3 (SDSS-DR3) quasar sample, and find that MSDLAs comprise \textasciitilde 5\% of the entire DLA population with \textit{z}_{\text{abs}} \textgtrsim 2.2 found in QSO sightlines with \textit{r} < 19.5. We have also acquired 27 Keck ESI follow-up spectra of metal-strong candidates to evaluate our automated technique and examine the MSDLA candidates at higher resolution. We demonstrate that the rest equivalent widths of strong \textit{Zn} \textsubscript{II} \textit{\lambda}2026 and \textit{Si} \textsubscript{II} \textit{\lambda}1808 lines in low-resolution SDSS spectra are accurate metal-strong indicators for higher-resolution spectra, and predict the observed equivalent widths \textit{W}_{\text{obs}} and signal-to-noise ratios (SNRs) needed to detect certain extremely weak lines with high-resolution instruments. We investigate how the MSDLAs may affect previous studies concerning a dust-obscuration bias and the N(HI)-weighted cosmic mean metallicity < \textit{Z}(z) >. Finally, we include a brief discussion of abundance ratios in our ESI sample and find that underlying mostly Type II supernovae enrichment are differential depletion effects due to dust (and in a few cases quite strong); we present here a handful of new Ti and Mn measurements, both of which are useful probes of depletion in DLAs. Future papers will present detailed examinations of particularly metal-strong DLAs from high-resolution Keck/HIRES and VLT/UVES spectra.

Subject headings: Galaxies: Quasars: Absorption Lines, Abundances; Galaxies: Evolution

1. INTRODUCTION

Damped Ly\textalpha systems (DLAs) are the subset of quasar absorption line (QAL) systems classically defined to have neutral hydrogen column densities \textit{N}_{\text{HI}} \textgtrsim 2 \times 10^{20} \text{ atoms cm}^{-2} (Wolfe, Gawiser & Prochaska 2005). They are identified by their wide damped Ly\textalpha absorption profiles, and all DLAs (to date) show associated metal-line absorption (Prochaska et al. 2003). DLAs dominate the neutral gas content of the universe and may be expected to constitute the primary reservoir of star-forming gas at high redshift (Wolfe et al. 1995; Prochaska & HerbertFort 2004; Prochaska, Herbert-Fort and Wolfe 2005, hereafter PHW05). Therefore, measurements of DLA chemical abundances at high redshift help quantify the chemical evolution of the young universe.

Echelle observations of DLAs allow one to accurately measure the gas-phase abundances of a number of elements and thereby examine processes of nucleosynthetic enrichment and differential depletion in these galaxies (e.g. Lu et al. 1996; Vladilo et al. 2001; Prochaska & Wolfe 2002; Dessauges-Zavadsky et al. 2003). However, Pettini et al. (1994) showed that high-redshift DLAs are generally metal-poor. Their results and subsequent studies (Pettini 1999; Prochaska et al. 2003; Kulkarni et al. 2005) have tracked the enrichment of the ISM of galaxies reaching back to the first few Gyrs. The majority of DLAs show detections of Fe\textsubscript{II}, Ni\textsubscript{II}, Si\textsubscript{II}, and Al\textsubscript{II} transitions. It is unfortunate that the signatures of Type-II SNe enrichment (Woosley & Weaver 1995) and differential depletion (e.g. Savage & Sembach 1996) are nearly degenerate for this small set of elements. As such, progress in interpreting the gas-phase abundance patterns of the damped Ly\textalpha systems has been difficult, although recent works on S, Zn, N and O have made advances.

Prochaska, Howk, and Wolfe (2003) reported the discovery of a metal-strong DLA at \textit{z}_{\text{abs}} = 2.626 towards the quasar FJ0812+32 (hereafter DLA-B/FJ0812+32). In contrast with the majority of damped Ly\textalpha systems, the authors detected over 20 elements in this single DLA system and revealed the detailed chemical enrichment pattern of this galaxy. Many of the detected transitions had never before been observed outside of the Local Group and are important diagnostics to theories of nucleosynthesis and galaxy enrichment. The authors suggested that this system was enriched mainly by short-lived, massive stars and that it is the progenitor of a massive elliptical galaxy (see also Fenner, Prochaska, & Gibson 2004). The goal of this work is to speed the discovery and analysis of more systems like DLA-B/FJ0812+32; these rare DLAs are unique laboratories for the study of nucleosynthesis, galaxy enrichment, dust depletion, and ISM physics in the high-redshift universe. We hereafter refer to this special subset of DLA as the metal-strong DLA (MSDLA) systems.

Whilst our primary motivation for defining MSDLAs as those absorbers with high metal column densities (see § 2), we note that our definition also corresponds to an empirical upper bound to N(Zn\textsuperscript{+}) noted by Boissé et al. (1998) for a sample of DLAs in the literature at that time.
Boissé et al. interpreted the upper bound to $N(Zn^+)$ as a selection bias related to dust obscuration (i.e. very large dust-to-gas ratio). However, our statistics on MSDLAs (in sightlines with $r < 19.5$) now lead us to argue that the paucity of high $N(Zn)$ absorbers is not due to dust, but simply an indication of their intrinsic rarity (see also Johansson & Efstathiou 2006).

We will show that only a few percent of all DLAs are truly metal-strong, and so thousands of quasar sightlines must be searched in order to discover just a handful of MSDLAs. Therefore, automated detection algorithms used on large quasar surveys are critical to metal-strong DLA research. This paper presents our automated method of detecting metal-strong absorbers in low-resolution Sloan Digital Sky Survey (SDSS) quasar spectra. We detail and release our search algorithms and present all of the metal-strong candidates from SDSS Data Release Three (SDSS-DR3; Abazajian et al. 2005).

As mentioned above, the elemental abundances from DLAs can be used to constrain and test processes of nucleosynthesis. For example, there are several different theories on the production of Boron. Woosley et al. (1990) suggested that B production results from neutrino spallation in the carbon shells of SNe, while Cassé et al. (1995) have argued for the spallation of C and O nuclei accelerated by SNe onto local interstellar gas. Other theories involve protons and neutrons being accelerated onto interstellar CNO seed nuclei, and each theory predicts how B may scale with the galaxy’s metallicity (and so here, for example, one must eventually acquire $N(HI)$, although it is not necessary for the project at hand). Measurements of such elements in DLA systems can thus help distinguish between the various theories. Other elements measured in the Galactic ISM would also impact our understanding of nucleosynthesis and star formation in young galaxies if these elements were observed in high redshift DLA. These include: (1) O – an unambiguous $\alpha$-element and the most abundant metal in the universe; (2) Sn and Kr – $r$-process elements (rapid neutron capture in high density and temperature regions); and (3) Pb – an $s$-process element (slow neutron decay and capture in low density and temperature regions). Unfortunately, these elements are rarely detected in typical DLA spectra because they have small absolute abundances and/or their dominant ions have transitions with either too large or small oscillator strengths (e.g. O I $\lambda\lambda 1302, 1355$). In MSDLAs, however, weaker transitions become available, allowing high-redshift studies of the processes mentioned above.

To gauge the success rate of our algorithms, we have obtained moderate-resolution follow-up observations of a subset of the SDSS-DR3 MSLDA candidates with the Echelle Spectrograph and Imager (Sheinis et al. 2002, ESI) on the 10m-class KeckII telescope. We present our ESI spectra of 27 MSDLAs candidates ($1.6 \leq z_{abs} \leq 3.1$ and $r < 19.5$) and discuss the implications of this candidate metal-strong subsample.

We define the MSDLAs and discuss the impact of $Ly\alpha$ on our study in § 2, present our automated technique for detecting metal-strong systems in SDSS, describe how we compiled our sample for medium-resolution observations, and report our SDSS search success rates in § 3. Section 4 gives a summary of our ESI follow-up observations, data reduction, and measurements. § 5 presents our analysis and discussion of metal-strong indicators in SDSS QSOs, using our ESI sample as a reference. Section 6 derives our predictions for detecting certain extremely weak lines with HIRES. Section 7 discusses our metal-strong sample and its relation to the proposed dust-obscuration bias, as well as a preliminary investigation of how this MSLDA population might influence previous detections of an evolution in the $N_{HI}$-weighted cosmic mean metallicity $< Z(z) >$. Section 8 concludes the discussion with a few abundance ratios from our ESI data with comments on SNe enrichment and depletion due to dust, and our summary and conclusions are blended together in § 9.

2. MSLDA DEFINITION AND THE IMPACT OF Lyα

With this paper we define the metal-strong DLAs (MSDLAs) to have log $N(Zn^+) \geq 13.15$ or log $N(Si^+) \geq 15.95$, based on the $Zn$ II and $Si$ II transitions measured in KeckII/HIRES data of DLA-B/FJ0812+32. These values are somewhat arbitrary, but chosen because they imply equivalent widths for weak transitions like B II 1362 that can be detected with current 10m-class telescopes. We have specifically chosen to define the MSLDA subset based on column density thresholds and not metallicity (i.e. not $[Zn/H]$ or $[Si/H]$), due to motivations from the DLA-B/FJ0812+32 study. Specifically, we aim to discover systems which may be used as high-redshift probes of the production of elements like B, O and Ge (among others) independent of the $N_{HI}$ value. Therefore, we do not require having $Ly\alpha$ measurements and corresponding metallicities (i.e. targeting metal-strong systems), although having $N_{HI}$ will eventually allow the calculations of ionization fractions and dust-to-gas ratios. We caution that choosing a metal column density threshold leads to a mixture of high-$N_{HI}$, low-metallicity, and low-$N_{HI}$, high-metallicity systems which may be very different in their properties. This may affect our conclusions about the nature or evolution of the metal-strong systems. We will address these issues in more detail with future papers on high-resolution metal-line observations complete with $N_{HI}$ measurements.

Also note that most systems presented here are not confirmed DLAs as they lack spectral coverage of $Ly\alpha$, but (as will be shown) the following analysis is largely independent of $H I$ measurements. Previous works (e.g. Khare et al. 2004) have attempted to estimate $N_{HI}$ from the reddening $E(B - V)_{g - i}$. But, we find that for the systems in our sample where $N_{HI}$ values exist, this method consistently overestimates $N_{HI}$, often dramatically so. This may be due to reddening contributions from both the QSO host and the absorber in question, as well as possible differences between the properties of local and high-redshift dust grains. We therefore avoid these rough estimations for $N_{HI}$ and await $Ly\alpha$ observations to comment on ionization corrections and dust-to-gas ratios of particular systems. A quantitative justification of the term ‘MSDLA’ is provided below in § 3.2.

1Note that the Zn criterion for a solar $Si/Zn$ ratio (Grevesse et al. 1996) implies log $N(Si^+)/N(Zn^+)$ $> 16.0$, and so we see that assuming solar $Si/Zn$ for DLA-B/FJ0812+32 is not well supported (yet not glaring in difference). The difference may be attributed to depletion effects due to dust, and we comment on the role of dust in MSDLAs (and in the overall DLA population) in § 7.
3. METAL STRONG ABSORBERS IN THE SDSS

The SDSS is a tremendous survey conducted using a 2.5-meter telescope at the Apache Point Observatory (APO, Sunspot, NM). Millions of objects have been observed by this wide-field digital telescope. All of the SDSS spectra analyzed here were reduced using the SDSS spectroscopic pipeline. The third dataset, SDSS-DR3, contains all data taken through June 2003, and we retrieved the quasar spectra from http://www.sdss.org. With rare exception, the fiber-fed SDSS spectrograph provides full-width half-maximum FWHM ≈ 150 km/s spectra of each quasar for the wavelength range λ ≈ 3800 − 9200Å. The 1σ Poisson noise from counting statistics is also calculated and recorded during the reduction. For our metal-strong subset, we chose a limiting magnitude of r = 19.5 mag to facilitate follow-up observations with 10-m-class telescopes. The signal-to-noise ratios (SNRs) of this subset of SDSS spectra range from ≈ 5 to 30 per pixel, with a typical value of ≈ 12.

Figure 1 shows the SDSS spectrum of the metal-strong DLA system first identified by Prochaska, Howk, & Wolfe (2003). The successful detection of more than 20 elements in this DLA (DLA-B/FJ0812+32) motivated us to develop an automated procedure to identify a complete catalog of similarly metal-strong systems in SDSS.

![Figure 1: Sloan Digital Sky Survey spectrum of DLA-B/FJ0812+32 (plate 861, fiber 333), with wavelengths in Å along the x-axis, flux (f3 × 10^{-17} erg s^{-1} cm^{-2} Å^{-1}) along the y-axis, and the 1σ error in gray. This example shows a bit of the Lyα forest region redward of the QSO Lyα emission peak, many of them associated with the DLA system (marked; the longer dashes show the key metal-strong transitions Si II 1808 and Zn II 2026). This is a bright QSO (r = 17.46 mag) and therefore this spectrum has high SNR for SDSS data.](image)

3.1. SDSS Search Algorithm and Visual Inspection

This section describes the codes we developed to identify metal-strong DLA candidates in the SDSS quasar spectra. These algorithms are now available as part of the XIDL package developed by J.X. Prochaska; see http://www.ucolick.org/~xavier/IDL/index.html. Our strategy was to identify all significant absorption features redward of the Lyα forest and search for sets of these lines which have a common absorption redshift. The search is complicated by the (possible) presence of other metal lines associated with separate systems along the same sightline as well as telluric lines from our atmosphere.

We set the minimum redshift of this survey to z_{abs} = 1.6 because the Earth’s ozone (O_3) layer blocks UV radiation below 3000 Å and, therefore, the Lyα profile cannot be observed at z_{abs} < 1.6 with ground-based telescopes. Follow-up UV observations are largely unattainable because of the current lack of space-based UV facilities with the requisite wavelength coverage and resolution. SDSS spectra have a starting wavelength at ≈ 3800Å such that systems with z_{abs} < 2 have their Lyα profile blueward of the SDSS spectra. It is nevertheless worthwhile to extend the search to z = 1.6 rather than z = 2.1, because we expect to observe more metal-strong systems at lower redshift given: (1) galaxies enrich in time (Prochaska et al. 2003); and (2) the QSO luminosity function peaks at z_{em} ∼ 2 providing many additional targets at z < 2.2. Also, extending the search to z = 1.6 is worthwhile simply because we’d like to increase our chances of of finding potentially rare metal-strong DLAs. Many of our metal-strong candidates are detected at z_{abs} < 2 and therefore have no corresponding Lyα profile in the SDSS spectra. Follow-up observations with medium-sized ground-based telescopes will provide the H I measurements necessary for determining metallicities and ionization fractions of the systems.

The first step in our analysis is to process every quasar with the algorithm sdss_qsolin. This routine fits a continuum to each spectrum using a principle component analysis (PCA) developed by S. Burles. It then convolves each spectrum with a Gaussian of FWHM=2.5 pixels (chosen to match the width of unresolved metal profiles in SDSS) and records any resulting absorption features that are detected to be ≥ 3.5σ. Finally, the code records the wavelengths of all features separated by more than 4 pixels; multiple features identified with smaller separation are recorded as a single line. We restrict the metal search to the spectral region redward of the QSO Lyα emission to (1) avoid misidentifying Lyα forest lines as metal absorption, and (2) simplify the automated continuum fitting. We estimate that a negligible amount of candidate metal-strong systems are missed by avoiding the Lyα forest in our metal search, largely due to the possibility of lone Mg II systems being retained by the algorithm, as well as the broad λ_{rest} range of other typically strong lines used in the search (see Table 1). Also note that this issue is particularly negligible when considering the MSDLA fraction computed in § 7.1, due to the availability of Lyα absorption and high λ_{rest} transitions (eg. Mg II & Fe II).

The wavelengths of the detected features are then sent to sdss_search (the controlling code for sdss_metals, sdss_compare and sdss_dla, the latter detailed in Prochaska & Herbert-Fort 2004) where they are matched against 14 redshifted metal transitions (see Table 1). These 14 transitions were chosen due to their frequent occurrence in high-redshift DLAs; the ions are typically present in large amounts (due to SNe enrichment from massive stars) and/or
have large oscillator strengths. We systematically redshift the 14 lines from \( z = 1.6 \) to \( z_{\text{em}} \) in increments of 0.0001 in \( z \). For each corresponding absorption feature in the observed spectrum within the local dispersion \( \Delta \lambda \) of the spectrograph (roughly 1 \( \text{Å} \) pixel\(^{-1} \) near 4000 \( \text{Å} \) to 2 \( \text{Å} \) pixel\(^{-1} \) near 8000 \( \text{Å} \)), the algorithm records a match. The matched wavelengths are also restricted to be greater than \( 1230 \times (1+z_{\text{em}}) \) to avoid misidentifying QSO-associated Ly\( \alpha \) absorption as metal absorption, and regions of the spectrum containing severe atmospheric effects (particularly in the red) are avoided. If more than 10 lines were identified redward of 8000 \( \text{Å} \), this region is flagged for severe sky effects and is not included in any further analysis. Otherwise, the search terminates at 9200 \( \text{Å} \).

At each redshift, we calculate a percentage-based detection to be the ratio of matches to the number of possible matches: \( P = n/m \), where \( n \) is the number of matched transitions and \( m \) is the number of possible matched transitions, specifically those lying in the spectral coverage (excluding the Ly\( \alpha \) forest) and not in a masked sky area. We are especially interested in detecting the Si \( \text{II} \) 1808 transition (after examining many SDSS spectra we have determined that it is an excellent metal-strong indicator; see § 5 below); therefore, we do not include it as a possible match (the \( m \) of our percentage-based detection), but do increment \( n \) if this line is detected. We then define candidate absorption systems to be at those redshifts where \( P > 60\% \) and \( n > 1 \). If two or more of these systems lie within \( \Delta z = 0.01 \) we combine them into one system (to account for wide absorption line systems and the low resolution of SDSS spectra). Finally, the redshift, the percentage of detection and number of line matches, \( n \), of each detected metal system are recorded. The latter two are then used to assign each system an overall quality rating in \textit{sdss\_compare}.

The final step was to visually inspect every detected system with a customized tool, \textit{sdss\_finchk}, and visually rate the strengths of the metal absorptions. Each system was subjectively rated as either ‘bizarre’, ‘none’, ‘weak’, ‘medium’, ‘strong’, or ‘very strong’, depending on the amount and strengths of the lines present in the system. We mostly used the presence of Si \( \text{II} \) 1808 to judge ‘strong’ and ‘very strong’ systems in SDSS, as \( \text{Zn II} \) may often be buried in the noise of low-SNR SDSS spectra. If the minimum depth of the Si \( \text{II} \) 1808 profile \( F_{\text{min}}/F_q \approx 0.9 \) where \( F_q \) is the quasar flux, then the system was rated as ‘strong’. If the normalized intensity was \( F_{\text{min}}/F_q \leq 0.85 \) the system was rated ‘very strong’. Note that this is a subjective visual inspection and the minimum depths were chosen based on experience of looking at many SDSS Si \( \text{II} \) 1808 absorption profiles. Any other metals present were also taken into account, especially if the \( \text{Zn II} \) 2026 line was covered. Candidates that were found as a result of confusion with severe noise or sky lines were rated ‘bizarre’. For reference, a summary of our subjective metal-rating scale is shown in Table 2.

All 435 ‘strong’ and ‘very strong’ candidate systems from our search in SDSS-DR3 \( (z_{\text{abs}} \geq 1.6) \) are compiled in Table 3. The complete table is available in the electronic (online) version of this paper; we present only a sample here. Table 3 lists SDSS plate, MJD, and fiber, together with RA, Dec, \( r \), \( z_{\text{em}} \), \( z_{\text{abs}} \), the overall quality rating of each system \((18 \text{ is the highest with a strong candidate DLA automatically detected by sdss\_dla, otherwise 10 if the system lacks Ly\( \alpha \) coverage) and our metal rating from visual inspection \( (4=\text{‘strong’}, 5=\text{‘very strong’}) \). Most \( (\frac{4}{5} \approx 63\%) \) systems in our ESI sample (described below) were taken from the ‘very strong’ category, while the remainder are all classified as ‘strong’. Broad absorption line (BAL) spectra (see Barlow & Junkkarinen 1994) were avoided if determined to be too severe (via subjective visual inspection), as these are often associated with the QSO itself and can significantly confuse any subsequent absorption analysis. Approximately 3\% of the SDSS-DR3 quasar sample were flagged as BALs (PHW05).

### 3.2. SDSS Search Results

Of the 19,435 SDSS-DR3 QSO sightlines with \( z_{\text{QSO}} \geq 1.6 \), 2,352 systems show metal absorption ranging from ‘weak’ to ‘very strong’ (ie. all but the ‘bizarre’ and ‘none’ categories). 16,649 sightlines \( (86\% \text{ of those searched}) \) were without sufficient features resembling DLA and/or metal absorption to be retained by the algorithm (note that, for example, a single C IV absorption system won’t satisfy our search criteria). From the set of 2,352 candidate metal absorbers \( (\text{not yet limited to } r < 19.5) \), we rated 285 \( (12\%) \) as ‘strong’ \( (S) \) and 150 \( (6\%) \) as ‘very strong’ \( (\text{VS}) \) systems (see Table 3). Of the 78 systems categorized as ‘strong’ with \( z_{\text{abs}} \geq 2.2 \), 74 \( (95\%) \) show a corresponding DLA, while 3 of the 4 others have \( N_{\text{HI}} \) within 1\( \sigma \) of the DLA threshold. The exception at \( z = 2.44 \text{ toward J150606.82+041513.1} \) (SDSS plate and fiber \([589,547]\)) has a measured \( \log(N(\text{HI}) = 19.65 \pm 0.15 \) at \( z_{\text{abs}} = 2.44 \) and represents a rare subset of the super-LLS population. Therefore, we report that \( \leq 5\% \text{ of S absorbers in our sample (with observable Ly\( \alpha \) profiles in SDSS) are not DLAs. Of the 41 VS systems with \( z_{\text{abs}} \geq 2.2 \), 100\% show a corresponding DLA in the SDSS spectra. Even allowing for an evolution in the \( N_{\text{HI}} \) distribution of metal-strong candidates between redshifts \( 1.6 < z < 2.2 \), we contend that only a very small fraction of our MSDLA candidates are not truly DLAs. We are therefore confident in having identified a metal-strong DLA population while lacking Ly\( \alpha \) coverage on most systems. However, the presence of a larger fraction of lower \( N_{\text{HI}} \) systems cannot be excluded until \( N_{\text{HI}} \) values are obtained for all systems in our sample.

Note, however, that we do have one confirmed super-LLS case in our sample – discussed below; also see Péroux et al. (2006) for another possible example of such a system, although note that the \( N_{\text{HI}} \) value of the Péroux et al. (2006) system was within 0.5\( \sigma \) of the DLA threshold, and an independent analysis of the same data from Rao et al. (2005) found it to be a bona fide DLA with \( \log(N(\text{HI}) = 20.54 \pm 0.15 \). Other systems with low \( N_{\text{HI}} \) and high metallicity have also been found at lower redshifts \( (z < 1) \) by Pettini et al. (2000) and Jenkins et al. (2005; note that this system lies at \( z \approx 0.08 \), ie. far below the range studied in this work).
4. ESI Observations, Data Reduction and Measurements

4.1. ESI Observations and Data Reduction

To test our automated selection methodology we compiled a list of our strongest candidate metal absorption systems from SDSS and acquired 27 moderate-resolution spectra using ESI on UT December 20th, 2003, and September 10th and 11th, 2004, at the 10m Keck II telescope. The SNRs of our ESI spectra range from \(|10 - 20| \) per pixel with a typical value of \(|16| \). ESI has a pixel size of \(|11 \text{ km s}^{-1}| \), and a 0.5" slit covers 3 pixels for a FWHM of \(|34 \text{ km s}^{-1}| \). The wavelength coverage is roughly 4,000 \(\AA\) - 10,200 \(\AA\). Table 4 presents a log of our observations listing QSO name, SDSS plate, MJD and fiber, QSO emission redshift \((z_{\text{em}})|\), \(r\) magnitude, exposure time, slit width, and observation date.

The data were reduced with the ESIRedux software package (Prochaska et al. 2003a; see http://www2.keck.hawaii.edu/inst/esi/ESIRedux/). This package converts 2D echelle spectra into 1D, wavelength-calibrated spectra. The 1\(\sigma\) array is also calculated during the reduction process. We continuum-fit each QSO separately with custom software, \(z_{\text{cont}}\), by fitting high-order polynomials to separate pieces of the spectrum containing no significant absorption. The fit pieces are patched together to create a smooth trace of the QSO continuum. We caution the reader that no errors from our continuum-fitting are taken into account. This is a significant source of error when measuring very weak lines and so we report many such cases as upper limits. Note that continuum error will be comparable to the statistical error for \(<4\sigma\) detections but negligible otherwise.

4.2. Measurements from ESI data

Ionic column densities are determined using the apparent optical depth method (AODM; Savage & Sembach 1991, also Jenkins 1996), except when determining \(N(\text{Zn II})\) (discussed below in § 4.2.2). Only lines that have been detected at \(\geq 3\sigma\) are listed as measurements. We begin a measurement by plotting the continuum-normalized profile in velocity space with an arbitrary zero-velocity centered on the redshift \(z_{\text{abs}}\) of the system (usually determined from the strongest of all visible transitions). As examples, selected velocity plots from two systems are shown in Figures 2 and 3. Our full ESI velocity plot sample can be retrieved from the electronic edition of the journal. If an absorption line is determined to be saturated (equivalent width \(W > 600 \text{m}\AA\); see Prochaska et al. 2003 and below), \(N(X)\) may be treated as a lower limit to the true column density. However, note that saturation effects based on \(W\) measurements alone may be misleading for systems with wide velocity widths, as is clearly the case with SDSS0016–0012 (integrated velocity width \(|1000 \text{ km s}^{-1}|\) wide). See below for more discussion of saturation effects and its impact on MSDLA classification for Keck ESI data. The \(N(X)\) values are reported as upper limits if a feature is detected at less than \(3\sigma\) statistical significance.

The electronic edition of the journal also presents tables of ionic column densities for each QAL system in our metal-strong sample. Each table lists ions, rest wavelengths in \(\AA\), a flag (0-5) distinguishing primary/non-primary ions and/or limits, \(N(\text{ion})\) as determined from the AODM and \(N(\text{element})_{\text{adopt}}\) (determined to be the weighted mean of the primary ion column densities). Any solar values used in the analysis are taken from Grevesse et al. (1996).

4.2.1. Saturation of ESI spectra and the MSDLA definition

Here we emphasize the importance of saturation effects in Keck ESI spectra. We find (in this study and from previous experience with ESI data) that absorption profiles extending below normalized intensities \(F_{\text{min}}/F_{\text{q}} < 0.4\) are typically saturated and must be treated as lower limits to the true column densities. In light of this, we treat systems with saturated Zn II or Si II profiles above \(\log N(\text{Zn}^+) \geq 13.0\) or \(\log N(\text{Si}^+) \geq 15.8\) as MSDLAs; however, note that true MSDLAs are defined to have \(\log N(\text{Zn}^+) \geq 13.15\) or \(\log N(\text{Si}^+) \geq 15.95\) and we are simply accounting for ESI saturation effects. Indeed, DLA-B/FJ0812+32 clearly illustrates this effect: ESI data show \(\log N(\text{Zn}^+) \approx 13.04\) while Keck/HIRES yields \(\log N(\text{Zn}^+) \approx 13.15\) because the lines are not fully resolved in the ESI spectrum. Also, ESI data of \(N(\text{Si}^+)\) from DLA-B/FJ0812+32 shows \(\log N(\text{Si}^+) > 15.78\) whereas HIRES data yields \(\log N(\text{Si}^+) \approx 15.95\), again due to line saturation. Also note the possibility that some very narrow saturated components of these transitions may not even be resolved by HIRES, in which case...
the true column densities could be even higher, and so some systems below the ESI-saturation MSDL A threshold might also truly be MSDLAs. Such cases could raise the MSDL A fraction higher than is reported below (§ 7.1).

4.2.2. Mg I and Cr II contributions to Zn II

Pettini et al. (1994) emphasized (for the DLAs) that the Zn II 2026 profile is blended with a weak yet potentially important Mg I 2026 transition. York et al. (2006) have recently shown that in some cases (eg. their Sample 21) that Mg I may dominate the absorption profile at \( \lambda_{\text{rest}} = 2026 \AA \) (as we also find in a few systems), causing concern for any study examining Zn II abundances, particularly for strong systems. Although the Mg I 2026 line has not been well surveyed in the damped Ly\( \alpha \) systems (Prochaska & Wolfe 2002), we suspect that this contribution (in MSDL A candidates) is significantly larger than the average. The likely explanation is that the metal-strong absorbers correspond to higher density regions (sightlines probing nearer the enriched central regions of galaxies) and so one observes a higher fraction of Mg\(^0\) atoms per Zn\(^+\) ion.

Because our observations generally include the Mg I 12852 transition, we can estimate the equivalent width of the Mg I 2026 transition (assuming the linear curve of growth, or COG) from the column density measured for Mg I 12852 (with the AODM) and therefore its contribution to the line-profile at \( \lambda_{\text{rest}} = 2026 \AA \). In turn, we can measure a more reliable value for \( N(Zn^+) \) from the equivalent width of the remaining Zn II transition at \( \lambda_{\text{rest}} = 2026 \AA \) (again assuming the linear COG). An inspection of Table 5 shows that the equivalent width of the Mg I 2026 line often contributes > 20% (with a large scatter) of the total equivalent width measured at \( \lambda_{\text{rest}} = 2026 \AA \). For those cases where we expect a saturation correction for Mg I 2852, we have incremented the column density by 0.1 dex. This rather small adjustment is due to the fact that the line-profiles are generally not heavily saturated (specifically, follow-up observations with HIRES indicate a 0.1 to 0.2 dex correction is appropriate given the observed peak optical depth of these lines at ESI resolution). We caution that this correction may be misleading for the strongest Mg I systems and that such cases could lead to an overestimate of \( N(Zn^+) \). Higher-resolution data will be useful for examining this effect in particular systems. Furthermore, we have visually inspected every Zn II 2026 profile and find no evidence for severe Mg I 2026 contamination for those DLAs where we report a \( N(Zn^+) \) value. Also note that in many cases (see Table 5) the profile of this transition is either noisy (due to low SNR in a particular section of our echelle data), blended with sky and/or profiles from unrelated systems, or simply weak and perhaps at < 3\( \sigma \) statistical significance if considering continuum-placement errors, and we report \( N(Zn^+) \) as an upper limit.

Similar to the Mg I blending issue is the blending of Cr II and Zn II at \( \lambda_{\text{rest}} = 2062 \AA \). This effect was estimated in the same manner as with Mg I (above; yet with both Cr II transitions at \( \lambda_{\text{rest}} = 2056 \) and 2066 \( \AA \) whenever possible) and we calculate an independent value of \( N(Zn^+) \) at \( \lambda_{\text{rest}} = 2062 \AA \), whenever possible. We find that Cr II significantly dominates the 2062 profile in most cases. When taken together we find (and list in the tables) the Mg I and Cr II blend-corrected values of \( N(Zn^+) \). Nevertheless, one must always keep in mind the limited resolution of the ESI and that equivalent width measurements may also underestimate \( N(Zn^+) \).

5. SDSS METAL-STRONG INDICATORS

Having identified all potential metal-strong systems in SDSS-DR3, we determine rest equivalent widths \( W \) for transitions detected in both the SDSS and ESI spectra. \( W \) is the normalized, intensity-weighted width of a line (here in m\( \AA \)), and corresponds to the fractional energy absorbed by the transition. This quantity is independent of instrument resolution and is a good predictor of column density for weak lines. Strong lines tend to be saturated; in this regime, \( W \) grows with \( \log N(X) \) and so a line has roughly the same \( W \) as \( N(X) \) increases. As a result, \( W \) is not a reliable column density predictor for strong lines and we must identify the most reliable weak lines as metal-strong indicators in low-resolution spectra.

We have determined that Si II 1808 and Zn II 2026 are usually evident in the metal-strongest absorption systems in SDSS. These two elements are typically only mildly depleted, making them useful indicators of MSDLAs. We measured \( W \) values for Si II 1808 and Zn II 2026 in both the SDSS and ESI spectra for the subset of systems observed with ESI. However, recall that the Zn II 2026 transition is typically blended with Mg I 2026. Table 6 lists the QSO name, SDSS plate and fiber, \( z_{\text{em}}, z_{\text{abs}}, \)
$r$, log$N_{\text{HI}}$ if available, log$N$(SiII 1808), log$N$(ZnII 2026) (blend-corrected), and $W_r$(1808) and $W_r$(2026) from both SDSS and ESI data. The idea here is to roughly estimate $W_r$ values in SDSS data to gauge a system’s metal-strong potential when observed at higher resolution. We assign conservative $\sigma_W$ estimates on SDSS data of 50 mÅ. Figure 4 shows a plot of our $W_r$ measurements for the absorption profiles at $\lambda = 1808$ and 2026Å from SDSS and ESI observations, for systems with secure column density values. The majority of measurements lie within 2$\sigma$ of each other, although weaker lines are found to have a systematically higher, false contribution from noise in lower-resolution and lower-SNR SDSS data. Overall, however, we conclude that using $W_r$(1808) and $W_r$(2026) from SDSS is a reliable means of gauging a system’s metal-strong potential in higher resolution spectra.

We now investigate how $W_r$ estimates from SDSS correlate with column density values measured from the ESI data. Figures 5 and 6 show $W_r$ from SDSS vs. log$N$ from ESI for Si II 1808 and Zn II 2026, respectively (exact $\sigma_N$ values can be found in the abundance tables of the electronic version of the paper; roughly 0.07 dex for Si II 1808 and 0.10 dex for Zn II 2026). We expect smaller $W_r$ values to be more reliable indicators of $N$ (they are weak, unsaturated lines), and indeed we see a larger scatter in the larger and possibly saturated $W_r$(Si II 1808) values. We therefore expect that Zn II 2026, although less often detected in SDSS spectra, is a more reliable indicator of potential MSDLAs than is Si II 1808. Considering Figure 6, we tentatively expect that most SDSS systems with $W_r$(Zn II 2026) $> 300$ mÅ will be truly metal-strong when measured at higher resolution, supporting a choice to skip the moderate-resolution confirmation observations of such systems. Note that our ESI measurements of Zn II lines near log$N$(Zn II 2026) $\approx 13.0$ are systematically underestimated by 0.1 to 0.2 dex due to line saturation. Si II 1808, however, is detected more often than Zn II 2026 in the SDSS spectra and may be the only indicator for low-resolution, low-SNR data. We therefore propose a similar tentative $W_r$(Si II 1808) metal-strong threshold of 450 mÅ, past which we will skip medium-resolution observations (also note here that our ESI measurements of Si II lines near log$N$(Si II 1808) $\approx 15.8$ may be viewed as understimated due to line saturation). For optically-thin gas, a $W_r$(Zn II 2026) $= 300$ mÅ profile corresponds to log$N$(Zn$^+$) $\approx 13.2$, and a $W_r$(Si II 1808) $= 450$ mÅ profile corresponds to a log$N$(Si II 1808) $\approx 15.9$. With the overall goal of this project being to discover more systems like DLA-B/FJ0812+32 we are excited to see that many systems far surpass it in $N$(Si$^+$) and $N$(Zn$^+$). These systems may show transitions not yet observed in the young universe and could be used to constrain theories of nucleosynthesis and galaxy evolution, as did DLA-B/FJ0812+32. We will present detailed results of Keck/HIRES and VLT/UVES observations of these new systems in upcoming papers.

6. EQUIVALENT WIDTH AND SNR ESTIMATES FOR DETECTING VERY WEAK LINES

To reliably constrain theories on the production of elements like B, O, Sn, Pb and Kr, higher-resolution data is needed. Some of these lines (BiI λ1362, O I λ1355, SiII λ1400, Pb II λ1433, and KrI λ1235) are still out of reach to modern instruments and with reasonable integration times. Nevertheless, it is interesting to estimate how strong they might be in our sample of metal-strong DLA galaxies for which we have reliable measurements of other elements. These extremely weak lines are presumed to lie buried in our metal-strong ESI data, yet it may be possible to bring them out with lengthy HIRES observations (assuming that they lie in detectable spectral regions). As a
brief exercise we predict the SNRs it would take to detect such features at $3\sigma$.

Because we are interested here in detecting weak lines, we will make use of the weak limit of equivalent width,

$$W_{\text{obs}}(X) = \frac{\pi e^2}{m_e c^2} \lambda^2(1+z) N(X)f,$$

where $W_{\text{obs}}(X)$ is the observed equivalent width of transition $X$ and $N(X)$, $\lambda_r$ and $f$ are the column density, rest wavelength, and oscillator strength of the line, respectively. Because we have not yet measured the weak lines, we must first estimate their $N$ values from other reliable line measurements in their corresponding systems. To do this, we assume that the column densities scale with their solar abundances (ie. $[X/Y]=0$ with $X$ the undetected element and $Y$ a detected reference element) with no corrections. Next, a reliable reference element is chosen. Because Fe is highly refractive, we will choose the mildly depleted element Si (we have the most measurements of Si after Fe). Using

$$\log \left[ \frac{N(X)}{N(X)_\odot} \right] = \log \left[ \frac{N(\text{Si})}{N(\text{Si})_\odot} \right]$$

(2)

to scale the abundances to solar values, one can easily solve for $N(X)$ and hence $W_{\text{obs}}(X)$.

To determine what SNR is needed for a $3\sigma$ detection, it can be shown that

$$\text{SNR} = \frac{3}{W_{\text{obs}}} \sqrt{\frac{\lambda_{\text{obs}} \Delta \lambda}{c}},$$

(3)

assuming $\sigma_l$ (the normalized error of the spectrum) and $\Delta \lambda$ are constant across the $V$ velocity width feature. This is a reasonable assumption for metal lines in the weak limit (and if they are narrow features). Here $\Delta \lambda$ is the HIRES dispersion element in mÅ/pixel at the wavelength of the feature and $c$ is the speed of light.

Figure 7 shows the limiting $W_{\text{obs}}$ detection lines vs. SNR (per 2 km s$^{-1}$ pixel) for a $V = 20$ km s$^{-1}$ absorption profile detected at $3\sigma$ and plotted for $\lambda_{\text{obs}} = 4000$ Å (black) and 5000 Å (gray). As an example, we investigate predictions for the observed B II 1362 line in the DLA-B/FJ0812+32 HIRES spectrum from Prochaska, Howk, & Wolfe (2003) ($V \approx 20$ km s$^{-1}$, $\lambda_{\text{obs}} = 4940$ Å). The dotted line shows $W_{\text{obs}}$ of B II in DLA-B/FJ0812+32 as predicted from ESI data assuming $[B/\text{Si}] = 0$ ($W_{\text{obs}} > 6$ mÅ; a lower limit because $\log N(\text{Si}^{+}) > 15.78$ in the ESI data). The dashed line is the predicted $W_{\text{obs}}$ of B II using the $\log N(\text{Si}^{+}) = 16.0$ measurement from HIRES as reference. In the HIRES spectrum, we measure the B II $W_{\text{obs}} \approx 18$ mÅ for a SNR $\approx 30$ (per 2 km s$^{-1}$ pixel). The offset between the observed and predicted $W_{\text{obs}}$ values is due to our assumption that the column densities scale with their solar abundances with no corrections. Indeed, in this case the gas-phase B/Si abundance is super-solar and we therefore expect the observed value to be found above the predicted value.
Many of the predicted Sn, Pb, and Kr equivalent widths are currently out of reach (for example $W_{\text{abs}} = 2.5, 1.8$ and 4.3 mÅ respectively, for DLA-B/FJ0812+32 assuming $\log N(\text{Si}^+)=16.0$), but our SDSS metal-strong sample includes a number of excellent candidates for observations with future instruments.

7. IMPLICATIONS FOR DAMPED Lyα SYSTEMS

7.1. Metal-Strong DLAs

Given the results from our ESI observations, we may now return to our SDSS MSDLA candidates and estimate the fraction of DLAs that are truly metal-strong. This may help us determine if previous analyses of DLA chemical evolution have suffered from small sample sizes. Our SDSS-DR3 DLA Survey (PHW05) presents a number of excellent candidates for observations with future instruments.

Figure 8 presents a histogram of $\log N(\text{Zn}^+)$ from our ESI data. Measurements are plotted as filled gray in the top panel, upper limits as black lines in the bottom panel, and the metal-strong threshold ($\log N(\text{Zn}^+) = 13.15$) as a dashed black line. We emphasize that ESI measurements of Zn lines near $\log N(\text{Zn}^+) = 13.0$ (dashed gray line) are systematically underestimated by 0.1 to 0.2 dex due to line saturation. Therefore, nearly half of the detections in Figure 8 probably match or exceed the metal-strong threshold.

As mentioned in Boissé et al. (1998) and originally developed in Fall & Pei (1993), significant dust extinction might preferentially select QSO systems having a low metal content. This follows from the argument that metal-strong systems having a high metal content would likely also have significant dust columns, thereby considerably dimming the background QSO. In magnitude-limited surveys, therefore, one might expect to find the most metal-strong absorbers towards the faint end of the QSO-sightline magnitude distribution.

Figure 9 presents $\log N(\text{Zn}^+)$ vs. $r$ magnitude from our ESI sample. Keeping in mind that systems near $\log N(\text{Zn}^+) \approx 13.0$ (dashed gray line) are likely underestimated due to saturation, one notices a significant scatter in the $r$ magnitudes consistent with no statistically significant dust bias; a Spearman rank correlation test on the measured values (ie. excluding limits) gives a linear correlation coefficient of 0.49 at < 2σ statistical significance. However, we emphasize that the true test of this debate lies in observing fainter QSOs. Indeed, our strongest Zn absorber (SDSS1610+4724) does lie among the faintest QSOs in our metal-strong sample; this system in particular is most likely affected by dust obscuration (the results presented in § 8 find it to have the highest [Mn/Fe] value in the sample, +0.2 ± 0.1 dex, as well as high [Zn/Fe]0.7 ± 0.1 dex, both telltale signatures of dust). And, we also observe a lack of clearly
metal-strong systems along the brightest QSO sightlines.

![Graph](image_url)

Fig. 9.— $\log N(Zn^+)$ vs. $r$ magnitude from our ESI sample. The metal-strong threshold, $\log N(Zn^+) = 13.15$, is marked as a dashed black line. DLA-B/FJ0812+32 is marked in gray. Note that systems with $\log N(Zn^+) \approx 13$ (dashed gray line) may be underestimated due to line saturation in ESI spectra. A nearly 2 magnitude statistically constant scatter in the magnitudes of metal-strong sightlines is observed; a Spearman rank correlation test on the measured values (excluding limits) gives a linear correlation coefficient of $0.49$ at $< 2\sigma$ statistical significance. Finding MSDLAS along fainter QSO sightlines (i.e. $r > 19.5$) will provide a better means to test the effects of dust on this population.

The Boissé et al. (1998) sample contained 37 DLAs, and considering the MSDLA fraction is $\approx 5\%$ it is not surprising that the number of MSDLAS described in that work was zero (also note that the limiting magnitude there was significantly brighter than ours, near $r \approx 18.5$, so systems predicted to be the most strongly affected by dust, the MSDLAS, were even more unlikely to be found in that sample). We contend, however, that a significant dust bias is not evident in either our ELM or MS absorber samples and that MSDLAS are not often discovered at high redshift simply because they are rare. However, we acknowledge the hindrance of not having HI measurements for most of these systems; we have therefore not computed dust-to-gas ratios or ionization fractions for the absorbers in our sample. These values would be critical for a thorough analysis of dust extinction in metal-strong absorbers, and we plan to confront such issues in future papers.

Other works have also been unable to find evidence supporting a significant dust bias on the overall DLA population. Murphy & Liske (2004) presented a spectroscopic survey of over 70 DLA sightlines from SDSS-DR2 comparing the spectral index distribution of these DLA sightlines with a large control sample and found no evidence for dust-reddening at $z \approx 3$. They placed a limit on the shift of the spectral index $|\Delta \alpha| < 0.19$ (3$\sigma$), corresponding to $E(B-V) < 0.02$ mag (3$\sigma$) for SMC-like dust, and preliminary SDSS-DR3 results show $\Delta \alpha = -0.063 \pm 0.014$ (1$\sigma$ error; $\Delta \alpha$ significant at $\approx 4.5\sigma$), corresponding to $E(B-V) = 0.0071 \pm 0.0016$ mag and $A_r \approx 0.02$ mag for SMC-like dust (Murphy et al. 2006; in prep.). The $E(B-V)$ value is derived by (de-)reddening the DLA QSO spectra according to the SMC-like dust law with different values of $E(B-V)$ in a maximum likelihood analysis. The authors caution, however, that this preliminary result does not yet include any correction for the color selection of the QSOs in SDSS. They expect their $E(B-V)$ result to be somewhat more positive and significant once this is taken into account, with a very preliminary, rough estimate of $\approx 40\%$ effect. This comes from estimates of SDSS completeness at different values of the spectral index in Murphy & Liske (2004). Although the nature of dust in high-redshift galaxies is not well understood, these results indicate a very small reddening of the DLA QSO sightlines and that dust obscuration is therefore not very important for the overall DLA population. The results are inconsistent with earlier studies of Fall, Pei and collaborators, which the authors attribute to the small sample sizes used in previous works.

Furthermore, CORALS I (Ellison et al. 2001) demonstrated that $z > 2$ samples of DLAs toward radio-selected quasars show no significant difference from optically-selected samples, and CORALS II (Ellison et al. 2004) indicates only a mild effect at lower redshifts where integrated star formation histories are most significant. Ellison et al. (2005) finds $E(B-V) < 0.04$ in CORALS DLAs when comparing optical-to-infrared colors of QSOs with and without intervening absorbers. Finally, Akerman et al. (2005) also found no evidence for increased dust depletions in CORALS DLAs and stated that large scale optical QSO surveys give a fair census of the high-redshift absorber population. However, it should be noted that the CORALS results come from small sample sizes and may not be fully representative of the overall DLA population.

If a significant dust bias did exist one would expect to observe higher $N_{HI}$ values towards fainter QSOs, as these systems would likely have a higher dust content. The SDSS-DR3 DLA Survey (PHW05) presents results that we argue are contradictory to this idea. That work (which includes 525 SDSS DLAs with $z_{abs} > 2.2$) shows higher $N_{HI}$ systems towards brighter QSOs. In the paper, PHW05 discuss a variety of systematic effects that may be responsible and conclude with the possibility of gravitational lensing (GL). Indeed, Murphy & Liske (2004) measured an $\approx 2\sigma$ excess of bright and/or deficit of faint SDSS-DR2 QSOs with intervening DLAs and attributed this to GL. That group is currently examining this effect with the increased SDSS-DR3 DLA sample. However, we caution that the effects of dust and GL are quite difficult to disentangle and prefer to refrain from further comment until the interplay between these competing effects is better understood.

In the interest of a balanced discussion of the dust bias on DLAs, we wish to mention recent works supporting the dust bias and touching on strong metal-absorption systems. Notably, Vladilo & Péroux (2005) derived a relation between the extinction of a DLA system and its $N_{HI}$ value, metallicity $Z$, fraction of iron in dust, $f_{Fe/Z}$, and redshift $z_{abs}$. The authors argued that this relation predicts that $\approx 30 - 50\%$ of all DLAs are missed as a result of their own extinction in magnitude-limited surveys, and show that the empirical thresholds of $\log N(Zn^+) = 13.2$ and $\log N_{HI} = 22$ are also quantitative predictions of their model. We claim that such systems are simply rare and therefore not often discovered. Of the handful of MSDLAS we do find in a quasar set of nearly 20,000, we make special
Note of SDSS1610+4724 with log N(Zn$^+$) = 13.40 ± 0.03, clearly above the proposed extinction ‘threshold’ (yet admittedly in a faint QSO sightline, r = 19.22). The author has proposed that the extinction per metal column density might drop in interstellar environments with extremely high density owing to coalescence of dust grains, and that SDSS1610+4724 could be one of those rare, very interesting cases (G. Vladilo, private communication). If this is not the case, however, SDSS1610+4724 may pose a (perhaps minor) challenge to their model of dust obscuration. Unfortunately, the current lack of Zn measurements (perhaps minor) challenge to their model of dust obscuration. The authors also found that the absorber rest frame color excess, E(B-V), derived from the extinction curves, depends on the absorber properties and ranges from < 0.001 to 0.085 for various sub-samples. While a notable result, we argue that even systems with E(B-V) ≈ 0.1 are unlikely to provide a statistically significant dust obscuration bias on the overall DLA population.

Some highly dusty systems have also been discovered at lower redshifts (z ≃ 1) by Wild & Hewett (2005) and Wild et al. (2006), via strong Ca II absorption. Note that these systems are inferred DLAs from their corresponding Mg II, Mg I and Fe II absorption features. A composite spectrum from the Wild & Hewett (2005) sample yields E(B-V) ≈ 0.06, while the absorbers from Wild et al. (2006) have on average E(B-V) > 0.1.

Finally, to add an overlying word of caution to this entire debate, note the study of Hopkins et al. (2004) who examined SDSS quasars and found that reddening along these lines of sight is dominated by SMC-like dust at the quasar redshifts; that is, not even primarily due to intervening absorbers.

7.3. Effects on the $N_{\text{HI}}$-weighted Cosmic Mean Metallicity < Z( z ) >

Prochaska et al. (2003) demonstrated a statistically significant evolution in the $N_{\text{HI}}$-weighted cosmic mean metallicity < Z( z ) > from $z_{\text{abs}}$ > 2 DLAs absorbers. Here we will investigate how MSDLAs could influence their measurements. The chemical-enrichment (C-E) sample of Prochaska et al. (2003) included 113 DLAs with $z_{\text{abs}}$ ≥ 1.6 and in QSO sightlines with r < 19.5 mag and 95 DLAs with $z_{\text{abs}}$ ≥ 2.2. When considering the $z_{\text{abs}}$ ≥ 1.6 C-E sample, we find an evolution in < Z( z ) > to be m = −0.27 ± 0.03, consistent with the Prochaska et al. (2003) value (not cut for $z_{\text{abs}}$ ≥ 1.6). Recall that 5% of all $z_{\text{abs}}$ ≥ 2.2 DLAs in QSO sightlines with r < 19.5 mag are expected to be metal-strong. We may then roughly estimate the number of MSDLAs expected in a given DLA sample; we might expect to find roughly five MSDLAs in the $z_{\text{abs}}$ ≥ 2.2 C-E DLA sample. That sample currently contains only one such system, DLA-B/FJ0812+32, the defining MSDLA (recall that log N(Zn$^+$) = 13.04 from ESI, whereas HIRES data shows log N(Zn$^+$) = 13.15; an example of the above-mentioned ESI saturation issue).

To estimate the effect of a single MSDLA, we add SDSS1610+4724 (our strongest absorber in Zn, log N(Zn$^+$) = 13.40 ± 0.03, and with measured log N(HI) = 21.15 ± 0.15; [Zn/H]= −0.42 ± 0.15) to the C-E sample. We justify this exercise by the reasoning stated above (ie. expecting ∼ 5 MSDLAs in this sample), yet we note that adding many more of these systems without also including their corresponding non-MSDLAs would bias the C-E sample to an unjustifiable extent. Figure 10 illustrates that adding this one MSDLA raises $< Z >$ in the z ≃ 2.6 bin by +0.12 dex, ie. ≃ 2σ. Including this system does not significantly change m, however, just a slight increase in the scatter: now $m$ = −0.27 ± 0.04 dex.

![Fig. 10. — $N_{\text{HI}}$-weighted cosmic mean metallicity < Z( z ) >. DLAs are shown as squares scaled to the $N_{\text{HI}}$ of the system (open are from the CE sample, filled are the added SDSS1610+4724 MSDLA). $< Z( z ) >$ is plotted for 5 bins with 1σ uncertainties given by bootstrap analysis. The dark gray errors for the $z_{\text{abs}}$ ≃ 2.6 & 4 bins are the new $< Z >$ values in each bin (offset by 0.1 in z for presentation) after one MSDLA, SDSS1610+4724, is added.](image)
We therefore suggest that MSDLAs could have a modest impact on the \( <Z > \) of a single bin yet little impact on the overall DLA \( <Z(z) > \) evolution. However, in the unlikely event that one MSDLA was found in each bin under similar statistics, the effect on the linear \( <Z(z) > \) evolution slope could be larger.

8. ABUNDANCE ANALYSIS FROM THE ESI SAMPLE

We now examine certain abundance ratios from our ESI data and comment on the dust depletion vs. SNe enrichment ‘debate’. Although HIRES data is superior, ESI can still be used to examine global abundance trends.

Before we begin, we must mention here that one system, SDSS0927+5621 (\( z_{abs} = 1.78 \)), has a confirmed \( \log N_{HI} = 19.00^{+0.10}_{-0.25} \) (Prochaska et al. 2006, submitted). This system was selected by its metal-strong signature, and metal-strong systems usually are in the \( N_{HI} \) range of DLAs. Why is this object both H I-poor and metal-strong? Prochaska et al. (2006, submitted) use HIRES data and find that SDSS0927+5621 is highly ionized, with an ionization factor \( x \approx 0.9 \) (based on inferences made from the observed \( N_{HI} \) and Al\(^{++} \) values). In this case, the QAL system is too far from the QSO to be ionized by it (\( z_{em} = 2.28 \)). The extragalactic UV background (EUVB; from QSOs and/or galaxies not in the sightline) is surely a part of the responsible ionizing radiation, but the dominant component likely comes from young, massive stars within the host galaxy. If massive stars are present, one might expect strong-metal absorption (observed), assuming some previous enrichment and energetic feedback processes. Indeed, the authors find SDSS0927+5621 to have wide, complex velocity profiles and propose that such kinematic structure is indicative of feedback processes correlated with star formation. The authors also (tentatively) find SDSS0927+5621 to have the highest gas metallicity of any astrophysical environment and total metal surface density exceeding nearly every known DLA. This system clearly falls into a separate category of QAL systems, the (super-solar) super-LLS, and so we remove it from the following abundance analysis. We caution the reader that the possibility of other assumed DLAs (with \( z_{abs} < 2.2 \)) falling into this ‘ionized’ category remains. However, recall that only \( \approx 1\% \) of our candidate MS SDSS sample with \( z_{abs} \geq 2.2 \) was below the DLA threshold. We await \( N_{HI} \) measurements from upcoming observations to further comment on this issue.

We also require the systems to have Fe measurements due to the important role of Fe in abundance ratios; therefore, SDSS0316+0040 and SDSS1235+0017 are also excluded from the following analysis. Also note that the relative abundances to be plotted will not involve \( N_{HI} \).

We have assumed a conservative lower limit of 0.10 dex error (1\( \sigma \)) for all measurements and emphasize that such large errors are the most significant hindrance to doing abundance-ratio analysis with this moderate-resolution data.

Figure 11 shows a plot of \( [\text{Ti}/\text{Fe}] \) vs. \( [\text{Si}/\text{Fe}] \). It is evident here that all the systems in our sample show enhanced Si/Fe ratios. This can be interpreted as either Type II SNe enrichment or depletion of Fe onto dust, or both. Also note that at low \( [\text{Si}/\text{Fe}] \) the \( [\text{Ti}/\text{Fe}] \) values are enhanced. Although Ti behaves like a refractory iron-peak element, in Galactic stars it shows a similar trend as the \( \alpha \) elements and is thus generally accepted as an \( \alpha \) element; therefore, because both Ti and Fe are refractory and because Ti is more heavily depleted than Fe (Savage & Sembach 1996), an overabundance of \( [\text{Ti}/\text{Fe}] \) at super-solar \( [\text{Si}/\text{Fe}] \) implies nucleosynthetic \( \alpha \)-enrichment (Dessauges-Zavadsky, D’Odorico, & Prochaska 2002). An underabundance of \( [\text{Ti}/\text{Fe}] \), however, may be attributed to depletion of gas onto dust, and we present a few of these candidates here as well. Overall, this plot may suggest Type II SNe enrichment in many of the MS systems presented here.

Figure 12 shows a plot of \( [\text{Mn}/\text{Fe}] \) vs. \( [\text{Si}/\text{Fe}] \). The \( [\text{Mn}/\text{Fe}] \) ratios are mostly sub-solar, and agree with previous measured values attributed to nucleosynthetic enrichment (Lu et al. 1996; Ledoux et al. 1998) including from Type Ia SNe (Dessauges-Zavadsky, D’Odorico, & Prochaska 2002). We expect these observations to support metallicity-dependent Mn yields from both Type Ia and Type II SNe (McWilliam, Rich, & Smecker-Hane 2003), but require \( \log N_{HI} \) measurements to be certain. In a future paper, we will investigate the differences in Mn yields from Type Ia- and Type II SNe-dominated systems; recent models indicate that particular distinction may soon be discovered at high \( [\text{Mn}/\text{Fe}] \) values. We also aim to address the range of dust-depletion levels in the MSDLAs. Here we present a new super-solar \( [\text{Mn}/\text{Fe}] \) value and another just shy due to the error; these systems present strong evidence for substantial dust depletion.

Figure 13 shows \( [\text{Si}/\text{Zn}] \) vs. \( [\text{Zn}/\text{Fe}] \) for systems in our sample with both Si and Zn measurements. One would expect systems displaying subsolar \( [\text{Si}/\text{Zn}] \) values to be spanning roughly 1,000 km s\(^{-1} \). We do not place much confidence in measurements resulting from integrating shallow absorption across such wide profiles.
more affected by dust depletion than by nucleosynthetic effects because Si is more refractory than Zn. What is observed suggests that some MS systems may indeed contain high amounts of dust (points at high [Zn/Fe] and low [Si/Zn]). Also supporting this idea is Figure 14, where we plot [Si/Ti] vs. [Zn/Fe]. Because Ti is the most refractive, Si/Ti enhancements at super-solar Zn/Fe are likely due to the depletion of Ti and Fe onto dust grains. Prochaska & Wolfe (2002) state that a correlation between these ratios is strong evidence for dust depletion, and although there is a large scatter the limits suggest a weak overall correlation. While some MSDLAs likely contain a large amount of dust and may eventually be observed to have their own dust-obscuration bias (MSDLA samples toward fainter QSOs will best address this issue), we maintain that the overall DLA population is not significantly affected by a dust bias (see previous sections).

9. SUMMARY AND CONCLUSIONS

To confirm that our automated technique works well, we summarize our metal-strong detections as follows. Our algorithms searched 19,429 SDSS-DR3 QSO sightlines with $z_{QSO} \geq 1.6$ and found 435 visually-confirmed candidate metal-strong absorbers. Of these metal-strong candidate systems with Lyα wavelength coverage available in the SDSS, we find <5% (and likely near ≈1%) are without corresponding DLAs, i.e., systems belonging to the super-LLS population.

Our metal-searching technique is most sensitive to systems with large $W$ metal profiles, but recall that a large $W$ is not a reliable predictor of $N$ for a saturated transition. Therefore, we focused on weak lines as metal-strong indicators. We plan to use these MS indicators to determine which systems may be directly observed at high resolution without first obtaining medium-resolution confirmation spectra. We argued that $W_r$ ([Si II] 1808) is not as reliable an indicator as Zn II 2026 but that it can still be useful for faint QSO sightlines.

All of our ESI (27 metal-strong systems with $r < 19.5$ mag) sample had the highest score possible from our SDSS-searching algorithms. Our ESI sample is a collection of 10 and 17 subjectively-rated S and VS systems in the SDSS, respectively. Finally, we have measured (with ESI) 11 systems with $N$([Si I]) values near or greater than DLA-B/FJ0812+32 (as measured from ESI data) and 5 with $N$([Zn II]) greater than or equal to the Zn detection from DLA-B/FJ0812+32 (in the ESI data – recall the importance of saturation effects in MSDLA classification; the HIRES spectrum of DLA-B/FJ0812+32 yields $\log N(Zn^{+}) \approx 13.15$). Therefore, ≈40% of the systems in our ESI sample yielded $N$([Si I]) or $N$([Zn II]) measurements consistent with or higher than DLA-B/FJ0812+32. PHW05 demonstrated that our automated SDSS DLA-finding technique
also works well, and we will search future SDSS Data Releases for MSDLAs and publish updated metal-strong candidate lists periodically.

We estimated the feasibility of detecting certain weak transitions at 3σ, predicting what SNRs we would need to reach with HIRES-grade instruments. We find that lines with \( W_{\text{obs}} \geq 5 \text{ m}\AA\) would be detectable with observations similar to DLA-B/FJ0812+32, and therefore that a handful of B II 1362 and O I 1335 lines may soon be observed in our metal-strong ESI sample. As the collecting power of modern and future telescopes continues to increase (and with it SNRs), we will begin detecting Sn, Pb, and Kr lines in these high-redshift systems. We are currently testing our predictions with KeckI/HIRES and VLT/UVES observations.

Taking our SDSS and ESI results together, we predict that \( \approx 5\% \) of all \( z_{\text{obs}} \geq 2.2 \) DLAs in QSO sightlines with \( r < 19.5 \) are truly metal-strong. This result is of particular importance when considering previous results from DLAs studies with small sample sizes, especially those proposing a significant dust-obscuration bias on the overall DLA population. Along separate lines of research and with additional results from our SDSS-DR3 DLA Survey, we find no evidence in support of a statistically significant dust-obscuration bias for the overall DLA population. We await a larger, deeper metal-strong DLA sample, complete with UV Lyα measurements to further comment on this issue and its relevance to the MSDLAs population.

We then investigated how a single MSDLA might affect the \( N_{\text{H}} \)-weighted cosmic mean metallicity \( <Z(z)> \) as determined from previous DLA studies. We find that adding our strongest Zn absorber (SDSS1610+4724) to the current C-E sample raises \( <Z> \) near \( z \approx 2.6 \) by \( +0.12 \) dex (\( \approx 2\sigma \)). When the same MSDLA is instead added at higher redshift (albeit a more extreme and perhaps currently unrealistic proposition), we find a \( +0.32 \) dex increase (\( \approx 2\sigma \)) in the \( z \approx 4 \) bin. The overall linear slope of the \( <Z(z)> \) evolution remains essentially unchanged in both cases. We therefore contend that MSDLAs may be significant when considering \( <Z> \) in a particular bin, yet given the current statistics are not a strong influence on the evolution of \( <Z(z)> \) from the overall DLA population.

Although the conservative errors assumed for the relative abundances from our Keck ESI (medium-resolution) data are large, and we lack many Lyα measurements for computing ionization fractions and dust-to-gas ratios, we concluded with a brief discussion of abundance ratios from our ESI sample and find evidence for significant dust depletion in a handful of systems underlining largely Type II SNe enrichment.

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### Table 1
**Atomic Data**

| Transition | $\lambda$ (Å) | $f$  | Ref. |
|------------|---------------|------|------|
| H I-A 1215 | 1215.6701     | 0.4164 | 1    |
| Kr I 1235  | 1235.8380     | 0.1871 | 1    |
| Si II 1260a| 1260.4221     | 1.007  | 1    |
| O I 1302a  | 1302.1685     | 0.04887 | 1   |
| Si II 1304a| 1304.3702     | 0.094  | 2    |
| Ni II 1317 | 1317.2170     | 0.058  | 14   |
| C II 1334a | 1334.5323     | 0.1278 | 1    |
| C II* 1335 | 1335.7077     | 0.1149 | 1    |
| O I 1355   | 1355.5977     | 1.25E-6 | 1   |
| B II 1362  | 1362.4610     | 0.987  | 1    |
| Ni II 1370 | 1370.1300     | 0.0769 | 3    |
| Si IV 1400 | 1400.4000     | 1.0274 | 12   |
| Si IV 1402 | 1402.7700     | 0.262  | 1    |
| Pb II 1433 | 1433.9056     | 0.87   | 1    |
| Ni II 1454 | 1454.8420     | 0.0323 | 4    |
| Ni II 1467 | 1467.2590     | 6.3E-3 | 4    |
| Ni II 1467 | 1467.7560     | 9.9E-3 | 4    |
| Si IV 1526 | 1526.7066     | 0.127  | 5    |
| C IV 1548  | 1548.1950     | 0.1908 | 1    |
| C IV 1550  | 1550.7700     | 0.09522 | 1   |
| Fe II 1608 | 1608.4511     | 0.058  | 6    |
| Fe II 1611 | 1611.2005     | 1.36E-3 | 7   |
| Al II 1656 | 1656.9293     | 0.1405 | 1    |
| Al II 1670a| 1670.7874     | 1.88   | 1    |
| Ni II 1703 | 1703.4050     | 0.006  | 4    |
| Ni II 1709 | 1709.6000     | 0.0324 | 4    |
| Ni II 1741 | 1741.5490     | 0.0427 | 4    |
| Si II 1751 | 1751.9100     | 0.0277 | 4    |
| Si II 1808a| 1808.0126     | 2.18E-3 | 8   |
| Mg I 1827  | 1827.9351     | 0.00522 | 1   |
| C II 1854  | 1854.7164     | 0.539  | 1    |
| Al III 1862| 1862.7895     | 0.268  | 1    |
| Fe II 1901 | 1901.7730     | 1.009E-4 | 1   |
| Ti II 1910 | 1910.7800     | 0.2020 | 17   |
| Zn II 2026 | 2026.1360     | 0.489  | 9    |
| Cr II 2066 | 2066.1610     | 0.0515 | 9    |
| Fe II 2249 | 2249.8768     | 1.82E-3 | 11  |
| Fe II 2260 | 2260.7805     | 2.44E-3 | 11  |
| C II 2325 | 2325.4029     | 4.78E-8 | 17  |
| C II* 2326| 2326.1126     | 5.32E-8 | 17  |
| C II* 2328 | 2328.8374     | 2.72E-8 | 17  |
| Si II 2335 | 2335.1230     | 4.25E-6 | 17  |
| Fe II 2344a| 2344.2140     | 0.114  | 12   |
| Fe II 2374 | 2374.4612     | 0.0313 | 12   |
| Fe II 2382a| 2382.7650     | 0.32   | 12   |
| Mn II 2576 | 2576.8770     | 0.3508 | 1    |
| Fe II 2586a| 2586.6500     | 0.0861 | 12   |
| Mn II 2594 | 2594.4900     | 0.271  | 1    |
| Fe II 2600a| 2600.1729     | 0.239  | 12   |
| Mn II 2606 | 2606.4620     | 0.1927 | 1    |
| Mg II 2796b| 2796.3520     | 0.6123 | 13   |
| Mg II 2803b| 2803.5310     | 0.3054 | 13   |
| Mg II 2852 | 2852.9642     | 1.81   | 1    |
| Ti II 3073 | 3073.8770     | 1.091  | 1    |
| Ti II 3230 | 3230.1310     | 0.0687 | 15   |
| Ti II 3242 | 3242.9290     | 0.232  | 16   |
| Ti II 3384 | 3384.7400     | 0.358  | 17   |

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**References.** — 1: Morton (1991); 2: Tripp et al. (1996); 3: Fedchak, & Lawler (1994); 4: Fedchak, Wiese, & Lawler (2000); 5: Schectman et al. (1998); 6: Bergeson et al. (1996); 7: Raassen & Uylings (1998); 8: Bergeson & Lawler (1993); 9: Bergeson & Lawler (1993b); 10: Verner et al. (1994); 11: Bergeson, Mullman, & Lawler (1994); 12: Morton (2001); 13: Verner (1996); 14: Dessauges-Zavadsky et al. (2006); 15: Bizzarrri et al. (1993); 16: Pickering, Thorne, & Perez (2008); 17: Morton (2003)

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a: Member of the *sdss Metals* search (see § 3.1).
Table 2

**Summary of Subjective Metal Ratings of SDSS Candidates**

| Metals         | Label | Rating | Description                                                                 |
|----------------|-------|--------|-----------------------------------------------------------------------------|
| Bizarre        | B     | 0      | Noise, sky, or unclear detection                                            |
| None           | N     | 1      | No metals observed                                                           |
| Weak           | W     | 2      | Usually weak Al II 1670 and/or few other strong metals                      |
| Medium         | M     | 3      | Usually strong Al II 1670 or Fe II, Mg II but no significant Si II 1808     |
| Strong         | S     | 4      | Strong Si II 1808 ($F_{\text{min}}/F_q \approx 0.90$), perhaps weak Zn II 2026 |
| Very Strong    | VS    | 5      | Very strong Si II 1808 ($F_{\text{min}}/F_q \leq 0.85$) and likely Zn II 2026 |

Table 3

**Metal-Strong Candidates from SDSS-DR3**

| SDSS plate | MJD   | SDSS fiber | RA (J2000) | Dec (J2000) | $\gamma$ | $z_{\text{em}}$ | $z_{\text{abs}}$ | Quality<sup>a</sup> | Metals<sup>b</sup> |
|------------|-------|------------|------------|-------------|----------|-----------------|------------------|-------------------|-----------------|
| 651        | 52139 | 494        | 00:08:15.33| −09:58:54   | 18.38    | 1.951           | 1.768            | 10                | 5               |
| 388        | 51792 | 607        | 00:10:17.80| +01:04:50   | 18.84    | 1.817           | 1.687            | 10                | 5               |
| 389        | 51793 | 332        | 00:10:25.93| +00:54:47   | 19.09    | 2.847           | 2.154            | 9                 | 5               |
| 752        | 52247 | 194        | 00:13:41.74| +14:35:31   | 19.39    | 1.933           | 1.922            | 10                | 4               |
| 389        | 51793 | 497        | 00:15:49.08| +00:17:31   | 19.64    | 3.066           | 2.338            | 7                 | 5               |
| 389        | 51793 | 178        | 00:16:02.40| +00:12:24   | 18.03    | 2.087           | 1.973            | 10                | 5               |
| 753        | 52227 | 430        | 00:20:28.97| +15:34:35   | 18.79    | 1.764           | 1.652            | 10                | 5               |
| 753        | 52227 | 550        | 00:26:15.58| +15:27:13   | 19.85    | 2.914           | 1.954            | 9                 | 4               |
| 418        | 51813 | 452        | 00:37:49.19| +15:52:08   | 20.03    | 4.072           | 3.816            | 17                | 5               |
| 655        | 52160 | 51         | 00:42:05.22| −10:39:57   | 19.17    | 2.490           | 2.283            | 10                | 5               |
| 656        | 52147 | 269        | 00:42:19.74| −10:20:09   | 18.66    | 3.881           | 2.753            | 14                | 4               |
| 655        | 52160 | 635        | 00:43:49.53| −09:37:44   | 18.49    | 2.130           | 1.764            | 10                | 5               |
| 393        | 51793 | 495        | 00:44:39.32| +00:18:22   | 18.20    | 1.866           | 1.725            | 10                | 4               |
| 393        | 51793 | 62         | 00:47:15.88| −00:36:44   | 18.73    | 2.198           | 2.029            | 10                | 5               |
| 395        | 51783 | 121        | 00:57:09.50| −00:54:50   | 18.86    | 1.885           | 1.791            | 10                | 4               |
| 420        | 51869 | 12         | 00:57:57.32| +14:19:00   | 19.38    | 2.154           | 1.782            | 9                 | 5               |
| 395        | 51783 | 445        | 00:58:14.31| +01:15:30   | 17.69    | 2.495           | 2.011            | 10                | 5               |
| 658        | 52143 | 490        | 00:59:45.10| −09:51:55   | 20.61    | 3.036           | 2.979            | 8                 | 5               |
| 396        | 51813 | 535        | 01:06:48.02| +00:46:27   | 18.59    | 1.877           | 1.774            | 10                | 5               |

<sup>a</sup>The automatically-assigned overall quality from sdss<sub>search</sub>; 18.0 is the highest rating (for metal-strong systems showing corresponding candidate DLAs detected by sdss<sub>dla</sub>), otherwise 10.0 for metal-strong systems without Ly$\alpha$ coverage. Three quality points are deducted if no candidate DLA is detected when Ly$\alpha$ coverage is present.

<sup>b</sup>4='strong'; 5='very strong'; determined from visual inspection of our SDSS sample.

Note. — The complete version of this table is in the electronic edition of the paper. The printed edition contains only a sample.
### Table 4: Keck ESI Observations

| RA (2000) | Dec. (2000) | Plate | SDSS MJD | Fiber | $z_{em}$ | $r$ (Mag.) | Metal Rating | Exp. (s) | Slit width $\theta$ | Obs. date |
|-----------|-------------|-------|----------|--------|----------|------------|--------------|----------|----------------|-----------|
| 00:08:15.33 | -09:58:54.3 | 651   | 52141    | 494    | 1.95     | 18.38      | 5            | 900      | 0.75            | Dec. 20, 2003 |
| 00:16:02.40 | -00:12:25.0 | 389   | 51795    | 178    | 2.09     | 18.02      | 5            | 600      | 0.50            | Sept. 10, 2004 |
| 00:20:28.96 | +15:34:35.8 | 753   | 52233    | 430    | 1.76     | 18.78      | 5            | 1800     | 0.50            | Sept. 10, 2004 |
| 00:44:39.32 | +00:18:22.8 | 393   | 51794    | 495    | 1.87     | 18.20      | 4            | 600      | 0.75            | Dec. 20, 2003 |
| 00:58:14.31 | +01:15:30.2 | 395   | 51783    | 445    | 2.49     | 17.66      | 5            | 900      | 0.50            | Dec. 20, 2003 |
| 01:20:20.37 | +13:24:33.5 | 424   | 51893    | 286    | 2.57     | 19.23      | 5            | 900      | 0.75            | Dec. 20, 2003 |
| 02:25:54.85 | +00:54:51.9 | 406   | 51869    | 572    | 2.97     | 18.92      | 4            | 1800     | 0.50            | Dec. 20, 2003 |
| 03:16:09.83 | +00:40:43.1 | 413   | 51929    | 387    | 2.92     | 18.67      | 4            | 1200     | 0.50            | Dec. 20, 2003 |
| 08:40:32.96 | +49:42:52.9 | 445   | 51873    | 043    | 2.08     | 19.00      | 5            | 1800     | 0.75            | Dec. 20, 2003 |
| 08:44:07.29 | +51:53:11.2 | 447   | 51877    | 272    | 3.20     | 19.22      | 5            | 1800     | 0.75            | Dec. 20, 2003 |
| 09:12:47.59 | -00:47:17.3 | 472   | 51955    | 210    | 2.86     | 18.67      | 5            | 900      | 0.50            | Dec. 20, 2003 |
| 09:27:05.90 | +56:21:14.1 | 451   | 51908    | 071    | 2.28     | 18.24      | 5            | 900      | 0.75            | Dec. 20, 2003 |
| 10:42:52.32 | +01:17:36.5 | 506   | 52022    | 137    | 2.44     | 18.42      | 5            | 600      | 0.50            | Dec. 20, 2003 |
| 10:49:15.43 | -01:10:38.1 | 275   | 51910    | 006    | 2.12     | 19.78      | 5            | 600      | 0.50            | Dec. 20, 2003 |
| 11:51:22.14 | +02:04:26.3 | 515   | 52051    | 223    | 2.40     | 18.00      | 4            | 600      | 0.50            | Dec. 20, 2003 |
| 12:35:59.29 | +00:17:16.4 | 290   | 51941    | 463    | 2.26     | 18.84      | 4            | 600      | 0.50            | Dec. 20, 2003 |
| 12:49:24.86 | -02:33:39.7 | 336   | 51999    | 073    | 2.12     | 17.79      | 5            | 900      | 0.50            | Dec. 20, 2003 |
| 14:35:12.94 | +04:20:36.9 | 585   | 52027    | 628    | 1.95     | 19.04      | 5            | 600      | 0.50            | Dec. 20, 2003 |
| 16:10:09.42 | +47:24:44.4 | 813   | 52354    | 621    | 3.22     | 18.75      | 5            | 1800     | 0.50            | Sept. 11, 2004 |
| 16:17:18.3 | +00:28:27.2 | 346   | 51693    | 488    | 1.94     | 19.07      | 4            | 850      | 0.50            | Sept. 11, 2004 |
| 16:58:16.47 | +34:28:09.8 | 972   | 52435    | 480    | 1.70     | 18.40      | 4            | 1200     | 0.50            | Sept. 11, 2004 |
| 17:09:09.28 | +32:58:03.4 | 973   | 52426    | 629    | 1.89     | 19.22      | 5            | 1800     | 0.50            | Sept. 11, 2004 |
| 20:44:31.12 | -05:42:39.7 | 634   | 52164    | 634    | 1.90     | 18.67      | 4            | 1200     | 0.50            | Sept. 11, 2004 |
| 20:59:22.42 | -05:28:42.7 | 636   | 52176    | 610    | 2.54     | 19.12      | 5            | 1200     | 0.50            | Sept. 11, 2004 |
| 21:00:25.03 | -06:41:45.9 | 637   | 52174    | 370    | 3.14     | 18.19      | 5            | 1200     | 0.50            | Sept. 11, 2004 |
| 22:22:56.11 | -09:46:36.2 | 729   | 52296    | 203    | 2.93     | 17.97      | 4            | 600      | 0.50            | Sept. 10, 2004 |
| 22:44:52.22 | +14:29:15.1 | 740   | 52263    | 390    | 1.96     | 18.92      | 4            | 1800     | 0.50            | Sept. 11, 2004 |

*aSee Table 2*
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Table 5
Zn Analysis

| QSO         | $W_{2026}$ (mÅ) | $W_{2852}$ (mÅ) | $W$(Mg) $^a$ (mÅ) | log $N$(Zn$^+$)$_{2026}$ | $W_{2062}$ (mÅ) | $W$(Cr) $^b$ (mÅ) | log $N$(Zn$^+$)$_{2062}$ | log $N$(Zn$^+$)$_{2062}$ |
|-------------|-----------------|-----------------|-------------------|-------------------------|-----------------|-----------------|-------------------------|-------------------------|
| F10812+32   | 173 ± 9         |                  |                   | 12.99 ± 0.02           | 72 ± 6          |                | 11.46 ± 1.12     | 12.84 ± 0.03           |
| SDSS0008-0958 | 383 ± 20       | 934 ± 27        | 37                | < 13.34                 | 280 ± 22        | 159             | 13.10 ± 0.09       | 13.10 ± 0.09           |
| SDSS0016-0012 | 190 ± 36       | 997 ± 25        | 39                | 12.93 ± 0.10           | 8 ± 34          |                | < 13.02            | 12.93 ± 0.10           |
| SDSS0020+1534 | 170 ± 36       | 843 ± 35        | 37                | < 13.06                 |                | 88              | < 13.06            | < 13.06                |
| SDSS0044+0018 | 50 ± 23        | 597 ± 28        | 21                | < 12.59                 |                |                | < 12.59            | < 12.59                |
| SDSS0058+0115 | 90 ± 12        | 675 ± 22        | 24                | 12.57 ± 0.08           | 93 ± 16        | 101             | < 12.90            | 12.57 ± 0.08           |
| SDSS0120+1324 | 65 ± 59        | 616 ± 61        | 24                | < 13.00                 | 58 ± 55        |                | < 13.23            | < 13.00                |
| SDSS0225+0054 | 125 ± 30       |                  |                   | 12.85 ± 0.10           |                |                | 12.85 ± 0.10       | < 13.08                |
| SDSS0316+0040 | 48 ± 29        | 691 ± 40        | 32                | < 12.69                 | 1 ± 30          |                | < 12.97            | < 12.69                |
| SDSS040+0492  | 224 ± 74       | 1091 ± 70       | 46                | < 13.26                 | 88 ± 59        |                | < 13.26            | < 13.26                |
| SDSS0844+5153 | ...            |                  |                   | ...                     | 187 ± 22        | 184             | < 13.08            | < 13.08                |
| SDSS0912-0047 | 168 ± 27       | 543 ± 48        | < 23               | 12.91 ± 0.09           | 130 ± 34       |                | 13.13 ± 0.11       | 12.96 ± 0.07           |
| SDSS0927+5621 | 94 ± 28        | 674 ± 47        | 25                | < 12.68                 | 138 ± 29       | 78              | < 13.18            | < 12.68                |
| SDSS1042+0117 | 72 ± 31        | 716 ± 101       | 34                | < 12.72                 | 83 ± 28        | 88              | < 13.13            | < 12.72                |
| SDSS1049+0110 | 132 ± 52       | 754 ± 28        | 28                | < 12.94                 | 118 ± 37       | 128             | < 13.35            | < 12.94                |
| SDSS1151+0204 | 375 ± 56       | 1606 ± 57       | 66                | < 13.37                 | 333 ± 49       | 161             | < 13.41            | < 13.37                |
| SDSS1235+0017 | ...            | 188 ± 66        | < 7                | ...                     | 46 ± 33        |                | < 13.01            | < 13.01                |
| SDSS1249-0233 | 208 ± 19       | 695 ± 24        | 28                | 13.01 ± 0.04           | 279 ± 19       | 238             | < 12.97            | 13.01 ± 0.04           |
| SDSS1435+0420 | 286 ± 97       | 948 ± 51        | 41                | < 13.21                 | 272 ± 57       | 155             | < 13.48            | < 13.21                |
| SDSS1610+4724 | 470 ± 27       | 361 ± 143       | 19                | 13.40 ± 0.03           | ...            | 218             | ...                 | 13.40 ± 0.03           |
| SDSS1617+0028 | 269 ± 36       | 1332 ± 41       | 58                | < 13.20                 | 169 ± 51       | 124             | < 13.42            | < 13.20                |
| SDSS1658+3428 | 378 ± 35       | 1252 ± 25       | 50                | < 13.35                 | 50 ± 26        | ...             | < 12.92            | < 12.92                |
| SDSS1709+3258 | 309 ± 22       | 598 ± 30        | 24                | 13.21 ± 0.03           | 324 ± 24       | 215             | 13.05 ± 0.12       | 13.19 ± 0.03           |
| SDSS2044-0542 | 113 ± 22       | 333 ± 29        | 13                | 12.75 ± 0.09           | 114 ± 24       | 104             | < 13.11            | 12.75 ± 0.09           |
| SDSS2050-0529 | 138 ± 37       | 600 ± 60        | 25                | 12.81 ± 0.14           | 60 ± 35        | 104             | < 13.04            | 12.81 ± 0.14           |
| SDSS2100-0641 | 213 ± 16       |                  |                   | < 13.14                 |                | 145             | < 13.14            | < 13.14                |
| SDSS2222-0946 | 103 ± 17       | 787 ± 63        | 33                | < 12.77                 |                |                | < 12.77            | < 12.77                |
| SDSS2244+1429 | 261 ± 18       | 759 ± 32        | 32                | 13.11 ± 0.03           | 114 ± 22       | 78              | < 13.07            | 13.11 ± 0.03           |

$^a$Estimated equivalent width for the MgI 2026 transition from the column density measured from MgI 2852. For those cases where we expect a saturation correction, we have incremented the column density by 0.1 dex.

$^b$Estimated equivalent width for the CrII 2062 transition from the measured Cr$^+$ column densities.

Note. — This analysis assumes the linear curve-of-growth for all equivalent width calculations. We may be underestimating the Zn$^+$ column density of those systems with equivalent width > 300 mÅ. Entries with ‘...’ are cases of upper limits to the value (i.e. non-detections).
| QSO name | SDSS   | z_em  | z_abs | r   | logN_{HI} | logN(SII 1808) | W_r(1808) | W_e(1808) | logN(ZnII 2026) | W_r(2026) | W_e(2026) |
|----------|--------|-------|-------|-----|-----------|----------------|----------|----------|----------------|----------|----------|
| F0812+32 | 861-333 | 2.70  | 2.626 | 17.46 | 21.35* | > 15.78 | 250 ± 50 | 285 ± 8 | 13.04 ± 0.02 | 190 ± 50 | 173 ± 9  |
| SDSS0098-0958 | 651-494 | 1.95  | 1.768 | 18.38 | < 15.51 | 100 ± 50 | 183 ± 31 | < 12.59 | 60 ± 50 | 50 ± 23  |
| SDSS0016-0012 | 389-178 | 2.09  | 1.970 | 18.02 | 20.83** | 15.48 ± 0.11 | 330 ± 50 | 165 ± 46 | 12.93 ± 0.10 | 340 ± 50 | 190 ± 36 |
| SDSS0200+1534 | 753-430 | 1.76  | 1.652 | 18.78 | < 15.51 | 100 ± 50 | 183 ± 31 | < 12.59 | 60 ± 50 | 50 ± 23  |
| SDSS0316+0040 | 393-495 | 1.87  | 1.725 | 18.20 | < 15.51 | 100 ± 50 | 183 ± 31 | < 12.59 | 60 ± 50 | 50 ± 23  |
| SDSS1042+0117 | 506-137 | 2.44  | 2.011 | 17.66 | < 15.82 | 370 ± 50 | 361 ± 25 | 12.57 ± 0.08 | 110 ± 50 | 90 ± 12  |
| SDSS1120+1324 | 424-286 | 2.57  | 2.000 | 19.23 | < 15.82 | 370 ± 50 | 361 ± 25 | 12.57 ± 0.08 | 110 ± 50 | 90 ± 12  |
| SDSS1225+0054 | 406-752 | 2.97  | 2.714 | 18.92 | 21.00*** | 15.61 ± 0.07 | 260 ± 50 | 227 ± 35 | 12.85 ± 0.10 | 240 ± 50 | 125 ± 30 |
| SDSS1316+0040 | 413-387 | 2.92  | 2.181 | 18.67 | < 15.41 | 130 ± 50 | 137 ± 25 | < 12.69 | 150 ± 50 | 48 ± 29  |
| SDSS1429+0233 | 336-073 | 2.12  | 1.781 | 17.79 | 21.45* | 15.80 ± 0.03 | 400 ± 50 | 313 ± 23 | 13.01 ± 0.04 | 210 ± 50 | 208 ± 19 |
| SDSS1435+0420 | 585-628 | 1.95  | 1.656 | 19.04 | 21.25* | 15.92 ± 0.07 | 510 ± 50 | 408 ± 54 | < 12.21 | 330 ± 50 | 286 ± 97 |
| SDSS1610+4724 | 813-621 | 3.22  | 2.508 | 19.22 | 21.15 | < 16.15 | 630 ± 50 | 632 ± 23 | 14.30 ± 0.03 | 520 ± 50 | 470 ± 27 |
| SDSS1617+0028 | 346-488 | 1.94  | 1.616 | 19.07 | < 15.89 | 450 ± 50 | 385 ± 36 | < 13.20 | 240 ± 50 | 269 ± 36 |
| SDSS1658+3428 | 972-480 | 1.70  | 1.608 | 18.40 | < 15.79 | 360 ± 50 | 338 ± 25 | < 13.35 | 280 ± 50 | 378 ± 35 |
| SDSS1709+3258 | 973-629 | 1.89  | 1.830 | 19.22 | < 16.11 | 550 ± 50 | 528 ± 20 | 13.21 ± 0.03 | 370 ± 50 | 309 ± 22 |
| SDSS2044-0542 | 634-634 | 1.91  | 1.787 | 18.81 | < 15.68 | 360 ± 50 | 217 ± 26 | 12.75 ± 0.09 | 300 ± 50 | 113 ± 22 |
| SDSS2059-0529 | 630-610 | 2.54  | 2.210 | 19.01 | 20.80 | 15.36 ± 0.10 | 370 ± 50 | 113 ± 31 | 12.81 ± 0.14 | 280 ± 50 | 138 ± 37 |
| SDSS2100-0641 | 637-370 | 3.14  | 3.092 | 18.12 | 21.05 | 15.89 ± 0.02 | 420 ± 50 | 422 ± 35 | < 13.14 | 300 ± 50 | 213 ± 16 |
| SDSS2222-0946 | 720-203 | 2.93  | 2.354 | 17.97 | 20.50 | 15.45 ± 0.05 | 260 ± 50 | 156 ± 19 | < 12.77 | 140 ± 50 | 103 ± 17 |
| SDSS2244+1429 | 740-390 | 1.96  | 1.816 | 18.92 | 15.62 ± 0.04 | 250 ± 50 | 225 ± 20 | 13.11 ± 0.03 | 220 ± 50 | 261 ± 18 |

Note. — Only confirmed logN_{HI} values are shown; all have an error of ±0.15 dex except SDSS0016-0012 (±0.05 dex), SDSS0927+5621 (±0.10 dex), and SDSS2059-0529 (±0.20 dex). All metal-line abundances can be found in the electronic edition of the paper. W_r values are given in mÅ and do not account for minor blends, low SNR or saturation effects. This table does not account for possible W_r (MgII 2026) contribution to W_r (ZnII 2026) (although logN(ZnII 2026) values are blend-corrected); this issue is dealt with in Table 5.

*Measurement from Prochaska et al. (2006)

**Measurement from Petitjean et al. (2002)

***Measurement from Prochaska & Herbert-Fort (2004)
