CNO in the Universe

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CNO abundances in the Damped Lyα clouds

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Abstract. Damped Lyα clouds provide information on the chemistry of distant and metal poor regions of the universe. In these clouds for observational difficulties N and O are among the last elements to be measured, and C has still to be measured with precision. In combining the extant CNO abundances, we avail of a sample which includes 33 N measurements or significant limits, a dozen of O measurements, and only few tentative measurements for C. O is found to track both S and Si rather closely without signatures of any peculiar behaviour and the few [O/Zn] ratios available show a mild α/iron-peak enhancement which reinforces earlier evidence. The few tentative C measurements point to roughly solar [C/Zn] and [C/Si] ratios.

N abundances are rather complex with N/α ratios showing a bimodal distribution. The majority of the values form a first plateau at [N/Si]=−0.82 (± 0.13) and about 25 % form a second plateau at [N/Si]=−1.45 (± 0.05). The high values are at the level of the Blue Compact Dwarfs but they extend further towards lower metallicities. The lower plateau is a new feature of DLAs with no other counterparts. The two plateaux are found for different values of the N abundance with the transition at [N/H]≈ -3.0. We argue that this results from the delayed release of N between massive and intermediate mass stars with the lower plateau produced by massive stars (M≥ 8 M☉ only, which accounts for the small dispersion. The systems on the lower plateau are relatively young and imply a continuous formation of the DLAs. While the interpretation of the N/O in the DLAs needs to be confirmed, these observations could ultimately prove crucial for the interpretation of the early N nucleosynthesis.

1. Introduction

In the previous ESO workshop dedicated to the Production and Distribution of C,N,O elements held in Garching in May 1985 the information on CNO elements coming from absorption systems along distant QSO were just at the starting point and the first tentative results were reviewed by Max Pettini. We had to wait for one decade for the first N measurement in a damped Lyα system (DLA), even longer for O, and the time for C has probably not arrived yet.

DLAs are intervening absorption systems with large hydrogen column densities particularly appropriate for the determination of accurate chemical abundances. Typical abundances are −2.5< [Fe/H]< −1 with a moderate chemical
evolution. The increase in metallicity is of the order of 0.3 dex per unit of decreasing redshift and suggests that DLAs do not trace the population of galaxies responsible for the bulk of star formation in the universe. A floor of abundances at about -2.5 is observed at all redshifts up to z=5.28 (Songaila et al 2002) quite suggestive of a prompt enrichment at very early phases. At redshift 5 the age of the universe is about one billion years and there is hope to find young systems where we can better recognize the imprints of the first generation of stars.

The observed abundances are gas phase abundances and in general suffer from possible dust and ionization corrections. The large neutral hydrogen column densities of the DLAs shield the clouds from the IGM field effectively. New evidence comes from the recently measured Ar which is particularly sensitive to ionization effects. The [Ar/Si] is often very close to solar or mildly deficient, which rules out significant ionization (Molaro et al 2001, Vladilo et al 2003). Dust is definitely present in the DLAs as revealed by a number of indications such as the systematic deficiency of Fe compared with Zn, the anti-correlation between refractory elements and the elemental column density, the correlations between [Fe/Zn] and H$_2$ and the correlation between [Si/Fe] and [Zn/Fe] (Molaro 2001 and references therein). CNO elements are all mildly refractory and are virtually free from this complication (Savage & Sembach 1996).

The determination of the abundances of the CNO elements have proven to be very challenging. This because the most accessible lines for CNO are either saturated, despite the low metallicities of the DLAs, or they fall in spectral regions strongly contaminated by the neutral H absorptions of the Lyα forest. The OI 1302 Å line is generally nicely placed redwards the Lyα forest but is always found strongly saturated. Conversely the OI 1355 Å has never been detected and provides, together with the previous line, high and low bounds to the oxygen abundance. A similar situation holds for C where the only suitable lines are the CII resonance lines at 1334.53 Å and CII 1036.33 Å which are heavily saturated in all DLAs. A more favourable circumstance is found for NI which has several multiplets offering a relevant dynamical range in the line strengths. However, the more accessible NI multiplets are λλ 1134.16, 1134.42, 1134.98 Å and 1199.55, 1200.22, 1200.71 Å which fall in the Lyα forest.

2. Oxygen

First measurements of O were performed at last through observations of OI 925 Å and OI 950 Å in the Ly-α forest, associated with the $z_{abs}$=3.39 DLA towards QSO 0000-2621 (Molaro et al 2000). Partial contamination by hydrogen clouds is taken into account using a model for the absorber constructed on lines falling redwards the Ly α forest. This approach has been followed in the DLA at $z_{abs}$=4.49 towards the J 0307-4945 (Dessaugues-Zavadsky et al (2001), and towards QSO 0347-381 through the measurement of a dozen OI lines (Levshakov et al 2002). Probably the best available measure due to the simplicity of the absorber and to the quality of Keck data has been realized by Prochaska et al (2001) in the DLA at $z$=2.844 towards QSO 1946+76 were several OI lines have been detected allowing an OI measure of log(OI)=14.819 ± 0.007. Pettini et al (2002) targeted few systems with low elemental abundances and low HI column density and succeeded in measuring O from an almost unsaturated OI 1302 Å in
Figure 1. \([\text{O/Zn}]\), filled circles, or \([\text{O/Fe}]\), empty circles

A couple of DLAs. OI measurements have been provided for other DLAs towards QSO 1202-0725 (D’Odorico et al 2003) QSO 2059-360 (Dessaugues-Zavadsky et al 2003), QSO 2243-6031, QSO 1104-1805 (Lopez et al 1999, Lopez et al 2002). A total of a dozen of systems with some information on the O abundance is presently available.

The \([\text{O/Zn}]\) and \([\text{O/Fe}]\) are shown in Fig 1 with filled and empty circles respectively, and the solar O abundance taken from the recent revision by Holweger (2001). O and Zn do not require any dust correction and two \([\text{O/Zn}]\) reveal a moderate enhancement in \(\alpha\)-elements at the level of 0.2 dex or so, while in one case the ratio is of \(\approx 0.6\) dex. There are also few \([\text{O/Fe}]\approx 0.2\) which give stringent values. Most likely these systems are dust-free, as QSO 0000-2621 where \([\text{O/Zn}]\approx [\text{O/Fe}]\). If dust is present the effect is to increase the intrinsic Fe abundance and further lower the \([\text{O/Fe}]\) ratio. Overall there is a low overabundance of O relative to Zn, which is consistent with previous indications obtained from \([S/Zn]\) measurements or from \([\text{Si/Fe}]\) once expected dust depletion is accounted for (Centurión et al 2000, Vladilo 2001).

In the sample there are two DLAs with O and S measured. The \([\text{O/S}]\) ratio is \(\approx 0\) showing that there is no particular behaviour of O with respect to the other \(\alpha\) elements. Si is generally available but it is a refractory element and may be partially depleted onto dust grains. In all but two DLAs the \([\text{O/Si}]\) is found \(\approx 0\), which implies that Si is only moderately locked up into dust grains in DLAs. If this is the case it is rather interesting to consider the behaviour of Si with comparison of the undepleted element Zn. The average value of the 26 DLAs with both elements measured is \(<[\text{Si/Zn}]=-0.07 \pm 0.2\), providing additional evidence of a moderate, if any, enhancement of \(\alpha\)-elements. Overall the low \(\alpha\) over iron-peak element ratio appears as a prominent characteristic of the DLA. Cases of genuinely \(\alpha\) enhancement exist such as the DLA towards J0347-3819 but they look as an exception rather than the rule (Levshakov et al 2002).
3. Carbon

In the survey by Prochaska et al 2001 there are 14 lower limits of C abundances, all obtained from the saturated CII 1335 Å line. CI is observed in a few cases but it traces very cool gas and being strongly ionised is not very informative of the total C. Levshakov et al (2002) and Lopez et al (2002) through detailed modelling of all absorption features in the effort to account for the saturation of the CII lines, claimed measurements with a reasonable error. In these two DLAs Zn is also measured and for both [C/Zn]≈0.25, which suggests a rather normal behaviour. Highly supersolar [Si/C] values at the level of 0.5-1.5 dex are predicted by PopIII SNe, hypernovae or pair-instability SNe of very massive stars (Umeda and Nomoto 2001) for which there is no evidence in DLAs where [Si/C] is solar. Better prospects to measure C rely on the observations of very high redshift DLAs if abundances finally decrease, or in the class of sub-DLAs (cf Dessauges-Zavadski, these proceedings). In the z_{abs}=4.383 DLA towards BR 1202-0725 the CII line is found only moderately saturated and [C/Fe]=−0.03 (±0.15) and [Si/C]=0.15 ±0.11 are derived (D’Odorico et al 2003). In the z_{abs}=5.8 DLA towards SDSS 1044-0125 identified by Songaila and Cowie (2002), in which log N(HI)= 20.5 cm$^{-2}$ and [Fe/H]= −2.65, the CII 1334 transition is unsaturated providing a [C/Fe]=−0.6, which suggests a possible drop in the C abundance at very high redshift. At redshift about 6 we may be within 100 million years from the epoch of star formation, which puts tight constraints to the C build-up processes (Molaro et al 2003).

4. Nitrogen

Among the CNO triplet N was the first to be observed. In their first attempt Pettini et al (1995) failed in detecting the element in the DLA towards QSO 2348-146 but established a very low upper limit at [N/H]<−3.15, which has been slightly improved with Keck observations to [N/H]<−3.28 (Prochaska and Wolfe 1999). This failure was followed by the detection of N in the DLA at z_{abs}=3.39 towards QSO 0000-2621 and towards QSO 1331+17 with the N abundances [N/H]=−2.77 ± 0.17, and [N/H]= −2.73, respectively (Molaro et al 1996, Kulkarni et al 1996). The three DLAs showed a difference by ≈ 0.6 dex in their [N/Si] ratios and introduced since the beginning the notion of significant scatter in the [N/Si] abundances. It is just amazing that this became evident with the first two systems and that the first one to be observed was a Nitrogen poor system.

The early findings were confirmed and extended on larger samples, of which the most important for the number of objects are those of Centurión et al (1998), Lu et al (1998), Pettini et al (2002) and Prochaska et al (2002). In the following we use the complete and updated compilation of Centurión et al (2002, Table 9) who contributed with some new N observations as well. The sample of N observations or limits now comprises 33 systems, out of which 28 have at least one of O, Si or S measured and provide informative ratios.

In Fig 2 the [N/α] are plotted versus [α/H]. For the α element either of O, S or Si are taken in the order. As discussed in the previous section they trace each other rather well so that it does not matter very much which α element is used. The data for the BCG are also shown in the figure with smaller symbols.
The data show a peculiar pattern. Most of the sample form a plateau at $[\text{N/Si}] \approx -0.82 (\pm 0.13)$, while few points show lower N/O ratios. The possibility of a gap between low and high values rather than a pure scatter has been pointed out by Prochaska et al (2002) who suggested a bimodal distribution. To the two measurements and to one upper limit with low N/O considered originally by Prochaska et al we add the value towards J0307-4945. Dessauges-Zavadsky (2001), rejected by Prochaska et al (2002) for a possible ionization effect, and the most recent one towards QSO 2059-360 from Dessauges-Zavadsky et al (2002). Two new upper limits quite separate from the high values and consistent with a bimodal distribution are provided by Pettini et al (2002). The average of the four determinations is $[\text{N/Si}] \approx -1.45 (\pm 0.05)$, strongly suggestive of a second plateau even with a narrower dispersion. The low N/O values are mostly observed at the lowest metallicities, but with an overlap over the higher plateau in the range $-2.0 < [\text{O/H}] < -1.5$. In Fig 3 the plot of $[\text{N/H}]$ versus $[\text{Si/H}]$ clearly shows the primary-like behaviour of N in both plateau.

The high N/O values look as an extension of the BCG towards lower metallicities and give definitive evidence of a plateau, which was not so clear from the BCG only. The sharing of the same N/O between DLAs and BCG suggest that the two populations experienced similar chemical evolution.

N synthesis is thought to occur in Intermediate Mass Stars (IMS) (4 to 7 $M_{\odot}$) through Hot Bottom Burning in the AGB phase. The nucleosynthesis by IMS implies a delay in the N production when compared to that of O as well as a sensitivity of N production to the low mass regime of the IMF. The general interpretation of the observed data is that N is primary at low metallicities and secondary at high metallicity (Henry et al 2000). The Henry et al model is able to reproduce the plateau by reducing the SFR and thus by preventing the rapid O build up by massive stars. For high SFR the elemental build up is fast and the system enters very soon in the secondary production regime without undergoing a primary behaviour at all. Thus the presence of an extended plateau in the N/O
suggests low SFR in the DLA, which may also explain the failure of imaging DLA galaxies. The lower plateau is a new feature of DLA with no other counterparts. Izotov et al (1999) argued that the low N/Si were resulting from an inflated Si column density by additional Si formed in the ionized region. However, the recent direct O measurements provided five genuine low N/O obtained by means of truly oxygen observations, shown in Fig 2, which rule out such possibility.

4.1. About the origin of the low N/O plateau

Low N/O values have been interpreted in a context of a delayed N released model as the result of a relatively young age (Molaro 2001, Pettini 2002,) or as being the system observed close to a recent episode of star formation (Lu et al 1998, Centurión et al 1998). According to Henry et al the necessary scale time to attain a significant N production by IMS is of at least 250 Myrs. It is therefore possible that DLAs are caught in the early formation times when the IMS had not yet expelled their N. However, as Prochaska et al pointed out one should expect to find values everywhere below the plateau and it is difficult to account for the fact that the low N/O show a characteristic value at [N/O]=-1.4. In the low N/O plateau the scatter is so small that these systems are unlikely in a transient phase towards the upper plateau.

A second possibility to explain the low N/O values is a variation in the IMF. A top-heavy IMF or an IMF truncated below a mass threshold of \( \approx 5 \, M_\odot \) which exclude low mass stars has been suggested by Prochaska et al (2002) . However, it remains unclear what produces the change in the IMF. As discussed by Henry at this meeting it is rather appealing to think that it is related to the formation of PopIII stars.

A further possibility is that we are dealing with variable N yields as a function of the metallicity since the low N/O values occur preferably at the lowest metallicities. This may affect the efficiency of the 3rd dredge-up or of the mass-loss rate along the AGB phase somewhat altering the characteristic N.
Figure 4. [N/Si] versus [N/H]

yields of the IMS. However, it is not clear how to account for the fact that both high and low N/O values occur at equal metallicities.

Fresh clues for the interpretation of the low N/O plateau can be obtained plotting the [N/Si] values with respect to [N/H] as shown in Fig 4. The distribution does not show a degeneracy with the metallicity any longer but reveal two different regimes with a transition occurring at [N/H] ≈ −3. The low N/O are in the region with [N/H] < −3 and the high N/O for [N/H] > −3. Since there is no obvious link between N yields and the amount of N content in the systems we think that what we see is most likely a temporal effect. In fact, since the O abundance is more sensitive to the SFR history while N depends from IMS evolutionary time-scales, N could be a better indicator of the age of system. Thus the two regimes reflect probably two epochs.

We propose that the higher plateau is produced by IMS after they had time to evolve and release their N, while the lower plateau is produced by more massive, namely M > 8 M\(_\odot\), and relatively younger stars. At later times (or [N/H] ≈ -3) the contribution from the massive stars is overwhelmed by that from the IMS. In fact a hint of connection between the two plateaux can be recognized in the two DLAs which lie just below the primary plateau at [N/Si] ≈ -1.1 and [N/H] ≈ -2.8 as shown in Fig 4. No objects are expected to be found below the low N/O plateau and therefore it would be rather crucial to improve the three upper limits to the levels at which they can probe the existence of the plateau. We note that for the DLA at z\(_{\text{abs}}\)=2.456 towards QSO 1409+095 the upper limit is only 0.17 dex above the plateau and in fact there is a hint of the presence of the NI 1200 Å lines (Pettini et al 2002, their Fig 2).

Standard models do not predict N synthesis by massive stars but the situation is far from being settled (Heger and Woosley 2002). Chieffi et al (2001) found that also Pop III stars of intermediate mass do experience thermal pulses and the third dredge-up arguing that stars with primordial composition are sources of C and N. If we take the models of Limongi and Chieffi (2002) for zero metallicity, computed with FRANEC code CF85, with no mix of the H shell
and a mass loss parameter of $\eta=6$, and we integrate with a Salpeter IMF over the whole mass spectrum 4-80 $M_\odot$ we get a $[N/O]=-0.85$, namely very close to the higher plateau. On the other hand the integration in the mass range between 15 and 80 $M_\odot$ gives $[N/O]=-1.5$, which is very close to the lower plateau. The models for low metallicity stars with rotational mixing or overshooting of Meynet and Maeder (2002) predict N production for massive stars and can also reproduce the ratio observed in the lower plateau. The observations of DLAs might actually offer crucial guidelines for N production in massive stars.

The fraction of systems on the two plateaux and their relative abundances can be envisaged as two important tests to probe the origin of the two plateaux. Presently the fraction of the systems forming the low N/O plateau is of 25% of the total. We can compute the expected ratio assuming that we need roughly 250 Myrs for significant N production and computing the age of the systems from the formation epoch to the observed redshift by means of a look- back time $t = 0.538[(1+z)/10]^{-3/2}$ Gyrs. The formation epoch is unknown but to get the observed statistics we need to place it at $z \approx 4$, which is quite conceivable. Few systems with low N/O have $z_{abs}$ of about 2-3 suggesting a rather continuous formation of the DLA. The case of QSO 1202-0725 with high N/O and $z_{abs}=4.38$ is rather remarkable and pushes back the epoch of star formation considerably. If the synthesis of N observed by IMS require about 0.25-0.5 Gyrs then the time of star formation is shifted to a redshift greater than six.

An $\alpha$- element enhancement over iron-peak element is expected in the case that massive stars are responsible for the low N/O plateau. Fe is produced considerably by Type Ia SNe and should lag O similarly to N. In Fig. 5 the $[\text{Si/Zn}]$ and $[\text{Si/Fe}]$ are plotted versus $[\text{N/Si}]$. Unfortunately there are no $[\text{Si/Zn}]$ values for DLAs in the low N/O plateau and the $[\text{Si/Fe}]$ are between 0.2 and 0.4 which is rather common among the DLAs. In absence of dust these ratios would imply an $\alpha$ enhancement, but unfortunately there is no Zn information, and the test is not presently conclusive.
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