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# Abundances in Sub-DLAs: Implications for the Cosmological Evolution of Metals

C. PÉROUX[1], M. DESSAUGES-ZAVADSKY[2], S. D'ODORICO[2], T. S. KIM[2,3], and R. G. McMAHON[3]
*(1) Osservatorio Astronomico di Trieste, Italy*
*(2) European Southern Observatory, Garching-bei-München, Germany*
*(3) Institute of Astronomy, Cambridge, UK*

**Abstract**

Damped Ly$\alpha$ Systems (DLAs), with N(HI) $> 2 \times 10^{20}$ cm$^{-2}$, observed in the spectra of quasars have allowed to quantify the chemical content of the Universe over cosmological scales. Such studies can be extended to lower column densities, in the sub-DLA range ($10^{19} <$ N(HI) $< 2 \times 10^{20}$ cm$^{-2}$), which are systems believed to contain a large fraction of neutral hydrogen at $z > 3.5$. We use a homogeneous sample of sub-DLAs constructed from ESO UVES archives to determine the chemical abundance and ionization fraction of this class of quasar absorbers, and compare the results with a compilation of abundances from more than 70 DLAs taken from the literature. As previously reported, the individual metallicities traced by [Fe/H] of these systems evolve mildly with redshift. We also compute the HI column density weighted mean abundance which is believed to be an indicator of the Universe's metallicity. Our study suggests a slightly stronger evolution of this quantity in the sub-DLA range. Observational arguments support the hypothesis that the evolution we probe in the sub-DLA range is *not* due to their lower dust content. Therefore these systems might be associated with a different class of objects which better trace the overall chemical evolution of the Universe. Finally, we present abundance ratios of [Si/Fe], [O/Fe], [C/Fe] and [Al/Fe] for sub-DLAs in conjunction with DLA measurements from the literature. The elemental ratios in sub-DLAs are comparable with the one from DLAs.

## 1.1 Introduction

In addition to traditional emission studies, absorption systems along the line-of-sight to distant quasars provide a completely independent probe of galaxy evolution. The highest column density Damped Ly$\alpha$ systems (hereafter DLAs) have N(HI) $> 2 \times 10^{20}$ atoms cm$^{-2}$. The reason why damped systems are a cosmologically important population is that they contain most of the neutral gas in the Universe at $z > 1$ (Lanzetta et al. 1991; Wolfe et al. 1995; Storrie-Lombardi et al. 1996). Since the metal content of these systems can be determined with rather high precision up to high redshift, they are a powerful tool to study the stellar and chemical evolution of galaxies. In particular, a way to trace the metallicity of the Universe is provided by estimating the ratio of the total metal content to the total gas content measured in these systems (Pettini et al. 1997; Pei, Fall & Hauser 1999). Using

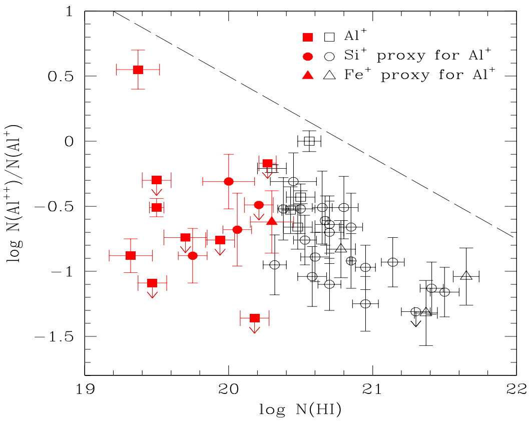


Fig. 1.1. Al III/Al II column density ratios versus H I column densities in sub-DLAs (filled symbols) and DLAs (open symbols). The dashed line represents a possible upper band limit of an increasing dispersion in the log Al III/Al II ratios with lower H I column densities. The slope of this upper band limit is equal to the slope of the observed log Al III/Al II – log N(H I) anti-correlation in DLAs.

such techniques, Prochaska & Wolfe (2002) find that the hydrogen column density weighted [Fe/H] metallicities have similar values from $1.5 < z < 3.5$. The results are in disagreement with expectations since models of cosmic chemical evolution (e.g. Fall & Pei 1995) predict evolution of global metallicity with cosmic time.

In a recent study, Péroux et al. (2003a) have shown that sub-DLAs, defined as systems with $10^{19} <$ N(HI) $< 2 \times 10^{20}$ atoms cm$^{-2}$, are to play a major role, especially towards higher redshifts. The authors postulate that at $z > 3.5$, 45% of the neutral gas mass is in sub-DLAs. These predictions are based on an extrapolation of the quasar absorber column density distribution, $f(N)$, derive from Péroux et al. (2001) data sample, to lower column densities assuming the distribution can be fitted by a gamma function. Following similar line of thoughts as for DLAs, these results suggest that sub-DLAs metallicities should be studied in details in order to obtain a complete picture of the redshift evolution of the Universe's metallicity. For this purpose, we have constructed a homogeneous sample of sub-DLAs based on high-resolution quasar spectra from the ESO UVES/VLT archives (Dessauges-Zavadsky et al. 2003, hereafter Paper I) and analyze several of their properties (Péroux et al. 2003b, hereafter Paper II).

We briefly summarize here the main findings of our study concerning abundances. The first section introduces the sub-DLA sample and the measurements of the column densities of a variety of elements. The ionization correction is estimated thanks to photoionization models. The second section details the metallicity evolution with redshift and with H I column density as well as the weighted mean metallicity. Finally, measurements of relative abundances are presented in the last section.

## 1.2 Abundance Determination in Sub-DLAs

We use 22 high-resolution quasar spectra from the ESO/UVES archives to search for sub-DLA systems (see Paper I). These systems can be easily picked up since at these column densities damping wings are already formed and the rest equivalent width is $W_{\rm rest} > 2.5$ Å. The absorbers are identify thanks to an automated algorithm as well as a visual inspection. The resulting sample is composed of 12 sub-DLAs in the range $z = 1.8$ to 4.3 and with $19.32 < \log$ N(H I) $< 20.21$. Nevertheless, only 3 of these systems are located at $z > 3.5$, where sub-DLAs are expected to play an important role. The present study is therefore limited in that respect.

The abundance are determined using standard Voigt profile fittings. Eleven elements (O, C, Si, N, S, Mg, Al, Fe, Ni, Zn and Cr) have been detected in this sample of sub-DLAs. In addition, thanks to their low H I column densities, several measurements of O I and C II are possible while these lines are often saturated in DLA systems. The draw back of the relatively low column density is that it implies that some of the gas might be ionized. The ionization state of the sub-DLAs has been investigated in details using photoionization models of the CLOUDY software package (see Paper I). The determination of the ionization parameter $U$ for a given absorber system crucially depends on the detection of intermediate-ionization transitions. In addition, the photoionization model relies on several input parameters related to the nature of the absorber and the characteristics of the radiation field. In this context we choose to extract from our analysis a global ionization correction rather than individual corrections limited by partial informations. We find the correction to be $< 0.3$ dex for most elements down to N(HI)= 19.3 cm$^{-2}$. We also note that the correction to apply is quite different from one ion to another. In the case of O I or C II, for example, the ionization fraction is small, while it becomes important for such elements as Al II or Zn II. One needs to keep these facts in mind while interpreting the various figures presented in the following sections. Finally, a study of the Al III/Al II ratios, an indicator of the ionization state, shows that the correlation with H I column densities observed in DLAs (Vladilo et al. 2001) do *not* hold in the sub-DLA regime (see Figure 1.1). This implies that the sub-DLAs are likely affected by ionization corrections to the same extend as DLAs on the average, and this despite their lower H I column densities.

## 1.3 Metallicity Evolution

### *1.3.1 Metallicity of Individual Systems*

**[Fe/H]:** Knowing that the ionization correction on the Fe II column density is within the observational errors, the abundance measurements of the sub-DLAs can be directly compared with the one of the DLAs gathered from various sources in the literature. We use the abundance ratios with respect to solar values defined in the usual manner * and presented in Paper I. The top panel of Figure 1.2 presents the evolution with redshift of the [Fe/H] absolute abundances in individual systems. We applied the order ranking Kendall's test to several sub-sets of the sample ignoring all upper and lower limits (see Paper II). As previously reported (e.g. Prochaska & Wolfe 2002; Dessauges-Zavadsky et al. 2001), there are evidences for a mild evolution of the individual [Fe/H] in DLAs (correlation coefficient of –0.29 at 99.53% confidence level). The analysis suggests a stronger correlation of the [Fe/H] in sub-DLAs although the significance of test is weakened by low number statistics (correlation coefficient of –0.50 at 84.27% confidence level for a total of 17 sub-DLAs). The effect is predominant at $z < 2$ and most of the evolution observed lies in this redshift range. We fitted the two populations of absorbers assuming a linear correlation and found a slope

* $[X/H] = \log[N(X)/N(H)]_{DLA} - \log[N(X)/N(H)]_{\odot}$

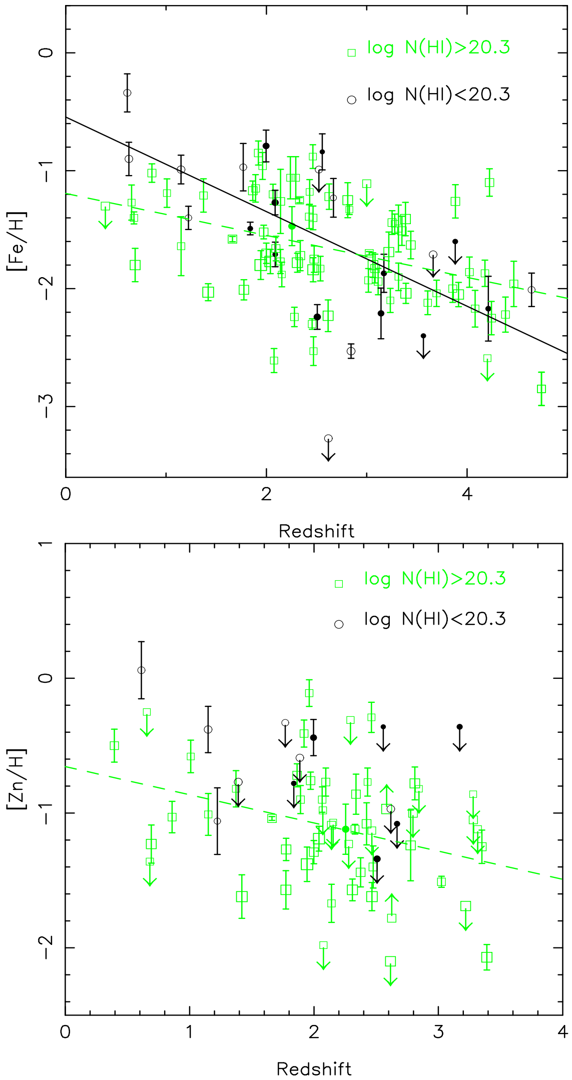


Fig. 1.2. [Fe-Zn/H] metallicities for DLAs (squares) and sub-DLAs (open circles for data from the literature, filled circles for the sub-DLAs issued from this work) as a function of redshift. The evolution with redshift of the [Fe/H] ratio is more pronounced for sub-DLAs than for DLAs (solid and dashed lines, respectively).

of $\alpha = -0.18 \pm 0.12$ for DLAs and $\alpha = -0.40 \pm 0.22$ for sub-DLAs (dashed and solid line of the top panel of Figure 1.2 respectively). The evolution with redshift of the [Fe/H] ratio might be more pronounced for sub-DLAs than for DLAs. This difference, if confirmed by a larger sample of data, suggests that the detection of DLAs is more biased by dust at low redshift or that the sub-DLAs are associated to a class of galaxies which traces better the overall chemical evolution of the Universe.

**[Zn/H]:** The well-known draw back of using Fe II for abundance determination is the fact that this element is sensitive to depletion onto dust grains (Pettini et al. 1997). An alternative to overcome the dust depletion issue is provided by Zn, an element known to be only mildly depleted. The bottom panel of Figure 1.2 present the evolution of the [Zn/H] with redshift. In our sample of sub-DLAs, most of the Zn II lines are weak or undetected and thus we can only provide upper limits. In addition, the ionization correction in sub-DLAs is important for Zn II and thus the interpretation of the abundances are more complicated. We applied again the order ranking Kendall's test to the sub-sets of the Zn II sample (see Paper II). When considering both DLAs and sub-DLAs (and excluding all limits), we determine a slope $\alpha = -0.28 \pm 0.23$, i.e. slightly shallower than the one derived by Vladilo et al. (2000) and Dessauges-Zavadsky et al. (2001) ($\alpha \sim -0.3$) since the latter works loosely include sub-DLAs in their samples. Nevertheless, the significance of this results is low (correlation coefficient of –0.25 at 84.27% confidence level for a total of 40 abundances). Analyzing DLAs only leads to a slope $\alpha = -0.21 \pm 0.25$ for 36 systems. There are not enough Zn II measurements in the sub-DLAs range to allow such analysis. An important point, however, is the fact that the slope in the Zn II DLA sub-set ($\alpha = -0.21 \pm 0.25$), a tracer of true metallicity evolution, is not as steep as in the Fe II sub-DLA sub-set ($\alpha = -0.40 \pm 0.22$). This suggests that the evolution we probe in these latter absorbers is *not* due to the hidden effect of dust.

### *1.3.2 Weighted Mean Metallicity*

Figure 1.3 presents the column density weighted mean Fe II abundances of $n$ systems in redshift bins of $\Delta z = 1$ (solid bins) and in constant HI interval (dashed bins), for various sub-samples of quasar absorbers. Although more advanced statistical methods have been recently suggested (Kulkarni & Fall 2002), we choose to follow the prescription from Pettini et al. (1997):

$$[\langle \mathrm{Fe/H_{DLA}} \rangle] = \log \langle (\mathrm{Fe/H})_{\mathrm{DLA}} \rangle - \log\, (\mathrm{Fe/H})_{\odot} \tag{1.1}$$

where

$$\langle (\mathrm{Fe/H})_{\mathrm{DLA}} \rangle = \frac{\sum_{i=1}^{n} N(\mathrm{FeII})_i}{\sum_{i=1}^{n} N(\mathrm{H_{total}})_i} \tag{1.2}$$

Figure 1.3 presents the results of these calculations for different sub-set of quasar absorbers (see Paper II). The top panel includes all quasar absorbers (DLAs + sub-DLAs) as well as systems with N(HI) $> 10^{21.0}$ atoms cm$^{-2}$. The bottom panel shows DLA and sub-DLAs separately. We note that the evolution of $[\langle \mathrm{Fe/H_{DLA}} \rangle]$ is clearly more pronounced for sub-DLAs than for DLAs, but this result is not apparent when all absorbers with N(HI) $> 10^{19.0}$ atoms cm$^{-2}$ are considered. Indeed, in our sample the number of DLAs (72) is much larger than the number of sub-DLAs (17). On the contrary, in the Universe we expect the number of sub-DLAs to be up to 3 times (at $z \sim 4$) the number of DLAs (Péroux et al. 2002). Since high column density systems dominate the HI weighted mean metallicity, it will be important to increase the sub-DLA sample size to better probe $[\langle \mathrm{Fe/H_{DLA}} \rangle]$. Nevertheless, these results show that the HI column density weighted mean metallicity Fe II of sub-DLAs *do* evolve with redshift more markedly than for the DLA population. The dotted bins correspond to constant HI intervals and therefore present similar number of systems.

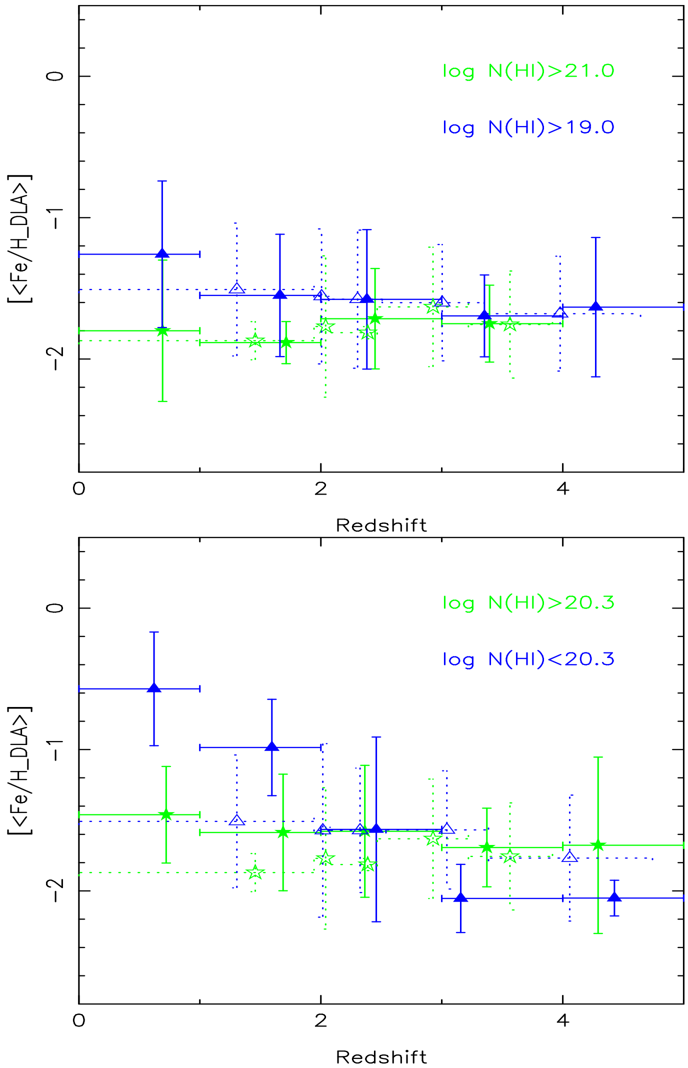


Fig. 1.3. HI column density weighted mean metallicities for various sub-sets of quasar absorbers. The dotted bins are for constant HI intervals and the solid bins are for constant redshift intervals. The evolution of $[\langle Fe/H_{DLA}\rangle]$ is clearly more pronounced for sub-DLAs than for DLAs, but this result is not apparent when all absorbers with N(HI) $> 10^{19.0}$ atoms cm$^{-2}$ are considered. Indeed, in our sample the number of DLAs (72) is much larger than the number of sub-DLAs (17).

They also present an increase of metallicity with decreasing redshift, showing that this result is not an artifact of the low number of sub-DLAs known at $z < 2$. Starting from a metallicity 1/100 solar at $z \sim 4.5$, the sub-DLAs evolve up to a metallicity 1/3 solar at $z \sim 0.5$. The ionization correction cannot explain the evolution observed since we have shown in Paper I that for [Fe II/HI], it *does not* exceed 0.2 dex. These results again reinforce the hypothesis where sub-DLAs better trace the global metallicity evolution and therefore should be

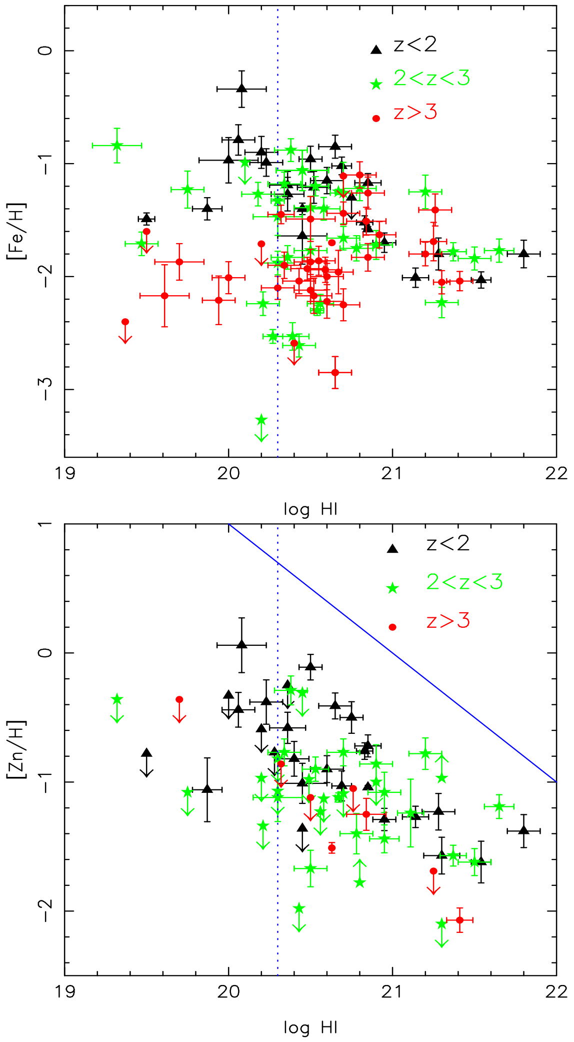


Fig. 1.4. [Fe/H] and [Zn/H] as a function of HI column densities in DLAs and sub-DLAs. The dotted line marks the DLA formal definition. In the bottom panel, the solid line corresponds to the "dust filter" proposed by Boissé et al. (1998), namely [Zn/H]+logN(HI) >21.

included in the quasar absorber's metallicity determination to obtain a complete picture of their abundances.

### *1.3.3 Metallicity Evolution with H* I *Column Density*

Figure 1.4 presents [Fe-Zn/H] as a function of HI column densities in DLAs and sub-DLAs for three different redshift ranges: $z < 2$, $2 < z < 3$ and $z > 3$ (see Paper II). In the top panel ([Fe/H]), the spread of values is larger at lower HI column densities. This suggests that we are sampling different class of objects or at least different parts of the same object as suggested by e.g. Boissier, Péroux & Pettini (2002). An other possibility is that dust is to play an important role, which will not affect all systems in the same way, but rather gradually according to say star formation histories. On the contrary, there is little spread in the [Fe/H] ratio at very high HI column densities (log N(HI)$>$ 21). It thus might be of interest to investigate the nature of these systems in particular and understand why their properties differ from the other quasar absorbers. This might indicate that systems with such column densities belong to one population of objects. More probably, the lack of apparent spread is the result of a bias against high column density, high metallicity absorbers due to their high dust content (Boissé et al. 1998). Indeed the bottom panel of Figure 1.4 shows that the observational bias noted by Boissé et al. in the HI versus [Zn/H] relation still holds (i.e. no data are situated above the [Zn/H]+logN(HI) $>$21 solid line). A direct dust diagnostic in sub-DLAs is not straight forward to make since Zn II is seldomly detected. Using the three Zn II available in our sample of 12 systems, we find that the [Zn/Fe] value is around 0.3-0.4 dex. This suggests that the amount of dust is not negligible although naturally there are too few detections to draw any firm conclusions. In addition, a study of absorbers issued from a radio-selected quasar sample (CORALS) does *not* indicate that a dust bias greatly affects DLAs studies (Ellison et al. 2001), but in the authors own words the conclusions are only tentative due to the limited size of the data set. Furthermore, in the range 20.0 $<$log N(HI)$<$ 21.0, i.e. the bulk of the data available, the high redshift objects are less evolved than the others. In any case, we find that the metallicity evolution of quasar absorbers is a strong function of the HI column density. In addition, we have shown that the ionization correction in Fe II (see Paper I) is similar within a group of systems with similar column densities. In the sub-DLA range, it will tend to increase the Fe II column density measured by 0.1-0.2, thus not affecting the apparent evolution.

## 1.4 Relative Abundances

The comparison of elemental ratios, independent of HI column densities as a function of metallicity is also very important. In Paper II, we concentrate in particular on the $\alpha$ (i.e. O, Si) over Fe-peak element ratios versus [Fe/H] metallicities, since this relation provides information on the star formation histories of quasar absorbers. The $\alpha$-elements are typical products of Type II supernovae, which are likely to dominate the early stages of galaxy formation. Fe-peak elements on the contrary are products of Type Ia supernovae, which play a role later on evolution stages. Therefore, high overabundances of $\alpha$-elements at low [Fe/H] indicates recent star formation rate, while solar $\alpha$-element abundances at low [Fe/H] suggests a lower star formation rate or bursts separated by quiescent periods. Nevertheless, the interpretation of these elemental ratios is once again complicated by differential depletion: Fe II and Si II are known to be depleted onto dust grains in different proportions while O I is expected to remain unaffected by dust depletion.

**[Si/Fe]:** Figure 1.5 shows that [Si/Fe] is similar in both DLAs and sub-DLAs, averaging around +0.5 dex. This value is typical of Galactic metal-poor stars and is a strong indicator of $\alpha$ enhancement if dust depletion does not play a major role. Nevertheless, the differential depletion of these two elements can lead to the same enhancement as the one observed.

**[O/Fe]:** O I is not often measured in DLAs, since the most predominant line, O I 1302, is often saturated. On the contrary, in sub-DLAs where the column densities are considerably smaller, this line is well suited for the abundance determination of oxygen. This element, which is not affected by dust depletion, is also a typical product of Type II supernovae. The

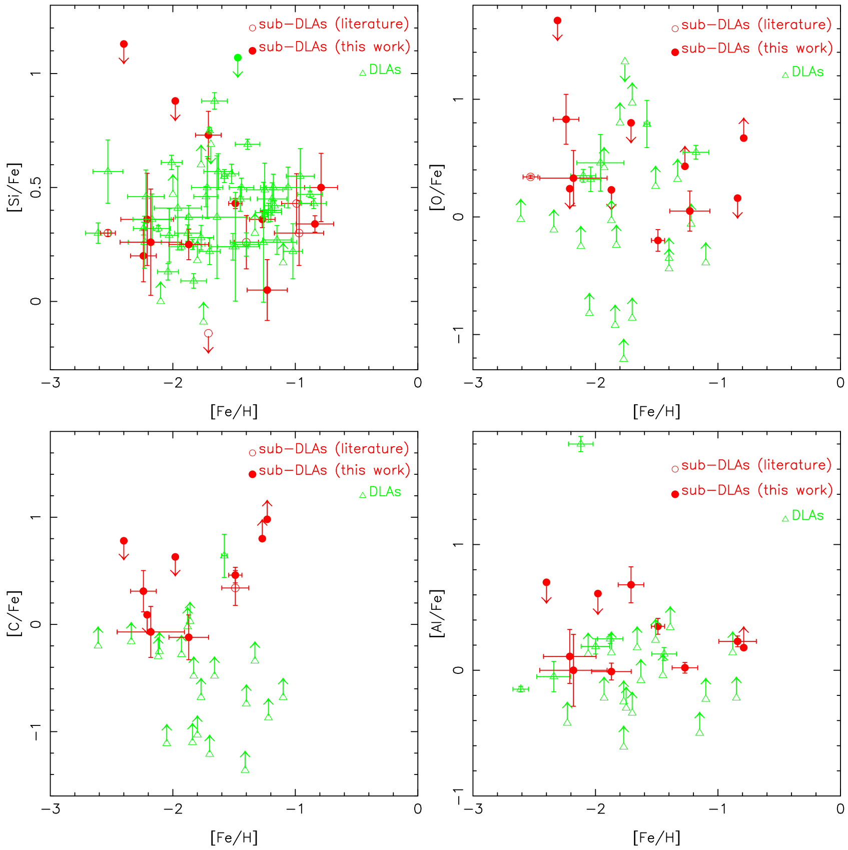


Fig. 1.5. [Si/Fe], [O/Fe], [C/Fe] and [Al/Fe] ratios as a function of metallicity. [Si/Fe] is similar in both DLAs and sub-DLAs. Sub-DLAs generally have low [O/Fe], some of which are sub-solar. But they are more over-solar than DLAs in [C/Fe] and [Al/Fe].

prospect of measuring O I in large samples of sub-DLAs means that we will have a good indicator of $\alpha$ over Fe-peak element ratios.

Figure 1.5 shows the evolution of the [O/Fe] ratio as a function of metallicity. In most cases, this ratio is larger in sub-DLAs than in DLAs (assuming the limits in the latter systems are significant), being sub-solar at high metallicities ([Fe/H]>-1.6). However, [O/Fe] are still over-solar at low metallicities. Similarly, Galactic metal-poor stars present an important enhancement comprised between 0.35 and 1. However in the case of high [O/Fe] ratio, one cannot decipher which from dust depletion or nucleosynthesis produces such high values. In the case of low [O/Fe] however, we know that the intrinsic values cannot be much smaller than the values observed.

**[C/Fe]:** For the same reasons as O I, the first comprehensive set of measurements of C II has been made in high HI absorbers. [C/Fe] is approximately solar in the majority of the Galactic stars. Previous studies of DLAs only allowed for lower limit determinations (see Figure 1.5), but measurements of C II in sub-DLAs provide a tracer of Fe-peak elements regardless of dust depletion. Both the [C/Fe] measurements and limits obtained in the sub-DLA ranges are well above the one derived in DLAs thanks to the lowest column densities. Some of the [C/Fe] ratios in sub-DLAs are clearly over solar, at the level of the overabundance observed in the two tentative [C/Fe] measurements in the DLAs. Since C is a mildly refracted element in the interstellar medium, these measurements provide our best indicator of the dust content of sub-DLAs. Indeed, although C and Fe do not have the same nucleosynthetic production, in the Milky Way stars C and Fe show identical behaviors, i.e. [C/Fe]=0. Therefore the deviation from zero observed in sub-DLAs are suggestive of either the presence of dust in these systems or a different behavior of C relative to Fe relatively to the Milky Way stars.

**[Al/Fe]:** The metallicity evolution of the [Al/Fe] ratio is presented in Figure 1.5. In DLAs, this ratio follows a trend similar to the one observed in metal-poor stars (Prochaska & Wolfe 2002). In the sub-DLAs cases, this ratio is strongly affected by ionization correction which will increase the amount the real abundance of Al with respect to that measure from Al II only. The [Al/Fe] ratio will consequently rise by a factor of 0.3 dex in the worst case (see Paper I). Again sub-DLAs are characterized by a mean [Al/Fe] elemental ratio larger than DLAs.

## 1.5 Conclusion

We have constructed and fully analyzed a homogeneous sample of 12 sub-DLAs. We study the chemical content of these absorbers in conjunction with DLAs from the literature. The metallicity of absorbers as traced by [Fe/H] shows a slightly more pronounced slope for sub-DLAs than for DLAs. We find that the evolution of $[\langle \mathrm{Fe}/\mathrm{H}_{\mathrm{DLA}} \rangle]$ might also be stronger for sub-DLAs than for DLAs. Abundance ratios for [Si/Fe], [O/Fe], [C/Fe] and [Al/Fe] appear to resemble abundance ratios observed in DLAs. The question thus remains open whether the two classes of objects have similar chemical evolution histories or whether there are objects with different ages and star formation histories but in a similar stage of chemical evolution. Finally, this data sample provides the first comprehensive sets of measurements of O I and C II in high H I column density systems.

**Acknowledgments**

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