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METALLICITY EVOLUTION IN THE EARLY UNIVERSE

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ABSTRACT

Observations of the damped Lyα systems provide direct measurements on the chemical enrichment history of neutral gas in the early universe. In this Letter, we present new measurements for four damped Lyα systems at high redshift. Combining these data with [Fe/H] values culled from the literature, we investigate the metallicity evolution of the universe from $z \approx 1.5$ to 4.5. Contrary to our expectations and the predictions of essentially every chemical evolution model, the N(H I)–weighted mean [Fe/H] metallicity exhibits minimal evolution over this epoch. For the individual systems, we report tentative evidence for an evolution in the unweighted [Fe/H] mean and the scatter in [Fe/H], with the higher redshift systems showing lower scatter and lower typical [Fe/H] values. We also note that no damped Lyα system has $[\mathrm{Fe/H}] < -2.7$ dex. Finally, we discuss the potential impact of small number statistics and dust on our conclusions and consider the implications of these results on chemical evolution in the early universe.

Subject headings: galaxies: abundances — quasars: absorption lines

1. INTRODUCTION

The damped Lyα systems—neutral hydrogen gas layers identified in the absorption-line spectra of background quasars—dominate the neutral hydrogen content of the universe at all epochs. At high redshift, these systems are widely accepted as the progenitors of present-day galaxies for the following reasons: (1) their very large H I column densities [$N(\mathrm{H\ I}) > N_{\mathrm{thresh}} = 2 \times 10^{20}$ cm^{-2}] imply overdensities $\delta\rho/\rho \gg 100$, i.e., these are virialized systems at high redshift; (2) they contain the majority of neutral gas in the early universe and are therefore the reservoirs for galaxy formation; and (3) their gas density Ω_{gas} at $z \approx 2$–3 is consistent with the mass density of stars today (Wolfe et al. 1995). While the physical nature of the damped Lyα systems is still controversial (Prochaska & Wolfe 1997; Haehnelt, Steinmetz, & Rauch 1998; Maller et al. 2000; Le Brun et al. 1997), by studying the chemical abundances of the damped Lyα system one directly traces the chemical enrichment history of the universe at high redshift. Observing damped Lyα systems is equivalent to poking sight lines through the interstellar medium of protogalaxies. Because these observations are biased to H I cross section and the H I gas mass of a system is proportional to $\int \sigma N$, one can measure global properties of the universe simply by weighting the measurement from each damped system by N(H I). The observations also afford an efficient means for examining the characteristics of individual protogalaxies in the early universe. In this Letter, we examine the metallicity of the damped Lyα systems from $z \approx 1.5$ to 4.5, which places tight constraints on chemical evolution models (e.g., Pei, Fall, & Hauser 1999), as well as a valuable consistency check on star formation rate (SFR) observations (Pettini 2000).

Over the past decade, several groups have surveyed the metallicity of the damped Lyα systems from $z \approx 1$ to 4 (Pettini et al. 1994, 1997, 1999; Lu et al. 1996; Prochaska & Wolfe 1999). To date, the chemical abundances of over 40 systems have been measured, the majority with $z = 1.5$–3 where the identification and follow-up observations of damped Lyα systems are most efficient. These studies argue that at $z \approx 2$, the mean metallicity of the damped systems is approximately 1/10–1/30 solar metallicity ($[\mathrm{Zn/H}] \approx -1.1$, $[\mathrm{Fe/H}] \approx -1.5$) with a large scatter from nearly solar to less than 1/100 solar metallicity. At very high redshift ($z > 3$), the picture is far less certain. Focusing on a sample of seven $z > 3$ damped Lyα systems, Lu, Sargent, & Barlow (1997) noted that the metallicity of these systems is significantly lower than the $z < 3$ observations. In turn, they argued that $z \approx 3$ marked the epoch at which significant star formation begins, a claim with important implications for the processes of galaxy formation.

In this Letter, we present new measurements on the metallicity of four damped Lyα systems (including three at $z > 3.5$) and together with the data from Prochaska & Wolfe (1999) double the sample at $z > 3$. The new full sample—including the systems from Lu et al. (1996, 1997)—reveals evidence for little change in the N(H I)–weighted mean metallicity of the neutral universe from $z \approx 1.5$ to 4.5, contrary to the predictions of essentially every chemical evolution model. On the other hand, we find tentative evidence for an evolution in the unweighted mean and scatter of [Fe/H] for individual damped Lyα systems. Finally, we comment on the robustness of these results, speculate on the implications for chemical enrichment, and discuss the prospects for future advances.

2. OBSERVATIONS AND ANALYSIS

To determine the metallicity of a damped Lyα system, one must accurately measure the neutral hydrogen column density N(H I) and a metallicity indicator, typically either Zn or Fe. In stellar population studies of the Galaxy, one traditionally uses Fe as the metallicity indicator, primarily as a matter of convenience. Since we are studying gas-phase abundances, however, we must account for the possible depletion of Fe onto dust grains or instead choose an element like Zn which is minimally affected by depletion. Unfortunately, there are both

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TABLE 1

New Metallicity Measurements

QSO	$z_{\rm abs}$	N(H I)	N(Fe$^+$)	[Fe/H]
BRI 0952−0115	4.024	20.50 ± 0.1	14.054 ± 0.07[a]	−1.95
BRI 1108−0747	3.608	20.50 ± 0.1	13.860 ± 0.03[b]	−2.14
Q1223+1753	2.466	21.50 ± 0.1	14.812 ± 0.06[c]	−2.19
PSS 1443+2724	4.224	20.80 ± 0.1	15.325 ± 0.10[c]	−0.98

[a] Average of Fe II λ1144 (log gf = 0.105) and Fe II λ1608.

[b] Fe II λ1608.

[c] Fe II λ1611.

theoretical and observational disadvantages to using Zn as the metallicity indicator. Theoretically, Zn has a very uncertain chemical origin. It is referred to as an Fe peak element because it traces Fe in Galactic stars (Sneden, Gratton, & Crocker 1991), yet the leading theory on the production of Zn proposes that it forms in the neutrino-driven winds of Type II supernovae (Hoffman et al. 1996). Furthermore, recent measurements of [Zn/Fe] in metal-poor stars (Johnson 1999) and thick disk stars (J. X. Prochaska et al. 2000, in preparation) suggest that Zn/Fe is enhanced relative to the Sun by +0.1 to +0.3 dex, perhaps consistent with a Type II origin. Observationally there are complications with measuring Zn in the damped Lyα systems, where one must rely on two weak Zn II transitions with $\lambda_{\rm rest} \approx 2000$ Å. The transitions are so weak that even at high resolution and high signal-to-noise ratio, Zn can only be detected in damped systems when log [N(H I)] + [Zn/H] > 19.0 (e.g., [Zn/H] > −1.3 for systems with N(H I) ≈ $N_{\rm thresh}$). Most important to this study, however, the large rest wavelength of the Zn II transitions prevents one from readily measuring Zn in $z > 3$ damped Lyα systems because it is difficult to make sensitive observations at $\lambda \approx 8000$ Å with current high-resolution spectrographs. In fact, at the time of publication, *we are not aware of a single accurate* Zn *measurement for any* $z > 3$ *damped Ly*α *system.* Therefore, we will focus on Fe in this Letter, which has two singly ionized transitions at $\lambda_{\rm rest} \approx$ 1600 Å with a complement of f-values ideal for measuring the abundance of Fe in damped systems. We restrict the analysis to Fe measurements made with HIRES on the Keck I telescope (Vogt 1992), specifically the systems observed by Prochaska & Wolfe (1999) and Lu et al. (1996, 1997) and the additional systems introduced here. In addition to providing a homogeneous data set which has been analyzed with the same techniques, these observations account for nearly every damped system with an accurate Fe abundance at $z > 1.5$ and every system with $z > 3$.

Table 1 summarizes the new N(Fe$^+$) measurements derived from observations we acquired in 1998 February and 1999 March with HIRES on the Keck I 10 m telescope. The data was reduced with the MAKEE software package developed by T. Barlow, and the column densities were derived primarily from the Fe II λλ1608, 1611 transitions with the apparent optical depth method (Savage & Sembach 1991). We adopt the oscillator strengths from Cardelli & Savage (1995), noting that our conclusions on the evolution of [Fe/H] in the damped Lyα systems are not sensitive to their values. The N(H I) values for these systems are taken from the literature (Wolfe et al. 1995; Storrie-Lombardi & Wolfe 2000) and are the dominant source of error in the [Fe/H] values. Finally, we evaluate [Fe/H] assuming the meteoritic Fe abundance [ϵ(Fe) = 7.50; Grevesse & Sauval 1999] without adopting any ionization corrections, which is an excellent assumption for all but possibly the lowest N(H I) damped systems (Prochaska & Wolfe 1996). Together with the published measurements of Prochaska & Wolfe (1999) and Lu et al. (1996, 1997), the total [Fe/H] sample is 39 systems, 15 with $z > 3$. The systems were chosen independent of any prior metallicity measurements; the only possible biases are due to the magnitude-limited selection of the quasars (e.g., Fall & Pei 1993), which will be discussed in the following section.

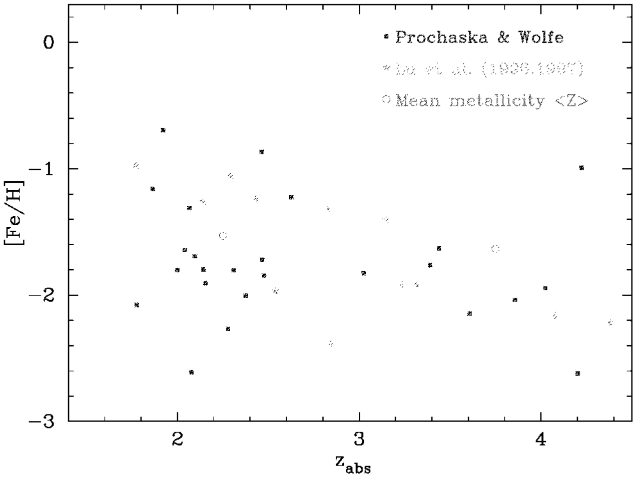

Fig. 1.—Thirty-nine [Fe/H], $z_{\rm abs}$ pairs for the damped Lyα systems observed by Prochaska & Wolfe (1999) and in this study (*squares*) and Lu et al. (1996, 1997; *stars*) with HIRES on the Keck I telescope. The open circles correspond to the N(H I)–weighted mean metallicity for the systems at $z_{\rm low}$ = [1.5, 3] and $z_{\rm high}$ = (3, 4.5]. Note that the difference in these means is small, ≈0.1 dex.

3. RESULTS AND DISCUSSION

Figure 1 plots the 39 [Fe/H] values versus $z_{\rm abs}$ for the Prochaska & Wolfe sample (*squares*) and the sample of damped Lyα systems observed by Lu et al. (1996, 1997) (*stars*). To explore evolution in the metallicity of the damped Lyα systems, we consider three moments of the metallicity data in two redshift intervals, $z_{\rm low}$ = [1.5, 3] and $z_{\rm high}$ = (3, 4.5]. These are: (1) the N(H I)–weighted mean metallicity of neutral gas, $\langle Z \rangle$; (2) the unweighted mean metallicity, $\langle$[Fe/H]$\rangle$, of the set of damped Lyα systems at $z_{\rm low}$ and $z_{\rm high}$; and (3) the standard deviation of [Fe/H] in these protogalaxies, σ([Fe/H]).

The first moment represents the global metallicity of all neutral gas at a given epoch, $\Omega_{\rm metals}/\Omega_{\rm H\,I}$. It is evaluated by weighting each [Fe/H] measurement by the corresponding H I column density, $\langle Z \rangle \equiv \log [\sum N({\rm Fe}^+)/\sum N({\rm H\,I})] - \log ({\rm Fe/H})_\odot$. Computing the mean for the damped Lyα systems at the two epochs, we find $\langle Z \rangle_{\rm low} = -1.532 \pm 0.036$ and $\langle Z \rangle_{\rm high} = -1.634 \pm 0.049$. The errors on the $\langle Z \rangle$ values reflect only the statistical uncertainty in measuring N(Fe$^+$) and N(H I) and were derived with standard error propagation techniques. Below we estimate the uncertainty due to small number statistics. Comparing the $\langle Z \rangle$ values, we note that they favor no significant evolution in the mean metallicity of neutral gas from z = 1.5 to 4.5. If we include the tentative result from Pettini et al. (1999) that the Zn mean metallicity does not change from $z \approx 1$ to 3, then one concludes there is no evidence for significant metallicity evolution from z = 1 to 4.5, an interval spanning more than 3 Gyr. The other two moments, the unweighted mean $\langle[{\rm Fe/H}]\rangle = (1/n) \sum_n [{\rm Fe/H}]$ and the scatter σ([Fe/H]), are more sensitive to the chemical enrichment history within individual protogalaxies since each damped system is given equal weight. For the two intervals, we find that the mean logarithmic abundance is $\langle[{\rm Fe/H}]\rangle_{\rm low} = -1.61$ and $\langle[{\rm Fe/H}]\rangle_{\rm high} = -1.83$. Meanwhile, the scatter in [Fe/H] is $\sigma([\mathrm{Fe/H}]) = 0.50$ and $\sigma([\mathrm{Fe/H}]) = 0.35$ for the z_{low} and z_{high} samples, respectively. Performing the Student's t-test and the F-test on the two moments, we find that the $\langle[\mathrm{Fe/H}]\rangle$ and $\sigma([\mathrm{Fe/H}])$ statistics for the two epochs are inconsistent at the 90% and 80% confidence level. Therefore, there is tentative evidence for chemical evolution in the individual damped Lyα systems with the $z < 3$ sample showing a higher typical metallicity and a larger scatter in [Fe/H] from system to system.

To address the robustness of these results, one must consider several issues. First, because $\langle Z\rangle$ is dominated by the systems with the largest $N(\mathrm{H\ I})$ values, this mean is robust only in so far as the total $N(\mathrm{H\ I})$, $\mathrm{H\ I}_T \equiv \sum_n N(\mathrm{H\ I})$, well exceeds that of a single damped Lyα system. Figure 2 plots the [Fe/H], $N(\mathrm{H\ I})$ pairs for all 39 systems; the circles are members of the z_{low} sample and the triangles those of the z_{high} sample. Note that there are four systems with $N(\mathrm{H\ I}) > 10^{21}$ cm^{-2} at $z < 3$ but only a single system in the z_{high} sample. For the z_{low} sample, $\mathrm{H\ I}_T = 10^{22.30}$ cm^{-2}, which is a factor of 4 larger than the largest $N(\mathrm{H\ I})$ measured for any damped Lyα system [Q0458−0203; $N(\mathrm{H\ I}) = 10^{21.7}$] and 10 times greater than most of the known damped Lyα systems. As such, we consider the mean derived from the z_{low} sample to be reasonably robust. The primary potential pitfall is if the optical surveys have systematically missed damped systems with $N(\mathrm{H\ I}) > 10^{22}$ cm^{-2}, a possibility if dust obscuration is significant (discussed further below). The situation is far more uncertain for the $z > 3$ sample where $\mathrm{H\ I}_T = 10^{21.84}$ cm^{-2}, comparable to the $N(\mathrm{H\ I})$ of the Q0458−0203 system from the z_{low} sample and only 3 times greater than the largest $N(\mathrm{H\ I})$ system in the z_{high} sample. While the most recent surveys suggest there are very few $z > 3$ damped systems with $N(\mathrm{H\ I}) > 10^{21}$ cm^{-2} (Storrie-Lombardi & Wolfe 2000), we caution that the mean we have derived for the z_{high} sample is a tentative result. For example, the system toward Q0000−2619 has significant bearing on $\langle Z\rangle_{\mathrm{high}}$ and its Fe abundance has been difficult to determine (Prochaska & Wolfe 1999; Lu et al. 1996). Ironically, removing it from the z_{high} sample would actually increase $\langle Z\rangle_{\mathrm{high}}$ into exact agreement with $\langle Z\rangle_{\mathrm{low}}$ because we have adopted $[\mathrm{Fe/H}] = -1.77$ based on the Fe II λ1611 profile from this system. Meanwhile, lowering [Fe/H] by 0.6 dex to establish consistency with the Ni and Cr abundances would decrease $\langle Z\rangle_{\mathrm{high}}$ by 0.1 dex. In short, while we have confidence in the $\langle Z\rangle_{\mathrm{low}}$ value, we caution the reader that small number statistics are still important in evaluating the $\langle Z\rangle_{\mathrm{high}}$. One can estimate the uncertainty associated with the small number statistics of the two samples by performing a bootstrap statistical analysis. For each sample, we independently calculated $\langle Z\rangle$ 500 times by randomly drawing n objects (n is the number of damped systems in a given redshift interval) from each interval. In turn, we can estimate the effects of cosmic variance on our results by calculating the standard deviation of the two bootstrap $\langle Z\rangle$ distributions: $\sigma^{\langle Z\rangle}_{\mathrm{low}} = 0.088$ dex and $\sigma^{\langle Z\rangle}_{\mathrm{high}} = 0.155$ dex. As one would expect, the $\langle Z\rangle_{\mathrm{high}}$ value, which is based on only 15 systems, is considerably less certain than the $\langle Z\rangle_{\mathrm{low}}$ measurement. The difference in the $\sigma^{\langle Z\rangle}$ values stresses the outstanding need for future observational programs to focus on $z > 3$ damped systems.

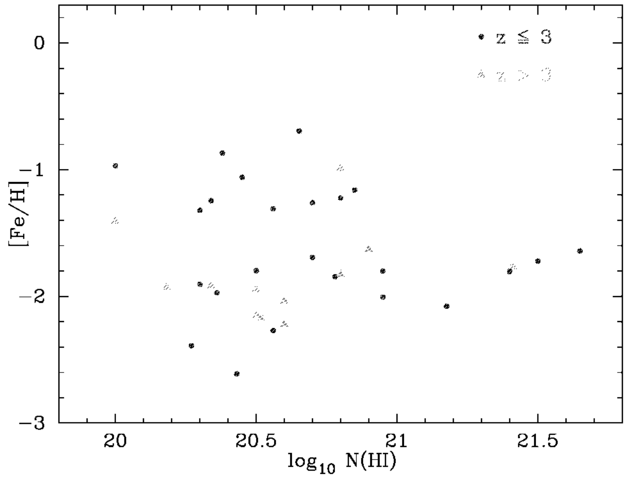

FIG. 2.—Thirty-nine [Fe/H], $N(\mathrm{H\ I})$ pairs for the damped Lyα systems in the full sample. The circles correspond to $z_{\mathrm{abs}} \leq 3$ systems, and the triangles are for $z_{\mathrm{abs}} > 3$. While the systems with $N(\mathrm{H\ I}) < 10^{21}$ cm^{-2} show a large scatter in [Fe/H], the large $N(\mathrm{H\ I})$ systems all have $[\mathrm{Fe/H}] \approx -1.8$.

Any study on the chemical abundances of the damped Lyα systems must assess the potential effects of dust. With respect to this analysis, where we have taken Fe as the metallicity indicator, there are two important aspects to consider. (1) If we need to correct the observed [Fe/H] values by some factor to obtain the true metallicity of each system, does the mean correction evolve in time and/or differ from system to system at the same epoch? (2) Dust obscuration could remove damped Lyα systems from the magnitude-limited samples, which would significantly alter the conclusions [e.g., metal-rich, high $N(\mathrm{H\ I})$ systems]. With respect to the first concern, we can estimate the maximum dust correction to [Fe/H] via the measured Zn/Fe ratio. Again, Zn is essentially undepleted in the gas phase so that $[\mathrm{Zn/H}] = [\mathrm{Fe/H}] + [\mathrm{Zn/Fe}]$ may be more representative of the true metallicity in the damped Lyα systems. This practice is limited, however, by the fact that Zn may be produced in Type II supernovae (Hoffman et al. 1996) such that supersolar Zn/Fe ratios would be representative of nucleosynthesis, not dust depletion. Furthermore, recent results on the [Zn/Fe] ratio measured in Galactic stars shows that $[\mathrm{Zn/Fe}] > +0.2$ dex in very metal poor stars ($[\mathrm{Fe/H}] < -2.5$; Johnson 1999) and even exhibits supersolar values ($[\mathrm{Zn/Fe}] \approx +0.1$ in 10 stars; J. X. Prochaska et al. 2000, in preparation) in thick disk stars with $[\mathrm{Fe/H}] > -1$. Therefore, while the typical [Zn/Fe] value in the damped Lyα systems is +0.4 dex with relatively small scatter (Pettini et al. 1997; Prochaska & Wolfe 1999), it is unclear what fraction is due to dust depletion. Nonetheless, if we take [Zn/H] as the true metallicity indicator, $\langle Z\rangle$ and the unweighted mean are enhanced by ≈0.4 dex, but there is very little change in the observed scatter. The potential effects of dust depletion on the statistical moments for the z_{high} sample are more speculative since there is *no accurate* Zn *determination* for any $z > 3$ damped Lyα system. To estimate the depletion level, we can compare the relative abundance patterns (in particular the Si/Fe ratio) of these systems with the z_{low} sample. In the few cases in which Si/Fe has been measured in the $z > 3$ systems, one finds $[\mathrm{Si/Fe}] \approx +0.3$ dex, nearly identical to the typical value of the $z < 3$ sample. While the similarity of a metal ratio like Si/Fe does not require similar dust depletion levels, the $z > 3$ [Si/Fe] values do imply depletion levels of at least 0.3 dex. Therefore, unless one takes the unlikely stance that the $z > 3$ systems are significantly more depleted than the z_{low} sample, we expect very minimal evolution in the depletion levels of the damped systems and no significant impact on any of our conclusions. The effects of biasing due to dust obscuration are more difficult to address. Note in Figure 2 the absence of any $N(\mathrm{H\ I}) > 10^{21}$ cm^{-2} systems with $[\mathrm{Fe/H}] \sim -1$. While this may be due to small number statistics or the fact that very few regions exist in the early universe with large N(H I) and [Fe/H] $\gtrsim -1$, the trend could also be explained by dust obscuration. Fall & Pei (1993) have presented an excellent framework for addressing the effects of dust depletion on damped Lyα statistics. Their calculations indicate that if the logarithmic scatter in the dust-to-gas ratio k is small (less than 1 dex), then only a small correction to the mean optical depth and in turn to $\langle Z \rangle$ is required (S. M. Fall 1999, private communication). For a constant dust-to-metals ratio—implied by the nearly constant [Zn/Fe] values—the logarithmic scatter in $k \approx \sigma$([Fe/H]), and we have shown σ([Fe/H]) ≤ 0.5 for the two samples. Therefore, we expect dust obscuration to have a minimal effect (<0.2 dex) on our results.

The results in this Letter on the evolution of the metallicity of neutral gas in the universe and individual protogalaxies present an unexpected picture. A number of groups have estimated the chemical evolution of neutral gas at high redshift (Malaney & Chaboyer 1996; Edmunds & Phillips 1997; Pei et al. 1999), and essentially every treatment predicts a substantial (>0.5 dex) increase in the mean metallicity from $z = 4$ to 2. While a 0.5 dex evolution is consistent with our results at the 3 σ level, the current observations favor a very mild evolution in $\langle Z \rangle$. If future observations lend further support for this conclusion, the theoretical models will require significant revision. Of course, these theoretical treatments depend sensitively on a number of factors that are uncertain: (1) the SFR, (2) the initial mass function, (3) the mass distribution of protogalaxies, (4) the loss of metals to the intergalactic medium, (5) the yield of various elements, etc. Therefore, there is considerable theoretical freedom to bring the models into agreement with the observed lack of evolution. Nonetheless, the Lyman break galaxies offer incontrovertible evidence that significant star formation is taking place from $z = 3$ to 4 (Steidel et al. 1998) such that the total metal content of the universe must be increasing. Unless these metals are enriching only ionized regions (an unlikely scenario), then to explain the minimal evolution in $\langle Z \rangle$ the total H I content of the universe must be increasing at nearly the same rate as the metal content. It is intriguing to note that this is qualitatively consistent with the evolution of $\Omega_{\rm gas}$ observed by Storrie-Lombardi & Wolfe (2000) for the damped Lyα systems.

The other statistical moments are sensitive to the chemical enrichment history within individual galaxies. Comparing the unweighted mean with the weighted mean, we find that $\langle$[Fe/H]$\rangle$ is less than $\langle Z \rangle$ at both epochs. While the difference is not large (≈0.1–0.2 dex), it does highlight the fact that many of the N(H I) $< 10^{21}$ cm^{-2} systems exhibit low metallicity. In particular, in the $z > 3$ sample only two of 15 damped systems show [Fe/H] > -1.5 dex. One possible explanation for the difference is systems that have just formed have preferentially low N(H I) and [Fe/H]. The trend is also suggestive of the correlation Cen & Ostriker (1999) find between overdensity and metallicity in their numerical simulations. The problem remains, however, in explaining why the highest metallicity systems of the $z_{\rm low}$ sample also have low N(H I). Lastly, recall that there is tentative support for an evolution in both the scatter and $\langle$[Fe/H]$\rangle$, with the $z_{\rm low}$ sample yielding larger values. If more recently formed systems tend to have lower metallicity, then the evolution may easily be explained by a larger mean and scatter in the age of the damped Lyα systems at $z \approx 2$. Furthermore, the systems at $z \approx 2$ may have larger masses and a greater variety of morphologies.

Finally, we stress that only two systems from the full sample have [Fe/H] < -2.5 and the large majority show [Fe/H] > -2. As first noted by Lu et al. (1997), there appears to be a threshold to the minimum metallicity of the damped Lyα systems at ≈1/100 solar metallicity. Therefore, even out to $z \approx 4.5$ there is no evidence for damped Lyα systems with primordial abundance. This places a further constraint on chemical evolution models. As we probe higher and higher redshift without detecting primordial gas, one may be forced toward one of the following conclusions: (1) star formation proceeds rapidly ($<10^7$ yr) to bring the metallicity to 1/100 solar after the formation of a damped system; (2) either the damped system or its progenitors have been undergoing star formation for a lengthy time; and/or (3) a generation of Population III stars has preenriched all of the gas.

The future prospects for improving the $z > 3$ observational sample are excellent. While fast progress with HIRES and similar instruments is limited by the faintness of $z > 4$ quasars, the new Echellette Spectrograph and Imager instrument on Keck II will be ideal for surveying the N(H I) and metal content of a large ($N > 20$) sample of very high redshift damped Lyα systems. We intend to pursue such a program over the next few years, taking full advantage of the ever increasing sample of known $z > 4$ quasars (Fan et al. 1999).

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