Abundances of Heavy Elements and CO Molecules in High Redshift Damped Lyman-alpha Galaxies

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Abstract.
Damped Ly\(\alpha\) systems seen in spectra of background quasars are generally thought to represent high redshift counterparts of present-day galaxies. We summarize observations of heavy element abundances in damped Ly\(\alpha\) systems. The results of a systematic search for CO and C \(\mathrm{ii}^*\) absorption in 17 damped Ly\(\alpha\) systems are also presented using observations obtained with the 10m Keck telescopes. The latter provides a useful constraint on the expected strength of [C \(\mathrm{ii}\)] 158\(\mu\)m emission from damped Ly\(\alpha\) galaxies. It is hoped that these results will be useful for planning future radio to millimeter wave observations of high redshift galaxies using next generation instruments which are now being built.

1. Damped Ly\(\alpha\) Systems as the Progenitor of Normal Galaxies

High redshift galaxies identified through their absorption line imprints on spectra of background quasars are remarkable in the sense that their selection is by their chance alignment with the background quasars and hence do not depend on their emission properties at any specific wavelength. Accordingly, any galaxy containing a significant amount of gas should be picked up without regard to its stellar content (but see section 6 for possible caveats). Consequently, these galaxies should be more representative of the high redshift universe than quasars, AGNs, radio galaxies, infrared luminous galaxies, or Lyman break galaxies; all of which have been detected at high redshifts.

It is generally agreed that the population of quasar absorption systems that are most closely related to the progenitor of normal galaxies is the so-called damped Ly\(\alpha\) (DLA) systems (Wolfe 1988). The strongest evidence linking DLA systems to the progenitors of normal galaxies is that the baryonic mass density contained in the neutral gas in DLA systems at redshift \(z \sim 3\) is comparable to the mass density contained in stars in galaxies today, implying the transformation of gas in DLA systems to stars in nearby galaxies over the last 10-15 billion years (Lanzetta, Wolfe, Turnshek 1995). DLA systems have neutral hydrogen column densities \(N(\mathrm{H} \, i) \sim 10^{20} - 10^{22} \, \text{cm}^{-2}\), similar to those obtained along sightlines through the Galactic disk. DLA systems are the only class of
Figure 1. Metallicity distribution of damped Ly\(\alpha\) systems as a function of redshift, where \([\text{Fe/H}] = \log(\text{Fe}/\text{H})_{\text{DLA}} - \log(\text{Fe}/\text{H})_{\odot}\) is the logarithmic abundance of Fe in damped Ly\(\alpha\) systems relative to the Sun. The age of the universe starting from Big Bang is given on the top axis for the assumed cosmological model.

As can be seen from Figure 1, typical DLA galaxies at \(z > 1.6\) have \(-2.5 < [\text{Fe/H}] < -1\), corresponding to \(1/300\) to \(1/10\) solar metallicity. The quasar absorption line systems that show 21-cm absorption against radio background sources (cf. Briggs 1988). Their low metallicities, low dust contents, and low molecular contents (see later sections of this article) are all consistent with properties expected of galaxies that are in the early stages of evolution. Consequently, they should be the prime targets for radio and millimeter wavelength studies of normal galaxies at high redshifts with future instruments. In this article, we discuss some of the properties of DLA systems at \(z > 1.6\) that may be helpful for planning future radio and millimeter observations.

2. Heavy Elements in Damped Ly\(\alpha\) Systems

Abundance determinations for DLA systems began in the late 70’s (Smith, Jura, & Margon 1979), but it was only recently that abundance estimates for a large number of systems became available (eg, Lu et al 1996; Pettini et al 1997a,b). In Figure 1 we show the distribution of \([\text{Fe/H}]\) vs \(z\) for a sample of DLA galaxies, where the data are taken from Table 16 of Lu et al (1996) with the addition of 14 new measurements based on unpublished work of our group and of Wolfe and Prochaska (5 systems) using the 10m Keck telescopes. The discussion below will be limited to systems at \(z > 1.6\) given the dearth of measurements at lower redshift. A more detailed review of DLA abundances in the context of galactic chemical evolution is given by Lu, Sargent, & Barlow (1998).

As can be seen from Figure 1, typical DLA galaxies at \(z > 1.6\) have \(-2.5 < [\text{Fe/H}] < -1\), corresponding to \(1/300\) to \(1/10\) solar metallicity. The
N(H i)-weighted mean metallicity is \( <[\text{Fe}/\text{H}] > \approx -1.5 \) at \( \langle z \rangle = 2.5 \). The low metallicities are consistent with them being young galaxies in the early stages of chemical enrichment. If DLA systems eventually evolve to solar mean metallicity at \( z = 0 \), their low metallicities at \( z > 2 \) suggest that most of the baryonic matter in these galaxies should be in the gas phase rather than in stars and that most of the star formation should occur at \( z < 2 \), consistent with results from deep galaxy redshift surveys (cf. Connolly et al 1997). The N(H i)-weighted mean metallicity in terms of Zn is about a factor of 2-3 higher than that of Fe (Pettini et al 1997b), possibly suggesting that some of the Fe atoms are locked up in dust grains in the DLA galaxies.

The mean metallicity of DLA systems clearly increases from \( z > 4 \) to \( z \sim 2 \) as expected. However, there is a factor of \( \sim 30 \) scatter in \([\text{Fe}/\text{H}]\) at \( 2 < z < 3 \), presumably reflecting differences in the formation epoch/star formation history of the galaxies and/or a mixture of morphological types. The metallicity distribution appears to reach a “plateau” value of \([\text{Fe}/\text{H}] \approx -2 \) to \(-2.5\) at \( z > 4 \). Coincidentally, this “plateau” metallicity is identical (within the measurement uncertainties) to that found for the intergalactic medium clouds at similar redshifts, as inferred from the C IV absorption associated with Ly\( \alpha \) forest clouds (Cowie et al 1995; Tytler et al 1995; Songaila & Cowie 1996). This coincidence suggests that the metals in DLA galaxies with \([\text{Fe}/\text{H}] \sim -2 \) to \(-2.5\) may simply reflect those in the intergalactic medium, possibly produced by Pop III stars (Ostriker & Snedin 1996). If this interpretation is correct, then significant star formation did not start in DLA galaxies until \( z \sim 3 - 4 \). Such an inference is consistent with the decline in the neutral gas content of DLA systems at \( z > 3 \) (Storrie-Lombardi, McMahon, & Irwin 1996) (presumably because DLA galaxies are still being formed at such high redshifts) and with the rapid decline in the space density of quasars at \( z > 3 \) (Schmidt, Schneider, & Gunn 1995). It will be important to study more DLA systems at the highest redshift possible to confirm the reality of the “plateau” metallicity, and to improve the accuracy of the metallicity determination for the Ly\( \alpha \) forest clouds, which at present may be uncertain by as much as a factor of 10 due to uncertain ionization corrections.

### 3. Dust in Damped Ly\( \alpha \) Systems

The low heavy element abundances in DLA systems provide a fundamental limitation to the amount of dust that can form in these galaxies: the highest dust-to-gas ratio that a galaxy with metallicity \( Z \) can have is \( Z/Z_\odot \) times the Galactic dust-to-gas ratio, when all the atoms from one or more elements have been incorporated into grains\(^1\). Since DLA systems at \( z > 1.6 \) generally have \([\text{Fe}/\text{H}] = -2.5 \) to \(-1\) or \([\text{Zn}/\text{H}] = -2 \) to \(-0.5\) (section 2), it can be concluded without any detailed analysis that typical DLA systems should have dust-to-gas ratios in the range of 0.01 to 0.1 times the Galactic value, or lower.

The presence of dust in DLA systems has been inferred from the modest reddening of quasars with DLA absorption in their spectra compared to those

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\(^1\)Here we ignore complications resulting from non-solar relative abundances or from different compositions of dust grains.
without (Pei, Fall, & Bechtold 1990), and from the sub-solar Cr/Zn (and Fe/Zn) ratios found in DLA systems which can be interpreted as a consequence of dust depletion (Meyer & Roth 1990; Pettini et al 1994). However, the extent to which DLA abundances are significantly affected by dust depletion and the nature of dust are still controversial (see, for example, Lu et al 1997 for a discussion and for references). If it is assumed that dust grains in DLA systems have the same composition as Galactic dust, then a typical dust-to-metal ratio of 40-80% of the Galactic value is deduced (Kulkarni, Fall, & Truran 1997; Pettini et al 1997a; Vladilo 1997). Consequently, typical DLA systems should have dust-to-gas ratios in the range 0.01-0.1 times the Galactic value.

DLA systems are defined to have $N$(H i) $\geq 10^{20}$ cm$^{-2}$ and are observed to have $N$(H i) up to $5 \times 10^{21}$ cm$^{-2}$. Adopting the Galactic extinction curve with $E_{B-V} = N$(H i)/$5 \times 10^{21}$ cm$^{-2}$ and $Z \approx 0.1 Z_{\odot}$, and should be much less for lower $N$(H i) and/or metallicity systems. Adopting Magellanic Clouds-type extinction curves, $E_{B-V} = N$(H i)/$2 \times 10^{22}$ for LMC and $E_{B-V} = N$(H i)/$10^{23}$ for SMC (Koornneef 1984), would result in even less reddening.

4. CO Molecules in Damped Ly$\alpha$ Systems

Molecules can have important effects on the chemical and physical properties of interstellar gas. In the Galactic interstellar medium, molecular hydrogen (H$_2$) and carbon monoxide (CO) have been particularly well studied through their UV absorption lines (Liszt 1997). Molecular hydrogen has numerous UV transitions at $\lambda < 1100$ Å from the Lyman and Werner bands. Similarly, CO has many UV transitions at $\lambda < 1550$ Å. At $z > 1.6$, many of these transitions are shifted into the optical wavelength, enabling their study from the ground.

Absorption from H$_2$ has been detected in only a few DLA systems. In general, the fraction of H$_2$ relative to total H is small compared to interstellar clouds in the Milky Way. This topic is discussed in detail by Ge (1997).

Wiklind & Combes (1994) searched for CO emission at millimeter wavelength from 8 DLA systems ($7$ at $z > 1.9$) and failed to detect any. They also reported non-detections of CO absorption ($N$(CO) $< 4 \times 10^{15}$ cm$^{-2}$) from two of these systems. In general, CO emission traces dense molecular clouds. Absorption lines of CO in the UV provide a much more sensitive means to probe diffuse interstellar gas, reaching $N$(CO) as low as $10^{12}$ cm$^{-2}$. A few nondetections of CO in DLA systems have been reported previously (Black, Chaffee, & Foltz 1987; Chaffee, Black, & Foltz 1988; Levshakov et al 1992; Ge et al 1997). We have searched for the 6 strongest CO $A^1\Pi - X^1\Sigma^+$ transitions (0-0,1-0,2-0,3-0,4-0,5-0, 6-0) at rest-frame wavelength 1544.451 ($f = 1.56 \times 10^{-2}$), 1509.750 ($f = 3.43 \times 10^{-2}$), 1477.568 ($f = 4.12 \times 10^{-2}$), 1447.355 ($f = 3.61 \times 10^{-2}$), 1419.046 ($f = 2.58 \times 10^{-2}$), and 1392.525 Å ($f = 1.61 \times 10^{-2}$) in 17 DLA systems for which we have Keck High Resolution Spectrometer (HIRES) observations. No CO absorption is convincingly detected in any of the systems, resulting in the 2$\sigma$ upper limits given in Table 1. These CO limits are roughly comparable to the values deduced for diffuse interstellar clouds in the Milky Way (eg, Federman et al 1980).
Figure 2. CO/H i ratio vs redshift for damped Lyα systems (solid triangles). All data points displayed are 2σ upper limits. The horizontal dotted lines indicate the CO/H ratios in the sample of Galactic sightlines studied by Federman et al (1980), where the highest ratio is for the ζ Oph cloud.

In Figure 2 the CO abundances in DLA systems are compared with those found in diffuse interstellar clouds in the Milky Way galaxy (Federman et al 1980), where we take N(CO)/N(H)≡N(CO)/(N(H i)+2N(H 2))≈N(CO)/N(H i) since the abundance of H 2 is generally negligible in DLA systems (Ge 1997). The CO/H upper limits are broadly consistent with observations of Galactic diffuse interstellar clouds, especially considering the low metallicities of DLA systems which should reduce the CO abundances in gas with the same physical conditions. The highest CO/H ratio found in Galactic interstellar clouds is toward ζ Oph, with CO/H≈1.6×10^{-6} (Ironically, the ζ Oph cloud is often quoted as a representative diffuse interstellar cloud).

In the Galactic interstellar medium, significant CO absorption (N(CO)>10^{12} cm^{-2}) is detected only in sightlines with N(H 2)>10^{19} cm^{-2} (Federman et al 1980). The main destruction mechanism of H 2 and CO in diffuse clouds is photodissociation by UV radiation. Once the column density of H 2 reaches some threshold value, self-shielding in the Lyman and Werner bands will prevent UV photons from penetrating the interior of the clouds, and the abundances of H 2 and CO build up quickly. This threshold H 2 column density appears to be around N(H 2)~10^{19} cm^{-2} in the Galactic ISM, above which the abundance of H 2, N(H 2)/N(H), jumps abruptly from 10^{-6} - 10^{-2} to ~10^{-1} (Savage et al 1977). Sightlines with such high N(H 2) generally have N(H)>5×10^{20} cm^{-2} and are fairly reddened (E_{B-V}>0.1). DLA systems, on the other hand, have very low H 2 abundances (N(H 2)<10^{19} cm^{-2}; Ge 1997), which is probably a direct consequence of their low dust-to-gas ratio (section 3). In these regards, the non-detection of CO in DLA systems is probably not too surprising. The low CO abundances in DLA systems may also be affected by the low metallicities of these systems.
Table 1. Abundances of CO Molecules in Damped Ly\(\alpha\) Systems

| QSO         | \(z_{DLA}\) | \(\log N(H\,\text{i})\) | \(\log N(CO)^a\) | \(N(CO)/N(H\,\text{i})^b\) | \(N(C\,\text{II}^*)^c\) |
|-------------|-------------|--------------------------|-----------------|----------------------------|--------------------------|
| 0000–2620   | 3.3901      | 21.41                    | \(\leq 12.80\)  | \(\leq 2.5 \times 10^{-8}\) | ...                      |
| 0100+1300   | 2.3090      | 21.32                    | \(\leq 12.58\)  | \(\leq 1.8 \times 10^{-9}\) | 13.59                    |
| 0216+0803   | 2.2931      | 20.45                    | \(\leq 13.31\)  | \(\leq 7.2 \times 10^{-8}\) | ...                      |
| 0528–2505   | 2.8110      | 21.20                    | \(\leq 13.91\)  | \(\leq 5.1 \times 10^{-8}\) | 14.22                    |
| 0528–2505   | 2.1410      | 20.70                    | \(\leq 13.35\)  | \(\leq 4.5 \times 10^{-8}\) | ...                      |
| 0930+2858   | 3.2352      | 20.18                    | \(\leq 12.98\)  | \(\leq 6.3 \times 10^{-8}\) | \(\leq 12.53\)          |
| 1055+4611   | 3.3172      | 20.34                    | \(\leq 12.78\)  | \(\leq 2.8 \times 10^{-8}\) | ...                      |
| 1104–1804A  | 1.6614      | 20.80                    | \(\leq 13.48\)  | \(\leq 4.8 \times 10^{-8}\) | ...                      |
| 1202–0725   | 4.3829      | 20.60                    | \(\leq 13.71\)  | \(\leq 1.3 \times 10^{-7}\) | \(\leq 13.06\)          |
| 1331+1704   | 1.7764      | 21.18                    | \(\leq 13.04\)  | \(\leq 7.2 \times 10^{-9}\) | ...                      |
| 1425+6039   | 2.8268      | 20.30                    | \(\leq 12.72\)  | \(\leq 2.6 \times 10^{-8}\) | ...                      |
| 1850+4015   | 1.9898      | 21.60                    | \(\leq 14.31\)  | \(\leq 5.1 \times 10^{-8}\) | ...                      |
| 1946+7658   | 2.8443      | 20.27                    | \(\leq 12.59\)  | \(\leq 2.1 \times 10^{-8}\) | \(\leq 12.46\)          |
| 2212–1626   | 3.6617      | 20.20                    | \(\leq 13.52\)  | \(\leq 2.1 \times 10^{-7}\) | \(\leq 12.90\)          |
| 2233+1310   | 3.1493      | 20.00                    | \(\leq 13.82\)  | \(\leq 6.6 \times 10^{-7}\) | \(\leq 13.53\)          |
| 2237–0608   | 4.0803      | 20.52                    | \(\leq 13.56\)  | \(\leq 1.1 \times 10^{-7}\) | \(\leq 12.53\)          |
| 2343+1232   | 2.4313      | 20.34                    | \(\leq 12.78\)  | \(\leq 2.8 \times 10^{-8}\) | 12.77                    |
| 2344+1228   | 2.5379      | 20.36                    | \(\leq 13.22\)  | \(\leq 7.2 \times 10^{-8}\) | \(\leq 12.95\)          |

\(^a\) All CO limits are 2\(\sigma\) estimates based on our Keck observations, except for the Q1331+1704 DLA system which is from Chaffee et al (1988).

\(^b\) Abundance of CO relative to H\,\text{i}, which may be taken as the abundance of CO relative to the total hydrogen since DLA systems contain negligible amount of H\(_2\) (Ge 1997).

\(^c\) Based on either our unpublished Keck observations or Table 18 of Lu et al (1996). All upper limits are 2\(\sigma\).

5. [C II] Emission from Damped Ly\(\alpha\) Systems

The [C II] 158\(\mu\)m far-infrared transition, which results from the two fine-structure levels of the ground state of the C\,\text{II} ion, is an important cooling agent for gas in the cool neutral and warm ionized medium (Kulkarni & Heiles 1987). A significant fraction of the far-infrared luminosity of nearby galaxies is contained in this line emission, hence the strength of the [C II] line can be a potentially important diagnostic of the physical conditions in high redshift galaxies (e.g., Phillips 1997; van den Werf 1997).

The cooling rate resulting from the [C II] line can be estimated from the column density of ions in the excited fine structure level, \(N(C\,\text{II}^*)\), through the relation (cf, Savage et al 1993)

\[
l_c = h\nu_{12}N(C\,\text{II}^*)A_{21}/N(\text{HI}),
\]

where \(A_{21} = 2.36 \times 10^{-6}\) s\(^{-1}\) is the Einstein \(A\)-coefficient. The column density of \(N(C\,\text{II}^*)\) can be estimated from the C\,\text{II} \(\lambda 1335.708\) UV transition. The
last column of Table 1 gives the \( \text{N}(\text{C} \, \text{ii}^+) \) estimates or 2\( \sigma \) upper limits in DLA systems based on our Keck HIRES observations. The resulting cooling rates are \( t_c = (6, 30, 8) \times 10^{-28} \text{ ergs s}^{-1} \text{ hydrogen}^{-1} \) for the three measurements, and the corresponding upper limits are in the range of \( 3 - 100 \times 10^{-28} \text{ ergs s}^{-1} \text{ hydrogen}^{-1} \). These measurements are at least two orders of magnitude lower than the average value found by Pottasch, Wesselius, & van Duinen (1979) for eight different sightlines through the Galactic disk. If we assume that a typical DLA galaxy contains \( 10^{10} M_{\odot} \) solar mass of hydrogen and that the DLA sightline provides a fair sample of the entire galaxy, the total luminosity contained in the [C ii] line would be only \( 10^6 - 10^7 M_{\odot} L_{\odot} \) based on the three measurements. These values are several orders of magnitude lower than the detection limit achievable with current instruments (cf, van den Werf 1997).

6. Words of Caution

The properties of DLA systems discussed above are based on the observed population of DLA systems. There are a number of factors that could potentially bias our view of these high redshift galaxies, including:

(1) More dusty (presumably more metal-rich also) galaxies should have a stronger effect dimming the background quasars through dust obscuration. Hence surveys of DLA systems using magnitude-limited quasar samples may preferentially exclude such dusty galaxies from the sample. The effect of such a selection bias is probably relatively small at \( z > 1.6 \) but could be large at lower redshift (Fall 1997). A direct check of this issue can be made by carrying out a survey of DLA systems using a complete sample of radio-selected quasars without regard to their optical brightness.

(2) The sampling rate provided by DLA systems of different morphological type of galaxies or different regions of the same galaxy depends on the relative absorption cross sections of these galaxies or regions. For example, the outer regions of disk galaxies will be much more heavily represented by DLA systems than the inner regions of disks. Hence properties revealed by DLA systems may not be representative of the overall extent of galaxies.

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