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Chemical Abundances in the Damped Lyα Systems

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Abstract

I introduce and review the data and analysis techniques used to measure abundances in the damped Lyα systems, quasar absorption-line systems associated with galaxies in the early Universe. The observations and issues associated with their abundance analysis are very similar to those of the Milky Way's interstellar medium. We measure gas-phase abundances and are therefore subject to the effects of differential depletion. I review the impact of dust depletion and then present a summary of current results on the age-metallicity relation derived from damped Lyα systems and new results impacting theories of nucleosynthesis in the early Universe.

1.1 Introduction

While high-resolution stellar spectroscopy provides the framework behind nearly all discussion of nucleosynthesis and chemical enrichment (see papers throughout this volume), these observational efforts are currently limited to the Milky Way and its nearest neighbors. Beyond the Local Group, it remains very difficult to precisely determine chemical abundances. Relative abundance measurements are limited to a few species (e.g., C, N, O, Ca, Mg) and a few dozen galaxies. At cosmological distances, the challenges related to galaxy spectroscopy are even more severe, and even the determination of a crude metallicity poses great difficulty (e.g., Kobulnicky & Koo 2000).

Within the Milky Way, absorption-line spectroscopy of the interstellar medium (ISM) provides abundance measurements for many elements in a range of physical environments. In terms of chemical abundance studies, this analysis is limited by two factors: (1) gas mixing occurs on short enough time scales that the majority of the ISM is chemically homogeneous (Meyer, Jura, & Cardelli 1998). Therefore, one cannot probe nucleosynthesis at a range of metallicity or age in the ISM; and (2) refractory elements like Si, Ti, Fe, and Ni are depleted from the gas phase. Their relative abundance patterns are principally reflective of differential depletion (see the review by Jenkins 2004). ISM absorption-line observations have also been carried out within the Magellanic Clouds (Welty et al. 1999, 2001). These observations reveal the metallicity of the LMC and SMC, but interpretations of the relative abundance patterns are complicated by dust depletion. Outside of the Milky Way and Magellanic Clouds, it is rarely possible to pursue ISM studies in other local galaxies. With current UV telescopes and instrumentation, there are too few bright UV sources behind nearby galaxies. The advent of the Cosmic Origins Spectrograph on the *Hubble Space Telescope* will improve the situation, but only to a modest degree.

Ironically, the laws of atomic physics, the expansion of the Universe, and the filtering of UV light by the Earth's atmosphere combine to make the early Universe the most efficient place for studying galactic elemental abundances. Quasar absorption-line spectroscopy provides a powerful, accurate means of studying nucleosynthesis and chemical enrichment in hundreds of galaxies over an epoch spanning several billion years at $z \approx 2-5$. These galaxies are called damped Lyα systems (DLAs). The name derives from the quantum mechanical damping of the Lyα profile owing to the large H I surface density that defines a DLA: N(H I) $\geq 2 \times 10^{20}\,\mathrm{cm}^{-2}$. At high redshift, the plethora of UV resonance transitions that ISM researchers study in our Galaxy are conveniently redshifted to optical wavelengths where they can be examined using high-resolution spectrographs on 10 m-class telescopes. In this fashion, we are able to study the ISM of galaxies near the edge of the Universe using data that competes with the observations taken in the Galaxy. The analysis of the DLAs has been the focus of our research since the commissioning of the Keck telescopes, and we are now joined by several groups at observatories across the globe.

In this paper, I will introduce the techniques used in the analysis of the DLAs to the broad audience attending the fourth Carnegie Symposium. By reviewing this topic at a pedagogic level, my goal is to encourage greater communication between the stellar and damped Lyα communities. These fields of research offer complementary analysis into theories of nucleosynthesis and chemical enrichment. Although the fields suffer from unique systematic uncertainties, a synthesis of their results will ultimately lead to a deeper understanding on the origin of the elements.

1.2 The Data and Standard Analysis

The data that drive current elemental abundance research in the DLAs is very similar to the spectroscopy obtained for stars in the Milky Way. The largest data sets to date have been acquired with the HIRES echelle spectrograph (Vogt et al. 1994) on the Keck I telescope and the UVES-VLT spectrograph (Dekker et al. 2000). These spectrographs do provide resolution $R \geq 60{,}000$, yet the majority of damped Lyα research is conducted with $R \approx 40{,}000$ observations. While the "clouds" of gas that comprise the velocity profiles of the galaxies presumably have thermal widths below the resolution of the spectrograph, tests for "hidden" saturation (e.g., Prochaska & Wolfe 1996) have demonstrated that line saturation is not an important issue. Even the lower-resolution DLA studies by Pettini et al. (1994, 1997) on 4 m-class telescopes gave rather accurate column density measurements for the weak, unsaturated Zn II and Cr II profiles.

Figure 1.1 presents a sample of data showing several metal-line transitions for a typical damped Lyα system. The dashed vertical lines identify four transitions related to the $z = 1.776$ DLA, and we also identify a C IV doublet and Fe II multiplet related to two other absorption systems along the sightline. The line density described by this figure is typical of quasar spectra redward of the Lyα forest, i.e. $\lambda > (1 + z_{\mathrm{QSO}}) \times 1215.67$ Å. Clearly, line blending is a rare phenomenon and spectral synthesis is generally unrequired. This is contrasted, of course, by analysis within the Lyα forest where contamination by coincident Lyα clouds is common. Another point to emphasize is that the majority of absorption systems along a quasar sightline tend to show absorption from C IV, Si IV, and Mg II doublets. These

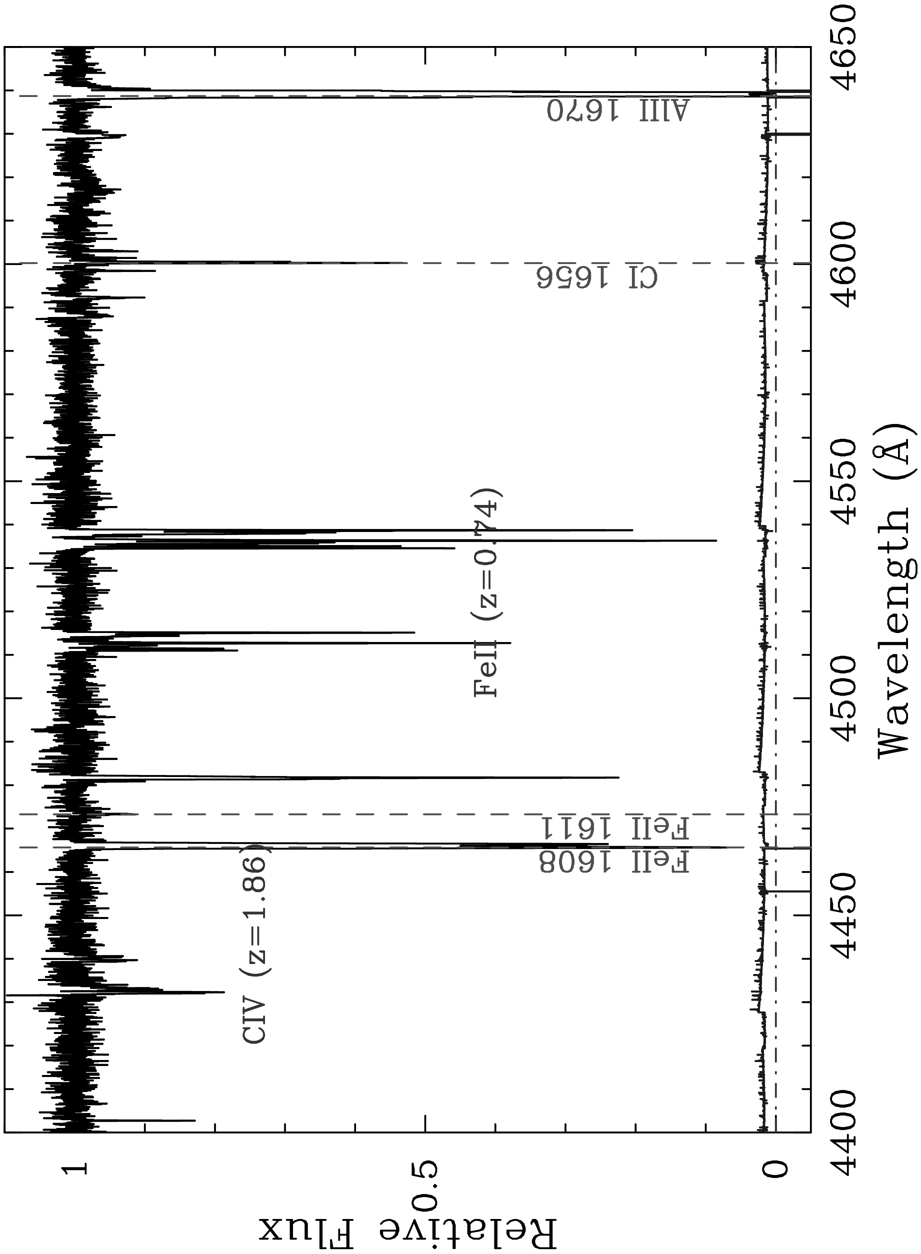

Fig. 1.1. A sample HIRES spectrum for the quasar Q1331+17, which exhibits a $z = 1.776$ DLA whose transitions are marked by vertical dashed lines. The S/N of these data is somewhat higher than most observations, while the resolution is typical (FWHM $\approx$ 7 km s^{-1}). In addition to the DLA transitions, there are several absorption lines arising from "metal-line systems" at $z = 0.74$ and $z = 1.86$.

are trivially identified, and therefore line misidentifications are very unlikely in the analysis of the damped Lyα systems.

For many transitions, one approaches 1% statistical error in the column density measurements with a signal-to-noise ratio (S/N) per pixel of only 30. Therefore, few (if any) of the damped Lyα systems have been observed at S/N > 100 per pixel or even the S/N of the data in Figure 1.1. Column densities are generally determined from either the summation of the observed optical depth (Savage & Sembach 1991) or through detailed Voigt-profile fitting. Oscillator strengths for the dominant transitions are almost exclusively from laboratory measurements and have typical errors of $< 20\%$. There are several important exceptions, however, notably the Fe II $\lambda 1611$ transition (one of the key Fe II transitions for metal-rich DLAs) whose best value is based on a theoretical calculation. Regarding the relative oscillator strengths, most of these transitions have been extensively analyzed in the Galactic ISM, and inaccuracies in the oscillator strengths have been corrected in the literature (e.g., Zsargó & Federman 1998; Howk et al. 2000).

Perhaps the most startling aspect of damped Lyα research for stellar spectroscopists is that the path from ionic column density measurements to elemental abundances is trivial. One often observes only one ion per element, the dominant species in a neutral hydrogen gas, and assumes no ionization corrections to compute gas-phase elemental abundances. The neglect of ionization corrections was unavoidable in the past (the first sets of observations provided few, if any, diagnostics) and was supported by theoretical expectations (Viegas 1994; Prochaska & Wolfe 1996) as well as observations of H I clouds in the Milky Way ISM with column densities comparable to the DLAs (see Jenkins 2004). Figure 1.2 shows a simple radiative transfer calculation for an ionizing flux incident on a plane-parallel, constant-density slab of hydrogen gas (Prochaska & Wolfe 1996). For an assumed number density of $n = 0.1\,\mathrm{cm}^{-3}$, we find that a damped Lyα system with $N(\mathrm{H\ I}) > 10^{20.3}\,\mathrm{cm}^{-2}$ would be $< 10\%$ ionized. More accurate and realistic calculations have come to similar conclusions (Vladilo et al. 2001), yet empirical confirmation remains an outstanding problem. Prochaska et al. (2002a) presented one of the few cases (the DLA at $z = 2.625$ toward Q1759+75) where transitions from multiple ionization states were unambiguously detected and argued that this DLA with $N(\mathrm{H\ I}) = 10^{20.65}\,\mathrm{cm}^{-2}$ requires significant ionization corrections, contrary to the theoretical expectation. These authors also argued, however, that the conditions in the DLA toward Q1759+59 are probably unusual. Indeed, this expectation is supported by more recent studies (e.g., Prochaska et al. 2002b).

Without ionization corrections, the gas-phase abundances are trivially computed from the ionic column densities (e.g., Fe/H = $N(\mathrm{Fe}^+)/N(\mathrm{H}^0)$), and the precision of the elemental abundances match those of the column densities. Owing to systematic errors related to continuum fitting near the Lyα profile, the principal source of error tends to lie in $N(\mathrm{H}^0)$, which generally limits the precision to ~ 0.1 dex. For relative abundance measurements the precision is often better than 0.05 dex at the 1σ level, surpassing all but the most accurate relative abundance measurements derived from stellar analyses. As we shall see in the next section, however, the precision achieved for these gas-phase abundances can be severely compromised by the effects of dust.

1.3 Dust

Since the pioneering studies by Strömgen (1948) and Spitzer (1954) on Ca^+ and Na^0 ions in the Milky Way ISM, astronomers have appreciated that refractory elements are

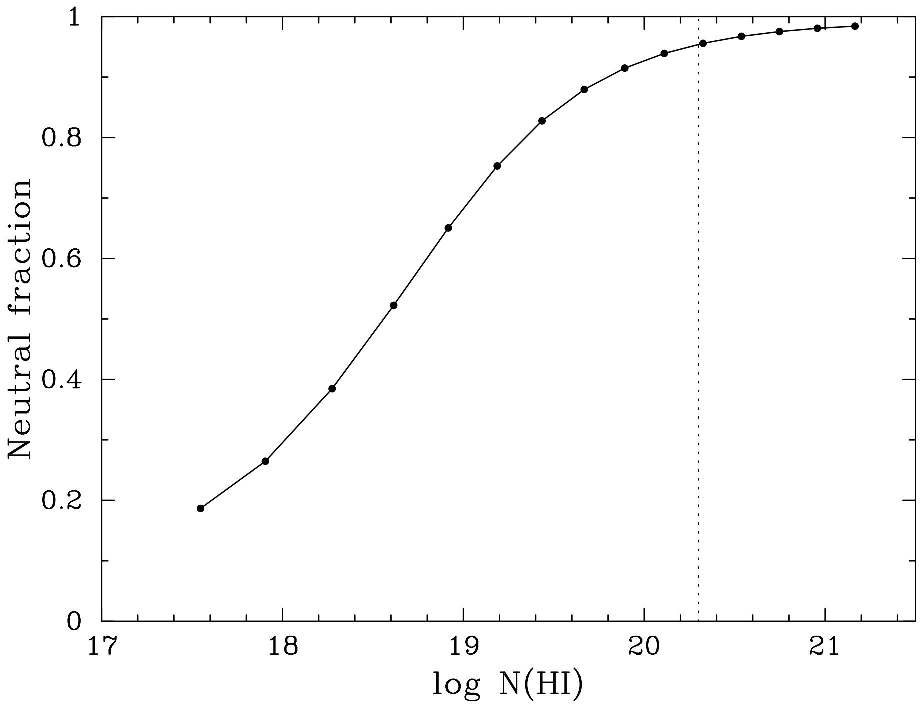

Fig. 1.2. Predicted neutral fractions for a plane-parallel slab of hydrogen gas with a range of H I surface densities N(H I). In this calculation, we assumed a hydrogen volume density $n_{\rm H} = 0.1\,{\rm cm}^{-3}$ and a standard extragalactic background radiation field. The results are based on a standard radiative transfer calculation (see Prochaska & Wolfe 1996 for more details).

depleted from the gas phase. These optical surveys gave the first convincing demonstration of depletion, and later UV spectroscopy revealed a more complete picture of dust. Similar observations of gas within the SMC and LMC have provided insight into depletion in other galactic systems and have suggested depletion is universal with a generic pattern (see the Jenkins 2004 review).

Presently, the majority of the uncertainty, confusion, frustration, and pain associated with studying chemical abundances in the damped Lyα systems stems from dust (see the reviews by Draine 2004 and Jenkins 2004 for a complete discussion of dust). Dust plays two roles in the observations, one direct and one indirect. The direct effect is that refractory elements in the DLA (e.g., Fe, Ni, Cr) are depleted from the gas phase into and onto dust grains. One expects the processes are similar to those observed for the ISM of the Milky Way, although it is difficult to confirm this at high redshift. It is clear, however, that depletion levels in the DLA are significantly lower than typical sightlines through the Milky Way, instead often resembling warm gas in our Galactic halo or the gas in the LMC and SMC.

Dust would not pose such a difficult problem in a discussion of the DLA abundances if not for two points: (1) spectra of the "typical" DLA generally allow abundance measurements for only a few elements, primarily Si, Fe, Ni, Cr, and Zn; (2) there is an unfortunate degeneracy between the differential depletion patterns of these few elements (Zn exempted) and the nucleosynthetic pattern expected for Type II supernovae (e.g., Woosley & Weaver 1995). To wit, differential depletion implies enhancements of Si/Fe and roughly solar Fe, Cr, and Ni abundances, as does Type II supernova nucleosynthesis*. It is for this reason, above all others, that the non-refractory element Zn, an element with a speculative nucleosynthetic origin *at best*, has received such great prominence in DLA abundance research. Empirically, Zn roughly traces Fe in stars with metallicity [Fe/H] > -3 (see the review by Nissen 2004), and Zn is very nearly non-refractory. Therefore, the majority of the DLA community has adopted Zn as a proxy for Fe and have imposed dust corrections on the gas-phase abundances under the assumption that Zn/Fe should be solar in the DLAs (e.g., Vladilo 1998). These are sensible approaches, but the uncertainty in the nucleosynthetic origin of Zn gives me pause (as do issues relating to ionization corrections; see Jenkins 2004). If the Zn/Fe ratio is intrinsically $\sim +0.2$ dex in the DLA, one may draw very different conclusions on the α/Fe ratios and ultimately the roles of various supernovae in the enrichment of these galaxies.

The other major issue related to dust in the DLAs is obscuration. The vast majority of DLAs have been identified toward bright quasars identified in optical or UV surveys. If the sightline to a given quasar penetrates a gas "cloud" with a large column of dust, it is possible the quasar will be removed from these magnitude-limited surveys. This was the concern of Ostriker & Heisler (1984), and Fall & Pei (1993) have developed a formalism to account for this selection bias. A full discussion of the likelihood that dust obscuration is influencing studies of damped Lyα abundances is somewhat beyond the scope of this paper. We will return to the topic in the next section, but we also refer the interested reader to the papers by Boissé et al. (1998), Ellison et al. (2001), and Prochaska & Wolfe (2002). My hope and current expectation is that the effects of dust obscuration are small at high redshift where the gas metallicities are lower and the observed sightlines show relatively low depletion levels and low molecular gas fractions (Ledoux, Petitjean, & Srianand 2004).

1.4 Chemical Evolution

The zeroth-order measure of a damped Lyα system (aside from its redshift) is the H I column density. By surveying the Lyα profile toward quasars at a range of redshifts, observers have traced the H I mass density of the Universe at a range of epochs (Wolfe et al. 1986; Lanzetta, Wolfe, & Turnshek 1995; Wolfe et al. 1995; Storrie-Lombardi & Wolfe 2000). The measurements for the damped systems provide a cosmic H I mass density because these galaxies dominate the neutral hydrogen gas density to at least $z = 4$ (see also Péroux et al. 2004).

The first-order measure of a DLA is its metallicity. This is determined from the gas-phase measurements of Fe^+, Si^+, Zn^+, Cr^+, and other ions. Because of dust depletion, one expects that the refractory elements (e.g., Fe, Ni, Cr) provide systematically lower metallicity values. When possible, therefore, observers have focused on non-refractory or mildly refractory elements, especially Zn. Indeed, this dictated the strategy of the first surveys by Pettini et al. (1994, 1997). These surveys provided the first ~ 20 DLA metallicities, which showed the mean metallicity of the DLA (i.e. the neutral gas of the Universe) is $\sim 1/10$ solar at $z = 2$.

In the 10 years since Pettini and collaborators initiated this field, the study of DLA abundances has evolved substantially, primarily owing to the birth of 10 m-class telescopes. Sur-

* I suspect that this degeneracy between seemingly very different processes may not be a simple coincidence but may be the result of condensation temperatures correlating with even-numbered nuclei.

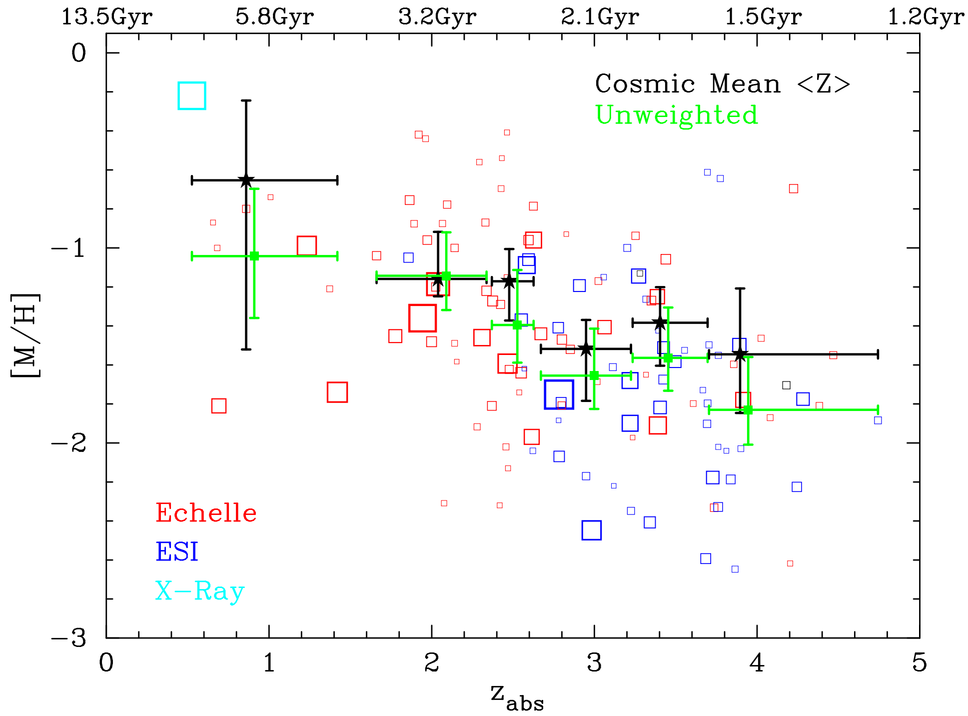

Fig. 1.3. Summary of the metallicity measurements vs. redshift for the 121 DLAs comprising the full, current sample. The area of the data points (squares) scales with the N(H I) values of the DLAs. The dark binned values with stars correspond to the cosmic mean metallicity $\langle Z \rangle$, which is the metallicity of the Universe in neutral gas.

veys with HIRES on the Keck Telescope (Lu et al. 1996; Prochaska & Wolfe 1999, 2000) have pushed the metallicity measurements to $z = 4$ and beyond and allowed the first examination of evolution in the mean metallicity. To extend the metallicity measurements above $z = 3$, these authors had to consider elements other than Zn because (1) it is difficult to measure its weak transitions along low-N(H I), low-metallicity sightlines and (2) the Zn II transitions are redshifted to observed wavelength $\lambda > 9000$ Å. The Prochaska & Wolfe (2000) survey was comprised of ~ 50 Fe measurements ranging from $z = 2$ to 4 and showed no statistically significant evolution in the mean metallicity. The advent of UVES on the VLT has led to an additional set of measurements (e.g., Molaro et al. 2000; Dessauges-Zavadsky et al. 2001), and the largest recent impact comes from new surveys using the Echellette Spectrograph and Imager (ESI) on the Keck II Telescope (Prochaska et al. 2003a, c). Owing to the high throughput of this moderate resolution spectrograph ($R \approx 10{,}000$) and an improved observing strategy, we have roughly doubled the sample of $z > 2$ metallicity measurements in $\sim 1/10$ the observing time. For the foreseeable future, instruments like ESI are going to lead this area of damped Lyα research.

Figure 1.3 presents a summary of the current set of damped Lyα metallicities, [M/H], as a function of redshift. A detailed discussion of these results is given in Prochaska et al. (2003b). In brief, both the unweighted and H I-weighted mean metallicities show evolution

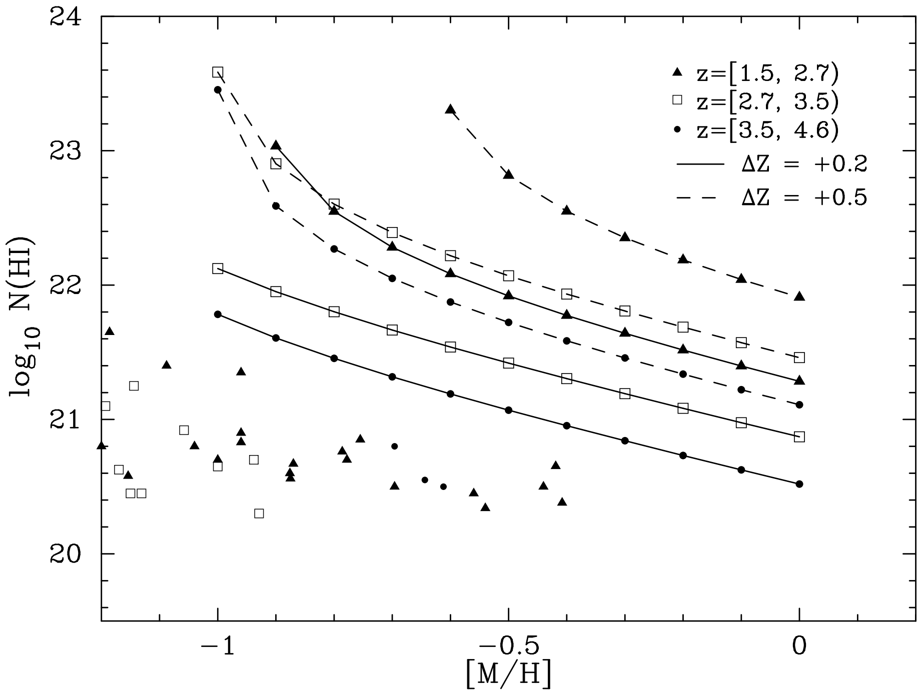

Fig. 1.4. This figure describes the robustness of the $\langle Z \rangle$ values presented in Fig. 1.3 to the presence of an outlier. We characterize the outlier by a range of H I column densities and [M/H] values. The curves are contours of constant ΔZ, the change in $\langle Z \rangle$ from including an outlier as a function of N(H I) and [M/H]. The point styles refer to three redshift intervals. The "free" points in the figure are observed DLA galaxies.

with redshift at 3σ significance with a slope $m \approx -0.25$ dex/Δz. The H I-weighted mean, often denoted $\langle Z \rangle$, is a true cosmic quantity; it represents the mean metallicity of the Universe in neutral gas. Its determination allows direct comparisons with chemical enrichment and galaxy formation models in the early Universe (Pei, Fall, & Hauser 1999; Mathlin et al. 2000; Somerville, Primack, & Faber 2001). At present, there is a significant disagreement between the metallicities implied by the DLAs and the metal production inferred from a derivation of their star formation rates via observations of the C II* λ1335 transition. (Wolfe, Gawiser, & Prochaska 2003). This "missing metals" problem raises an important challenge for future observations and theoretical efforts related to the production of metals in the early Universe.

Prochaska et al. (2003b) noted that the set of 121 damped systems is the first sample with sufficient size to present a determination of $\langle Z \rangle$ robust to "reasonable" outliers. This point is emphasized in Figure 1.4, where we plot contours of ΔZ, the change in $\langle Z \rangle$, as a function of log$N$(H I) and [M/H] values for an assumed outlier. The point types correspond to various redshift bins and the line style indicates the magnitude change in $\langle Z \rangle$. Pairs of log$N$(H I), [M/H] values for the observed DLA are also shown in the figure as isolated points with point type according to their redshift. Consider the interval $1.5 < z < 2.7$. To impart

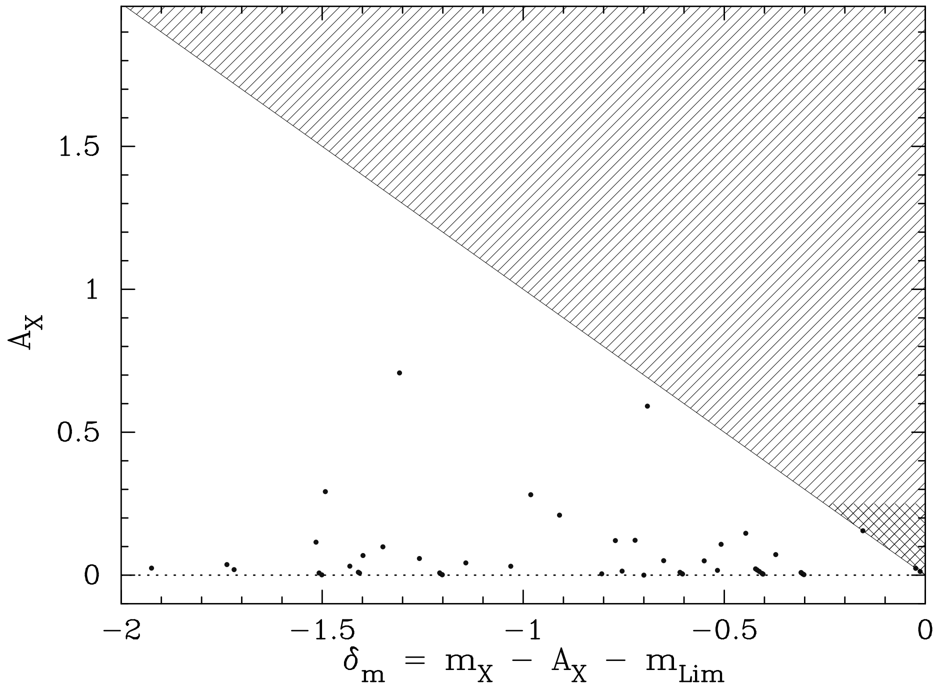

Fig. 1.5. Extinction corrections $A(X)$ derived from observed dust column densities against δ_m, the difference between the corrected brightness of the background quasar relative to the limiting magnitude of the damped Lyα survey (see Fig. 23 of Prochaska & Wolfe 2002). The shaded region denotes the area of parameter space that obscured quasars would occupy. The cross-hatched region designates the area of parameter space that we contend is populated by obscured quasars with foreground damped Lyα systems as inferred by the observed distribution of $A(X), \delta_m$ values.

a 0.2 dex change in $\langle Z \rangle$, one requires an outlier with 1/3 solar metallicity to have N(H I) $\approx 10^{22}\,\mathrm{cm}^{-2}$. An outlier with these characteristics would lie one magnitude off the observed distribution of N(H I), [M/H] values. Even in the highest-redshift interval, which has the smallest sample size, it would take an outlier with a product of N(H I) and metallicity that is 3 times larger than any current observation. By definition, of course, an outlier lies off the main distribution of observed values. At present, however, to impose a large increase in $\langle Z \rangle$, one would have to introduce an outlier that lies far beyond the distribution of observed values. If such an outlier is identified, it would strongly suggest the existence of a currently unidentified population of DLAs with log$N$(H I) + [M/H] > 20.6.

Indeed, Boissé et al. (1998) were the first to emphasize that the observed DLAs exhibit an upper limit to the sum log$N$(H I) + [M/H]. They interpreted this upper limit in terms of dust obscuration; DLAs with a large product of N(H I) and metallicity may have larger dust optical depths and therefore may significantly obscure background quasars at UV wavelengths. We have argued that no evidence exists for significant obscuration at $z > 2$, as Ellison et al. (2001) and Prochaska & Wolfe (2002) discuss. The former authors have conducted a

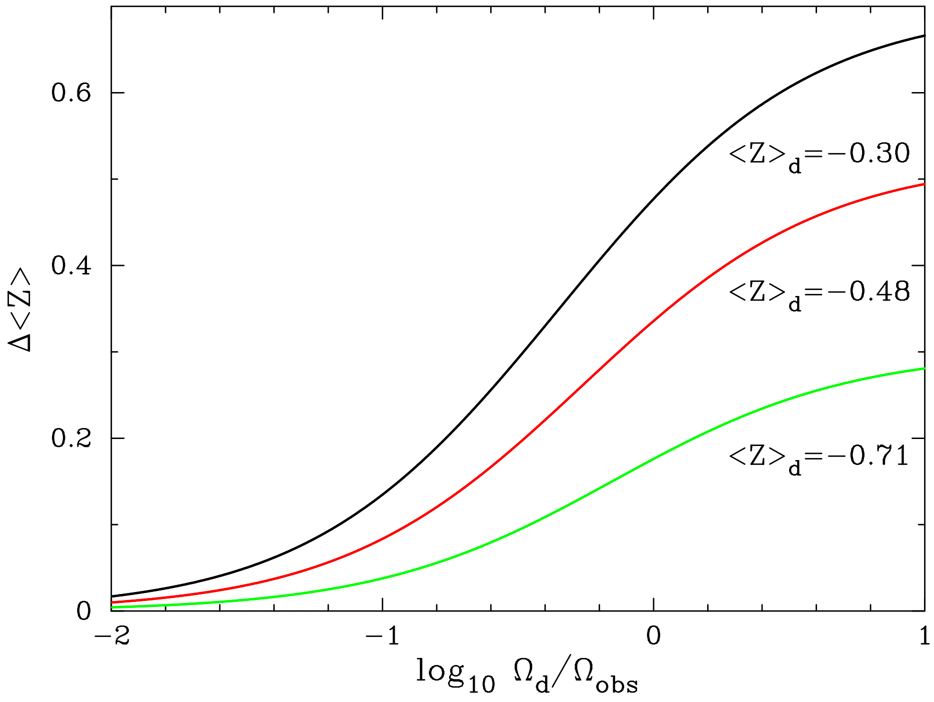

Fig. 1.6. Correction (ΔZ) to a $\langle Z \rangle$ value of 1/10 solar for an obscured gas component with mass density $\Omega_{\rm d}$ and average metallicity $\langle Z \rangle_{\rm d}$. The figure shows that if the observed gas mass density equals the observe quantity ($\Omega_{\rm d}/\Omega_{\rm obs} = 1$) and the observed gas has metallicity $\langle Z \rangle = 1/3$ solar, it would imply a factor of 2 correction to the observed mean metallicity.

survey of DLAs toward radio-selected quasars and found no significant difference in the H I content of these DLAs, contrary to the expectation for dust obscuration. The latter authors have argued that the observed distribution of inferred extinction values and apparent magnitudes indicate depletion plays a minor effect in the DLA analysis. In Figure 1.5, we present a figure similar to Figure 23 of Prochaska & Wolfe (2002), which includes the majority of the DLAs from our ESI survey. We refer the reader to the discussion in Prochaska & Wolfe (2002) for further details.

Independent of the above arguments, it is possible to assess the effects that dust obscuration will have on the measurements of $\langle Z \rangle$ for an assumed mass and metallicity of the obscured gas. Let $\langle Z \rangle_{\rm tru} = \langle Z \rangle + \Delta Z$ and $\Omega_{\rm tru} = \Omega_{\rm obs} + \Omega_{\rm d}$, where $\Omega_{\rm obs}$ is the observed neutral gas density and $\Omega_{\rm d}$ is the gas density that is obscured. Finally, assume that the obscured gas has mean metallicity $\langle Z \rangle_{\rm d}$. Figure 1.6 shows the correction ΔZ to an observed mean metallicity of $\langle Z \rangle = -1$ dex for a range of $\Omega_{\rm d}/\Omega_{\rm obs}$ values and three assumed $\langle Z \rangle_{\rm d}$ values. We emphasize that the results in Figure 1.6 hold independently of the number of DLAs observed in the determination of $\langle Z \rangle$. The CORALS survey (Ellison et al. 2001) has argued that $\Omega_{\rm tru} \approx \Omega_{\rm obs}$, implying that $\Omega_{\rm d}/\Omega_{\rm obs}$ is small. If $\Omega_{\rm d}/\Omega_{\rm obs}$ is as large as 1, then one must worry about a significant correction to $\langle Z \rangle$ for $\langle Z \rangle_{\rm d}$ values greater than 1/3 solar. If future surveys similar to CORALS demonstrate that Ω_d/Ω_{obs} is 1/10 or smaller, then it is unlikely dust obscuration will ever play a major role in the determination of $\langle Z \rangle$.

1.5 Nucleosynthesis

While echelle observations on 10 m-class telescopes have led to a greater number of DLA metallicity measurements at a greater range of redshifts, the most significant advances from large telescopes have come through studies of the relative chemical abundances. These observations reveal the processes of nucleosynthesis during the first few billion years of the Universe and ultimately provide insight into the nature of the DLA galaxies and scenarios of galaxy formation (see Calura et al. 2004).

As discussed above, typical DLA observations have yielded relative abundance measurements for Si, Fe, Cr, Ni, and Zn with accuracies better than 10%. The principal difficulty in applying these observations to studies of nucleosynthesis is the effects of differential depletion. Specifically, the standard ISM depletion patterns (Savage & Sembach 1996) are very similar to the patterns expected for the yields from Type II supernovae (e.g., Woosely & Weaver 1995). This degeneracy led to arguments over the appropriate interpretation of Si/Fe enhancements and other ratios resulting from the first DLA surveys (Lu et al. 1996; Vladilo 1998; Pettini et al. 1999; Prochaska & Wolfe 1999). These arguments are still being discussed and may never be unambiguously resolved. Therefore, the community has turned its attention toward obtaining observations of elements that are not heavily depleted (e.g., N, O, Si, S, Zn, P) or whose differential depletion pattern runs contrary to expectations from nucleosynthesis (e.g., Mn/Fe, Ti/Fe; Dessauges-Zavadsky, Prochaska, & D'Odorico 2002).

One example of a nucleosynthetic diagnostic that is nearly free of depletion effects is the N/α ratio (where α in the DLA is generally given by Si and S). This abundance ratio is an excellent diagnostic of the time scales of star formation owing to the belief that N production is dominated by intermediate-mass stars (see Henry 2004). For this reason, among others, observations of N/α have played an important role in several contributions to this Symposium (see papers by, e.g., Garnett 2004 and Molaro et al. 2004). Regarding the DLAs over the past two years, observers have built a sample of ~ 30 measurements with metallicities ranging from [α/H] = −2 to nearly solar (Pettini et al. 2002; Prochaska et al. 2002b; Centurión et al. 2003). In general, these measurements track the N/α values observed in H II regions and stars in the local Universe. With our sample (Prochaska et al. 2002b), however, we speculated that the DLAs at low metallicity show a bimodal distribution of N/α values. In particular, we found that a small but significant fraction of these DLAs have very low N/α values, much lower than any value observed locally. If confirmed by future surveys, this bimodality may require revised yields of N in massive stars (e.g., Molaro et al. 2004), an initial (Population III?) epoch of star formation characterized by a top-heavy or truncated initial mass function (Prochaska et al. 2002b), or some other unappreciated physical mechanism. We defer additional discussion of this topic to the paper by Molaro et al. (2004).

At this Symposium, we reported the discovery of a DLA whose large N(H I) and [M/H] values will allow the detection and analysis of over 20 elements in a single galaxy (Prochaska, Howk, & Wolfe 2003). Figure 1.7 shows the abundance pattern of this galaxy and a comparison with the solar abundance pattern scaled to the galaxy's oxygen abundance ([O/H] $\approx$ 1/3 solar). Aside from the analysis of stars in the Milky Way and its nearest neighbors (see, e.g., Hill 2004; Shetrone 2004; Venn et al. 2004), galaxies like this DLA will enable the most comprehensive nucleosynthetic analysis at any epoch in the Universe. The results

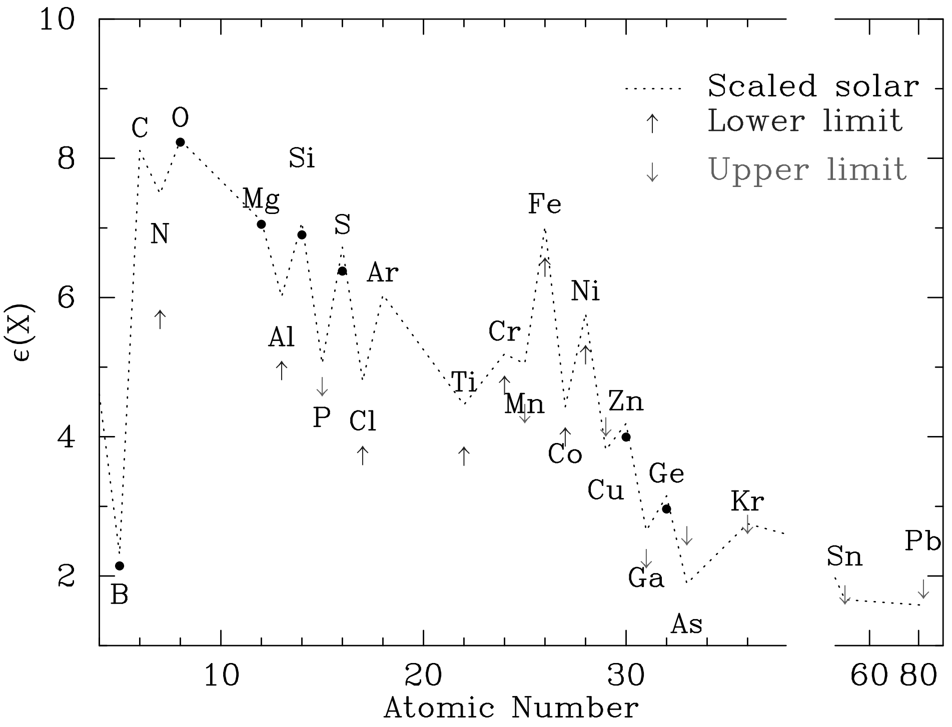

Fig. 1.7. Abundance pattern of the $z = 2.626$ DLA toward FJ0812+32. The solid circles and arrows represent detections and limits, respectively. The dotted line shows the solar abundances scaled to the oxygen abundance in the DLA.

presented in Figure 1.7 and future observations will have the following impacts on theories of nucleosynthesis.

(1) Observations of the B/O ratio test processes of cosmic ray and ν-wind spallation invoked to explain the production of the light elements B, Be, and Li (Fields & Olive 1999).

(2) Some of the galaxies will show measurements of all three CNO elements in the same DLA. These measurements yield clues to nucleosynthesis in intermediate-mass stars and place important time constraints on metal enrichment (Henry, Edmunds, & Köppen 2000).

(3) The relative abundances of the α-elements (e.g., O, Mg, Si, S) and the examination of odd-Z elements (e.g., P, Al, Ga, Mn) can be used to test predictions of explosive nucleosynthesis (e.g., Woosley & Weaver 1995). Furthermore, these abundances probe the initial mass function and mix of Type II vs. Type Ia supernovae in these protogalaxies. For the galaxy in Figure 1.7, the decline in relative abundance of the α-elements (e.g., [O/S] $\approx$ +0.3) and the enhanced "odd-even effect" (e.g., [P/Si] < 0) suggest an enrichment history dominated by massive stars.

(4) Observations of Pb, Kr, Sn, and Ge will constrain theories of the *s*-process and *r*-process, and particularly AGB nucleosynthesis (e.g., Travaglio et al. 2001). It is important to emphasize that this scientific inquiry takes place in a relatively metal-rich gas (O/H $\approx 1/3$ solar) in a system with a strict upper limit to its age of 2.5 Gyr. The latter point is particularly relevant to

theories on nucleosynthesis because this time scale limits the contribution from intermediate-mass stars.

While the results for the galaxy presented in Figure 1.7 will—on their own—place new constraints on theories of nucleosynthesis, the real excitement from its discovery is the promise of identifying many other galaxies with similar characteristics. We are currently pursuing several DLAs with N(H I) and [M/H] values similar to those of the $z = 2.626$ DLA toward FJ0812+32, whose observations should yield abundance measurements of ~ 20 elements in each DLA. These observations will reveal if the $z = 2.626$ DLA toward FJ0812+32 is a unique case or representative of the population of metal-rich DLAs. In addition to these efforts, we have begun a survey with ESI on Keck II to find an additional 10–50 of these DLAs. Several groups at this meeting are now involved with searches for extremely metal-poor stars at $z = 0$. Our complementary effort is to discover relatively metal-rich galaxies at very high z.

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