

## IONIZED GAS IN DAMPED Ly $\alpha$ SYSTEMS AND ITS EFFECTS ON ELEMENTAL ABUNDANCE STUDIES

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### ABSTRACT

Recent high-resolution observations of metal absorption lines in high-redshift damped Ly $\alpha$  systems have shown that Al III, a tracer of moderately ionized gas, very often has a velocity structure indistinguishable from that of low-ionization gas. Regions of ionized and neutral hydrogen in these systems are likely cospatial. The higher ionization Si IV and C IV absorption shows a much weaker or nonexistent correlation with the low-ionization material, implying that the regions traced by Al III are photoionized by a soft (stellar) spectrum, by a hard (power-law) spectrum with a very low ionization parameter, or a combination of both. We discuss the ionization of the damped Ly $\alpha$  systems and use photoionization equilibrium models to make quantitative estimates of its effects on abundance studies in these systems. We show that ionization effects may be large enough to account for the observed dispersion in absolute metal abundances in damped Ly $\alpha$  systems, causing systematically higher abundances in lower column density systems. The observed Si<sup>+</sup>/Fe<sup>+</sup> and Zn<sup>+</sup>/Cr<sup>+</sup> ratios may systematically overestimate the intrinsic Si/Fe and Zn/Cr ratios, respectively, if ionized gas is present in these systems, thereby mimicking the effects of  $\alpha$ -element enrichment or dust depletion.

*Subject headings:* galaxies: abundances — intergalactic medium — quasars: absorption lines — radiative transfer

### 1. EVIDENCE FOR PHOTOIONIZED GAS IN DAMPED Ly $\alpha$ SYSTEMS

Observations of damped Ly $\alpha$  systems (DLAs), which may represent the progenitors to modern disk galaxies, along the sight lines to high-redshift QSOs allow astronomers to trace the evolution of elemental abundances over 90% of the age of the universe. This is typically achieved by comparing the measured column density of a single ion of a given element,  $X^i$ , with that of neutral hydrogen, H<sup>0</sup>. The assumption is then made that the unobserved ionization stages make negligible contributions and  $N(X^i)/N(H^0) \approx N(X)/N(H)$ .

The total H I column densities of DLAs are, by definition,  $N(H\text{ I}) \geq 2 \times 10^{20} \text{ cm}^{-2}$ ; if collected in a single cloud, such a large column density would imply small ionization corrections. Although some of these systems include such monolithic absorbers, high-resolution data show that DLAs are often made up of a collection of several (in many cases  $\geq 5$ –10) lower column density clouds (Lu et al. 1996; Pettini et al. 1999; Prochaska & Wolfe 1999). Furthermore, both the Lu et al. (1996) and Prochaska & Wolfe (1999) surveys of DLAs find a very conspicuous correlation between the velocity structure seen in the absorption lines of low-ionization species (e.g., Si II, Fe II, and Zn II) and the structure observed in Al III, a tracer of moderately (photo)ionized gas [IP (Al<sup>+</sup>, Al<sup>+2</sup>) = (18.8, 28.4) eV]. Such an obvious correlation is not observed between the low-ionization species and the more highly ionized ions such as Si IV or C IV.

Similar arrangements of low and intermediate ions can be found along selected sight lines extending into the halo of the Milky Way. Toward HD 93521 (Spitzer & Fitzpatrick 1993) and  $\rho$  Leo (Howk & Savage 1999), the tracers of neutral and photoionized gas have relative velocity component distributions resembling those of Al III and low ions in DLAs. The total hydrogen column densities toward these stars are  $\log N(H\text{ I}) = 20.10$  and  $20.44$ , respectively (Diplas & Savage 1994). In the Milky Way, the scale height of Al III is consistent with that of the free electrons,  $h_z \sim 1$  kpc, which is more extended than the H I distribution (Savage, Edgar, & Diplas 1990).

Most singly ionized metal species that are dominant ionization stages in H I-bearing regions may also be produced in photoionized clouds where H<sup>0</sup> is a small fraction of the total hydrogen content. The formation of metal absorption lines in both ionized and neutral regions can have a significant effect on elemental abundance determinations. Ionization can be an important issue for high-precision studies of elemental abundances in the Milky Way (Sofia & Jenkins 1998; Howk, Savage, & Fabian 1999; Sembach et al. 1999). The Al III in DLAs, with velocity structure that is often indistinguishable from that of the low ions (Lauroesch et al. 1996), suggests the long-held assumption that ionization effects are negligible in these systems may be unwarranted. In this work we examine the contribution of photoionized gas to the observed metal-line absorption in damped Ly $\alpha$  systems.

### 2. THE IONIZING SPECTRUM

The major uncertainty in determining the ionization balance in the DLAs is the unknown shape of the ionizing spectrum. The two most likely origins for ionizing photons in DLAs are internal stellar and external background sources. Ionization of the DLAs by external sources, e.g., by the integrated light from QSOs, AGNs, starbursts, and normal galaxies (Haardt & Madau 1996, hereafter HM; Madau & Shull 1996), requires that the ionizing photons “leak” into the DLAs. This might seem unlikely given the large observed neutral hydrogen column densities, but the multicomponent nature of these systems implies that each individual cloud may have a much lower column density than the total. Furthermore, the ionization of the warm ionized medium (WIM) in the Milky Way requires  $\sim 15\%$  of the ionizing photon output of Galactic OB stars (Reynolds 1993). This implies that the gaseous structure of a present-day disk galaxy is such that ionizing photons can travel very large distances from their origin and of order 5% may escape the Galaxy completely (Bland-Hawthorn & Maloney 1999). We assume a similar arrangement in the DLAs. For the external ionization case, we adopt an updated version of the HM QSO

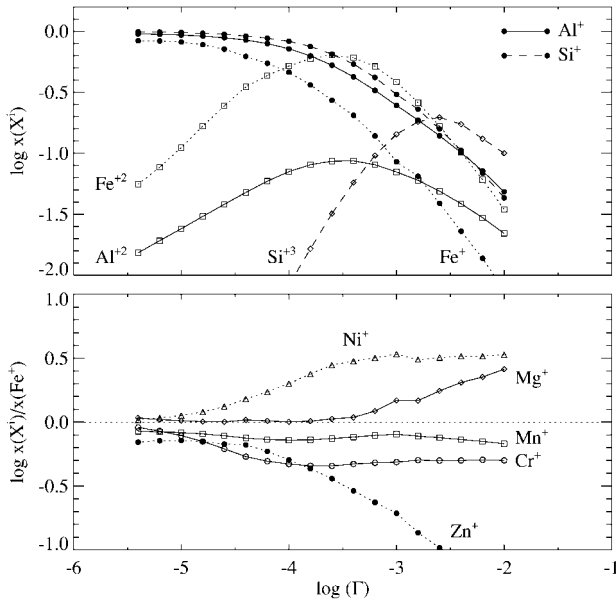


FIG. 1.—Ionization fractions as a function of ionization parameter  $\Gamma$  for several ions assuming a Haardt & Madau (1996) UV background spectrum appropriate for  $z = 2.0$ . The top panel shows the ionization fractions of ions of Fe, Al, and Si, all of which have multiple potentially observable ionization states. The bottom panel shows the ionization fractions of several commonly observed singly ionized species relative to that of  $\text{Fe}^+$ . These ionization fractions are appropriate for the fully ionized gas in a system. The atomic input data used for Cr and Zn, in particular, are somewhat uncertain (see text).

ultraviolet background in our photoionization models. This modified background spectrum (F. Haardt 1999, private communication) assumes  $q_0 = 0.5$  (instead of 0.1), a power-law index for the QSO emission spectrum of  $\alpha = 1.8$  (rather than 1.5), and a redshift evolution of the QSO number density that follows the trend described by Madau, Haardt, & Rees (1999).

Internal ionization, in this work, refers to photoionization by stellar sources internal to the DLAs. If DLAs represent the early phases of massive disk galaxies (e.g., Wolfe & Prochaska 1998), it is reasonable to expect some star formation in these systems. Searches for Ly $\alpha$  and H $\alpha$  emission from DLAs imply low star formation rates:  $\dot{M}_* \approx 5\text{--}20 M_\odot \text{ yr}^{-1}$  (Bunker et al. 1999; Lowenthal et al. 1995), with one detection of Ly $\alpha$  emission suggesting  $\dot{M}_* \approx 1 M_\odot \text{ yr}^{-1}$  (Warren & Møller 1996). In the Milky Way, where ionizing photons from early-type stars must leak through the neutral ISM to ionize the WIM, the star formation rate is of order  $2\text{--}5 M_\odot \text{ yr}^{-1}$  (Mezger 1987; McKee 1989; McKee & Williams 1997). The perpendicular column density of ionized hydrogen in the WIM is about one-fourth that of neutral hydrogen at the solar circle, thus demonstrating that a relatively large fraction of interstellar hydrogen can be ionized with a modest level of star formation. For the internal ionization case, we adopt the spectrum of a typical late-O star as the ionizing spectrum. We use an ATLAS line-blanketed model atmosphere (Kurucz 1991) with an effective temperature  $T_{\text{eff}} = 33,000 \text{ K}$  and  $\log g = 4.0$ . Our work on the ionization of the Galactic WIM (Sembach et al. 1999) suggests that such a spectrum is able to match the constraints imposed by emission-line observations of the ionized gas (Reynolds & Tuft 1995; Reynolds et al. 1998; Haffner, Reynolds, & Tuft 1999).

We consider only a single-temperature stellar source for the internal case and a QSO-dominated spectrum for the external ionization case. The reader should be aware that the true ion-

izing spectrum may be a combination of soft (internal) and hard (external) ionizing spectra. The lack of associated Si IV absorption with the low ions favors either the softer stellar spectrum or a very low ionization parameter.

### 3. PHOTOIONIZATION MODELS

We use the CLOUDY ionization equilibrium code (Ferland et al. 1998; Ferland 1996) to model the ionization of DLAs. We assume a plane-parallel geometry with the ionizing spectrum incident on one side. Rather than match the total H I column density in our models, we stop the integration at the point at which the local ionization fraction of neutral hydrogen climbs above 10%, i.e.,  $x(\text{H}^0) \equiv N(\text{H}^0)/N(\text{H}_{\text{tot}}) > 0.1$ . Our models therefore treat the (almost) fully ionized regions assumed to envelop the neutral, H I-bearing clouds. The relative mix of neutral and ionized material can be inferred from observations of adjacent ions, e.g., Al II/Al III. Our models assume a base metal abundance of 0.1 solar, with relative heavy-element abundances equivalent to those observed in the Galactic warm neutral medium (Sembach et al. 1999; Howk et al. 1999). We include interstellar grains for heating and cooling processes (see Ferland 1996 and Baldwin et al. 1991), with a dust-to-gas ratio 0.1 of the Galactic value. Our models are only as accurate as the input atomic data for the CLOUDY code, and we refer the reader to Ferland (1996) and Ferland et al. (1998) for discussions of the uncertainties (see also our earlier work with CLOUDY: Sembach et al. 1999; Howk & Savage 1999). In particular, the dielectronic recombination coefficients for elements in the third and fourth row of the periodic table are typically not well known, and the radiative recombination coefficients for many of the heavier elements (e.g., Zn and Cr) are often based on somewhat uncertain theoretical considerations.

We have computed CLOUDY models for the  $z \approx 2.0$  HM spectrum and for the Kurucz model atmosphere over a range of ionization parameters  $\Gamma$ . In this case  $\Gamma$  is the dimensionless ratio of total hydrogen-ionizing photon density to hydrogen particle density at the face of the cloud. In Figure 1 we present the ionization fractions of several ions,  $x(X^i)$ , for the HM spectrum as a function of the assumed ionization parameter. The top panel shows  $x(X^i)$  for elements with at least two potentially measurable ionization stages: Si, Fe, and Al. The bottom panel shows the effects of ionization on relative metal abundances, tracing values of  $x(X^i)/x(\text{Fe}^+)$  for several commonly measured ions. These plots can be used to correct for ionization effects if one is able to estimate  $\Gamma$ .

For large values of  $\log \Gamma (\geq -3.0)$  the predicted strength of the Si IV becomes large, with  $x(\text{Si}^+)/x(\text{Si}^{+3}) \lesssim 2$ , contrary to observations. At  $\log \Gamma = -4.0$  this ratio is  $\approx 100$ . We note that the behavior of the ratio  $x(\text{Ni}^+)/x(\text{Cr}^+)$  in Figure 1 also suggests a low ionization fraction, given that the observed ratio  $N(\text{Ni}^+)/N(\text{Cr}^+)$  is typically very near the solar Ni/Cr ratio.<sup>1</sup> The utility of this ratio as an indicator of the ionization parameter would be improved with better atomic data. Figure 1 shows that while Al III is a tracer of ionized gas, it accounts for less than 10% of the total aluminum column density, even in regions of fully ionized hydrogen (where Al II or Al IV dominate). Unfortunately, this implies that past arguments for a lack of

<sup>1</sup> This result relies on new  $f$ -value determinations by Fedchak & Lawler (1999). Using these new oscillator strengths, we find a (weighted) average abundance  $[(\text{Cr}/\text{Ni})] = +0.013 \pm 0.023$  in the 11 DLAs containing both elements in the Prochaska & Wolfe (1999) sample.

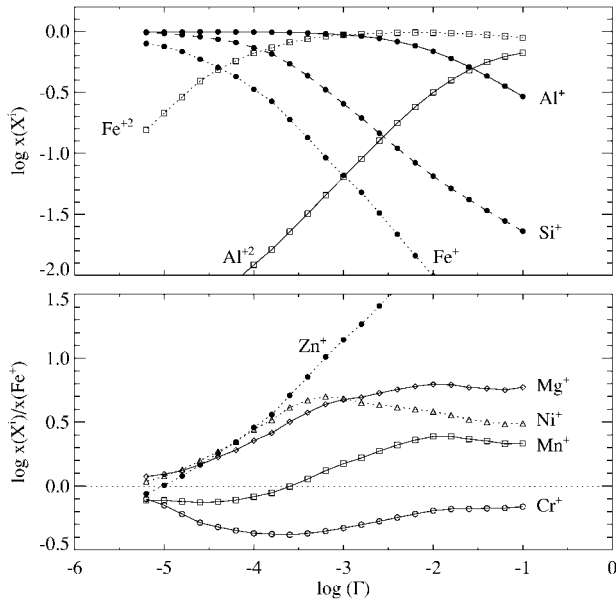


Fig. 2.—As in Fig. 1, but assuming an internal source of ionization approximated by a Kurucz (1991) model atmosphere with  $T_{\text{eff}} = 33,000$  K.  $\text{Si}^{+3}$  is not seen on this plot because for all ionization parameters considered,  $\log x(\text{Si}^{+3}) < -3$ .

ionized gas in DLAs based upon a relatively large Al II/Al III ratio are possibly erroneous.

Figure 2 shows the CLOUDY photoionization calculations performed assuming internal sources of ionizing photons, i.e., star formation. Again, the fraction of aluminum in Al III is relatively small. If we assume that the properties of the ionized gas in the DLAs are similar to those of the WIM in the Milky Way, a relatively low ionization parameter is preferred (e.g.,  $\log \Gamma \lesssim -3.7$  is adopted by Sembach et al. 1999). The  $x(\text{Ni}^+)/x(\text{Cr}^+)$  ratio suggests a low value of  $\Gamma$ , as in the external ionization case. For the adopted stellar spectrum, the fraction of silicon in the form of  $\text{Si}^{+3}$  never rises above 0.1% for the range of ionization parameters considered. Note that this is a considerably smaller fraction than found for high- $z$  Lyman-limit systems (Steidel & Sargent 1989; Prochaska 1999) and Ly $\alpha$  forest clouds (Songaila & Cowie 1996).

#### 4. DISCUSSION

Figures 1 and 2 show that even in the case in which the Al II/Al III ratio is large, the amount of ionized gas in DLAs can be significant. Comparing certain metal ions to hydrogen may very well systematically *overestimate* the abundances of DLAs. Figure 3 shows the implied fraction of ionized hydrogen in DLAs,  $f(\text{H}^+)$ , for the stellar and QSO ionizing spectra in the top panel, where we have plotted the results for several different values of  $\log \Gamma$ . In the middle panel we show the logarithmic error introduced into measurements of  $[\text{Zn}/\text{H}]$ , defined as

$$\epsilon(\text{Zn}/\text{H}) \equiv \log \frac{N(\text{Zn II})}{N(\text{H I})} \Bigg|_{\text{measured}} - \log \frac{N(\text{Zn})}{N(\text{H})} \Bigg|_{\text{intrinsic}} \quad (1)$$

for changing mixtures of neutral and ionized gas, as traced by the Al II/Al III ratio, while the bottom panel shows the equivalent  $\epsilon(\text{Si}/\text{H})$ . The predicted values of  $\epsilon(\text{Zn}/\text{H})$  and  $\epsilon(\text{Si}/\text{H})$  vary

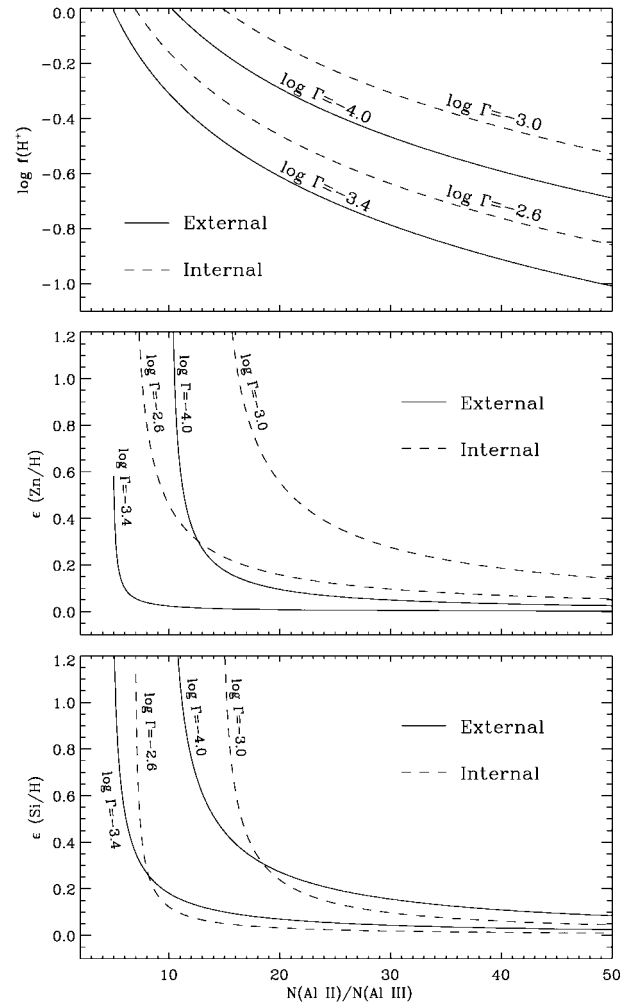


Fig. 3.—Ratio  $N(\text{Al II})/N(\text{Al III})$  as an indicator of the ionized gas content of DLAs. The top panel shows the fraction of ionized material,  $f(\text{H}^+)$ , in DLAs as a function of the measured  $N(\text{Al II})/N(\text{Al III})$  assuming the labelled ionization parameters. The bottom two panels show the error (in dex) of the implied  $[\text{Zn}/\text{H}]$  and  $[\text{Si}/\text{H}]$  abundances if no correction for ionization is made (see text). The  $\epsilon(\text{Zn}/\text{H})$  results are mostly schematic given the uncertainties in the atomic data for zinc.

significantly with the adopted ionizing spectrum and ionization parameter. Errors in the derived values of  $[\text{Zn}/\text{H}]$  or  $[\text{Si}/\text{H}]$  of a few tenths of a dex are easily achievable even when  $N(\text{Al II}) \gg N(\text{Al III})$ .

It should be pointed out that the atomic data for zinc are quite uncertain, with the recombination coefficients being derived from extrapolations of the results for other elements. The atomic data for silicon are more reliable, although the abundance of this element is complicated by its possible inclusion into dust grains. The behavior of  $\epsilon(\text{Zn}/\text{H})$  and  $\epsilon(\text{Si}/\text{H})$  observed in Figure 3 is a common feature for those elements predominantly found in their singly ionized stage in neutral gas. Figure 3 shows that DLAs with  $f(\text{H}^+) \approx (0.5, 0.4, \text{ and } 0.2)$  can have errors of  $\epsilon(\text{Si}/\text{H}) \approx (0.1, 0.07, \text{ and } 0.04)$  and  $\epsilon(\text{Zn}/\text{H}) \approx (0.3, 0.2, \text{ and } 0.1)$  dex in the case of internal ionization for  $\log \Gamma = -3.0$ . This error is larger for smaller ionization parameters. For the external ionizing spectrum, these values are  $\epsilon(\text{Si}/\text{H}) \approx (0.3, 0.2, \text{ and } 0.05)$  and  $\epsilon(\text{Zn}/\text{H}) \approx (0.1, 0.07, \text{ and } 0.03)$  dex.

The large spread in total metal abundances  $[\text{Zn}/\text{H}]$  (Pettini et al. 1997b, 1999) in DLAs at a given redshift could in part

be due to differing ionization conditions. The *total* spread in abundance at a given redshift can be as high as almost 2.0 dex (Pettini et al. 1997b, 1999), which is not easily explained by ionization effects. However, the standard deviations of measurements in a given redshift interval are of order 0.3–0.4 dex (Pettini et al. 1997b). This degree of variation is consistent with a range of  $f(\text{H}^+)$  values between  $\sim 0.0$  and  $\sim 0.6$  in these systems.

If ionization is playing a significant role in determining the apparent distribution of metallicity in DLAs, we might expect lower column density systems to show higher inferred abundances, on average. This is consistent with the claim by Pettini et al. (1999) that the “census” of metals in known DLAs is dominated by high column density, low-metallicity systems, while those higher apparent metallicity systems tend to be of lower neutral hydrogen column densities (see also Wolfe & Prochaska 1998). However, one should also be wary of the possible selection effects in identifying high-metallicity, high column density absorbers (Pei & Fall 1995; Wolfe & Prochaska 1998; see also Pettini et al. 1999).

Systematic errors in the relative metal abundances can also be significant, depending on the ions compared. Unfortunately, systematic errors in excess of 20% can begin to mimic other effects such as nucleosynthetic enrichment or dust depletion. For example, if the internal stellar ionizing spectrum is appropriate, the errors in the [Si/Fe] abundances inferred from  $N(\text{Si}^+)/N(\text{Fe}^+)$  can mimic the preferential inclusion of iron into dust grains or the enhancement of  $\alpha$ -elements over iron. For  $f(\text{H}^+) \approx (0.5, 0.4, \text{ and } 0.2)$ , the systematic errors in [Si/Fe] are  $\epsilon(\text{Si/Fe}) \approx (+0.4, +0.3, \text{ and } +0.2)$ . Similarly, systematic errors in the [Cr/Zn] abundances can mimic the inclusion of chromium into dust:  $\epsilon(\text{Cr/Zn}) \approx (-0.3, -0.2, \text{ and } -0.1)$  for the same  $f(\text{H}^+)$  values. The values  $f(\text{H}^+)$  required to explain

the dispersion in inferred [Zn/H] metallicities are also sufficient to provide the dispersion in inferred [Cr/Zn] values (Pettini et al. 1997a).

There are some ionic ratios that are accurate tracers of relative metal abundances even if ionized gas makes a substantial contribution. For  $f(\text{H}^+) < 0.5$ , the ratios of Mn II and Mg II to Fe II should trace Mn/Fe and Mg/Fe to within  $\sim 10\%$  in the case of the external (hard) ionizing spectrum. The ratio of Si II to Al II should be a reasonable proxy for Si/Al. For the softer stellar spectrum, the ratios of Ni II and Mg II to Si II are reliable tracers of Ni/Si and Mg/Si.

Fe III is a much better tracer of ionized gas than Al III in the sense that it is the dominant ionization stage of iron in the photoionized gas. The  $\lambda 1122$  transition of Fe III may be lost in the Ly $\alpha$  forest toward high-redshift quasars, but in select cases this important transition may be useful for providing further information on the ionized gas in the DLAs.

Our calculations suggest that ionized regions may make a significant contribution to the total column density of metal ions in DLAs and that this contribution can lead to systematic errors in the determination of abundances in these systems. Observational studies of abundances in DLAs should take ionization into account whenever possible, or at the very least assess its possible impact on the derived results.

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