Chemical Abundances in High-redshift Neutral Clouds

Paolo Molaro

Abstract. Neutral hydrogen clouds with high column density detected towards distant quasars are unique probes of elemental nucleosynthesis and chemical evolution in the low metallicity regime. They provide measurements for several elements at very early times which are unfeasible in other astrophysical environments. Comparison between refractory and non-refractory elements provides evidence for the presence of dust, and the recently measured Ar probes photoionization. A prominent characteristic is the dominance of a solar abundance pattern, which is somewhat unexpected at low metallicities. It is argued that this property and Nitrogen observations can be used to constrain the age of the Damped Lyα systems and the epoch of star formation.

1 Introduction

Quasar absorption systems characterized by a large hydrogen column density, \( \log N(HI) \geq 20.2 \text{ cm}^{-2} \) (hereinafter DLAs), are observed at all redshifts up to \( z \approx 4.5 \) (Dessaugues-Zavadsky et al 2001) although there is some evidence for a lack of large HI column density systems for \( z \geq 4 \) (Peroux et al 2001). DLAs are the largest reservoir of neutral hydrogen and there is little doubt that they are the progenitors of the present day galaxies. However, the main galactic population which originates the DLAs has still to be clearly identified. At low redshift deep imaging has revealed a heterogeneous population of dwarfs, low surface brightness, irregulars and also spirals galaxies (Le Brun et al 1997, Rao & Turnshek 2000).

Some sort of chemical information is available for almost half of the \( \approx 180 \) DLAs presently known. Frequently measured ions are SiII, FeII, CrII, ZnII, NiII, AlII, MnII, TiII, while there is relatively less information for elements such as SII, Ni ArI, PII, and OI whose useful transitions are mixed and often blended by the intervening Lyman forest. Recently, the D/H ratio has also been successfully measured in a DLA (Levshakov et al 2002). Abundances in the DLAs can be rather accurate with errors of the order of 25% - 10%, or even better in case of optically thin lines and simple velocity structure. There are no other techniques applied to the high redshift universe where chemical abundances can be obtained with comparable precision. However, different elements show different sensitivities to the radiation field, or affinity with dust, which somewhat confuses the nucleosynthetic pattern and complicates the interpretation of the observed abundances.
2 Dust, Argon and ionization

The presence of dust in the clouds affects the abundance of those elements which are locked up into dust grains and are therefore depleted from the diffuse phase. Several indications suggest the presence of dust in DLAs. Pettini et al (1997) pointed out that Fe and Cr are generally deficient in comparison to the undepleted Zn, as is found in the dusty Galactic disk and at variance with what is observed in the metal poor stars of the Galactic halo where Zn tracks Fe closely. We note here that in DLAs iron is always found slightly more deficient than Cr, which may indicate the presence of a differential depletion of the two elements as it also found in warm interstellar clouds of our own Galaxy (Savage and Sembach 1996). Hou et al (2001) found that the abundances of refractory elements anti-correlate with the elemental column density, which mimics the well known pattern between these elements and the hydrogen column density observed in the Milky Way. New evidence for the presence of dust is provided by the few systems where molecular hydrogen has been detected. Levshakov et al (2002) found that the fraction of molecular hydrogen increases in the DLAs showing more dust-depletion inferred from the [Fe/Zn] ratios, as expected since dust is needed in the process of H₂ formation.

The large hydrogen column densities shield efficiently the clouds from the surrounding IGM radiation field (Viegas 1995). Thus, DLAs are essentially HI regions with the lower ionization elements as the dominant state. High ionization species such as CIV and SiIV are often observed but show different velocity structure and originate quite likely in different regions. Recently it has been pointed out that AlIII and AlIII have similar profiles suggesting the presence of HII interfaces. However, Vladilo et al (2001) showed that even when such interfaces are accounted for, the corrections remain negligible for all elements with the possible exception of possibly Al. A radically different model where the DLAs are an ensemble of neutral metal-free gas and ionized gas containing metals has been proposed by Izotov et al (2001). These models foresee significant ionization and can be tested with Argon, which has been recently measured in a couple of DLAs (Molaro et al 2001; Levshakov et al 2002). Argon has a photoionization cross-section which is ≥10 times higher than of HI and therefore is very sensitive to ionization effects (Sofia and Jenkins 1998). Space observations showed that in the LISM the (Ar/H) gas-phase is below solar by −0.3 to −0.6 dex varying with the line of sight. Argon is not expected to be depleted in the interstellar medium and the observed deficiency has been interpreted by Jenkins and Sofia as due to partial ionization by UV stellar radiation. The fact that the Ar abundances in the two DLAs where Ar has been measured are almost in line with the abundances of O, S and Si, requires that ionization effects are relatively unimportant. In fact, by applying the Izotov et al correction to Ar would result in an Ar overabundances by one dex or more, which is quite unlikely. At the same time these measures imply that in this DLA no intense star formation is taking place along the line of sight. New measures of Ar in other DLAs
would be of great importance for probing general ionization effects either due to the intergalactic radiation field or to star forming regions inside the clouds themselves.

3 The chemical pattern and the (S/O), (Ar/O) ratios

Once the effects of ionization and dust are considered it is possible to address the issue of the presence of a specific chemical pattern for the DLAs. The ratio between $\alpha$ elements and the iron-peak elements, which is related to the relative contribution of Type II and Type I supernovae, is a key piece of information for tracing back the chemical history. The early works focussed on the fact that the $[\text{Si}/\text{Fe}]$ ratio is $\approx 0.4$ on average, as is observed in the Galactic halo stars, and this was readily interpreted as the signature of Type II SN. However, a similar ratio is observed also in the warm phase gas of the LISM, and the former interpretation is valid only in complete absence of dust, which we regard as unlikely. Fig 1 shows the $[\text{Si}/\text{Fe}]$ versus the $[\text{Fe}/\text{Zn}]$ ratios. The strong correlation between the two quantities is very suggestive of the presence of differential depletion of Fe relatively to both Si and Zn. The intercept for $[\text{Fe}/\text{Zn}]=0$, gives $[\text{Si}/\text{Fe}] \approx 0.1$, providing evidence for only a mild enhancement of the $[\text{Si}/\text{Fe}]$ ratios in the less dusty clouds. It is also rather interesting to note that both the behaviour and the range of the $[\text{Si}/\text{Fe}]$ and $[\text{Fe}/\text{Zn}]$ ratios in the DLAs are similar to those observed in isolated Galactic clouds presented by Lew Hobbs in this conference.

Different approaches have been followed to resolve the degeneracy in the interpretation of the $[\text{Si}/\text{Fe}]$ ratio (Molaro 2002). Some authors have tried to correct for dust (Vladilo 1998), or considered only systems showing little evi-
Figure 2: The log(S/O) in the DLAs (diamonds). The small exagons are the BCGs from Izotov and Thuan (1999), with the mean dispersion shown by the dotted line.

Evidence for dust (Pettini et al. 1999) or considered only non-refractory elements such as the [S/Zn] (Centurion et al. 2000). The picture that is emerging favours a variety of chemical patterns with both halo-like and solar chemical patterns present in DLAs. The latter, which are somewhat unexpected on theoretical grounds are in fact those more frequently found. Solar ratio at low metallicity requires that the yields of SNe Ia have already become effective in determining the global metallicity of the system. This can be achieved either with a slow SFR or from a burst of SF followed by a long quiescent period in which SNe Ia evolve (Matteucci et al. 1997). If the relatively modest $\alpha$ enhancement is due to the action of SNe Ia, there are at least two important implications. The first is that SNe Ia are not suppressed at low metallicity as argued by Nomoto and collaborators. The second is that the epoch of star formation in the systems has to be anticipated to cope at least with SNe Ia lifetimes and subsequent elemental mixing.

Henry and Worthey (1999) pointed out that the observed ratios of (S/O) and of (Ar/O) are found to be independent from metallicity in a large variety of objects including the Milky-Way, HII spirals and Blue Compact Galaxies (BCG). New UVES-VLT observations provided for the first time information for these three elements so that these abundances can be discussed in the same context. The log(S/O) ratios in the DLAs, shown together with those of the BCGs in Fig. 2, taken from Izotov & Thuan (1999) are indistinguishable from the BCGs, and the same occurs for the log(Ar/O). The universal constancy of the log(S/O) and log(Ar/O) ratios found in different galaxies is extended now also to the DLAs, at least in the few cases where such measures have become available, and probed to an even lower value of log(O/H) + 12. This is partic-
ularly significant considering that DLAs and BCGs in the local universe may have formed at totally different epochs. Since the O yields are more sensitive to progenitor mass than S and Ar, the constancy in the ratios between these $\alpha$ elements has been interpreted by Henry & Worthey (1999) as evidence for a universal IMF in different galaxies, and this argument can be now developed to include also the DLAs.

4 Special elements: Phosphorus & Nitrogen

Phosphorus is a recent entry in the set of elements measured in the DLAs with 3 measures reported in the systems towards QSO 0000$-$2621 (Molaro et al 2001) GB1759+7539 (Outram et al 1999) and QSO 0347$-$3819 (Levshakov et al 2002). Phosphorus cannot be measured in halo stars and DLAs offer a unique site where it can be measured at metallicities significantly lower than solar. The $^{31}\text{P}$ is an odd-element which is likely produced by $n$-capture in C and Ne shell burning. In the dust free DLA towards QSO 0000$-$2621 phosphorus is found slightly below iron, $[P/Fe] = -0.2$, which requires a sort of mildly metallicity dependent yields to arrive at solar values later on. The relative ratios of P with the closeby nuclei S and Si, $[P/Si, S]$ = $-0.3$, show evidence for a mild odd-even effect, but it is somewhat lower than what is predicted by the theoretical models of Limongi et al (2000). P is not depleted in the LISM and, once the nucleosynthetic properties of this element are better defined with additional observations, it may become a useful proxy for Zn and a potential tracer of the metallicities for very high redshift damped systems where Zn is difficult to detect.

The available Nitrogen measures in the DLAs are shown in Fig. 3 where the log($N/O$) versus log $O^{+12}$ are plotted. The N observations are taken from different sources as described in the caption. O is directly measured in only 3 DLAs towards QSO 0000$-$2621, BR J0307$-$4945 and QSO 0347$-$3819. So that for the remaining ones we use S as a proxy for O. Nitrogen has a rather complex nucleosynthesis. Its production occurs mainly in intermediate mass stars with 4$-$8 $M_\odot$, which undergo HB burning and expel large amounts of primary N at low $[\text{Fe/H}]$ and secondary-tertiary N at higher metallicities. A primary production at low metallicities by massive stars with M$>$8 $M_\odot$ has also been suggested. The theoretical curves corresponding to these different scenarios are shown in the figure, together with the measurements in the Blue Compact Galaxies by Izotov and Thuan (1999). As it is possible to see from the figure the DLAs data points show values close to the theoretical curve for secondary production and other values in correspondence of the theoretical curve for primary behaviour. In particular, in some DLAs log($N/O$) is much lower than any other measurement in the BCGs. Izotov et al argued that ionization effects may lower the NI/SII ratios, and therefore the $N/O$, if S is taken as a proxy for O. However, the new direct oxygen measurements show that this is not the case since the argument does not apply to OI. The low
Figure 3: Curves are for secondary production only (bottom), primary production in $1 < M_\odot < 8$, and primary for $M_\odot > 8$ (top). Data points are from Centurion et al (1998 and unpublished), Ellison et al (2001), Dessauges-Zavadsky et al (2001). The small diamonds are the BCGs from Izotov & Thuan (1999).

$log(N/O) = -2.4$ in BR J0307$-4945$ obtained from a direct measure of O shows that low values of $log(N/O)$ are real and provides some evidence against the possibility of a primary origin of N in massive stars.

The observed scatter can be interpreted as due to the delayed release of N relatively to O. For instance only 6 Myrs are required for a 25 M$_\odot$ star to release O, while N requires longer timescales, i.e. about 250 Myrs for a 4 M$_\odot$ star. Within this model the $log(N/O)$ measurements offer the way to constraint the ages of the clouds. The low-$log(N/O)$ cases would correspond to young objects, $\leq 250$ Myrs, while high $N/O$ to older systems. In support of this interpretation there is also a hint of correlation between the $log(N/O)$ and the $\alpha$-element enhancement. DLAs with low $\alpha$-enhancement such as QSO 0000$-2621$ or QSO 0930+2858 show a tendency for high $N/O$ abundances, while low $N/O$ values are observed in $\alpha$-element enriched DLAs such as the one towards QSO 0347$-3819$. The former two DLAs are at $z_{abs} \approx 3.4$ and require the epoch of star formation at earlier times to produce both considerable amount of N and to make the TypeIa yields effective in reducing the $\alpha$ over iron-peak ratios. Assuming an indicative time interval of 500 Myrs the star formation is placed at $z \geq 5$, for a $\Lambda$CDM cosmology with $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $\Omega_b = 0.05$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. Thus it may well be possible that at high redshift some neutral clouds are rather passive systems chemically enriched by an earlier stellar population. This would also explain the *normal* Ar abundances, the
absence of detectable Lyα flux and the apparent lack of chemical evolution of DLAs with redshift.

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