*From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution*
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# Zn and Cr Abundances in DLA Systems from the CORALS Survey

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**Abstract.** We have recently completed the measurement of the abundances of the elements Zn and Cr in a small, but complete, sample of damped Lyman alpha systems selected irrespectively of their dust content (the CORALS radio sample). We find that at a mean redshift $z = 2.4$ their metallicity and degree of dust depletion are statistically indistinguishable from those of larger samples of DLAs assembled from optical surveys. Thus we conclude that reasons other than a dust-induced bias must be found to explain the lack of redshift evolution in the metallicity of the galaxies giving rise to DLAs, and their generally low degree of chemical enrichment compared with luminous galaxies observed at the same epoch.

**Keywords.** Galaxies: abundances, galaxies: evolution, ISM: dust, extinction, quasars: absorption lines

## 1. Introduction

Spectroscopic studies of damped Lyman$\alpha$ systems (DLAs) are an important source of information regarding the chemical evolution history of neutral gas in the universe. They dominate the neutral hydrogen content of the universe available for star formation up to $z \geqslant 4$ (e.g. Storrie-Lombardi & Wolfe 2000; Peroux *et al.* 2003) and are thought to include among them the progenitors of the disk galaxies we see today. DLAs have therefore been used as a tool for probing the evolution of galaxies, especially at high redshift where direct measurements are more difficult.

If indeed DLAs are representative of the galaxy population at a given redshift, then one would expect that the evolution of their neutral hydrogen fraction and metallicity would track that of the general galaxy population as a whole. However, no strong evolution of either $\Omega_{\rm DLA}$ or metallicity ($Z_{\rm DLA}$) has been seen in studies from $z \sim 3.5$ down to $z \sim 0.5$ (e.g. Rao & Turnshek 2000; Ryan-Weber *et al.* 2003; Kulkarni *et al.* 2005).

Furthermore, it is now well established that DLAs are generally at the low end of the metallicity distribution of galaxies at redshifts $z = 2 - 3$ (see, for example, Figure 32 of Pettini 2004). The typical DLA metallicity at this epoch is only $Z_{\rm DLA} \simeq -1.2$, or $\approx$1/15 of solar (Pettini *et al.* 1999; Kulkarni *et al.* 2005), while near-solar metallicities are common for luminous galaxies detected directly in their rest-frame ultraviolet, optical, and far-infrared light (e.g. Pettini *et al.* 2002; Shapley *et al.* 2004; de Mello *et al.* 2004; Swinbank *et al.* 2005).

This difference could have a number of causes, but perhaps the one that has received the most attention is the possibility that damped Ly$\alpha$ systems which are both metal- and gas-rich do exist, but are systematically underrepresented in current samples drawn from magnitude-limited QSO surveys. The hypothesis is that even moderate amounts of dust associated with intervening galaxies may be sufficient to preferentially exclude reddened QSOs from optical surveys, and that the statistics of DLAs would accordingly be skewed by such bias against dusty absorbers. Previous studies have been inconclusive—we know that dust is present but we do not know the extent to which it may have been affecting our results. It is this question which we address here.

## 2. The CORALS sample

It is to assess quantitatively the importance of dust-induced bias for the statistics of DLAs that the Complete Optical and Radio Absorption Line System (CORALS) survey was originally conceived. As the name implies, this programme aims at measuring the properties of DLAs in a complete sample of QSOs selected at radio wavelengths, where dust obscuration is not expected to be an issue. In the first stage of the project, Ellison *et al.* (2001) identified a sample of 22 DLAs from intermediate dispersion spectroscopy of all the QSOs (66) with emission redshift $z_{\rm em} \geqslant 2.2$ in the Parkes quarter-Jansky sample of flat-spectrum radio sources (Jackson *et al.* 2002). The optical spectra were of sufficient quality to measure $N$(H I) in the 22 DLAs, enabling Ellison *et al.* (2001) to determine both the number density of DLAs per unit redshift, $n(z)$, and the corresponding comoving mass density of neutral gas, $\Omega_{\rm DLA}$. They found values which were only marginally higher than the corresponding quantities previously determined from optically selected QSO samples. In particular, within the limitations imposed by the small size of their sample, Ellison *et al.* (2001) concluded that selection effects due to intervening dust may at most account for an underestimate by a factor of $\sim$2 in $\Omega_{\rm DLA}$.

The H I results alone, however, do not tell us about the metal and dust content of CORALS DLAs and whether they are higher, on average, than those of the optically selected DLAs which have been studied extensively over the last fifteen years. These are the questions which we explore in the present work.

Specifically, we have conducted a follow-up programme of high resolution spectroscopy of the CORALS DLAs aimed at measuring in particular the abundances of zinc and chromium. Pettini, Boksenberg & Hunstead (1990) first drew attention to the diagnostic value of these two elements. Both are iron-peak elements, whose abundances track that of Fe to within $\pm\, 0.1-0.2$ dex in Galactic stars of metallicities from solar to about 1/100 of solar (Chen, Nissen & Zhao 2004; Cayrel *et al.* 2004 and references therein). In the interstellar medium of the Milky Way, on the other hand, Zn is one of the few elements which show little affinity for dust grains, unlike Cr which is usually highly depleted (Savage & Sembach 1996). In combination, therefore, these two elements can be used to obtain approximate measures of the overall degree of metal enrichment, via the [Zn/H] ratio, and the fraction of refractory elements locked up in solid form, via the [Cr/Zn] ratio.† Both elements have absorption lines of their dominant ionisation stages in H I regions conveniently located at $\lambda\lambda 2026, 2062$ Å (Zn II) and $\lambda\lambda 2056, 2062, 2066$ Å (Cr II).

† We use the conventional notation whereby [Zn/H]= log (Zn/H) − log (Zn/H)$_\odot$.

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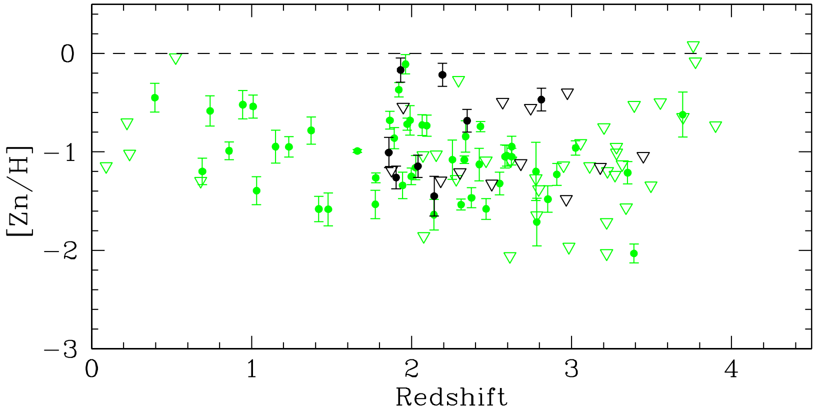


**Figure 1.** Comparison of the abundance of Zn measured in DLAs in the CORALS sample (black) and in the control sample by Kulkarni *et al.* 2005 (coloured). Upper limits, corresponding to non-detections of the Zn II doublet, are indicated by open triangles. The abundance of Zn is plotted on a logarithmic scale relative to the solar value (taken from Lodders 2003) shown by the broken line at [Zn/H] = 0.0.

We have obtained measurements (or upper limits) of the abundances of Zn and Cr in 20 out of 22 CORALS DLAs using mostly echelle spectrographs on the Keck, ESO-VLT and Magellan telescopes. Full details can be found in Akerman *et al.* (2005).

## 3. Metallicity and dust in the CORALS survey

Kulkarni *et al.* (2005) have recently published a compilation of all high quality (i.e. obtained mostly from 8-10 m telescope data) [Zn/H] measurements in DLAs available from the literature. This sample gives us the means to compare the Zn abundances deduced in our survey with those measured along sight-lines to optically selected QSOs (Figure 1). From a visual inspection of the plot we conclude that: (a) both the CORALS and the comparison sample of optically selected DLAs are generally metal-poor, with typical values of [Zn/H] well below solar; and (b) there is a hint that, overall, the CORALS DLAs may have marginally higher metallicities, although the considerable number of upper limits complicates the comparison. We now address these points quantitatively.

The quantity which is of interest for 'cosmic' chemical evolution models (Pei & Fall 1995) is the column density-weighted metallicity (the sum of the Zn II column densities in a given sample of DLAs divided by the sum of the H I column densities) which is a measure of the degree of metal enrichment of the DLA population as a whole. We find $[\langle(\mathrm{Zn/H})_{\mathrm{DLA}}\rangle] = -0.88 \pm 0.21$ for CORALS DLAs, and $[\langle(\mathrm{Zn/H})_{\mathrm{DLA}}\rangle] = -1.09 \pm 0.10$ for the control sample of Kulkarni *et al.* (2005), *computed over the same redshift interval spanned by the CORALS data.* These values, which differ at only the $1\,\sigma$ level, were calculated considering only the Zn II detections. Repeating the calculations, but now including the upper limits as if they were detections, we obtain $[\langle(\mathrm{Zn/H})_{\mathrm{DLA}}\rangle] = -0.87 \pm 0.13$ and $-1.17 \pm 0.07$ respectively.

These results are shown graphically in Figure 2. Again we see that the two samples are very similar. The marginally higher metallicity of the CORALS sample may be real. Alternatively it may be an artifact of small number statistics or, in the case where we include upper limits, it may be due to the higher proportion of upper limits skewing the results—over one half of the CORALS measures of [Zn/H] are upper limits, compared with one third for the control sample of Kulkarni *et al.* (2005). However, we can conclude

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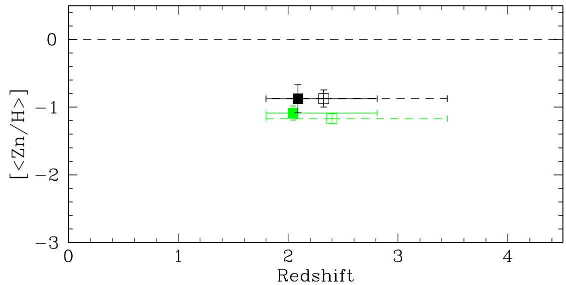


**Figure 2.** Column density-weighted metallicities of DLAs in the CORALS (black) and Kulkarni *et al.* 2005 (coloured) samples. For each sample we show two values of [⟨Zn/H⟩]; the solid squares correspond to the values obtained by considering only Zn II detections, while the open squares (and dashed error bars) are obtained if the upper limits to [Zn/H] in Figure 1 are included as if they were detections. The squares are plotted at the median redshift of the DLAs in each sample.

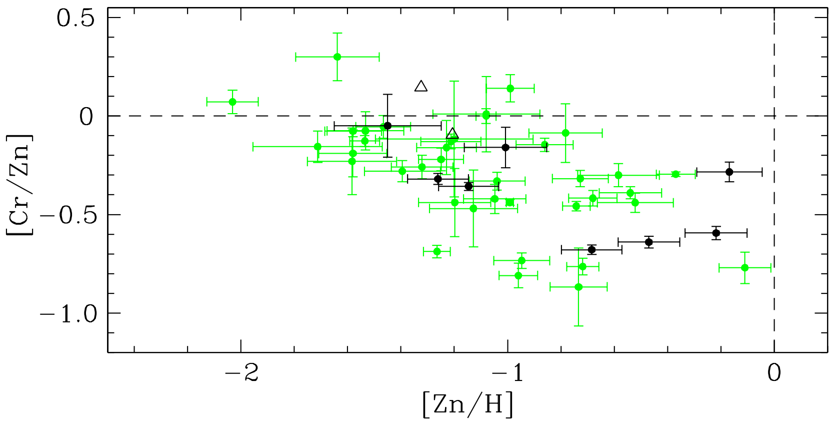


**Figure 3.** Cr/Zn ratio against Zn abundance for CORALS DLAs (black) and DLAs from the compilation by Kulkarni *et al.* (2005; coloured). Lower limits, corresponding to cases where Cr II lines are detected by Zn II lines are not, are indicated by open triangles. Abundance ratios are plotted in logarithmic units relative to the solar values shown by the broken lines at [Cr/Zn] = 0.0 and [Zn/H] = 0.0.

that CORALS DLAs do not exhibit significantly different metallicities from those of existing, larger, samples of DLAs assembled from optically selected QSO surveys.

An indication of the degree of depletion of refractory elements onto dust grains may be obtained from the ratio of the abundances of chromium to zinc, as explained in §2. In Figure 3 we plot this ratio against the metallicity [Zn/H] for each of the CORALS DLAs (coloured) together with analogous measurements (black) from the compilations by Khare *et al.* (2004) and Kulkarni *et al.* (2005), after rescaling their values to the same solar abundances used here.

Figure 3 shows the trend of increasing Cr depletion with increasing metallicity which was previously noted by Pettini *et al.* (1997a) and shown by Prochaska & Wolfe (2002) to be a general feature of refractory elements in DLAs. In systems with [Zn/H] $\lesssim -1.5$, [Cr/Zn] is approximately solar—indicating that there is little dust depletion at such low metallicities—while when [Zn/H] $> 1$, up to ∼90% of the Cr can be 'missing' from the gas phase and presumably be in solid form. Even so, in none of the DLAs do we see the extreme depletions of Cr, by two orders of magnitude, commonly measured in cold clouds of the Milky Way disk (Savage & Sembach 1996).

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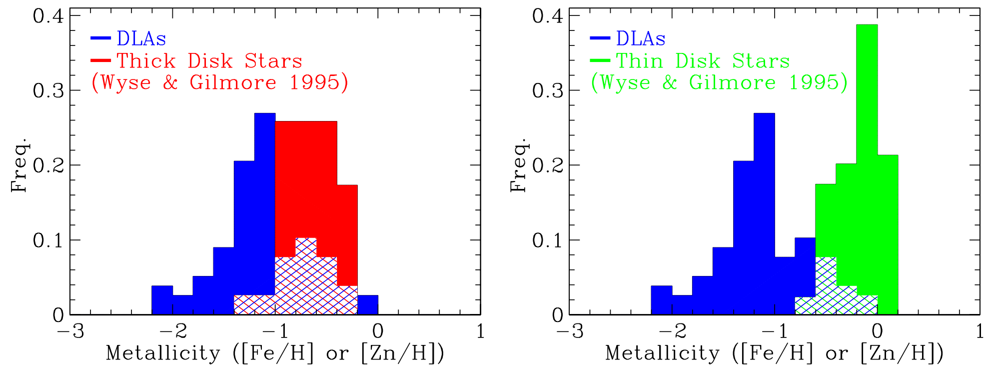


**Figure 4.** Comparison of the metallicity distribution of DLAs (determined from values of [Zn/H] for DLAs in the Kulkarni *et al.* 2005 and CORALS samples, with $1.9 < z < 3.5$) with Milky Way stellar populations (determined from values of [Fe/H] from Wyse & Gilmore 1995).

As far as the present work is concerned, it is evident from Figure 3 that the depletions of Cr in the CORALS sample conform to the overall pattern described above. The CORALS DLAs do not have extreme depletions of Cr, nor do they exhibit lower values of [Cr/Zn] at a given [Zn/H] than DLAs drawn from optically selected QSO samples. If there are any DLAs where the depletions of refractory elements approach the high values typical of cold clouds in the Milky Way disk, we have not found them yet.

## 4. Comparison with Milky Way stellar populations

We have found that the metallicities of radio selected DLAs do not appear to be significantly different to those from previous optically selected surveys. This conclusion gives us confidence that we have a true picture of the metallicity distribution of the DLA population. Consequently, we are now able to examine the common assumption that DLAs are the progenitors of today's disk galaxies by comparing their metallicities with those of different stellar populations of the Milky Way—the best studied disk galaxy—without serious concerns about sample bias. The look-back time of ∼12 Gyr which corresponds to the average redshift in the CORALS sample, $z \sim 2.5$, is similar to the typical age of stars in our Galaxy's thick disk (Freeman & Bland-Hawthorn 2002) and it is thus of interest to compare the metallicities of DLAs with those of Milky Way thick disk stars in particular. Figure 4 shows that there is some overlap between the two distributions, and that DLAs are certainly distinct from the Galactic thin disk which formed later. However, the DLA metallicity distribution is still not a good fit to that of the thick disk, particularly as we have treated upper limits as if they were detections when constructing the DLA histograms shown in Figure 4. Certainly, more work needs to be done in order to resolve the place of DLAs in the overall picture of galaxy formation.

## 5. Conclusions

The work described here concludes a project begun six years ago to test the extent to which existing DLA samples are biased by dust reddening against gas-rich galaxies of high metallicity. The first results, reported by Ellison *et al.* (2001), showed that $\Omega_{\rm DLA}$ had not been significantly underestimated. To that conclusion we now add the findings that:

(1) At redshifts $1.9 < z < 3.5$, the metallicity of CORALS DLAs, as measured by the [Zn/H] ratio, is only marginally higher (at a statistically *insignificant* level of only $1\,\sigma$) than that of DLAs drawn from optically selected QSOs over the same redshift interval.

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(2) The dust-to-metals ratio, as measured by the quantity [Cr/Zn], exhibits no systematic difference between the two samples—we unearthed no evidence to show that radio-selected QSOs should be more reddened by intervening systems than optically selected QSOs.

These results, together with recent reports of low dust extinction in large DLA samples drawn from the Sloan Digital Sky Survey (e.g. Murphy & Liske 2004), make it increasingly difficult to appeal to dust-induced selection effects to explain the observed properties of DLAs. It seems unlikely, for example, that the true metallicity of DLAs may have been underestimated by as much as a factor of five, as recently claimed by Vladilo & Péroux (2005). The challenge is now to understand, perhaps with more focused theoretical efforts, the rightful place of damped Ly$\alpha$ systems within the diverse population of galaxies known to inhabit the high redshift universe.

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