THE METALLICITY OF HIGH-REDSHIFT GALAXIES: THE ABUNDANCE OF ZINC IN 34 DAMPED Lyα SYSTEMS FROM \( z = 0.7 \) TO 3.4

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Received 1997 February 20; accepted 1997 April 14

ABSTRACT

We report new observations of Zn II and Cr II absorption lines in 10 damped Lyα systems (DLAs), mostly at redshift \( z_{\text{abs}} \geq 2.5 \). By combining these results with those from our earlier survey and other recent data, we construct a sample of 34 measurements (or upper limits) of the Zn abundance relative to hydrogen \([\text{Zn/H}]\); the sample includes more than one-third of the total number of DLAs known.

The plot of the abundance of Zn as a function of redshift reinforces the two main findings of our previous study. (1) Damped Lyα systems are mostly metal poor, at all redshifts sampled; the column density–weighted mean for the whole data set is \([\text{Zn/H}] = -1.13 \pm 0.38\) (on a logarithmic scale), or approximately 1/3 of solar. (2) There is a large spread, by up to 2 orders of magnitude, in the metallicities we measure at essentially the same redshifts. We propose that damped Lyα systems are drawn from a varied population of galaxies of different morphological types and at different stages of chemical evolution, supporting the idea of a protracted epoch of galaxy formation.

At redshifts \( z \geq 2 \), the typical metallicity of the damped Lyα systems is in agreement with expectations based on the consumption of \( \text{H} \text{I} \) gas implied by the recent measurements of \( \Omega_{\text{DLA}} \) by Storrie-Lombardi et al., and with the metal ejection rates in the universe at these epochs deduced by P. Madau from the ultraviolet luminosities of high-redshift galaxies revealed by deep imaging surveys. There are indications in our data for an increase in the mean metallicity of the damped Lyα systems from \( z > 3 \) to \( z \approx 2 \), consistent with the rise in the comoving star formation rate indicated by the relative numbers of \( U \) and \( B \) drop-outs in the Hubble Deep Field. Although such comparisons are still tentative, it appears that these different avenues for exploring the early evolution of galaxies give a broadly consistent picture.

At redshifts \( z < 1.5 \), DLAs evidently do not exhibit the higher abundances expected from a simple, closed-box model of global chemical evolution, although the number of measurements is still very small. We speculate that this may be due to an increasing contribution of low surface brightness galaxies to the cross section for damped Lyα absorption and to the increasing dust bias with decreasing redshift proposed by S. M. Fall and collaborators. However, more DLAs at intermediate redshifts need to be identified before the importance of these effects can be assessed quantitatively.

The present sample is sufficiently large for a first attempt at constructing the metallicity distribution of damped Lyα systems and comparing it with those of different stellar populations of the Milky Way. The DLA abundance histogram is both broader and peaks at lower metallicities than those of either thin or thick disk stars. At the time when our Galaxy’s metal enrichment was at levels typical of DLAs, its kinematics were closer to those of the halo bulge and a rotationally supported disk. This finding is at odds with the proposal that most DLAs are large disks with rotation velocities in excess of 200 km s\(^{-1}\), based on the asymmetric profiles of absorption lines recorded at high spectral resolution. Observations of the familiar optical emission lines from \( \text{H} \text{II} \) regions, which are within reach of near-infrared spectrographs on 8–10 m telescopes, may help resolve this discrepancy.

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

1. INTRODUCTION

In the last 12 months, there has been a dramatic increase in our ability to identify normal galaxies at \( z \approx 3 \), study their stellar populations, and measure the rates of star formation and metal production in the universe over most of the Hubble time (Steidel et al. 1996; Madau et al. 1996). The most prominent features in the spectra of field galaxies at high redshift (as is the case in the ultraviolet spectra of nearby, star-forming galaxies) are strong interstellar lines that are similar, both qualitatively (in the range of ionization stages seen) and quantitatively (in the strengths of the absorption), to those in damped Lyα systems; this similarity is consistent with the view that this class of QSO absorbers traces the material available for star formation at \( z \geq 2 \) (e.g., Wolfe 1995). The connection between normal galaxies and damped Lyα systems (DLAs) is a particularly important one to make, and clarifying several aspects of this connection remains a priority. The reason is simple: QSOs with known DLAs are typically more than 5 mag brighter than an \( L^* \) galaxy at the same redshift. Consequently, we will inevitably continue to rely mostly on QSO absorption-line spectroscopy for the study of the physical conditions in the early stages of galaxy formation.

Since 1990 (Pettini, Boksenberg, & Hunstead 1990), we have been conducting a survey of metallicity and dust in DLAs, taking advantage of the diagnostic value of weak

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transitions of Zn II and Cr II. As explained in that paper (see also the critical reappraisal of the technique in Pettini et al. 1997), [Zn/H] is a straightforward measure of the degree of metal enrichment analogous to the stellar [Fe/H], while [Cr/Zn] reflects the extent to which grain constituents are removed from the gas phase and thereby gives an indication of the dust-to-metal ratio. The major results of the survey were reported in Pettini et al. (1994). From the analysis of Zn and Cr abundances in 17 DLAs, mostly at z = 2, we concluded that the typical metallicity of the universe at a look-back time of ~13 Gyr (H₀ = 50 km s⁻¹ Mpc⁻¹; d₀ = 0.01) was Z_{DLA} = 1/10 Z_☉. Furthermore, we found that there is a considerable range—by up to 2 orders of magnitude—in the degree of metal enrichment reached by different damped Lyα galaxies at essentially the same epoch, and that, even at these early stages of galaxy formation, dust appears to be an important component of the interstellar medium (ISM), leading to the selective depletion of refractory elements from the gas.

A natural next step is to extend the Zn and Cr abundance measurements over a wider range of redshifts than that considered by Pettini et al. (1994), with the ultimate aim of identifying the emergence of heavy elements and dust in galaxies and following their buildup with time. To this end, we have continued our survey since 1994; the full sample now consists of 34 DLAs, more than one-third of the total number known (Wolfe et al. 1995). In this paper, we present the new data and consider the conclusions that can be drawn from the whole set of measurements of [Zn/H]; preliminary reports have appeared in conference proceedings (e.g., Pettini et al. 1995a; Smith et al. 1996). Our findings on the abundance of dust from consideration of the [Cr/Zn] ratio in the same sample have been reported separately (Pettini et al. 1997). Recently, Lu et al. (1996) have addressed similar questions from measurements of [Fe/H] in 20 DLAs using high-resolution echelle spectra acquired with the Keck telescope. These authors reach conclusions that are in agreement with those presented here regarding the emergence of heavy elements at high redshifts, although the analysis of [Fe/H] is complicated by the fact that this ratio, unlike [Zn/H], depends on both the metallicity and the dust content of the interstellar medium.

Before proceeding, it is useful to point out that in cases where DLAs from the present sample have been reobserved with HIRES on Keck (Wolfe et al. 1994; Wolfe 1995; Prochaska & Wolfe 1997a), [Zn/H] has been found to be in good agreement with the values measured in our survey, which is based on 4 m telescope data (see §2 below). While the exceptional quality of the Keck observations has made possible several new aspects of this work, including the study of the relative abundances of a wide range of elements and the analysis of the kinematics of the absorbing gas, the basic survey of metallicity in DLAs can be carried out satisfactorily with 4 m class telescopes. The main reason for this is the optically thin nature of the Zn II and Cr II lines in most DLAs proposed by Pettini et al. (1990) and confirmed by subsequent Keck spectra.

### 2. Observations and Data Reduction

The new data reported in this paper consist of observations of 10 DLAs in nine QSOs obtained between 1994 March and 1996 February (an additional candidate DLA from the low-dispersion survey by Storrie-Lombardi et al. 1996—at z_{abs} = 3.259 in the z_{em} = 4.147 BAL QSO 1144–073—was shown not to be a damped system by our higher resolution observations of the Lyα absorption line). In Table 1, we have collected relevant information for the 10 DLAs; the references listed in column (4) are the papers where the damped nature of the absorber was first identified. The absorption redshifts measured from associated metal lines in our blue and red spectra are listed in column (5); with six new DLAs at z_{abs} > 2.5, we have tripled the number of absorbers in this redshift regime compared with our earlier sample.

The observations, reduction of the spectra, and derivation of Zn and Cr abundances followed the procedures described in Pettini et al. (1994), and the interested reader is referred to that paper for a detailed treatment. Briefly, the observations were carried out mostly with the double-beam Cassegrain spectograph of the William Herschel Telescope (WHT) on La Palma, Canary Islands; additional red spectra were secured with the Cassegrain spectograph of the Anglo-Australian Telescope (AAT) at Siding Spring.

### Table 1

Damped Lyα Systems Observed

| QSO    | V (mag) | z_{em} | Reference | z_{abs} | Telescope | Resolution Time | S/N | W_{3σ}\footnotesize{(a)} |
|--------|---------|--------|-----------|---------|-----------|----------------|-----|------------------|
| 0000–263…... | 18      | 4.111  | 1         | 3.3901  | AAT       | 1.1            | 58,200 | 30               |
| 0056+014…... | 18.9    | 3.154  | 2         | 2.7771  | WHT       | 1.0            | 21,000 | 28               |
| 0836+113…... | 19.4    | 2.696  | 3         | 2.4651  | WHT       | 0.77           | 34,000 | 14               |
| 0841+129…... | 17      | 2.5:   | 4         | 2.3745  | WHT       | 0.76           | 20,000 | 30               |
| 0913+072…... | 17.1    | 2.785  | 5         | 2.6183  | WHT       | 0.75           | 19,800 | 46               |
| 1151+068…... | 18.8    | 2.762  | 6         | 1.7736  | WHT       | 0.81           | 14,400 | 44               |
| 1209+093…... | 18.5    | 3.297  | 7         | 2.5843  | WHT       | 0.82           | 18,000 | 29               |
| 1337+113…... | 18.2    | 2.919  | 3         | 2.7957  | WHT       | 0.75           | 18,000 | 9                |
| 2239–386…... | 18      | 3.511  | 8         | 3.2810  | AAT       | 1.1            | 65,875 | 18               |

\footnotesize{a} 3σ detection limit for the rest-frame equivalent width of an unresolved absorption line.

### References

—(1) Savaglio et al. 1994; (2) Wolfe et al. 1995; (3) Smith, Cohen, & Bradley 1986; (4) C. Hazard 1994, private communication; (5) Sargent, Boksenberg & Steidel 1988; (6) Turnshek et al. 1989; (7) Hazard, McMahon, & Morton 1987; (8) Lu & Wolfe 1994.

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4 We use the conventional notation where [X/Y] = log (X/Y)−log (X/Y)₀.
Figure 1.—Portions of the QSO spectra observed in our survey of Zn II and Cr II lines in DLAs. The x-axis is the wavelength in angstrom units; the y-axis is residual intensity. The vertical tick marks indicate the expected positions of the absorption lines, whether or not they have been detected. Line 1: Zn II λ2025.483; line 2: Cr II λ2055.596; line 3: Cr II λ2061.575 + Zn II λ2062.005 (blended); and line 4: Cr II λ2065.501. The spectra have been normalized to the underlying continua and are shown on an expanded vertical scale.

Observatory, Australia. At z_{abs} > 2.5, the Zn II λλ2025.483, 2062.005 and Cr II λλ2055.596, 2061.575, 2065.501 multiplets are redshifted longward of 7175 Å, where the quantum efficiency of CCDs falls with increasing wavelength. Using EEV and Tektronix CCDs, we generally found it necessary to integrate for longer than ~20,000 s (col. [8] of Table 1) in order to achieve a signal-to-noise ratio (S/N) between 9 and 46 (col. [9]). With a spectral resolution of 0.75–1.1 Å FWHM (col. [7]), the corresponding 3σ detection limits for the rest-frame equivalent widths of unresolved Zn II and Cr II absorption lines range from W(3σ) = 66 to 14 mA (col. [10]). The final “depth” of the survey—that is, the lowest metallicity that can be measured—depends on the combination of W(3σ) and the neutral hydrogen column...
density \( N(H^0) \). Since the values of \( N(H^0) \) in the new DLAs observed span 1 order of magnitude (see §3 below), it is the sight lines with the largest column densities of gas that provide the most stringent limits on metal abundances. Accordingly, we have tended to select DLAs for the present survey primarily on the basis of the value of \( N(H^0) \).

In Figure 1, we have reproduced portions of the QSO spectra encompassing the regions where the \( \text{Zn} \) \( \text{II} \) and \( \text{Cr} \) \( \text{II} \) lines are expected in the 10 DLAs in Table 1. As can be seen from the figure, the absorption lines sought are detected in approximately half of the cases. Table 2 lists redshifts and rest-frame equivalent widths for the detections; in the other cases, the 3 \( \sigma \) limits given in column (10) of Table 1 apply.

With the double-beam spectrograph on the WHT, we were able to record portions of the blue spectrum of each QSO, centered on the damped \( \text{Ly}\alpha \) line, simultaneously with the red arm observations aimed at the \( \text{Zn} \) \( \text{II} \) and \( \text{Cr} \) \( \text{II} \) lines. The blue detector was either the image photon...
TABLE 2
REDSHIFTS AND EQUIVALENT WIDTHS OF Zn II AND CIII LIINES

| QSO (1) | \( z_{\text{obs}} \) (2) | \( W_0 \) (mÅ) (3) | \( z_{\text{obs}} \) (4) | \( W_0 \) (mÅ) (5) | \( z_{\text{vel}} \) (6) | \( W_0 \) (mÅ) (7) | \( W_0 \) (mÅ) (8) |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0000−263...... | ... | \( \leq 25 \) | 3.3901 | \( z_{\text{vel}} \) | \( 22 \pm 7 \) | ... | \( \leq 25 \) |
| 0056+014...... | ... | ... | 2.7760 | 116 \( \pm 17 \) | 117 \( \pm 16 \) | 2.7769 | 49 \( \pm 12 \) |
| 0841+129...... | ... | \( \leq 26 \) | 2.3740 | 37 \( \pm 7 \) | 52 \( \pm 7 \) | ... | \( \leq 23 \) |
| 1151+068...... | 1.7737 | 49 \( \pm 9 \) | 1.7736 | 78 \( \pm 8 \) | 75 \( \pm 8 \) | 1.7736 | 34 \( \pm 6 \) |
| 1209+093...... | 2.5842 | 190 \( \pm 10 \) | 2.5846 | 185 \( \pm 15 \) | 195 \( \pm 15 \) | 2.5842 | 120 \( \pm 15 \) |

Notes.—Absorption redshifts are vacuum heliocentric. Equivalent widths are rest-frame values with \( \pm 1 \sigma \) errors. No redshifts are listed for line 3 as two absorption lines contribute to the feature.
* Blended with the atmospheric A band.

3. ZINC AND CHROMIUM ABUNDANCES
The main results of our survey are collected in Table 3, which includes the 10 DLAs in Table 1 and seven additional systems for which data have been published since our earlier study (Pettini et al. 1994). Values of the neutral hydrogen column density \( N(H^0) \) are listed in column (3) of Table 4; the typical accuracy of these measurements, including the uncertainty in the placement of the continuum, is \( \pm 20\% \). \( N(H^0) \) is likely to account for most of the neutral gas in each DLA given the low molecular fractions that apply to these absorbers at high redshifts (Levshakov et al. 1992; Ge & Bechtold 1997; Círković et al. 1997).

Columns (3) and (6) of Table 3 give the column densities of \( \text{Zn}^+ \) and \( \text{Cr}^+ \), respectively, deduced from the measured equivalent widths (or upper limits), assuming no line saturation. That this is generally the case is indicated by (1) the weakness of the absorption lines; (2) the equivalent width ratios of lines within each multiplet that, when measurable, are usually close to the ratios of the corresponding \( f \)-values (Bergeson & Lawler 1993); and (3) the resolved absorption profiles recorded with HIRES on Keck for many DLA...
systems, including some in common with the present survey (Lu et al. 1996; Prochaska & Wolfe 1997a). There are of course exceptions, such as the 2.5843 system in Q1209 + 093—see the discussion in § 3.12 below. The important point, however, is that it is usually possible, with the signal-to-noise ratio and resolution of our data, to assess the degree of saturation of the Zn II and Cr II lines. Column (4) lists the ratios \( N(\text{Zn}^+)/N(\text{H}^0) \) derived by dividing the entries in column (3) by those in column (3) of Table 4; comparison with the solar abundance of Zn, log \( (\text{Zn}/\text{H})_\odot = -7.35 \) (Anders & Grevesse 1989), then leads to underabundances of Zn by the factors given in column (5). The corresponding values for Cr, log \( (\text{Cr}/\text{H})_\odot = -6.32 \), are given in column (8), and column (9) lists the ratio

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**Figure 2**—Normalized portions of the blue spectra of QSOs in our survey centered on the damped Ly\( \alpha \) absorption line. The x-axis is the wavelength in angstrom units; the y-axis is residual intensity. In each panel, the short-dashed line shows the theoretical damping profile corresponding to the value of neutral hydrogen column density listed in col. (3) of Table 4.
N(Cr\(^\text{II}\))/N(Zn\(^\text{II}\)) in cases where it could be determined.

In taking the ratios N(Zn\(^\text{II}\))/N(H\(^\text{I}\)) and N(Cr\(^\text{II}\))/N(H\(^\text{I}\)) as measures of [Zn/H] and [Cr/H], we assume implicitly that there is little contribution to the observed Zn\(^\text{II}\) and Cr\(^\text{II}\) absorption from ionized gas (which would not produce Ly\(\alpha\) absorption). This is likely to be the case given the large significant differences in redshift between the Zn\(^\text{II}\) and Cr\(^\text{II}\) absorber in the survey, have been described in et al. Pettini (1995a). While Zn\(^\text{II}\) \(\lambda\)2025.483 remains undetected, despite the sensitive limit reached in a total exposure time of 58,200 s, we do record weak Cr\(^\text{II}\) absorptions at the 4 \(\sigma\) (2055.596) and 3 \(\sigma\) (2061.575) significance levels. Cr\(^\text{II}\) \(\lambda\)2055.596 is expected to be stronger than Zn\(^\text{II}\) \(\lambda\)2025.483 if the fraction of Cr locked up in dust grains is less than about 50%. With N(H\(^\text{I}\)) = \((2.5 \pm 0.5) \times 10^{21} \text{ cm}^{-2}\) (Savaglio, D’Odorico, & Moller 1994), this is one of the highest column density systems in our sample. We conclude that the abundance of Zn is less than 1/80 of the solar value; this estimate is \(\sim 5\) times more sensitive than the previous limit (Savaglio et al. 1994). The abundance of Cr, [Cr/H] \(\sim -2.2 \pm 0.1\), is similar to those of other elements measured by Molaro et al. (1996) and Lu et al. (1996), making this DLA one of the most metal poor in our sample.

### 3.1. Q0000 - 263; \(z_{\text{abs}} = 3.3901\)

Our observations of this DLA, the highest redshift absorber in the survey, have been described in Pettini et al. (1995a). While Zn\(^\text{II}\) \(\lambda\)2025.483 remains undetected, despite the sensitive limit reached in a total exposure time of 58,200 s, we do record weak Cr\(^\text{II}\) absorptions at the 4 \(\sigma\) (2055.596) and 3 \(\sigma\) (2061.575) significance levels. Cr\(^\text{II}\) \(\lambda\)2055.596 is expected to be stronger than Zn\(^\text{II}\) \(\lambda\)2025.483 if the fraction of Cr locked up in dust grains is less than about 50%. With N(H\(^\text{I}\)) = \((2.5 \pm 0.5) \times 10^{21} \text{ cm}^{-2}\) (Savaglio, D’Odorico, & Moller 1994), this is one of the highest column density systems in our sample. We conclude that the abundance of Zn is less than 1/80 of the solar value; this estimate is \(\sim 5\) times more sensitive than the previous limit (Savaglio et al. 1994). The abundance of Cr, [Cr/H] \(\sim -2.2 \pm 0.1\), is similar to those of other elements measured by Molaro et al. (1996) and Lu et al. (1996), making this DLA one of the most metal poor in our sample.

### 3.2. Q0056 + 014; \(z_{\text{abs}} = 2.7771\)

This QSO is from the Large Bright Quasar Survey by Chaffee et al. (1991). We deduce N(H\(^\text{I}\)) = \((1.3 \pm 0.2) \times 10^{21} \text{ cm}^{-2}\) from fitting the core of the damped Ly\(\alpha\) line, in reasonable agreement with the value of log N(H\(^\text{I}\)) = 21.0 reported by Wolfe et al. (1995).

As can be seen from Figure 1, the Zn\(^\text{II}\) and Cr\(^\text{II}\) absorption lines are broad and shallow in this DLA, spanning \(\approx 200 \text{ km s}^{-1}\). The stronger member of the Zn\(^\text{II}\) doublet, \(\lambda\)2025.483, falls within the atmospheric A band. Plotting the four absorption lines labeled in Figure 1 on the same velocity scale suggests that most of “feature 1” is not due to Zn\(^\text{II}\) \(\lambda\)2025.483, but rather to poorly corrected telluric absorption. From the equivalent widths of Cr\(^\text{II}\) \(\lambda\)2055.596 and \(\lambda\)2065.501 (features 2 and 4 in Fig. 1), which are consistent with the optically thin ratio of 2:1, we deduce a weighted
mean $N(Cr^+) = (2.8 \pm 0.4) \times 10^{13}$ cm$^{-2}$. This column density of $Cr^+$ produces an equivalent width $W_o = (82 \pm 12)$ mÅ for Cr II $\lambda 2061.575$; since we measure $W_o = (117 \pm 16)$ mÅ for feature 3, which is a blend of Cr II $\lambda 2061.575$ and Zn II $\lambda 2062.005$, we conclude that $W_o = (35 \pm 20)$ mÅ for the latter. This in turn corresponds to $N(Zn^+) = (3.5 \pm 2) \times 10^{12}$ cm$^{-2}$. Thus, both Zn and Cr appear to be $\approx 20$ times less abundant than in the Sun.

Our red spectrum also shows several Fe II lines from an absorption system at $z_{abs} = 2.3044$, including Fe II $\lambda 2344.214$ (visible in Fig. 1 at $\lambda_{abs} = 7748.46$ Å) with $W_o = (470 \pm 12)$ mÅ, Fe II $\lambda 2367.5905$ with $W_o = (64 \pm 6)$ mÅ, Fe II $\lambda 2374.4612$ with $W_o = (220 \pm 14)$ mÅ, and Fe II $\lambda 2382.765$ with $W_o = (640 \pm 12)$ mÅ.

3.3. $Q0201 + 365$; $z_{abs} = 2.462$

Keck observations of this DLA have been published recently by Prochaska & Wolfe (1996), who deduced relatively high abundances of Zn and Cr: $\sim \frac{1}{5} \times$ and $\sim \frac{1}{5} \times$ of solar, respectively. Evidently, even at redshifts as high as 2.5, some galaxies had already undergone significant chemical evolution and enriched their interstellar media in heavy elements to levels comparable to that of the Milky Way today.

3.4. $Q0302 - 223$; $z_{abs} = 1.0093$

Lanzetta, Wolfe, & Turnshek (1995) proposed this as a candidate DLA system on the basis of low-resolution IUE data; a subsequent UV spectrum secured with the Faint Object Spectrograph (FOS) on the Hubble Space Telescope (HST) confirmed that $N(H^0) = (2.15 \pm 0.35) \times 10^{20}$ cm$^{-2}$ (Pettini & Bowen 1997). Recent WHT observations of Zn II and Cr II lines by Pettini & Bowen (1997) have shown the abundances to be $\frac{1}{5}$ and $\frac{1}{5}$ of solar, respectively. After subtraction of the QSO radial profile from HST Wide Field Planetary Camera 2 images of the field, Le Brun et al. (1997) identified two galaxies that may be producing the absorption; at $z = 1.009$, they would have luminosities $L \approx 0.2L^*$ and $L^*_{\odot}$ ($q_\odot = 0.05$), and distances of 12 and 27 h$^{-1}$ kpc, respectively, from the QSO sight line.

3.5. $Q0454 + 039$; $z_{abs} = 0.8596$

The abundances of Zn and Cr reported by Steidel et al. (1995a) correspond to $[Zn/H] = -0.83 \pm 0.08$ and $[Cr/H] = -1.01 \pm 0.05$ if the experimentally measured f-values of the Zn II and Cr II multiplets (Bergeson & Lawler 1993) are adopted for consistency with the rest of the present study. Deep images of the QSO field both from the ground (Steidel et al. 1995a) and with HST (Le Brun et al. 1997) suggest that the absorber is a compact galaxy with $L \approx 0.25L^*$ at a projected distance of 8 h$^{-1}$ kpc from the QSO.

3.6. $Q0836 + 113$; $z_{abs} = 2.4651$

This is the faintest QSO in our survey (Hunstead, Pettini, & Fletcher 1990), and the S/N of the red spectrum remains modest, despite the considerable investment in exposure time (Table 1). Combined with the relatively low H I column density of $(3.8 \pm 0.4) \times 10^{20}$ cm$^{-2}$, the $3 \sigma$ upper limits to the Zn II and Cr II lines place limits on the abundances of Zn and Cr that are less stringent than in most other DLAs considered: $[Zn/H] \leq -0.8$ and $[Cr/H] \leq -1.2$.

The blue spectrum shown in Figure 2 was recorded with the IPCS on the WHT in 1994 March. Note that, of all the damped Ly$\alpha$ lines reproduced in Figure 2, this is the only instance where there appears to be weak emission in the core of the absorption line. The line flux, $(2 \pm 0.7) \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, agrees within the errors with the value of $(2.9 \pm 0.7) \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ reported by Hunstead et al. (1990) from independent data obtained in 1987 April with a different IPCS detector on the AAT. The two sets of observations were obtained with the same slit width (12") and at the same position angle on the sky (150°).

3.7. $Q0841 + 129$; $z_{abs} = 2.3745, 2.4764$

The spectrum of this bright ($V \approx 17$), high-redshift ($z \approx 2.5$, estimated from the onset of the Ly$\alpha$ forest) BL Lac object discovered by C. Hazard (1994, private communication) shows two DLAs (see Fig. 2), making it a highly suitable target for follow-up high-resolution observations.

As can be seen from Figure 1, in the lower redshift system we detect features 2 and 3; the strength of the latter indicates a significant contribution from Zn II $\lambda 2062.005$ to the blend. Following a procedure similar to that described for Q0056+014 in § 3.2, we deduce $N(Cr^+) = (9.5 \pm 2) \times 10^{12}$ cm$^{-2}$ from the equivalent widths of Cr II $\lambda 2055.596$ and $\lambda 2065.501$. This in turn leads us to estimate that approximately half of the equivalent width of feature 3 is due to Zn II $\lambda 2062.005$ with $W_o = (24 \pm 9)$ mÅ. Together with the $3 \sigma$ upper limit $W_o(2025.483) \leq 26$ mÅ for the stronger member of the doublet, this then implies $N(Zn^+) = (1.8 \pm 0.5) \times 10^{12}$ cm$^{-2}$.

Thus, we find that Zn and Cr at $z_{abs} = 2.3745$ are under-abundant by factors of 23 and 45, respectively, relative to solar values. Similar, or lower, abundances apply to the $z_{abs} = 2.4764$ DLA, given the lack of detectable Zn II and Cr II lines (see Table 3).

3.8. $Q0913 + 072$; $z_{abs} = 2.6183$

The signal-to-noise ratios of our spectra of this bright QSO are among the highest in the survey (see Table 1 and Figs. 1 and 2). The column density of neutral hydrogen, however, is comparatively low, $N(H^0) = (2.3 \pm 0.4) \times 10^{20}$ cm$^{-2}$. The lack of Zn II and Cr II absorption, even at S/N = 46, implies underabundances by factors of more than 14 and 32, respectively.

3.9. $Q0935 + 417$; $z_{abs} = 1.3726$

Lanzetta et al. (1995) estimated $N(H^0) = 2 \times 10^{20}$ cm$^{-2}$ for this candidate DLA from low-resolution IUE data; a subsequent HST FOS spectrum confirmed that $N(H^0) = (2.5 \pm 0.5) \times 10^{20}$ cm$^{-2}$ (K. M. Lanzetta & D. M. Meyer 1996, private communication). With this value of the hydrogen column density, the observations by Meyer, Lanzetta, & Wolfe (1995) imply $[Zn/H] = -0.80$ and $[Cr/H] = -0.90$.

3.10. $Q1104 - 180$; $z_{abs} = 1.6616$

Smette et al. (1995) identified this DLA in the spectrum of the brighter ($B = 16.7$) component of this gravitationally lensed QSO pair. From AAT observations obtained with an instrumental setup similar to that used in our survey, these authors estimated $N(H^0) = 6 \times 10^{20}$ cm$^{-2}$. They also reported detections of Zn II and Cr II absorption lines with equivalent widths $W_o(2025.483) = (75 \pm 20)$ mÅ and $W_o(2055.596) = (57 \pm 20)$ mÅ, respectively. If the lines are unsaturated, $[Zn/H] = -0.80$ and $[Cr/H] = -1.30$. 


3.11. \(Q1151 + 068; z_{\text{abs}} = 1.7736\)

Even though the damped Ly\(\alpha\) line falls in the crowded, near-UV spectrum of this \(z_{\text{em}} = 2.762\) QSO (see Fig. 2), our estimate of \(N(\text{H}^0) = (2.0 \pm 0.5) \times 10^{21} \text{ cm}^{-2}\) is in very good agreement with \(\log N(\text{H}^\alpha) = 21.3\) published by Turnshek et al. (1989). The ratios of equivalent widths within the Zn \(\Pi\) and Cr \(\Pi\) multiplets strongly suggest that the lines are optically thin; Zn and Cr are both underabundant by a factor of \(\approx 40\).

Our red spectrum, which covers the region 5500–5900 Å, shows three C \(\IV\) \(\lambda\lambda 1548, 1550\) doublets at \(z_{\text{abs}} = 2.5629, 2.7069,\) and 2.7551, respectively.

3.12. \(Q1209 + 093; z_{\text{abs}} = 2.5843\)

This is another high column density DLA; we measure \(N(\text{H}^0) = (2.0 \pm 0.5) \times 10^{21} \text{ cm}^{-2}\), which compares well with \(\log N(\text{H}^\alpha) = 21.4\) reported by Lu et al. (1993). The Zn \(\Pi\) and Cr \(\Pi\) lines are the strongest encountered in the entire survey of 34 DLAs (see Table 2). Fitting the absorption profiles requires \(b = 50 \text{ km s}^{-1}\) [as usual, \(b = (2)\sigma^2\), where \(\sigma\) is the one-dimensional velocity dispersion along the line of sight], indicating that several velocity components most likely contribute to the absorption. Similarly, Lu et al. found \(b = 122 \text{ km s}^{-1}\) from fitting a single curve of growth to the strongest UV absorption lines. Some of the components may well be saturated; so we quote our best estimates of \(N(\text{Zn}^+)\) and \(N(\text{Cr}^+)\) as lower limits. We conclude that Zn is more abundant than 1/9 solar, and Cr more abundant than 1/27 solar. Higher resolution observations are required to establish how close to these limits the true values are.

3.13. \(Q1328 + 307; z_{\text{abs}} = 0.6922\)

We have included here the measurements of Zn and Cr abundances in the spectrum of 3C 286 reported by Meyer & York (1992), after appropriate rescaling with the \(f\)-values of Bergeson & Lawler (1993). Although the measurements were discussed in Pettini et al. (1994), this intermediate-redshift DLA was not part of that sample, which consisted exclusively of DLAs at \(z_{\text{abs}} > 1.7\). CCD images of the QSO field obtained with ground-based telescopes (Steidel et al. 1994) and with \(HST\) (Le Brun et al. 1997) show a large (\(\approx 10–30 h_{50}^{-1}\) kpc), low surface brightness galaxy that has been proposed as the absorber.

3.14. \(Q1337 + 113; z_{\text{abs}} = 2.7957\)

Our measured \(N(\text{H}^0)\) of \((8 \pm 2) \times 10^{20} \text{ cm}^{-2}\) agrees very well with \(\log N(\text{H}^\alpha) = 20.9\) reported by Turnshek et al. (1989). When we observed this QSO, in 1994 March, we found it to be considerably fainter than the magnitude \(V \approx 18.2\) estimated by Hazard et al. (1986) from POSS plates. Although the S/N achieved is the lowest in the survey (see Table 1 and Fig. 1), it is still sufficient to establish that the abundances of Zn and Cr are less than 1/10 and 1/23 of solar, respectively.

3.15. \(Q1946 + 769; z_{\text{abs}} = 2.8443\)

This \(z_{\text{em}} = 3.051\) QSO, intrinsically one of the most luminous known, is sufficiently bright to have been studied extensively at echelle resolutions and high S/N with 4 m telescopes (Fan & Tytler 1994; Lu et al. 1995; Tripp, Lu, & Savage 1996). However, the hydrogen column density in the \(z_{\text{abs}} = 2.8443\) DLA is relatively low, \(N(\text{H}^0) = (2 \pm 0.5) \times 10^{20} \text{ cm}^{-2}\) (Lu et al.). Consequently, the upper limits \([\text{Zn}/\text{H}] \leq -0.82\) and \([\text{Cr}/\text{H}] \leq -1.00\) deduced by these authors are rather uninformative given that the true metallicity is ~30 times lower \([\text{Fe}/\text{H}] = -2.44 \pm 0.13]\).

3.16. \(Q2239–386; z_{\text{abs}} = 3.2810\)

This QSO is faint, and the absorber is at high redshift; the combination of these two factors resulted in the longest integration time in the survey (see Table 1). Adopting \(N(\text{H}^0) = 5.8 \times 10^{20} \text{ cm}^{-2}\) measured by Lu & Wolfe, we deduce Zn and Cr underabundances by factors of more than 11 and 13, respectively.

The Cr measurement is based on the weakest member of the triplet, Cr \(\Pi 2261.501, 2261.575\) is affected by a strong sky emission line, and \(\lambda 2055.596\), which, at \(z_{\text{abs}} = 3.2810\), is redshifted to \(\lambda_{\text{abs}} = 8802.82 \text{ Å}\), falls very close to Mn \(\Pi\) \(\lambda 2606.462\) at \(z_{\text{abs}} = 2.3777\), the redshift of a second DLA along this line of sight (Lu & Wolfe 1994). Based on the strengths of the other two members of the Mn \(\Pi\) triplet, \(2576.877\) at \(\lambda_{\text{abs}} = 8703.55 \text{ Å}\) and \(2574.499\) at \(\lambda_{\text{abs}} = 8763.97 \text{ Å}\), the feature labeled 2 in the last panel of Figure 1 is mostly Mn \(\Pi\) \(\lambda 2606.462\). The two strong absorption lines also visible in this figure are Fe \(\Pi\) \(\lambda\lambda 2586.6500, 2600.1729\) at \(z_{\text{abs}} = 2.3777\).

4. DISCUSSION

Our total sample, which consists of measurements (or upper limits) of \([\text{Zn}/\text{H}]\) in 34 DLAs over the redshift range \(z_{\text{abs}} = 0.6922–3.3901\), is constructed by combining data for the 17 DLAs in Table 3 with those for the 15 DLAs in Table 3 of Pettini et al. (1994), and with the further addition of two DLAs in Q0528–250 (Meyer, Welty, & York 1989) that were included in the sample considered by Pettini et al. (1994) but not listed in their Table 3. All the points in Figure 3 are based on the \(f\)-values of the Zn \(\Pi\) doublet by Bergeson & Lawler (1993) and the meteoritic solar abundance of Zn from the compilation by Anders & Grevesse (1989).\(^5\)

We now consider what implications can be drawn from this extensive survey on the chemical evolution of the neutral content of the universe and on the relationship of damped Ly\(\alpha\) systems to present-day galaxies.

4.1. Chemical Evolution of Damped Ly\(\alpha\) Systems

Figure 3 shows the abundance of Zn as a function of redshift. The enlarged sample confirms the two main conclusions reached by Pettini et al. (1994):

1. Damped Ly\(\alpha\) systems, at all redshifts probed, are generally metal poor and presumably arise in galaxies at early stages of chemical evolution.

2. There appears to be a large range in the values of metallicity reached by different galaxies at the same redshift, pointing to a protracted "epoch of galaxy formation" and to the fact that chemical enrichment probably proceeded at different rates in different DLA galaxies.

While we find gas with near-solar metallicities at redshifts as high as \(z \approx 2.5\), there are also examples of galaxies with abundances less than 1/10 solar at a time when the disk of the Milky Way differed little from its present-day composition. At redshifts \(z \approx 2–2.5\), the full range of metal abun-

\(^5\) This set of atomic parameters and solar abundance introduces a correction of \(-0.148\) to the values of \([\text{Zn}/\text{H}]\) published in Pettini et al. (1994).
Fig. 3.—The abundance of Zn for the 34 DLAs in the present survey plotted against redshift. Abundances are measured on a log scale relative to the solar value shown by the dashed line at [Zn/H] = 0.0. The upper limits, corresponding to nondetection of the Zn II lines, are indicated by downward-pointing arrows. For two damped systems, indicated by filled circles with upward-pointing arrows, we derive lower limits to the abundances, because the absorption lines may be saturated.

dances spans about 2 orders of magnitude. Although, for metallicities \( Z_{\text{DLA}} \lesssim 1/50 \ Z_{\odot} \), the Zn II lines become vanishingly small and only upper limits to the abundance of Zn can be deduced, we do now from echelle spectroscopy of more abundant astrophysical elements that values of \( Z_{\text{DLA}} \lesssim 1/100 \ Z_{\odot} \) are not uncommon at \( z_{\text{abs}} = 2-3 \) (see Fig. 1 of Pettini et al. 1995a).

These two results are considered quantitatively in Table 5, where in the last column we list, for various subsets of our sample, the column density–weighted mean abundance of Zn:

\[
[Zn/H] = \log \left( \frac{\langle Zn/H \rangle_{\text{DLA}}}{\langle Zn/H \rangle_{\odot}} \right), \tag{1}
\]

where

\[
\langle Zn/H \rangle_{\text{DLA}} = \frac{\sum_{i=1}^{n} N(Zn^{+})_{i}}{\sum_{i=1}^{n} N(H^{0})_{i}}, \tag{2}
\]

and \( \sigma' \), the standard deviation from the column density–weighted mean, defined as

\[
(n - 1)\sigma'^{2} = \sum_{i=1}^{n} \left( [Zn/H]_{i} - [\langle Zn/H \rangle_{\text{DLA}}] \right)^{2}. \tag{3}
\]

The summations in equations (2) and (3) are over the \( n \) DLA systems considered in each subsample.

Under the working assumption that DLAs account for most of the material available for star formation at high redshift, the quantity \( [\langle Zn/H \rangle_{\text{DLA}}] \) is a measure of the degree of metal enrichment reached by the universe at a given epoch. This is a general statement that follows from the column density distribution of Ly\( \alpha \) systems (Lanzetta et al. 1995) and that holds irrespective of the precise nature of the damped absorbers (disks, spheroids, gas clouds yet to collapse into galaxies, etc.), provided that there are no significant biases in the samples of DLAs from which our observations are drawn (Fall 1996).

The values of \( [\langle Zn/H \rangle_{\text{DLA}}] \) in Table 5 are strictly upper limits (with the exception of subsample 1), since the averages include systems for which only upper limits to the abundance of Zn are available. However, we expect the corrections to be small because the systems where the Zn II doublet is below our detection limits are preferentially those with the lowest values of hydrogen column density \( N(H^{0}) \). Specifically, the fractions of \( \sum_{i=1}^{n} N(H^{0}) \) contributed by DLAs with undetected Zn II lines are 28% for the full sample, and 16%, 16%, and 37%, respectively, for subsamples 2, 3, and 4. To show that including the upper limits as detections has only a modest effect on the mean values of metallicity deduced, we have recalculated \( [\langle Zn/H \rangle_{\text{DLA}}] \) for the full sample twice, substituting 2 \( \sigma \) and 1 \( \sigma \) limits, respectively, in place of the 3 \( \sigma \) limits used in Table 5 (indeed, it could be argued that 3 \( \sigma \) limits for the entire ensemble of Zn nondetections is an overly conservative approach). In this case, \( [\langle Zn/H \rangle_{\text{DLA}}] \) decreases from \(-1.13 \pm 0.38 \) (the

| Sample        | Redshift Range (Gyr) | Look-Back Time* (Gyr) | DLAs | Detections | Upper Limits |
|---------------|----------------------|-----------------------|------|------------|--------------|
| Full sample   | 0.6922–3.3901        | 7.8–14.7              | 34   | 19         | 15           | \(-1.13 \pm 0.38\) |
| Subsample:    |                      |                       |      |            |              |               |
| 1             | 0.50–1.49            | 6.3–11.4              | 4    | 4          | 0            | \(-0.98 \pm 0.33\) |
| 2             | 1.50–1.99            | 11.4–12.7             | 8    | 6          | 2            | \(-0.96 \pm 0.44\) |
| 3             | 2.00–2.49            | 12.7–13.6             | 12   | 6          | 6            | \(-1.23 \pm 0.38\) |
| 4             | 2.50–2.99            | 13.6–14.3             | 7    | 3          | 4            | \(-1.11 \pm 0.27\) |
| 5             | 3.00–3.49            | 14.3–14.8             | 3    | 0          | 3            | \(-1.39\)         |

\* \( H_{0} = 50 \ \text{km s}^{-1} \ \text{Mpc}^{-1} \); \( q_{0} = 0.01 \).
value listed in Table 5) to $-1.16 \pm 0.40$ and $-1.20 \pm 0.48$, respectively. On the other hand, all three measurements in subsample 5 ($z_{abs} = 3.0 - 3.5$) are upper limits, and accordingly we quote the value of $\langle[Zn/H]_{DLA}\rangle$ in this redshift interval as an upper limit.

For the full sample of 34 DLAs in the range $z_{abs} = 0.7 - 3.4$, we find $\langle[Zn/H]_{DLA}\rangle = -1.13 \pm 0.38$. This is the same value as obtained by Pettini et al. (1994) when account is taken of the different $f$-values and solar abundance scale used in our earlier study. For comparison, $[Zn/H]_{gas} = -0.19$ along unreddened sight lines in the solar vicinity (Roth & Blades 1995 and Sembach et al. 1995; both analyses used the same $f$-values and solar scale as here). If the interstellar medium (gas + dust) near the Sun has the same composition as the Sun, this would imply that approximately 35% of Zn is in solid form. On the other hand, Pettini et al. (1997) found that for the present sample of DLAs, the typical dust-to-metals ratio is approximately half that of the Galactic ISM. If we assume, therefore, that on average 83% of Zn in DLAs is in the gas phase, we obtain $\langle[Zn/H]_{DLA}\rangle = -1.13 \pm 0.38 + \log (1/0.83) = -1.004 \pm 0.38$ and conclude that the column density-weighted abundance of Zn in DLAs is 1/11 of that of the Milky Way ISM today.

One of the motivations of the present work was to determine the redshift evolution of the metallicity of DLAs and thereby trace the increase of heavy elements in the universe from the epoch of galaxy formation to the present time. From Figure 4, where our measures of $\langle[Zn/H]_{DLA}\rangle$ from Table 5 are plotted versus redshift, it can be seen that any such evolution is only mild in the present sample. Between $z = 3$ and 1.5, to which 80% of the sample refers, there appears to be little change from the typical $\langle[Zn/H]_{DLA}\rangle = -1.13$. This is less surprising, however, when one considers that this redshift interval spans a period of only $\approx 3$ Gyr from 14.3 to 11.4 Gyr ago ($H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$; $q_0 = 0.01$), and that at these epochs evidently there was a large spread in the chemical enrichment of different DLA galaxies.

On the other hand, the upper limit $\langle[Zn/H]_{DLA}\rangle \leq -1.39$ at $z > 3$ is lower than the means in the other redshift bins, providing tentative evidence for a rapid buildup of elements with time at this epoch. This suggestion is strengthened by the data of Lu et al. (1996), who found that $[Fe/H] \leq -2$ in three additional DLAs at $z > 3$. (The correction to $[Fe/H]$ for the fraction of Fe in solid form is likely to be small—probably less than a factor of 2—at such low metallicities [Pettini et al. 1997].) The lowest metallicities measured in DLAs, $Z_{DLA} \approx -2.5$, are comparable to those thought to apply to the ionized intergalactic medium (IGM) producing the Ly$\alpha$ forest at redshifts $z = 2-3.5$ (Hellsten et al. 1997), although the large ionization corrections involved make estimates of $Z_{IGM}$ considerably more uncertain than $Z_{DLA}$. It is tempting, therefore, to interpret the rapid increase in metal abundances at $z < 3$ as an indication of the onset of star formation in galaxies and to speculate that $Z \approx -2.5$ may be an approximate "base" level of metallicity on which galactic chemical evolution subsequently builds.

The recently realized ability to image high-redshift galaxies directly in their ultraviolet stellar continua has led to the first attempts to sketch the global history of star formation over $\approx 80\%$ of the age of the universe (Madau et al. 1996 and references therein). Determinations of the volume-averaged star formation rate (SFR) from the so-called $B$ and $U$ drop-outs (galaxies with the Lyman limit in the $B$ and $U$ bands, respectively) in ground-based surveys (Steidel, Pettini, & Hamilton 1995b) and in the Hubble Deep Field (Madau 1996) do indeed suggest an increase in the SFR from $z \approx 4$ to $z \approx 2.75$. As discussed by Madau et al., it is possible to convert the integrated UV luminosity density into a metal ejection rate $\dot{\phi}_Z$ per comoving volume at redshift $z$. Since the massive stars that are the main contributors to the far-UV continuum are also the major producers of heavy elements (at least those released into the ISM by Type II supernovae), the conversion does not depend sensitively on the shape of the initial mass function in these primordial galaxies. Rather, the principal sources of uncertainty arise from the cosmology assumed and from the amount of dust extinction suffered by the UV continuum.

Bearing in mind these uncertainties, it is of great interest to compare the values of $Z_{DLA}$ deduced here with the metallicities that may be expected on the basis of Madau's metal ejection rate. Integrating $\dot{\phi}_Z$ in Figure 3 of Madau (1996) from $z = 5.5$ to the present time yields a total density of metals $\rho_Z(z = 0) \approx 6.2 \times 10^8 M_\odot$ Mpc$^{-3}$. This corresponds to an approximately solar metallicity if the present-day density of baryons in galaxies is $\approx (2.7 \pm 0.4) \times 10^8 M_\odot$ Mpc$^{-3}$, or $\Omega_0 \approx (4 \times 10^{-3}) (H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$; Madau et al. 1996). In a closed-box model, assuming that $\Omega_4(z = 0) \approx \Omega_{DLA}(z = 4)$ (Storrie-Lombardi, McMahon, & Irwin 1996a), we can take

$$Z(z) \approx Z(0) \left( \frac{\rho_Z dz}{\Omega_4 \rho_Z dz} \right),$$

provided the gas consumption into stars from $z = 5.5$ to $z$ is low and $\Omega_{DLA}(z) \propto \Omega_4(z)$. The redshift evolution of $\Omega_{DLA}$ (Storrie-Lombardi et al. 1996a) suggests that this may well

\[ \frac{Z(z)}{Z(0)} \approx \frac{\Omega_4(z)}{\Omega_4(0)} \frac{\rho_Z dz}{\Omega_4 \rho_Z dz} \tag{4} \]
be the case up to \( z \approx 2 \) (as we proposed in Pettini et al. 1994).

The dashed line in Figure 4 shows the increase of \( Z(z)/Z_{\odot} \), with decreasing redshift calculated from equation (4) and Madau's (1996) estimates of \( \rho_2 \). Evidently, there is rough agreement between the predicted and observed values of \( Z_{\text{DLA}} \). Given the current uncertainties, we consider it premature to read too much into this comparison. For example, Madau's \( \rho_2 \) refers primarily to oxygen and the \( x \)-elements that presumably are more abundant than zinc and iron by a factor of 2–3 at these low metallicities (Edvardsson et al. 1993; Carney 1996). On the other hand, the dashed line in Figure 4 may well underestimate the metal production rate by similar factors if star-forming galaxies at high redshift are reddened by small amounts of dust, corresponding to \( E(B-V) \approx 0.1 \), as suggested by the observed slopes of the UV continua (Steidel et al. 1996).

Nevertheless, taken at face value, Figure 4 does seem to indicate that in the DLAs, we see roughly the same level of metal enrichment as expected from direct observations of star-forming galaxies at these redshifts. More complex of galactic chemical evolution models that use the gas consumption indicated by the redshift evolution of \( \Omega_{\text{DLA}} \) as a starting point (Pei & Fall 1995; Fall 1996) also reproduce the degree of metal enrichment of DLAs and the comoving rate of star formation at \( z \gtrsim 2 \). Thus, it appears that, to a first approximation at least, these three independent avenues to exploring the epoch of galaxy formation—the consumption of neutral gas, the metal abundance of the absorbers, and the UV luminosity of high-redshift galaxies—give a broadly consistent picture of the early evolution of galaxies.

### 4.1. Abundances at \( z < 1.5 \)

The situation is less clear at lower redshifts. Only four measurements make up subsample 1 in Table 5, even though this bin spans a larger interval of time than all the other subsets put together—\( \approx 5 \) Gyr from 11.4 to 6.3 Gyr ago (again for \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\); \( q_0 = 0.01 \)). Evidently \( [\text{Zn}/\text{H}_{\text{DLA}}] = -0.98 \pm 0.33 \) is below an extrapolation of Madau’s curve in Figure 4. However, it is difficult to assess how firm this conclusion is, given that 65% of \( N(\text{H}^0) \) for subsample 1 is due to the \( z_{\text{abs}} = 0.6922 \) absorber in 3C 286, which appears to be a large, low surface brightness galaxy (see § 3.13 above). It is quite possible that such galaxies, whose low metallicities at the present time are thought to be the result of low star formation efficiencies (McGaugh 1994; Padoan, Jimenez, & Antonuccio-Delogu 1997), come to dominate the cross section for DLA absorption at \( z \lesssim 1 \), if, by this epoch, most high surface brightness galaxies have already processed a significant fraction of their gas into stars. Furthermore, the buildup of dust that goes hand in hand with the production of metals is likely to introduce an increasing bias (with decreasing redshift) against galaxies in advanced stages of chemical evolution, since existing samples of damped Ly\( \alpha \) systems are drawn mostly from magnitude-limited optical QSO surveys (Fall & Pei 1993; Pei & Fall 1995).

At \( z_{\text{abs}} < 1.5 \), imaging of DLA absorbers is within current observational capabilities. Although positive identifications based on spectroscopic redshifts have not been achieved yet, the candidates that have been proposed suggest a very diverse population of galaxies. While in some cases the absorbers could be on evolutionary paths similar to that of the Milky Way, the \( z_{\text{abs}} = 1.0093 \) DLA in Q0302—223 being a good example (Pettini & Bowen 1997), there are also several instances where galaxies of low luminosity \( (L_r < 0.1 L^* \) or of low surface brightness are indicated (Steidel et al. 1994, 1995a, 1997; Le Brun et al. 1997).

Thus, both effects considered above—a shift of the DLA population away from “normal” \( L^* \) galaxies and an increasing dust bias—may contribute to the finding that \( Z_{\text{DLA}} \) does not increase significantly at \( z_{\text{abs}} < 1.5 \) in Figures 3 and 4, contrary to the simple expectations in a closed-box model of chemical evolution. However, it really will not be possible to proceed further, and quantify the relative importance of these two effects, without a larger sample of DLAs at intermediate redshifts. Identifying such a sample remains an urgent priority.

### 4.2. Comparison with Stellar Populations of the Milky Way

Damped Ly\( \alpha \) systems are commonly thought of as the high-redshift counterparts of present-day galactic disks, although we and others (Pettini et al. 1990; York 1988) have often made the point that high column densities of neutral gas are not the prerogative of disk galaxies alone. The sample of \([\text{Zn}/\text{H}]\) measurements now available is sufficiently large to allow a comparison to be made of the distribution of metallicities in DLAs with those of different stellar populations in the Milky Way. In the solar cylinder, stars in the halo, thick disk, and thin disk have distinct dynamical and abundance properties, although the distributions overlap in either parameter taken separately. It is the combination of chemical abundance and kinematic data that studies of Galactic evolution have focused on; here we attempt to use this information to throw light on the nature of DLA galaxies.

Our measurements of \([\text{Zn}/\text{H}]\) from Figure 3 have been plotted in the top panel of Figure 5 after converting redshift to look-back time in a cosmology compatible with stellar ages. The bottom panel in Figure 5 shows the age-metallicity relationship for disk stars determined in the landmark study by Edvardsson et al. (1993). This sample includes stars with the kinematics of both thin and thick disks, defined in terms of the mean velocity perpendicular to the Galactic plane: \( W = 19 \) km s\(^{-1}\) and \( \approx 42 \) km s\(^{-1}\) for thin and thick disk stars, respectively (Freeman 1991). In constructing their sample, Edvardsson et al. aimed to include approximately equal numbers of stars in each metallicity bin above \( Z = 0.1 Z_\odot \); consequently, metal-poor stars are relatively overrepresented in Figure 5.

Stellar ages are notoriously uncertain, as is the mapping of redshift to look-back time. However, even allowing for an arbitrary sliding of the points in Figure 5 along the \( x \)-axes, the metallicity measurements in DLAs evidently do not match the chemical evolution of the Milky Way disk. The typical value \( Z_{\text{DLA}} = -1.13 \) is lower than that of even the most metal-deficient stars in the Edvardsson et al. survey, and at all ages the spread of chemical abundances in the disk is smaller than that of the DLA sample.

This point is reinforced by Figure 6, where we compare the metallicity distribution of DLAs with those of stars in the thin disk, thick disk, and halo populations; in Figure 7, we show the comparison with the metallicity histogram for globular clusters. Values for disk stars are from the work by Wyse & Gilmore (1995). These authors combined spectroscopic determinations of \([\text{Fe}/\text{H}]\) for a sample of F and G stars located 1–5 kpc from the plane with data for samples
Fig. 5.—*Top*: available measurements of metallicity in DLAs plotted as a function of look-back time for \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( q_0 = 0.01 \). *Bottom*: metallicities of 182 F and G dwarf stars in the Galactic disk with measured iron abundances and ages from the large-scale study by Edvardsson et al. (1993).

near the Sun, paying particular attention to including only stars with potential main-sequence lifetimes greater than 12 Gyr. That is, their combined sample should be complete, in the sense of not missing disk stars that by now have evolved away from the main sequence, and the resulting metallicity distributions presumably provide an integrated record of the chemical evolution of the disk. The thin disk distribution in Figure 6 includes the low-metallicity tail discussed by Wyse & Gilmore (1995); similarly, the thick disk histogram is consistent with the metal-weak tail shown in Figure 22 of Beers & Sommer-Larsen (1995). The halo sample is from the survey of high proper-motion stars in the solar neighborhood by Laird et al. (1988), while the histogram in Figure 7 is based on the distribution of [Fe/H] in 40 globular clusters plotted in Figure 16 of Carney et al. (1996).

The comparison between the metallicity distribution of DLAs and those of stellar populations in the Galaxy is complicated by the fact that about half of the values that make up the bins with \([Zn/H]_{DLA} \leq -0.8\) in Figures 6 and 7 correspond to upper limits of \([Zn/H]\) in our survey. If we excluded the upper limits from the sample, the resulting distribution would be skewed to higher metallicities. This is also the case if they are included in the sample as detections, as we have done; therefore, the true distribution of \(Z_{DLA}\) is both broader and shifted toward lower metallicities (by undetermined amounts) than the histogram reproduced in Figures 6 and 7.

Bearing this in mind, the middle and bottom panels of Figure 6 show that the metallicity distribution of DLA galaxies is different from those of long-lived stars in the Galactic disk. Although there is some overlap with the thick disk histogram, the bulk of stars in the disk of the Milky Way apparently formed from gas that was significantly more metal rich than that giving rise to damped Ly\(\alpha\) systems. The narrow distributions for disk stars in Figure 6 reflect the finding by Edvardsson et al. (1993) that the average metallicity has increased very little over the lifetime of the disk; the scatter at any age in the bottom panel of Figure 5 is nearly as large as the difference in mean metallicity over the entire time span considered. This is also the case for the old open clusters of the Milky Way disk (Friel 1995).

The width of the \(Z_{DLA}\) distribution is comparable to those of halo stars and globular clusters, but it peaks at a higher metallicity. This is probably a real effect, rather than being due to the inclusion of upper limits in our sample (as discussed above), since the column density–weighted mean metallicity is \(\langle Zn/H_{DLA} \rangle = -1.13\). We consider it unlikely that the offset between the observed and true peaks of the \(Z_{DLA}\) distribution is as large as required to bring the histograms in the top panel of Figure 6 and in Figure 7 into agreement. Rather, we favor the interpretation that, as a whole, the population of DLA galaxies is genuinely more metal enriched than the stellar components of the Galactic halo.

The comparisons discussed above lead to two possible conclusions concerning the nature of damped Ly\(\alpha\) galaxies. The most straightforward interpretation is that a wide range of galaxy morphological types, at different stages of chemical evolution, make up the DLA population. Available imaging data at \(z \lesssim 1\) are certainly consistent with this view. A more intriguing possibility is that DLA systems at high redshift arise primarily in the spheroidal component of
the present-day galaxy population, analogous to the interpretation of the $U$ drop-out galaxies put forward by Steidel et al. (1995b, 1996). In the Milky Way, the halo and inner bulge may well be related, with the halo having lost $\approx 90\%$ of its mass to the bulge (e.g., Wyse, Gilmore, & Franx 1997); in this picture, the halo-bulge system is an evolutionary sequence parallel to that of the thick disk–thin disk. One could speculate, then, that the distribution of $Z_{\text{DLA}}$, with its peak at a higher metallicity than halo stars and globular clusters, reflects different stages in the transition from metal-poor halo to a predominantly metal-rich bulge (Ibata & Gilmore 1995).

4.2.1. Divergent Clues from the Absorption-Line Profiles?

The message conveyed by Figure 6 contrasts with the interpretation by A. M. Wolfe and collaborators of the complex absorption-line profiles, often extending over more than $100 \text{ km s}^{-1}$, revealed by high-resolution spectroscopy of DLAs (Wolfe 1995; Prochaska & Wolfe 1997b). These authors have argued that in many cases, the different components that make up the absorption lines are not distributed at random in velocity; rather, there appears to be a more regular trend of decreasing optical depth with increasing velocity difference from the wavelength where the absorption is strongest. This “edge-leading asymmetry” is the pattern that would be produced by a rotating thick disk, intersected at some distance from the center, if the average density of gas falls off with distance from the center and from midplane. Prochaska & Wolfe show that the frequency with which such absorption profiles are encountered is consistent with expectations for randomly oriented disks; this leads them to conclude that most, if not all, DLAs arise in large ($R > 10 \text{ kpc}$) disks with high rotation velocities ($v_{\text{rot}} \gtrsim 200 \text{ km s}^{-1}$). Such structures, if common at $z \gtrsim 2$, are very difficult to explain in currently favored models of galaxy formation (e.g., Baugh et al. 1997).

The Milky Way is the only galaxy for which we have a record of both chemical abundances and kinematics over its past history. Based on this body of data, the metallicities we measure in the damped Ly$\alpha$ systems appear incompatible with the rotating disk interpretation put forward by Prochaska & Wolfe. This can be appreciated by considering compilations of metallicities and velocities now available for large samples of stars, such as that published recently by Carney et al. (1996). From their Figures 1 and 3, it can be seen that, of the stars with metal abundances similar to those of DLAs, approximately half have retrograde motions; at a metallicity $Z = -1.1$, the mean velocity relative to the disk rotation is $\langle V \rangle \approx -150 \text{ km s}^{-1}$. This point is best illustrated by Figure 5 of Carney et al., which shows the metallicity histograms in various intervals of $V$; our distribution of $Z_{\text{DLA}}$ corresponds to values of $V$ in the range $\approx -100 \text{ km s}^{-1}$ to $\approx -200 \text{ km s}^{-1}$. Evidently, when our Galaxy had an average metallicity of $\lesssim 1/10$ of solar, it did not exhibit the kinematics of a disk rotating at $\approx 200 \text{ km s}^{-1}$.

Reconciling these contrasting clues to the nature of damped Ly$\alpha$ galaxies is an important task for the future. Here we put forward three possible ways out of the current impasse:

1. Our Galaxy is atypical, and the physical processes that gave rise to its stellar populations were not shared by most other galaxies at high redshifts. Although this possibility cannot be discounted, it is not a very constructive hypothesis to take refuge in, since it will be difficult to test it observationally—at least in the near future.

2. The absorption profiles are being overinterpreted. A possible concern here is that material whose motion is due not to rotation but to energetic events, such as supernova
shocks, may contribute to the ultraviolet absorption lines, since these transitions are sensitive to even relatively small column densities of gas. The “edge-leading asymmetry” interpretation was first proposed by Lanzetta & Bowen (1992) in their analysis of 13 Mg II absorption components spread over 250 km s\(^{-1}\) in the \(z_{\text{abs}} = 0.39498\) DLA in Q1229 — 021. However, it is far from clear that this is really a massive disk; from their analysis of HST images of the field, Le Brun et al. (1997) propose that the absorber is instead a faint \((L_\text{B} < 0.1L_\odot)\) low surface brightness galaxy. Furthermore, strong Mg II absorption spanning \(\approx 300\) km s\(^{-1}\) also can be produced by galaxies that are nearly face-on, such as M61 (Bowen, Blades, & Pettini 1996). All these factors cast some doubts on a detailed correspondence between the profiles of ultraviolet absorption lines and the large-scale kinematics of the intervening galaxies.

3. A third option, and one that we have proposed already, is that DLA galaxies comprise a mix of different morphological types. Thus, it is conceivable that some do exhibit the kinematics of rapidly rotating disks, while others may be spheroids or irregular star-forming galaxies with less-ordered velocity fields. This is a hypothesis that can be tested. As more cases become available where both kinematics and chemical abundances are measured in the same DLA, it will be of great interest to examine whether there is any correlation between these two parameters, as found in the stellar populations of the Milky Way.

5. SUMMARY AND SUGGESTIONS FOR FUTURE WORK

We have assembled the largest sample of damped Ly\(\alpha\) systems for which metallicities have been measured free from the complications introduced by dust depletions. The expanded data set reinforces the two main conclusions reached in our earlier study (Pettini et al. 1994): (1) DLAs are generally metal poor, at all redshifts sampled, and (2) there is a large spread in abundances at all epochs. We interpret these findings as evidence for a protracted epoch of galaxy formation, and propose that galaxies of different morphological types and at different stages of chemical evolution make up the DLA population.

The metallicity distribution of DLAs is broader and peaks at lower metallicities than those of either the thin or thick disk of our Galaxy. Thus, the chemical abundance data presented here do not support the interpretation of the absorption-line profiles in terms of thick disks with rotation velocities \(v_{\text{rot}} \gtrsim 200\) km s\(^{-1}\) most recently discussed by Prochaska & Wolfe (1997b). This apparent discrepancy may be resolved by additional work on both the kinematics and the abundances. With the near-infrared spectrographs now being built for 8–10 m telescopes, it will be possible to detect the familiar optical emission lines from star-forming regions in the absorbing galaxies. The widths of these features are likely to be more representative of the global kinematics than the ultraviolet absorption lines that can be so easily affected by local phenomena such as interstellar shocks. On the abundance front, the ratios of chemical elements manufactured in different nucleosynthetic processes have been used to good effect in unraveling the history of star formation in our Galaxy; the same techniques are now beginning to be applied to high-redshift DLAs (Pettini, Lipman, & Hunstead 1995b; Lu et al. 1996).

The column density–weighted mean metallicity of DLAs at \(z \gtrsim 2\) is in agreement with expectations based on the metal ejection rate deduced by Madau (1996) from the integrated ultraviolet luminosity of star-forming galaxies at these redshifts. Our data, when combined with the [Fe/H] measurements by Lu et al. (1996), appear to reflect the rapid increase in the comoving star formation rate between \(z \approx 4\) and \(\approx 2\) indicated by the relative numbers of B and U drop-outs in the Hubble Deep Field. While these comparisons are of necessity still very approximate, the implication seems to be that observations of DLAs provide a reasonably accurate census of metal enrichment at these epochs. It is encouraging that the three independent methods applied to the quest for the epoch of galaxy formation—the global star formation rate deduced from the ultraviolet luminosity of high-redshift galaxies, the rate of consumption of neutral gas implied by the redshift evolution of \(\Omega_{\text{DLA}}\), and the metallicity of DLAs—apparently give a broadly consistent picture of the universe at \(z \gtrsim 2\).

This is not the case at \(z \lesssim 1.5\), where \(Z_{\text{DLA}}\) apparently does not rise as expected from simple models of cosmic chemical evolution. There are a number of plausible explanations for this, including the effects of dust, as discussed extensively by S. M. Fall and collaborators, and an increasing contribution of low surface brightness galaxies to the cross section for DLA absorption. The major obstacle to progress in this area is still the paucity of DLAs with measured element abundances at intermediate redshifts. And yet it is essential to follow the evolution of the DLA population to the present time in order to be confident in our interpretation of the high-redshift data. New DLAs at \(z \lesssim 1\) are still being identified, and the sample is slowly growing. With STIS on the HST, measurements of [Zn/H] can be extended to redshifts lower than the limit \(z_{\text{abs}} \approx 0.65\) of ground-based observations. In the next few years, the 2dF and Sloan sky surveys (Taylor 1995; Gunn & Weinberg 1995) are expected to increase the number of known DLAs by 1 order of magnitude. With 8–10 m telescopes, it then will be possible to repeat surveys such as this one toward substantially fainter, and potentially more reddened, QSOs. Such programs should lead to a better assessment of the significance of dust bias in current DLA samples. Finally, with large telescopes, we will soon be able to measure element abundances from the optical emission lines of galaxies at redshifts \(z \approx 0.1–0.5\). Such data will complement in a very important way the information provided by galaxies selected from their absorption cross section.

We are grateful to the UK and Australian Time Assignment committees for generous allocations of telescope time on the WHT and the AAT, and to the technical staff at both observatories for excellent support with the observations. The WHT Service Observations scheme helped bring this demanding observing program to completion. We would like to express our sincere thanks to C. Hazard and P. Hewett for supplying us with positions and finding charts of QSOs with candidate damped Ly\(\alpha\) systems; J. Lewis for assistance with the reduction of some of the spectra; J. Laird and R. Wyse for providing the stellar data used in Figures 6 and 7; C. Jenkins and K. Lipman for help with some statistical aspects of the analysis; M. Fall, G. Gilmore, P. Madau, and S. Ryan for illuminating discussions on several issues relating to stellar populations and galactic chemical evolution; and C. Steidel, J. Prochaska, and D. York for useful comments on an earlier version of the paper. R. W. H. acknowledges financial assistance from the Australian Research Council.
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