CHEMICAL ABUNDANCES OF THE DAMPED Lyα SYSTEMS AT Z > 1.5

JASON X. PROCHASKA$^\dagger$ & ARTHUR M. WOLFE$^\dagger$

DEPARTMENT OF PHYSICS, AND CENTER FOR ASTROPHYSICS AND SPACE SCIENCES;
UNIVERSITY OF CALIFORNIA, SAN DIEGO;
C–0424; LA JOLLA; CA 92093

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ABSTRACT

We present chemical abundance measurements for 19 damped Lyα systems observed with HIRES on the 10m W.M. Keck Telescope. We perform a detailed analysis of every system, deriving ionic column densities for all unblended metal-line transitions. Our principal goal is to investigate the abundance patterns of the damped systems and thereby determine the underlying physical processes which dominate their chemical evolution. We place particular emphasis on gauging the relative importance of two complementary effects often invoked to explain the damped Lyα abundances: (1) nucleosynthetic enrichment from Type II supernovae, and (2) an ISM-like dust depletion pattern.

Similar to the principal results of Lu et al. (1996), our observations lend support both for dust depletion and Type II SN enrichment. Specifically, the observed overabundance of Zn/Fe and underabundance of Ni/Fe relative to solar abundances suggest significant dust depletion within the damped Lyα systems. Meanwhile, the relative abundances of Al, Si, and Cr vs. Fe are consistent with both dust depletion and Type II supernova enrichment. Our measurements of Ti/Fe and the Mn/Fe measurements from Lu et al. (1996), however, cannot be explained by dust depletion and indicate an underlying Type II SN pattern. Finally, the observed values of [S/Fe] are inconsistent with the combined effects of dust depletion and the nucleosynthetic yields expected for Type II supernovae. This last result emphasizes the need for another physical process to explain the damped Lyα abundance patterns.

We also examine the metallicity of the damped Lyα systems both with respect to Zn/H and Fe/H. Our results confirm previous surveys by Pettini and collaborators, i.e., [Zn/H] = −1.15 ± 0.15 dex. In contrast with other damped Lyα surveys at z > 1.5, we do not formally observe an evolution of metallicity with redshift, although we stress this result is based on the statistics from a small sample of high z damped systems.

Subject headings: cosmology: observations — galaxies: abundances — galaxies: chemical evolution — quasars: absorption lines — nucleosynthesis

1. INTRODUCTION

The damped Lyα systems dominate the neutral gas content of the universe and at high redshift are widely believed to be the progenitors of present-day galaxies (Wolfe et al. 1995). Therefore, one can directly measure the chemical evolution of the early universe by tracing the chemical abundances of the damped systems. Pettini and collaborators have performed the most extensive surveys on the metallicity of the damped Lyα systems to date (Pettini et al. 1994, Pettini et al. 1997). Working on the premise one can measure accurate column densities of Zn$^+$ and Cr$^+$ from unresolved line profiles, they have successfully observed over 30 damped Lyα systems with the Anglo-Australian, William Herschel, and Hale Telescopes. Their results indicate a mean metallicity of Zn/H ≈ 1/10 solar abundance with a notably large dispersion. These measurements indicate the damped systems are chemically young at z > 2 and lend further support to the interpretation of damped systems as the progenitors of modern galaxies (e.g. Malaney and Chaboyer 1996). In addition to an analysis of Zn, Pettini et al. performed accurate measurements of N(Cr$^+$) aided by the coincidence in wavelength of the strongest metal-line transitions for the two species. Comparing the relative abundances of Cr and Zn, they noted an underabundance of Cr to Zn relative to solar abundances (a typical value is [Cr/Zn] ≈ −0.5 dex). In the ISM, Cr is significantly depleted onto dust grains while Zn is only lightly depleted. Therefore, Pettini and others have argued that the relative underabundance of Cr to Zn is indicative of dust in the damped Lyα systems. They also point out the Cr/Zn measurements imply a dust-to-gas ratio much lower than that observed in dusty ISM regions when typical values for [Cr/Zn] are less than −1.0 dex. Establishing the level of dust depletion in damped Lyα systems is very important as dust could significantly bias the results from the damped Lyα surveys against high N(HI) systems (Fall & Pei 1993).

More recently, Lu et al. (1996) have offered an alternate interpretation for the abundance patterns of the damped systems. Unlike the Pettini et al. sample, Lu et al. measured abundances for a large number of elements including Zn, Cr, Fe, S, N, O, Si, Ni, and Mn with HIRES on the 10m W.M. Keck Telescope. The primary result of their analysis is that the damped Lyα systems exhibit abundance patterns typical of nucleosynthetic yields for Type II supernova. The tell-tale signature of Type II SN enrichment is the overabundance of α-process elements (e.g. Si and S) relative to Fe. Empirical measurements of the abundance patterns for Type II SN are commonly derived from the metal-poor halo stars (Erdsson et al. 1993).
which presumably were primarily enriched by Type II supernova. As expected for Type II SN abundances, Lu et al. found an abundance of Si/Fe in every case and further noted that the relative abundances of Fe, Cr, Mn, N, O, and S all match the metal-poor halo star observations. Furthermore, Lu et al. stress the measured ratios of Mn/Fe and N/O cannot be explained in terms of dust depletion. Lastly, we investigate the evolution of the observed metallicity of the damped Lyα systems with increasing redshift.

In §5 we summarize the observational sample and data reduction techniques. The individual damped systems are briefly discussed in §4 and measurements of the ion column densities and velocity plots of the metal-line transitions are presented. §5 discusses the observed abundance patterns of the damped Lyα systems. Finally, the metallicity of the damped Lyα systems is investigated in §6 and a brief summary is given in §7.

2. OBSERVATIONAL SAMPLE

Table 1 presents a journal of our observations. In addition to exposure times and dates, we estimate the typical signal-to-noise ratio per pixel (SNR) and resolution of the spectra, and include the emission redshift, $z_{em}$, of the quasar. All of the data were acquired with the 10m W.M. Keck I telescope. The data were reduced with the HIRES software package developed by T. Barlow. This package converts the 2D echelle images to fully reduced, 1D wavelength-calibrated spectra. We then continuum fit these spectra with a program similar to the IRAF package continuum and optimally coadded multiple observations.

Our observational sample of QSO’s all have at least one known intervening damped Lyα system. The systems exhibit a range of N(HI) values and absorption redshifts ($z_{abs} = 1.8 – 4.2$). In several cases, we have identified additional metal-line systems with very large ion column densities which suggest they are damped systems. In the following, however, we restrict our analysis to systems with measured HI column density, N(HI) $> 2 \times 10^{20}$ cm$^{-2}$. The metal-line transitions are identified by composing velocity plots of the absorption lines listed in Table 2 at the

### Table 1

QSO and Observational Data

| QSO       | Alternate Name | Date Time (s) | Exposure | $z_{em}$ | Resolution | SNR |
|-----------|----------------|---------------|----------|----------|------------|-----|
| Q0019−15  | BR 0019−1522   | F96           | 35000    | 4.528    | 7.5        | 18  |
| Q1000+13  | PHL 957        | S94           | 11700    | 2.69     | 7.5        | 40  |
| Q1049+33  | OC 383         | F97           | 17600    | 2.43     | 7.5        | 25  |
| Q2021+36  | UT 0201+3634   | F94           | 34580    | 2.49     | 7.5        | 35  |
| Q2034−38  | ...            | F96           | 12600    | 3.23     | 7.5        | 33  |
| Q458−02   | PKS 0458−020   | F95           | 28800    | 2.29     | 7.5        | 15  |
| Q841+12   | ...            | F97,F98       | 10800    | 7.5      | 30         |
| Q951−04   | BR 0951−0450   | S97           | 30600    | 4.369    | 7.5        | 13  |
| Q1215+33  | GC 1215+3322   | S94           | 14040    | 2.61     | 7.5        | 20  |
| Q1331+17  | MC 1331+170    | S94           | 36000    | 2.08     | 6.6        | 80  |
| Q1346−03  | BRI 1346−0322  | S97           | 31000    | 3.992    | 7.5        | 29  |
| Q1759+75  | GB1759+7539    | F96           | 10400    | 3.05     | 6.6        | 33  |
| Q2206−19  | ...            | F94           | 25900    | 2.56     | 7.5        | 40  |
| Q2230+02  | LBQS 2230+0232 | F97           | 18000    | 2.15     | 7.5        | 26  |
| Q2231−00  | LBQS 2230−0015 | F95           | 14400    | 3.02     | 7.5        | 30  |
| Q2348−14  | ...            | F96           | 9000     | 2.940    | 7.5        | 41  |
| Q2359−02  | UM 196         | F97           | 25000    | 2.31     | 7.5        | 17  |
| Transition | $\lambda$rest (Å) | $f^a$ |
|------------|------------------|-------|
| HI 1215    | 1215.6701        | 0.4164|
| OI 1302    | 1302.1685        | 0.04887|
| SiII 1304  | 1304.3702        | 0.0940|
| NiII 1317  | 1317.217         | 0.1458$^b$|
| CII 1334   | 1334.5323        | 0.1278|
| CuII 1358  | 1358.773         | 0.3803|
| NiII 1370  | 1370.131         | 0.144|
| SiIV 1393  | 1393.755         | 0.528|
| SnII 1400  | 1400.400         | 0.71 |
| SiIV 1402  | 1402.770         | 0.262|
| GaII 1414  | 1414.402         | 1.8  |
| NiII 1454  | 1454.842         | 0.0516|
| SiII 1526  | 1526.7066        | 0.1160|
| CIV 1548   | 1548.195         | 0.09522|
| CIV 1550   | 1550.770         | 0.09522|
| GeII 1602  | 1602.4863        | 0.135|
| FeII 1608  | 1608.4511        | 0.06196|
| FeII 1611  | 1611.2005        | 0.001020|
| AlII 1670  | 1670.7874        | 1.88 |
| PbII 1682  | 1682.15          | 0.156|
| NiII 1703  | 1703.405         | 0.01224|
| NiII 1709  | 1709.600         | 0.0666$^b$|
| NiII 1741  | 1741.549         | 0.0776$^b$|
| NiII 1751  | 1751.910         | 0.0638|
| SiIII 1808 | 1808.0126        | 0.00218|
| AlIII 1854 | 1854.716         | 0.539|
| AlIII 1862 | 1862.790         | 0.268|
| TiII 1910a | 1910.6           | 0.0975|
| TiII 1910b | 1910.97          | 0.0706|
| ZnII 2026  | 2026.136         | 0.489|
| CrII 2056  | 2056.254         | 0.1050$^c$|
| CrII 2062  | 2062.234         | 0.0780$^c$|
| ZnII 2062  | 2062.664         | 0.256|
| CrII 2066  | 2066.161         | 0.05150$^c$|
| FeII 2260  | 2260.7805        | 0.00244|
| FeII 2344  | 2344.214         | 0.1108|
| FeII 2374  | 2374.4612        | 0.03260|
| FeII 2382  | 2382.765         | 0.3006|
| MnII 2576  | 2576.877         | 0.3508|
| FeII 2586  | 2586.6500        | 0.0684|
| MnII 2594  | 2594.499         | 0.2710|
| FeII 2600  | 2600.1729        | 0.2132|
| MnII 2606  | 2606.462         | 0.1927|

$^a$Unless otherwise indicated, the $f$ and $\lambda$ values were taken from Morton (1991)
$^b$Zsargo & Federman (1998)
$^c$Tripp et al. (1996)
known redshift of the damped system and then correlating the profiles by eye. We performed a systematic search for other metal-line systems toward each QSO to account for possible line misidentification and blending. The data are presented in the following section.

3. Ionic Column Densities

All of the ionic column densities presented in this section were derived with the apparent optical depth method (AODM; Savage and Sembach 1991). Savage and Sembach (1991) have stressed measuring column densities by comparing multiple Voigt profiles to the line-profiles does not always account for hidden saturated components. They introduced a technique to correct for hidden saturation by comparing the apparent column density, $N_a$, for multiple transitions from a single ion. The analysis involves calculating $N_a(v)$ for each pixel from the optical depth equation

$$N_a(v) = \frac{m_e c \tau_a(v)}{\pi e^2 f \lambda}, \quad (1)$$

where $\tau_a(v) = \ln[I_a(v)/I_0(v)]$, $f$ is the oscillator strength, $\lambda$ is the rest wavelength and $I_a$ and $I_0$ are the incident and measured intensity. Comparing $N_a(v)$ deduced from two or more transitions of the same ion, one finds the stronger transition will have smaller values of $N_a(v)$ in those features where hidden saturation is present. Thus, one can ascertain the likelihood of saturated components for ions with multiple transitions.

In Wolfe et al. (1994), Prochaska & Wolfe (1996) and Prochaska & Wolfe (1997a), we showed the damped Lyα profiles are not contaminated by hidden saturation. Furthermore, we demonstrated the column densities derived with the AODM agree very well with line-profile fitting, which should give a more accurate measure of the ionic column densities when hidden saturation is negligible. As the AODM is easier to apply to a large data set, we have chosen this technique to measure the ionic column densities for the damped Lyα sample. Throughout the paper we adopt the wavelengths and oscillator strengths presented in Table 2 compiled by Morton (1991), Tripp et al. (1996), and Zsargó & Federman (1998).

Tables 3–21 present the results of the abundance measurements including an estimate of the 1σ error. For those transitions where the profile saturates (i.e. $I/I_a < 0.01$ in at least one pixel), the column densities are listed as upper limits. The values reported as upper limits are 3σ upper limits. We warn the reader of two points: (1) logarithmic errors are misleadingly small (e.g. a 0.1 dex error is ≈ 25% for a 13 dex measurement) and (2) we have ignored continuum error in our analysis which could significantly affect measurements of very weak transitions. In the following subsections we comment briefly on each of the damped Lyα systems, plot all of the identified metal-line transitions, and discuss the adopted N(HI) values. We note which systems are members of the LBQS sample (Wolfe et al. 1995) and advise the reader to refer to that paper for further details. In the velocity plots, $v = 0$ is chosen arbitrarily and corresponds to the redshift listed in the figure caption. We indicate regions where blends with other transitions occur (primarily through blends with other metal-line systems or the Lyα forest) by plotting with dotted lines.

3.1. Q0000–26, z = 3.390

This high redshift damped Lyα system has been previously observed with HIRES (Lu et al. 1996) and we adopt log N(HI) = 21.41 ± 0.08 based on that analysis. It is a member of the LBQS (Wolfe et al. 1995) statistical sample, one of the few with $z_{abs} > 3$. The velocity profiles are presented in Figure 8 and the derived ionic column densities are listed in Table 3. As our spectral coverage did not include FeII 1608, the Fe abundance is based solely on FeII 1611 which is a very weak transition and has a relatively low SNR. Interestingly, we find N(FeII) to be significantly higher than the lower limit derived from the FeII 1608 transition reported by Lu et al. (1996), which may be the result of an error in the continuum fit to our profile. We find N(SiII) to be significantly higher as well, however, both from the direct measurement of the SiII 1808 transition and by fitting a Voigt profile to the saturated SiII 1526 profile. We therefore note Lu et al. (1996) may have significantly underestimated the true metallicity. At the same time, we observe that the N(NiII) measurement coincides with the Lu et al. results. Because we have no unblended, unsaturated high SNR profiles for this system we have not included it in the kinematic analyses thus far (Prochaska & Wolfe 1997a, Wolfe & Prochaska 1998, Prochaska & Wolfe 1998).

| Ion | $\lambda$ (Å) | AODM | $N_{ion}$ (10$^{19}$ cm$^{-2}$) | [X/H] |
|-----|----------------|------|-------------------------------|-------|
| HI  | 1215           | 21.41 ± 0.080 | 21.41 ± 0.080 | 0.08 |
| CIV | 1548           | 14.707 ± 0.006 | 14.707 ± 0.006 | 0.00 |
| AlIII| 1854          | 12.772 ± 0.020 | 12.772 ± 0.020 | 0.02 |
| SiII| 1526           | 14.607 ± 0.016 | 15.086 ± 0.012 | −1.874 ± 0.081 |
| FeII| 1611           | 15.146 ± 0.037 | 15.146 ± 0.037 | −1.774 ± 0.088 |
| NiII| 1751           | 13.325 ± 0.029 | 13.325 ± 0.029 | −2.335 ± 0.085 |

3.2. Q0019–15, z = 3.439

This damped Lyα system comes from the high redshift survey by Storrie-Lombardi et al. (1996) and the adopted log N(HI) = 20.9 ± 0.1 was taken from recent Keck measurements of Storrie-Lombardi & Wolfe (1998). While our observations covered Lyα for this system, the profile extends over two echelle orders and an accurate measurement of N(HI) proved impossible. Figure 9 shows the metal-line transitions and Table 3 presents the measurements for this system. The Fe abundance is based on the marginally saturated FeII 1608 profile, yet should be reasonably accurate. The NiII lines are very weak and in poor SNR so these measurements are not reliable. The same is true for the Si measurements, although to a lesser extent. Note all of the high-ion profiles are blended with other metal-line transitions or Lyα forest clouds.

3.3. Q0100+13, z = 2.309

The majority of our results on PHL 957 (a.k.a. Q0100+13) were published by Wolfe et al. (1994). The major exception is we now present a measurement of the Fe abundance based on the previously unidentified FeII 1611 profile. Also, we measure column densities in light of new $f$
Fig. 1.— Velocity plot of the metal-line transitions for the damped Lyα system at \( z = 3.390 \) toward Q0000–26. The vertical line at \( v = 0 \) corresponds to \( z = 3.390 \). Figures 2-21 are not included here but can be downloaded from: http://mamacass.ucsd.edu:8080/people/xavier/WWW/DLA/abundfig.ps.gz
and λ values, in particular those for the CrII and NiII transitions. Note the O abundance is based on the very weak OI 1355 profile and we report it as a 3σ upper limit. Figure 3 presents the velocity plots and Table 5 lists the measured ionic column densities for this system. This damped system is included in the statistical sample of the LBQS survey.

### Table 5

| Ion   | λ  | AODM | \(N_{adopt}\) | [X/H]  |
|-------|----|------|----------------|--------|
| HI    | 1215 | 21.400 ± 0.050 |               |        |
| CIV   | 1548 | 13.241 ± 0.031 |               |        |
|      | 1550 | 13.303 ± 0.056 |               |        |
| OI    | 1355 | < 17.628 | < 17.628 | −0.702 |
| AIII  | 1854 | 12.635 ± 0.022 |               |        |
|      | 1862 | 12.715 ± 0.033 |               |        |
| SiII  | 1526 | > 14.722 | > 14.722 | −2.228 |
| SiIV  | 1393 | 13.127 ± 0.017 |               |        |
|       | 1402 | 13.146 ± 0.029 |               |        |
| CrII  | 1434 | 13.387 ± 0.15 | 1.693 ± 0.052 |        |
|      | 1467 | 13.303 ± 0.042 |               |        |
| FeII  | 1608 | > 14.599 | 15.096 ± 0.041 | −1.814 ± 0.065 |
|      | 1611 | 15.096 ± 0.041 |               |        |
| NiII  | 1454 | 13.621 ± 0.014 | −2.030 ± 0.052 |        |
|      | 1741 | 13.620 ± 0.015 |               |        |
| ZnII  | 2062 | 12.498 ± 0.028 | 12.494 ± 0.023 | −1.556 ± 0.055 |

### 3.4. Q0149+33, z = 2.140

This relatively metal-poor ([Fe/H] ≈ −1.8 dex) damped system is also a member of the LBQS statistical sample. Table 6 gives the measured column densities and Figure 4 plots the metal-lines. In the following analysis, we assume log N(HI) = 20.5 ± 1 [Wolfe et al. 1995]. As with PH957, the O abundance is based on the statistically insignificant OI 1355 profile and provides a very conservative upper limit. Finally the Al abundance is derived from the marginally saturated AII 1670 profile but should be a reliable value. The system is notable for exhibiting an atypical Cr to Zn ratio; [Cr/Zn] = +0.26 ± 0.1 dex. The Cr measurement is reasonably accurate and the ZnI 2062 transition places a rather strict upper limit to the Zn abundance. Therefore, it is very likely [Cr/Zn] > 0 which marks the first such occurrence in a damped system and indicates this system must be essentially undepleted.

### 3.5. Q0347−38, z = 3.025

The damped Lyα system toward Q0347−38 is another member of the LBQS statistical sample, one of the four with \(z_{abs} > 3\). We adopt log N(HI) = 20.8 ± 0.1 based on a measurement by Pettini et al. (1994). This is one of the few systems where we have an estimate of N(S\(^+\)), although we note SII 1259 is partially blended with the Lyα forest and should be considered an upper limit to the true S abundance, N(S\(^+\)) < 10\(^{14.7}\) cm\(^{-2}\). We discuss the S/Fe ratio in detail below, noting here that the value has particular impact on interpreting the abundances of the damped Lyα systems with respect to Type II SN enrichment and dust depletion. The system is also notable for the easily identifiable excited fine structure CII* 1335 transition. Unfortunately, the CII 1334 profile is so heavily saturated that no meaningful comparison can be made with the fine structure transition. Finally, we observe a very low Ni abundance for this system, [Ni/H] < −2.37 dex, implying [Ni/Fe] < −0.5 dex which may be difficult to explain within the leading explanations for the damped Lyα abundance patterns.

### 3.6. Q0458−02, z = 2.040

This damped Lyα system is ‘famous’ for exhibiting HI 21cm absorption. In particular, Briggs et al. (1989) have used VLBI radio observations to place a lower limit on its size of \(8 \, h_{100}^{-1}\) kpc. In our analysis we adopt log N(HI) = 21.65 ± 0.09 taken from Pettini et al. (1994). A plot of the metal-line profiles is given in Figure 4 and Table 6 lists the column densities. Note the CII* 1335 profile is heavily saturated. Assuming the \(P_{3/2}\) excited fine-structure state is populated by e− collisions and N(C\(^+\)) < 10\(^{17}\) cm\(^{-2}\) (which follows by assuming [C/H] < [Zn/H]), the limit on N(CII*) indicates \(n_e > 0.1\) cm\(^{-3}\). The system, with one of the highest measured N(HI) values, must have a high neu-
3.7. \textit{Q0841+12}, \(z = 2.375\) \& \(z = 2.476\)

The damped Ly\(\alpha\) systems toward this BL Lac object were first identified by C. Hazard and were subsequently analyzed by Pettini et al. (1997). We take \(N(\text{HI}) = 20.95 \pm 0.087\) for the system at \(z = 2.375\) and \(N(\text{HI}) = 20.78 \pm 0.097\) for the system at \(z = 2.476\) (Pettini et al. 1997). Figures 3 and 4 plot the metal-line profiles for these systems and Tables 8 and 10 list the ionic column densities. The profiles for the lower redshift system have good SNR and the derived column densities are accurate.

| Ion | \(\lambda\) | AODM | \(N_{\text{adopt}}\) | \([X/H]\) |
|-----|-----------|-------|-------------------|-------|
| HI  | 1215      | 21.650 \(\pm 0.090\) |
| CH  | 1334      | > 15.010 |
| CIV | 1548      | > 14.906 |
| OI  | 1302      | > 15.111 |
| AI\textsc{ii} | 1670 | > 13.720 |
| AI\textsc{iii} | 1854 | 13.334 \(\pm 0.018\) |
| Si\textsc{ii} | 1394 | > 15.955 > 15.955 > 2.105 |
| Cr\textsc{ii} | 1402 | > 14.481 |
| Cr\textsc{iii} | 1402 | 14.481 |
| Fe\textsc{ii} | 1608 | > 15.136 15.508 \(\pm 0.048\) | 1.652 \(\pm 0.102\) |
| Ni\textsc{ii} | 1327 | 13.985 \(\pm 0.024\) 13.853 \(\pm 0.019\) | -2.047 \(\pm 0.092\) |
| Zn\textsc{ii} | 2026 | 13.141 \(\pm 0.018\) 13.141 \(\pm 0.018\) | -1.159 \(\pm 0.092\) |

3.8. \textit{Q0951–04}, \(z = 3.857\) \& \(z = 4.203\)

The QSO Q0951–04 from the survey by Storrie-Lombardi et al. (1996) has two intervening damped Ly\(\alpha\) systems, both at very high redshift. The velocity plots and measurements for the \(z = 3.857\) system are given in Figures 1 and 11, while those for the \(z = 4.203\) system are presented by Figures 10 and Table 12. We adopt...
log $N$(HI) = 20.6 ± 0.1 for the system at $z = 3.857$ and log $N$(HI) = 20.4 ± 0.1 for the system at $z = 4.203$. Based on recent Keck measurements (Storrie-Lombardi and Wolfe 1998). Because all of the column densities are based on either marginally saturated profiles or weaker, low SNR profiles all of these measurements are somewhat tentative. In fact, we consider the limits on $N$(Fe II) for the system at $z = 4.203$ to be too conservative to include this system in the abundance analysis. Finally, we note the feature at $v = 180$ km s$^{-1}$ in the Ni II 1370 profile for the $z = 3.857$ system may be an unidentified blend, although it nearly coincides with a strong feature in the Si II 1526 profile.

### Table 11

| Ion      | $\lambda$ | AODM  | $N_{\text{adopt}}$ | [X/H] |
|----------|------------|-------|--------------------|-------|
| HI       | 1215       | 20.600 ± 0.100 |                   |       |
| AlII     | 1670       | 13.298 ± 0.022  | 13.298 ± 0.022    | −1.782 ± 0.102 |
| SiII     | 1526       | 14.645 ± 0.030  | 14.645 ± 0.030    | −1.505 ± 0.104 |
| SiIV     | 1393       | 13.900 ± 0.011  |                   |       |
| FeII     | 1608       | 14.062 ± 0.060  | 14.062 ± 0.060    | −2.048 ± 0.117 |
| NiII     | 1370       | 12.994 ± 0.099  | 12.994 ± 0.099    | −1.856 ± 0.141 |

### Table 12

| Ion      | $\lambda$ | AODM  | $N_{\text{adopt}}$ | [X/H] |
|----------|------------|-------|--------------------|-------|
| HI       | 1215       | 20.400 ± 0.100 |                   |       |
| OI       | 1302       | 14.607 ± 0.323  | 14.607 ± 0.323    | −2.723 ± 0.339 |
| SiII     | 1190       | 13.455 ± 0.050  | 13.392 ± 0.052    | −2.558 ± 0.105 |
| SiIV     | 1304       | 13.286 ± 0.060  |                   |       |
| FeII     | 1608       | < 13.281       | < 13.281          | −2.029 |
| NiII     | 1317       | < 12.589       | < 12.589          | −2.061 |
| NiII     | 1370       | < 12.625       |                   |       |

### Table 13

| Ion      | $\lambda$ | AODM  | $N_{\text{adopt}}$ | [X/H] |
|----------|------------|-------|--------------------|-------|
| HI       | 1215       | 20.950 ± 0.067 |                   |       |
| CIV      | 1548       | 13.605 ± 0.019 |                   |       |
| OI       | 1355       | < 17.952      | < 17.952          | < 0.072 |
| AlII     | 1670       | > 13.355      |                   |       |
| AlIII    | 1854       | 12.746 ± 0.017 |                   |       |
| SiII     | 1526       | > 14.681      | 15.030 ± 0.025    | −1.470 ± 0.072 |
| SiIV     | 1393       | 12.993 ± 0.039 |                   |       |
| CrII     | 2056       | 13.173 ± 0.034 | 13.130 ± 0.031    | −1.500 ± 0.074 |
| FeII     | 1608       | 14.648 ± 0.039 | 14.648 ± 0.039    | −1.812 ± 0.078 |
| NiII     | 1741       | 13.419 ± 0.040 | 13.344 ± 0.033    | −1.856 ± 0.075 |
| ZnII     | 2026       | 12.291 ± 0.058 | 12.291 ± 0.058    | −1.309 ± 0.089 |

### Table 14

| Ion      | $\lambda$ | AODM  | $N_{\text{adopt}}$ | [X/H] |
|----------|------------|-------|--------------------|-------|
| HI       | 1215       | 21.176 ± 0.041 |                   |       |
| Cl       | 1560       | 13.573 ± 0.013 |                   |       |
| CIV      | 1548       | > 15.073     |                   |       |
| AlII     | 1670       | > 13.573     |                   |       |
| AlIII    | 1854       | 13.004 ± 0.004 |                   |       |
| SiII     | 1526       | > 14.951     | 15.285 ± 0.004    | −1.441 ± 0.041 |
| CrII     | 2056       | 12.950 ± 0.017 | 12.919 ± 0.015    | −1.937 ± 0.044 |
| FeII     | 1608       | 14.601 ± 0.003 | 14.598 ± 0.001    | −2.088 ± 0.041 |
| NiII     | 1741       | 13.166 ± 0.017 | 13.235 ± 0.009    | −2.191 ± 0.042 |
| ZnII     | 2026       | 12.605 ± 0.009 | 12.605 ± 0.008    | −1.221 ± 0.042 |
| ZnII     | 2062       | 12.605 ± 0.013 |                   |       |

≈ 6 km s$^{-1}$ and SNR > 50). Table 14 lists the column densities for the metal-line transitions and Figure 12 plots their profiles. We assume log $N$(HI) = 21.176 ± 0.041 (Pettini et al. 1994). The SNR is excellent throughout the entire spectrum yielding very accurate column density measurements. This is one of the very few systems where CI absorption is detected and Songaila et al. (1994) have used measurements of the CI profile to estimate the cosmic background temperature at $z = 1.776$. Consider the feature at $v = +20$ km s$^{-1}$ which is fully resolved in the CI profiles, barely resolved in the Zn$^+$ profiles, and is unresolved in the stronger transitions even at 6 km s$^{-1}$ resolution. This suggest the gas in this component is at a temperature $T < 6000K$. While this system may be atypical because it is one of the few damped systems to exhibit CI absorption, it is worth noting a majority of observed damped Ly$\alpha$ profiles may be the result of the superposition of many narrow components.

### 3.9. Q1215+33, $z = 1.999$

This radio-selected damped system (Wolfe et al. 1986) was observed as part of the commissioning run for the HIRES instrument and is a member of the LBQS statistical sample. In the following analysis we assume log $N$(HI) = 20.95 ± 0.067 based on observations by Pettini et al. (1994). Figure 11 presents a plot of the metal-line transitions and the ionic column densities are listed in Table 13. As the FeII 1608 profile is saturated and the FeII 1611 transition is marginally detected, we establish only a lower limit to $N$(Fe II). We will include this system in the abundance analysis, however, by adopting log 10[$N$(Fe II)] = 14.648 ± 0.033 based solely on the FeII 1608 profile, noting this value may be an underestimate.

### 3.10. Q1331+17, $z = 1.776$

This famous damped Ly$\alpha$ system which exhibits 21 cm absorption (Wolfe & Davis 1973) has been studied by a number of authors (over 100 papers), yet never with the quality of data presented here (FWHM resolution
3.11. $Q1346-03$, $z = 3.736$

This very high $z$ damped Lyα system was taken from the survey of Storrie-Lombardi et al. (1996). We present the velocity plots and column densities in Figure 14 and Table 15. We adopt $\log N(\text{HI}) = 20.7 \pm 0.1$ (Storrie-Lombardi and Wolfe 1998) throughout the analysis. Unfortunately both FeII 1608 and FeII 1611 are blended with B-band sky lines. Therefore, we have no metallicity indicator for this system and it is not included in the subsequent analysis. Measuring $|\text{Si}/\text{H}| = -2.3$ dex, we expect this is a very metal-poor system.

### Table 15

**Ionic Column Densities: Q1346-03, $z = 3.736$**

| Ion  | $\lambda$ | AODM   | $N_{\text{adopt}}$ | [X/H] |
|------|-----------|--------|---------------------|-------|
| HI   | 1215      | 20.709 ± 0.100 |                     |       |
| CII  | 1334      | 14.422 ± 0.095 | 14.422 ± 0.095      | -2.838 ± 0.138 |
| AIII | 1670      | 12.546 ± 0.025 | 12.546 ± 0.025      | -2.634 ± 0.103 |
| SIII | 1304      | 13.961 ± 0.012 | 13.954 ± 0.011      | -2.296 ± 0.101 |
| SIV  | 1203      | 13.924 ± 0.026 |                     |       |
| SIV  | 1402      |                    | < 12.598            |       |
| NiII | 1370      | < 12.694         |                     |       |
| NiII | 1741      | < 13.024         |                     |       |

3.12. $Q1759+75$, $z = 2.625$

This system and the adopted $N(\text{HI}) = 20.8 \pm 0.1$ are taken from an ongoing survey by I. Hook. Figure 14 presents the velocity plots and Table 15 gives the measurements. The QSO is very bright and was observed at FWHM $\approx 6$ km s$^{-1}$ resolution. We expect all of the measured abundances are very accurate with the exception of $N(\text{Zn}^+)$ where the ZnII 2026 profile is blended with sky lines. Although the strongest feature appears unblended, we have chosen not to include Zn in the abundance analysis.

### Table 16

**Ionic Column Densities: Q1759+75, $z = 2.625$**

| Ion  | $\lambda$ | AODM   | $N_{\text{adopt}}$ | [X/H] |
|------|-----------|--------|---------------------|-------|
| HI   | 1215      | 20.800 ± 0.100 |                     |       |
| CIV  | 1548      | 14.636 ± 0.019 |                     |       |
| CIV  | 1550      | 14.647 ± 0.005 |                     |       |
| AIII | 1854      | 13.623 ± 0.004 |                     |       |
| SII  | 1526      | > 15.014       | 15.532 ± 0.008      | -0.818 ± 0.100 |
| SII  | 1808      | 15.532 ± 0.008 |                     |       |
| CrII | 2066      | 13.211 ± 0.062 | 13.211 ± 0.062      | -1.269 ± 0.117 |
| FeII | 1608      | > 14.980       | 15.076 ± 0.042      | -1.234 ± 0.108 |
| NII  | 1611      | 15.076 ± 0.042 |                     |       |
| NII  | 1454      | 13.589 ± 0.039 | 13.565 ± 0.011      | -1.485 ± 0.101 |
| NII  | 1709      | 13.615 ± 0.020 |                     |       |
| NII  | 1741      | 13.582 ± 0.017 |                     |       |
| NII  | 1751      | 13.506 ± 0.021 |                     |       |
| ZnII | 2026      | > 11.650       | > 11.650            | > -1.800 |

3.13. $Q2230+02$, $z = 1.864$

Figure 15 presents the velocity plots for the damped Lyα system toward Q2230+02 and Table 17 lists the measured ionic column densities. We adopt $\log N(\text{HI}) = 20.85 \pm 0.084$ (Pettini et al. 1994) for this LBQS damped system. We have wavelength coverage of 28 metal-line transitions and have determined accurate column densities for the majority of them. This system is notable for a $\sigma$ detection of $N(\text{Ti}^+)$ and the FeII 1608 and FeII 1611 are blended with B-band sky lines. Therefore, we have no metallicity indicator for this system and its effects in our abundance analysis.

3.14. $Q2231-00$, $z = 2.066$

This LBQS system is another damped Lyα system exhibiting significant ($5\sigma$) TiII 1910 absorption. As in the damped Lyα system toward Q2230+02, the TiII profiles overlap, hence we use the technique outlined above to determine $N(\text{Ti}^+)$. Throughout the analysis we adopt $\log N(\text{HI}) = 20.56 \pm 0.1$ (Pettini et al. 1994). The velocity plots are given in Figure 17 and the column densities are presented in Table 18. This is the other system in our data sample which was previously observed by Lu et al. (1996). We find our measurements match theirs in nearly every case, although their analysis did not include Ti$^+$.  

3.15. $Q2348-14$, $z = 2.279$

This very metal-poor system was first discussed by Pettini et al. (1994) and has been previously observed at high resolution by Pettini et al. (1995). In Figure 19 we plot the Lyα transition for this system. Overplotted are Voigt profiles centered at $z = 2.2794$ with $\log N(\text{HI}) = 20.56 \pm 0.075$ corresponding to the measurements made by Pettini et al. (1994). While the profiles provide a reasonable fit to the
left wing of the damped profile, the fit for \( v > 750 \text{ km s}^{-1} \) is clearly inconsistent for all of the assumed \( N'(\text{HI}) \) values. It is very difficult, however, to continue fit an order of HIRES data which includes a damped Ly\( \alpha \) profile: it is easier to fit intermediate resolution data. Therefore, we adopt \( \log N'(\text{HI}) = 20.56 \pm 0.075 \) from the Pettini et al. analysis, but note in passing that this may be an overestimate of the true \( N'(\text{HI}) \) value. Comparing our derived chemical abundances with the work of Pettini et al. (1995) we find reasonable agreement and note we have improved on their limits in a few cases (e.g. N and S).

The system is exceptional for a number of reasons. First, it is one of the few systems where we have a measure of \( N'(\text{S}^+) \) based on the SII 1259 transition. As discussed for the damped system toward Q0347–38, S/Fe is an excellent diagnostic of dust depletion. Here we find S/Fe = 0.17 dex which argues strongly against dust depletion if the system has an underlying Type II SN pattern.

Second, the system exhibits two distinct low-ion features, one at \( v \approx -100 \text{ km s}^{-1} \) (feature 1; this feature was not resolved in previous observations) and the more dominant at \( v \approx 0 \text{ km s}^{-1} \) (feature 2). Feature 1 is present in all of the SII transitions and is the strongest feature in the AIII, CIV and SiIV profiles. Comparing \( N(\text{Si}^+) \) for the two features in the SII 1526 profile, we find \( N(\text{Si}^+)/N(\text{Fe}^+)/2 = 0.18 \). At the same time, however, the feature is entirely absent in the OI 1302 and FeII 1608 profiles: \( \Delta N'(\text{O}^+)/N(\text{O}^+)/2 < 0.027 \) and \( \Delta N(\text{Fe}^+)/N(\text{Fe}^+)/2 < 0.07 \). While dust could possibly explain the absence of Fe where Si is present because Si is only lightly depleted in the ISM, it cannot account for the lack of OI absorption. The system corresponding to feature 1 must be significantly ionized such that the dominant states of O, Fe, and Si are higher ions. We have performed CLOUDY (Ferland 1991) calculations which demonstrate values of \( |\text{Si}^+|/|\text{O}^+| \approx 1.2 \text{ dex} \) and \( |\text{Si}^+/\text{Fe}^+| \approx 0.7 \text{ dex} \) are possible in a Lyman limit system provided the ionization parameter is significantly high. Therefore, we argue feature 1 marks the damped Ly\( \alpha \) system while feature 1 may be a significantly ionized satellite or halo cloud. The system is also notable for providing a meaningful estimate of N/O. Finally, the most remarkable characteristic of this damped system is the velocity width of the CIV profiles, \( \Delta v > 600 \text{ km s}^{-1} \), particularly in light of the very narrow \( \Delta v \) exhibited by the low-ion profiles. This kinematic observation poses a difficult challenge to any physical model introduced to explain the damped Ly\( \alpha \) systems.

**Table 17**

| Ion | \( \lambda \) | AODM | \( N_{\text{adopt}} \) | \([X/H]\) |
|-----|---------------|------|----------------|------|
| HI  | 1215         | 20.850 ± 0.084 |               |      |
| CIV | 1548         | 14.848 |               |      |
| AIII| 1670         | 14.020 |               |      |
| AI II| 1854      | 13.590 ± 0.006 |               |      |
| SiII| 1526         | 15.233 | 15.656 ± 0.010 | −0.744 ± 0.085 |
| SiII| 1808         | 15.656 ± 0.010 |               |      |
| FeII| 1608         | > 15.115 | 15.188 ± 0.016 | −1.172 ± 0.086 |
| TiII| 1910         | 12.985 ± 0.099 |               |      |
| CrII| 2056         | 13.403 ± 0.027 | −1.127 ± 0.088 |      |
| FeII| 2066         | 14.483 ± 0.041 |               |      |
| NiII| 1370         | 13.860 ± 0.014 |               |      |
| NiII| 1709         | 13.860 ± 0.014 |               |      |
| NiII| 1741         | 13.838 ± 0.023 |               |      |
| NiII| 1751         | 13.687 ± 0.028 |               |      |
| Zn II| 2026       | 12.800 ± 0.028 | 12.800 ± 0.028 | −0.700 ± 0.088 |

**Table 18**

| Ion | \( \lambda \) | AODM | \( N_{\text{adopt}} \) | \([X/H]\) |
|-----|---------------|------|----------------|------|
| HI  | 1215         | 20.560 ± 0.100 |               |      |
| CII | 1335         | 13.580 ± 0.040 |               |      |
| CIV | 1548         | 14.195 ± 0.005 |               |      |
| OI  | 1302         | > 15.543 | < 17.748 | < 0.258 |
| AI III| 1854   | 13.172 ± 0.010 |               |      |
| AI II| 1862       | 13.110 ± 0.023 |               |      |
| SII | 1304         | > 15.030 | 15.247 ± 0.019 | −0.863 ± 0.102 |
| SII | 1526         | > 15.014 | 15.247 ± 0.019 |      |
| SII | 1808         | 15.247 ± 0.019 |               |      |
| TiII| 1910         | 12.848 ± 0.071 |               |      |
| CrII| 2062         | 13.165 ± 0.034 | −1.075 ± 0.106 |      |
| FeII| 2066         | 13.130 ± 0.063 |               |      |
| FeII| 1608         | 14.750 ± 0.009 |               |      |
| NiII| 1709         | 13.306 ± 0.032 | −1.504 ± 0.105 |      |
| NiII| 1741         | 13.381 ± 0.033 |               |      |
| NiII| 1751         | 13.100 ± 0.091 |               |      |
| ZnII| 2026         | 12.463 ± 0.023 | 12.463 ± 0.023 | −0.747 ± 0.103 |

3.16. \( Q359-02, z=2.095 \) \& \( z=2.154 \)

This faint QSO exhibits two intervening damped Ly\( \alpha \) systems. Both are members of the LBQS statistical survey. The velocity plots and column densities for the \( z = 2.095 \) system are presented in Figure 20 and Table 20 and those
for the z = 2.154 are given by Figure 21 and Table 21. Both are part of the LBQS statistical sample and we have taken the HI column densities from Wolfe et al. (1995): log N(HI) = 20.7 ± 0.1 for the z = 2.095 system and log N(HI) = 20.3 ± 0.1 for the z = 2.154 system. The SNR is relatively low for most of the spectrum and therefore abundances established on the weakest transitions are suspect, particularly those for Zn. We intend to make further observations of these two systems to improve the accuracy of our abundance measurements.

Table 20

| Ion  | λ  | AODM   | N_{adopt} | [X/H]   |
|------|----|--------|-----------|---------|
| HI   | 1215 | 20.700 ± 0.100 |
| CH   | 1334 | > 15.146 |
| CIV  | 1548 | > 14.639 |
|      | 1550 | > 14.800 |
| AlII | 1670 | 13.662 ± 0.034 |
|      | 1854 | 13.835 ± 0.010 |
|      | 1862 | 13.396 ± 0.016 |
| SiII | 1526 | > 15.045 |
|      | 1808 | 15.408 ± 0.021 |
| SiIV | 1393 | > 14.072 |
|      | 1402 | > 14.517 |
| CrII | 2056 | 12.748 ± 0.091 |
|      | 2062 | 13.131 ± 0.057 |
|      | 2066 | < 12.897 |
| FeII | 1608 | 14.507 ± 0.025 |
|      | 1611 | < 15.077 |
| NiII | 1703 | < 13.693 |
|      | 1709 | 13.152 ± 0.127 |
|      | 1741 | 13.185 ± 0.072 |
|      | 1751 | 13.071 ± 0.107 |
| ZnII | 2026 | 12.595 ± 0.029 |
|      | 2062 | 12.486 ± 0.075 |

Table 21

| Ion  | λ  | AODM   | N_{adopt} | [X/H]   |
|------|----|--------|-----------|---------|
| HI   | 1215 | 20.300 ± 0.100 |
| CH   | 1334 | > 14.987 |
| CIV  | 1548 | > 14.880 |
|      | 1550 | > 14.966 |
| AlII | 1670 | 13.165 ± 0.016 |
|      | 1854 | 13.165 ± 0.016 |
|      | 1862 | 12.960 ± 0.021 |
| SiII | 1526 | 14.316 ± 0.015 |
|      | 1539 | > 14.568 |
|      | 1402 | > 14.528 |
| CrII | 2056 | < 12.549 |
|      | 2066 | < 12.946 |
| FeII | 1608 | 13.895 ± 0.032 |
|      | 1611 | < 14.017 |
| NiII | 1317 | < 13.152 |
|      | 1370 | < 13.248 |
|      | 1454 | < 13.063 |
|      | 1741 | < 12.949 |
|      | 1751 | < 13.200 |
| ZnII | 2026 | < 11.901 |

4. ABUNDANCE PATTERNS

Table 22 lists the relative logarithmic abundances for the damped Lyα systems, [X/H] = log[N(X)/N(H)] - log[N(X)/N(H)]⊙. For each system we adopt the value
Fig. 22.— Abundance patterns of the most common elements from our full damped Lyα sample. Following standard practice in stellar abundance analysis we plot \([\text{X/Fe}]\), the logarithmic abundance of element X to Fe relative to solar. We plot this quantity vs. \([\text{Fe/H}]\), an indicator of the metallicity of the system. The triangles printed in each panel represent the typical metal-poor halo value (McWilliam 1997). The circles indicate the observed pattern for lightly depleted ISM gas (Savage and Sembach 1996). In the lower right panel, the xs identify \([\text{S/Fe}]\) values and the squares mark \([\text{Ti/Fe}]\).
for \(N(\text{HI})\) indicated in the previous section, and calculate \(N(X)\) by performing a weighted mean of all direct measurements, i.e. no limits or blends. Included in Table 24 are the abundance measurements for the damped Ly\(\alpha\) systems toward Q0201+36 and Q2206−19. In a few cases the values differ from the published values in light of new oscillator strengths. It is well-established both observationally and theoretically that the damped Ly\(\alpha\) systems are primarily neutral (Viegas 1994, Prochaska & Wolfe 1996). Therefore we perform no ionization corrections in determining the abundances from the ionic column densities of the low-ions.

Figure 23 presents the abundance patterns for the most common elements in our full sample. We have chosen not to include error bars for presentation purposes; the derived errors are < 0.1 dex with only a few exceptions. Following Lu et al. (1996), along the x-axis of each panel we plot metallicity – here expressed with \([\text{Fe}/\text{H}]\) – in part because this is the primary metallicity indicator in local stellar populations and in part because we have \(N(\text{element})\) values for a greater number of systems. Examining the upper-left panel of Figure 23 we note a systematic overabundance of \(\text{Zn}/\text{Fe}\) which suggests \(\text{Fe}\) may be depleted onto dust grains. Therefore consider the \([\text{Fe}/\text{H}]\) values to be lower limits to the true metallicity. In one case where (Q0841+12A) we have no reliable \(\text{Fe}\) abundance measurement and have taken \([\text{Fe}/\text{H}] = [\text{Cr}/\text{H}]\) on the grounds that \([\text{Cr}/\text{H}] \approx [\text{Fe}/\text{H}]\) in the majority of damped Ly\(\alpha\) systems.

In the following, we discuss the evidence for dust depletion and Type II supernovae enrichment in light of the observed damped Ly\(\alpha\) abundance patterns. The former is determined by comparing against abundance patterns in depleted ISM clouds (Savage and Sembach 1996) while the latter is assessed by comparing against the abundance patterns of metal-poor halo stars presumed to exhibit nucleosynthetic patterns typical of Type II supernovae (McWilliam 1997). First, consider the top two panels of Figure 23 which lend support to the presence of significant dust depletion in the damped Ly\(\alpha\) systems. As described throughout the paper, the overabundance of \(\text{Zn}\) to \(\text{Fe}\) relative to solar abundances is suggestive of dust depletion both because (i) \(\text{Zn}\) is largely undepleted in dusty regions within the ISM whereas \(\text{Fe}\) is heavily depleted and (ii) \([\text{Zn}/\text{Fe}] \approx 0\) dex for stars of all metallicity observed within the Galaxy (Sneden et al. 1991). Similarly, the \([\text{Ni}/\text{Fe}]\) ratio is significantly lower than metal-poor halo stars, which is consistent with \(\text{Ni}\) being more heavily depleted than \(\text{Fe}\) in depleted regions of the ISM. Lu et al. (1996) have argued the underabundance is primarily due to an error in the oscillator strengths for the Ni\(\text{III}\) transitions. While a recent analysis by Zsargó & Federman (1998) indicates the Ni\(\text{III}\) \(f\)-values are poorly determined, it is not clear if this can entirely account for the discrepancy between the damped Ly\(\alpha\) observations and the metal-poor halo star abundances. For our analysis, we have adopted the updated \(f\)-values from Zsargó & Federman (1998) – which does include a decrease in \(f_{1714}\) by a factor of 1.34 – yet a significant underabundance of \([\text{Ni}/\text{Fe}]\) is still apparent. Therefore it is unclear if errors in the oscillator strengths can fully resolve the discrepancy between the observed \([\text{Ni}/\text{Fe}]\) pattern and that predicted for Type II SN yields.

In contrast to the top two panels, the middle panels and the \([\text{Al}/\text{Fe}]\) abundance pattern are generally consistent with both dust depletion and Type II SN enrichment. As emphasized by Lu et al. (1996), the overabundance of \(\text{Si}/\text{Fe}\) relative to solar is very suggestive of Type II supernovae enrichment (McWilliam 1997). In the case of \(\text{Si}/\text{Fe}\), the \(\text{Si}\) overabundance is explained as the result of the overproduction of \(\text{Si} – \alpha\)-element relative to \(\text{Fe}\) in Type II supernovae. Similarly, the \([\text{Cr}/\text{Fe}]\) and \([\text{Al}/\text{Fe}]\) patterns are consistent with those observed for the metal-poor halo stars. Contrary to the Lu et al. observations, however, we observe an overabundance of \(\text{Cr}/\text{Fe}\) at very low metallicity (for \([\text{Fe}/\text{H}] < -1.5, < [\text{Cr}/\text{Fe}] > +0.21\). This result is most likely due to the fact that we are biased to high \([\text{Cr}/\text{Fe}]\) values at low \([\text{Fe}/\text{H}]\) because low \([\text{Cr}/\text{Fe}]\) values would imply \(\text{Cr}^+\) column densities below our detection limit. In one system (Q0149+33) we observe \([\text{Cr}/\text{Zn}] > 0\) dex indicating it is essentially undepleted by dust grains. Furthermore, we measure an overabundance of \(\text{Si}\) relative to \(\text{Fe}\) in this system ([\text{Si}/\text{Fe}] = +0.12 dex) which is an indication of a Type II \(\alpha\)-enhancement although at a somewhat smaller level than most metal-poor halo stars. Lastly, while the \([\text{Al}/\text{Fe}]\) measurements are broadly consistent with the abundances observed in metal-poor halo stars, there may be a contradiction at very low \([\text{Fe}/\text{H}]\). For halo stars with \([\text{Fe}/\text{H}] < -2\) dex, \([\text{Al}/\text{Fe}] < -0.4\) dex (McWilliam 1997) yet if anything the damped Ly\(\alpha\) systems exhibit \([\text{Al}/\text{Fe}] > 0\) dex at this metallicity. This result may ultimately pose a serious challenge to the interpretation of Type II SN nucleosynthetic patterns.

While the abundances for \(\text{Cr}, \text{Al}\) and \(\text{Si}\) vs. \(\text{Fe}\) resemble those for the metal-poor halo stars, the patterns also tend to match the dust depletion patterns of lightly

![Fig. 23.— [Si/Fe], [Zn/Fe] pairs for the 9 damped Ly\(\alpha\) systems from the full sample exhibiting Si, Zn, and Fe. The positive correlation (Pearson’s correlation coefficient \(r = 0.86\) with the null hypothesis a 0.003 probability) is suggestive of dust depletion, but could possibly have a nucleosynthetic origin (see text).]
depleted regions within the ISM [Savage and Sembach 1996]. In these regions, Si is overabundant relative to Fe, [Cr/Fe] ≈ 0.1 dex, and recent measurements of the Al to Fe ratio towards three OB stars (Hoffman et al. 1996) suggest [Al/Fe] ≥ 0 dex. If the overabundance of Si/Fe relative to solar is indicative of dust depletion, then one might expect a correlation between [Si/Fe] and [Zn/Fe] with the most heavily depleted regions showing the largest Si/Fe and Zn/Fe ratios. A plot of [Si/Fe] vs. [Zn/Fe] for all the systems with accurate abundances for the three elements (Figure 23) reveals a positive correlation (the Pearson coefficient is 0.86 in log-space with a null hypothesis probability of 0.003), consistent with that expected for dust depletion. However, if Zn is produced in the neutrino-driven winds of Type II SN (Hoffman et al. 1996), one may also expect a correlation between the abundance of Si and Zn relative to Fe.

Now consider the observations of Ti/Fe (solid squares in the lower right hand panel) which pose a strong argument for Type II SN enrichment. As emphasized in Prochaska & Wolfe (1997a), Ti is more heavily depleted than Fe in dusty regions within the ISM (Lipman & Pettini 1997), yet we find [Ti/Fe] ≥ 0 in every damped Lyα systems where Ti is observed. As Ti is an α-element, this argues strongly for the Type II SN interpretation. Lu et al. (1996) have made similar arguments for the observed underabundance of Mn/Fe in the damped systems. Because Mn is less depleted than Fe in dusty regions of the ISM, the Mn/Fe underabundance cannot be explained by dust depletion. On the other hand one observes [Mn/Fe] < 0 dex for the metal-poor halo stars (McWilliam 1997). Furthermore, the [Mn/Fe] values show a similar trend with [Fe/H] (albeit in terms of an underabundance) to that of the α-elements. It is possible this trend indicates a metallicity dependent yield for Mn, but the plateau in [Mn/Fe] values at [Fe/H] ≈ −1 to −2.5 is better understood if Mn is overproduced relative to Fe by Type Ia supernovae (Nakamura et al. 1998). If the latter explanation is correct, then the low [Mn/Fe] values are significant evidence for Type II SN enrichment within the damped Lyα systems. At the very least, we wish to stress the damped [Mn/Fe] observations require that the underlying nucleosynthetic pattern does not simply match solar abundances.

For the elements considered thus far, the abundance patterns are broadly consistent with a combination of Type II SN enrichment and an 'ISM-like' dust depletion pattern. This is not the case for Sulphur. In the two cases from our full sample where we have accurate measurements for S/Fe we find: (i) [S/Fe] = 0.50 ± 0.02 for the damped system at z = 3.025 towards Q0347–38 and (ii) [S/Fe] = 0.17 ± 0.1 for the damped system toward Q2348–14. Similar to Silicon, Sulphur is an α-element and is observed to be overabundant relative to Fe in metal-poor halo stars by [Si/Fe]_I ≈ 0.3 – 0.5 dex. Like Zinc, Sulphur is undepleted in the ISM. Therefore, interpreting the positive [Zn/Fe] values as the result of dust depletion, one would expect typical values for [S/Fe]_dust > 0.3 dex on the basis of dust depletion alone. Given all of the damped systems – including those from Lu et al. (1996) – exhibit [S/Fe] ≤ 0.5 dex, the S abundance pattern is inconsistent with a combination of Type II SN enrichment and dust depletion because this would require [S/Fe]_obs = [S/Fe]_I + [S/Fe]_dust > 0.6 dex in every case. While this point has been discussed previ-
ously, it needs to be emphasized. If dust is playing the primary role in the observed abundance patterns of the damped Lyα systems, then the [S/Fe] measurements require one of two conclusions: (1) the damped Lyα systems were not primarily enriched by Type II SN or (2) all of the systems where S has been measured are atypical in that they are the few which are undepleted. The first conclusion is at odds with most theories of galactic chemical evolution and is inconsistent with the observations of the Milky Way. To adopt point (1), one would have to argue the chemical history of the damped systems is very different from that of the Milky Way. Point (2) is a possibility for Q2348–14, but the Ni/Fe ratio observed for Q0347–38 ([Ni/Fe] < −0.5) would indicate this system is significantly depleted. At present, then, any attempt to match the abundance patterns of the damped Lyα systems with a combination of Type II SN enrichment and ISM-like dust depletion must fail the S observations.

Synthesizing our results with those from previous studies, we contend the abundance patterns of the damped Lyα systems lack any convincing single interpretation. On the face of it this may not be surprising, as one would expect some differences in their chemical evolution. While this would explain variations of a particular X/Fe ratio, this is unlikely to account for any of the inconsistencies discussed thus far. While the majority of the patterns are in excellent agreement with the Type II SN enriched halo star abundance patterns, Zn/Fe and Ni/Fe are clearly inconsistent and are very suggestive of dust depletion, albeit at considerably lower levels than that observed in dusty ISM clouds. An 'ISM-like' dust depletion pattern on top of solar abundances accounts for a majority of the observations but fails for Mn/Fe and Ti/Fe. Attempts to match the observed abundance patterns with a combination of dust depletion and Type II supernovae enrichment have been largely unsuccessful (Lu et al. 1996, Kulkarni et al. 1997, Vladilo 1998). This failure is accentuated by our measurements of [S/Fe] which are inconsistent with a synthesis of dust depletion and Type II SN abundance patterns. Of course to eliminate either effect would have profound consequences. If the damped Lyα systems do not exhibit Type II SN abundances they have a very different chemical evolution history than the Milky Way, in that they do not match the stellar abundance patterns for [Fe/H] < −1 dex. This would beg the questions: Is the Milky Way unique? Or do the damped Lyα systems somehow not include the progenitors of present-day spiral galaxies? Also, why would the damped systems exhibit relative solar abundances for all elements except Mn and Ti? On the other hand, if there is no dust depletion at play, then is the Zn/Fe ratio observed in the Milky Way a special case? Also, are the [Al/Fe] observations at low metallicity consistent with the Type II SN interpretation?

At the heart of these questions lies the physical nature of the damped Lyα systems. If dust depletion is playing a principal role, then perhaps the damped systems are tracing gas-rich galaxies not unlike the Magellanic Clouds (Welty et al. 1997), whereas an underlying Type II SN pattern is more suggestive of the progenitors of massive spiral galaxies. What steps can be taken to resolve these issues? First, the overabundance of Ti/Fe must be confirmed. A more accurate measurement of the TiII 1910 f values would be particularly useful. This could be achieved
by performing observations of a system showing both the TiII 1910 and TiII 3073 transitions. Unfortunately, at present this requires high S/N, high resolution observations at wavelengths exceeding 9000 Å (i.e., z ≈ 2). One could much more easily measure [Ti/Fe] in a few low-z systems exhibit [Fe/H] pretation ([S/Si] ≈ 0.2 dex and [Si/Ti] ≈ 0.1 dex). Third, the conclusions we have drawn from the S/Fe ratio are based on very few damped Lyα systems. Given the importance of this particular ratio, further measurements of Sulphur would be particularly enlightening. Lastly, a more detailed abundance analysis of the lowest metallicity systems would allow one to investigate the chemical evolution of the damped systems. Assuming the extremely metal-poor systems are the least depleted, they should provide the most accurate indication of the underlying nucleosynthetic pattern.

5. METALLICITY

We now turn to examine the metallicity of our sample of damped systems. Given the debate on the presence of dust in the damped Lyα systems, we will consider both Zn/H and Fe/H. Figure 24 plots our complete sample of [Zn/H] and [Fe/H] measurements vs. redshift. The column density-weighted mean for Zn,

\[
<[Zn/H]> = \log \frac{\sum_i N(Zn^+)_i}{\sum_i N(H^0)_i} - \log(Zn/H)_\odot ,
\]

for our full sample is \([<Zn/H>]= -1.15 \pm 0.15 dex\). This result confirms that of Pettini et al. (1997). For Fe, we find \([<Fe/H>]= -1.64 \pm 0.11 dex\) for \(z < 3\) and \(-1.77 \pm 0.11 dex\) for \(z > 3\). Lu et al. (1997) have used similar measurements (in fact several of the values presented here) to conclude that \(z \approx 3\) marks the onset of significant star formation in the damped Lyα systems. Their interpretation is based on the fact that the damped systems exhibit a break in \([<Fe/H>]\) at \(z \approx 3\). Formally, our data does not support their conclusion, but the fact that the high redshift \([<Fe/H>]\) value is dominated by only three systems (Q0000−26, Q0019−15, and Q0347−38) suggests our result is probably suffering from small number statistics.

6. SUMMARY AND CONCLUSIONS

We have presented accurate ionic column density and abundance measurements for 19 damped Lyα systems observed with HIRES on the 10m W.M. Keck Telescope. Throughout the paper we have utilized the apparent column density techniques to analyze the damped Lyα profiles and have adopted \(N(HI)\) values from the literature. The main results of the paper are summarized as follows:

1. The abundance patterns of our 19 systems match those observed by Lu et al. (1996). Therefore, our analysis confirms their primary conclusion that the damped Lyα systems exhibit abundance patterns representative of Type II SN enrichment with the major exception of [Zn/Fe] and to a lesser extent [Ni/Fe]. The Zn and Ni patterns, however, are in accordance with what one would expect for dust depletion based on observations of the lightly depleted, ‘warm’ HI clouds in the ISM. While the combination of dust depletion and Type II SN enrichment fits the majority of the observations, this interpretation is ruled out by the observed values of [S/Fe].

2. A majority of the damped Lyα elemental abundances are consistent with a dust depletion pattern on top of an underlying solar abundance pattern. Observations of Titanium and Manganese, however, strongly contradict this interpretation. In every system where Ti is observed, we measure [Ti/Fe] ≥ 0 dex consistent with the observed overabundance found in metal-poor halo stars and therefore suggestive of Type II SN enrichment. Similarly, the observed underabundance of [Mn/Fe] (Lu et al. 1996) is opposite to the effects of dust depletion and therefore requires a nucleosynthetic explanation, albeit not necessarily Type II SN yields.

3. Our metallicity measurements confirm the principal results from the surveys of Pettini and collaborators. Specifically, we find: \([<Zn/H>]= -1.15 \pm 0.15 dex,\)

\([<Fe/H>]= -1.64 \pm 0.11 dex\) for \(z < 3\), and

\(-1.77 \pm 0.11 dex\) for \(z > 3\). Although we do not

Note the error estimate reflects the errors in the individual [Zn/H] measurements and not the size of the data sample.
observe an evolution in the column density-weighted Fe abundance with redshift – as claimed by Lu et al. (1997) – we expect this inconsistency lies in the small number statistics of our high z sample.

4. For a number of damped Lyα systems in our sample (e.g. Q1331, Q0201, Q2348), we observe metal-line systems within 500 km s$^{-1}$ of the damped system. In the case of Q2348, for example, a metal-line system exhibiting SiII, SiIV and AlIII transitions is located only 100 km s$^{-1}$ from the strongest damped Lyα component. The absence of FeII and OI absorption and the SiII/SiIV ratio for this component, however, indicates this system is significantly ionized. We believe the same is true for the majority of these neighboring metal-line systems (the system at z = 1.858 toward Q2230+02 is a notable exception). If they were identified independently of the damped system, these systems would be very strong Lyman limit systems. Their coincidence with the damped system suggests they lie within the halo enclosing the damped system or perhaps that of a neighboring protogalactic system. We expect a detailed analysis of these systems may provide important insight into the physical conditions surrounding the damped Lyα systems.

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FIG. 2.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 3.439 toward Q0019−15. The vertical line at v = 0 corresponds to z = 3.43866.

FIG. 3.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 2.309 toward Q0100+13. The vertical line at v = 0 corresponds to z = 2.309.

FIG. 4.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 2.141 toward Q0149+33. The vertical line at v = 0 corresponds to z = 2.140755.

FIG. 5.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 3.025 toward Q0347−38. The vertical line at v = 0 corresponds to z = 3.0247.

FIG. 6.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 2.040 toward Q0458−02. The vertical line at v = 0 corresponds to z = 2.03955.

FIG. 7.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 2.374 toward Q0841+12. The vertical line at v = 0 corresponds to z = 2.374518.

FIG. 8.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 2.476 toward Q0841+12. The vertical line at v = 0 corresponds to z = 2.476219.

FIG. 9.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 3.386 toward Q0951−04. The vertical line at v = 0 corresponds to z = 3.855689.

FIG. 10.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 4.203 toward Q0951−04. The vertical line at v = 0 corresponds to z = 4.202896.

FIG. 11.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 1.999 toward Q1215+33. The vertical line at v = 0 corresponds to z = 1.9991.

FIG. 12.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 1.776 toward Q1331+17. The vertical line at v = 0 corresponds to z = 1.77636.

FIG. 13.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 3.736 toward Q1346−03. The vertical line at v = 0 corresponds to z = 3.735830.

FIG. 14.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 2.625 toward Q1759+75. The vertical line at v = 0 corresponds to z = 2.6253.

FIG. 15.—Velocity plot of the metal-line transitions for the damped Lyα system at z = 1.864 toward Q2230+02. The vertical line at v = 0 corresponds to z = 1.864388.
Fig. 16.— Velocity plot of the metal-line transitions for the presumed damped system at \( z = 1.859 \) toward Q2230+02. The vertical line at \( v = 0 \) corresponds to \( z = 1.858536 \).

Fig. 17.— Velocity plot of the metal-line transitions for the damped Ly\( \alpha \) system at \( z = 2.066 \) toward Q2231−00. The vertical line at \( v = 0 \) corresponds to \( z = 2.06615 \).

Fig. 18.— Velocity plot of the metal-line transitions for the damped Ly\( \alpha \) system at \( z = 2.279 \) toward Q2348−14. The vertical line at \( v = 0 \) corresponds to \( z = 2.2794 \).

Fig. 19.— Ly\( \alpha \) profile for the damped system toward Q2348−14. The overplotted curves correspond to \( N(\text{HI}) = 20.56 \pm 0.075 \).

Fig. 20.— Velocity plot of the metal-line transitions for the damped Ly\( \alpha \) system at \( z = 2.095 \) toward Q2359−02. The vertical line at \( v = 0 \) corresponds to \( z = 2.095067 \).

Fig. 21.— Velocity plot of the metal-line transitions for the damped Ly\( \alpha \) system at \( z = 2.154 \) toward Q2359−02. The vertical line at \( v = 0 \) corresponds to \( z = 2.153934 \).
The image shows a series of spectral lines plotted against relative velocity. The lines are labeled with various atomic species, such as NiII 1454, SiII 1526, CIV 1548, and FeII 1608. Each line represents the flux of a particular element as a function of velocity. The y-axis represents relative flux, while the x-axis shows relative velocity in km/s. The plots display the absorption features of these elements in a stellar spectrum.
