A&A 451, 19–26 (2006)
DOI: 10.1051/0004-6361:20054328

Astronomy & Astrophysics

The most metal-poor damped Lyman α system at $z < 3$: constraints on early nucleosynthesis

P. Erni[1], P. Richter[1], C. Ledoux[2], and P. Petitjean[3,4]

[1] Argelander-Institut für Astronomie⋆, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
e-mail: perni@astro.uni-bonn.de
[2] European Southern Observatory, Alonso de Córdova 3107, Casilla 19001, Vitacura, Santiago, Chile
[3] Institut d'Astrophysique de Paris, CNRS, 98bis Boulevard Arago, 75014 Paris, France
[4] LERMA, Observatoire de Paris-Meudon, 61 avenue de l'Observatoire, 75014 Paris, France

Received 9 October 2005 / Accepted 27 January 2006

ABSTRACT

To constrain the conditions for very early nucleosynthesis in the Universe we compare the chemical enrichment pattern of an extremely metal-poor damped Lyman α (DLA) absorber with predictions from recent explosive nucleosynthesis model calculations. For this, we have analyzed chemical abundances in the DLA system at $z_{\rm abs} = 2.6183$ toward the quasar Q0913+072 ($z_{\rm em} = 2.785$) using public UVES/VLT high spectral resolution data. The total neutral hydrogen column density in this absorber is $\log N(\text{H I}) = 20.36 \pm 0.05$. Accurate column densities are derived for C II, N I, O I, Al II, Si II, and Fe II. Upper limits are given for Fe III and Ni II. With [C/H] = -2.83 ± 0.05, [N/H] = -3.84 ± 0.11, and [O/H] = -2.47 ± 0.05, this system represents one of the most metal-poor DLA systems investigated so far. It offers the unique opportunity to measure accurate CNO abundances in a protogalactic structure at high redshift. Given the very low overall abundance level and the observed abundance pattern, the data suggest that the chemical evolution of this DLA system is dominated by one or at most a few stellar generations. With reference to numerical model calculations, the chemical abundances in the DLA system are consistent with an enrichment from a single starburst of a zero-metallicity population of massive stars ($\sim$10−50 $M_\odot$) exploding as core-collapse Supernovae (SNe), i.e., the classical type II Supernovae (SNe II), and possibly as hyper-energetic ($E > 10^{51}$ erg) core-collapse Supernovae, so-called Hypernovae (HNe), as well. In contrast, models using non-zero metallicity progenitors or other explosion mechanisms, such as pair-instability Supernovae (PISNe) or type Ia Supernovae (SNe Ia), do not match the observed abundance pattern. Comparing our results with recent estimates for the global chemical evolution of the intergalactic medium (IGM) and early galactic structures shows that the observed metal abundances in the DLA system toward Q0913+072 are only slightly above the level expected for the intergalactic medium (IGM) at $z \approx 2.6$, but significantly lower than what is expected for the interstellar medium (ISM) in galaxies at that redshift. This implies that this DLA system has recently condensed out of the IGM and that local star formation in this protogalaxy has not yet contributed significantly to the metal budget in the gas.

Key words. galaxies: quasars: absorption lines – galaxies: quasars: individual: Q0913+072 – cosmology: observations – cosmology: early Universe – stars: formation – galaxies: abundances

1. Introduction

Recent theoretical studies (e.g., Omukai & Palla 2003) predict that the first (Pop III) stars must have been very massive ($\sim$100−600 $M_\odot$), thus indicating an initial mass function (IMF) that favors the formation of more massive stars (top-heavy IMF). Stellar evolution studies (Heger & Woosley 2002) show that primordial stars with main-sequence (ms) masses between $\sim$50−140 $M_\odot$ and above $\sim$260 $M_\odot$ inevitably collapse into black holes and are unable to eject their metals. Furthermore, stars with masses below $M_{\rm ms} \sim 10\ M_\odot$ do not significantly contribute to the chemical feedback on galactic scales (Ciardi & Ferrara 2005). Hence, only massive stars of $\sim$10−50 $M_\odot$, exploding as core-collapse S/HNe, or super-massive stars of $\sim$140−260 $M_\odot$, exploding as PISNe, will eventually enrich the ISM and subsequently the IGM.

It has been proposed that metal enrichment is the mechanism responsible for a transition from a top-heavy to a more conventional power-law IMF as observed in the present-day Universe (Bromm et al. 2001; Schneider et al. 2002). The metallicity is believed to reach a critical value at $[Z_{\rm cr}/\rm H] \approx -4$, marking a transition from a high-mass to a low-mass fragmentation mode of the protostellar gas cloud. Conversely, recent observations of hyper metal-poor (HMP) stars, e.g., HE0107−5240 with [Fe/H] = -5.2 ± 0.02 (Christlieb et al. 2002) or HE1327−2326 with [Fe/H] = -5.4 ± 0.02 (Frebel et al. 2005) might, at first sight, rule out a top-heavy IMF for

⋆ Founded by merging of the Institut für Astrophysik und Extraterrestrische Forschung, the Sternwarte, and the Radioastronomisches Institut der Universität Bonn.

Pop III stars. Other scenarios like a bimodal IMF (Nakamura & Umemura 2001; Omukai & Yoshii 2003), binary star formation, or a nonstandard nucleosynthesis (Oh et al. 2001) for Pop III stars could solve this disagreement.

In order to constrain the mass range and explosion mechanism for Pop III stars which contribute to the chemical feedback on galactic scales, we have analyzed an extremely metal poor protogalactic structure at high redshift by quasar absorption-line spectroscopy.

Quasar absorption-line (QAL) systems are important objects to study the IGM at low and high redshifts. QAL systems sample both low and high density regions in the Universe and thus provide important information about structure formation and early chemical evolution. Metal abundance measurements in QAL systems at high redshift are particularly important to learn about the first generations of stars in the Universe, as these objects should have left a characteristic signature in the abundance pattern of chemically young systems. Damped Lyman α (DLA) absorbers are QAL systems with large hydrogen column densities ($N(\mathrm{H\,I}) \geq 2 \times 10^{20}$ cm^{-2}), and most suitable for studies of the chemical evolution at high redshift (e.g., Péroux et al. 2003; Richter et al. 2005). Number statistics of DLA systems imply that these objects dominate the neutral gas content of the Universe at $z > 1$ (Lanzetta et al. 1995; Wolfe et al. 1995; Rao & Turnshek 2000). While most of the observable baryonic content of today's galaxies is concentrated in stars, in the past it must have been in the form of gas. The general agreement between the estimated baryonic mass density for DLA systems ($\Omega_{\rm DLA}$) at $z \approx 2$ and the baryonic mass density in stars at $z = 0$ makes DLA systems prime candidates to be the progenitors of present-day galaxies (Wolfe et al. 1995; Storrie-Lombardi & Wolfe 2000). The most important absorption lines of atomic and molecular species in DLA systems at high redshift ($z \approx 2{-}3$) fall into the optical band. Background quasars at these redshifts are usually faint ($V \approx 17^{\rm m}{-}20^{\rm m}$), however, so that one needs 8–10 m class telescopes to obtain high-resolution and high signal-to-noise (S/N) absorption spectra that provide accurate information on these objects.

The DLA system discussed in this paper is characterized by a very low overall metallicity. It exhibits an abundance pattern that points to an enrichment of only one or at most a few stellar generations. Thus, the UVES high-resolution data of the DLA system toward Q0913+072 provide us with a unique insight into the early enrichment history of a proto-galactic structure at $z \approx 2.6$.

2. The line of sight toward Q0913+072

An earlier analysis of the DLA system at $z_{\rm abs} = 2.6183$ toward Q0913+072 ($V = 17\overset{\rm m}{.}1$, $z_{\rm em} = 2.785$) has been presented by Ledoux et al. (1998). These authors have used the F/8 Cassegrain focus of the ESO 3.6 m telescope and the Nasmyth focus of the ESO 3.5 m New Technology Telescope (NTT) at La Silla, Chile. A total neutral hydrogen column density of $\log N(\mathrm{H\,I}) = 20.2 \pm 0.1$ was derived from a fit of the Ly α line. With a resolution of $R \sim 13\,000$, only a single component in the low-ionization absorption lines of O I, C II, and Si II could be identified. An analysis of these lines suggested metal abundances of [O/H] ≈ -2.8 and [Si/H] ≈ -2.4 together with a Doppler parameter of $b \approx 7$ km s^{-1}. At this resolution, however, the true velocity structure in the gas is barely resolved. This leads to systematic uncertainties for the derived metallicities, since for several unresolved components the true b values may be significantly lower, and thus the column densities could be underestimated. An analysis of this very interesting DLA system with higher-resolution data holds the prospect of deriving more accurate abundances for C, N, O, Si, and other elements and to investigate the abundance pattern in this system in the context of the metal enrichment of protogalactic structures at high redshift.

3. Metal abundance measurements

The data used in this study were obtained with the ESO Very Large Telescope (VLT) UV-Visual Echelle Spectrograph (UVES) between January 17 and February 16, 2002, mostly during dark time. The total integration time amounts to 6.8 h (Dic1 + Dic2) while the seeing-conditions were on average 1″. Q0913+072 was observed through a 1″-slit with two setups using dichroic beam splitters for the blue and the red arm (Dic 1 with B390 and R580 nm, and Dic 2 with B437 and R860 nm, respectively). This setup covers a wavelength range from ∼3250–10 200 Å with small gaps at ∼5750–5840 Å and ∼8520–8680 Å, respectively. The data have high spectral resolution ($R \sim 45\,000$) together with a high signal-to-noise ratio (S/N). The S/N typically varies between ∼30–70 per pixel (width = 1.9 km s^{-1}) over the wavelength range between 3500–6000 Å. The CCD pixels were binned 2 × 2 and the raw data were reduced using the UVES data-reduction pipeline implemented in the ESO-MIDAS software package. These data are public and can be found in the UVES database of ESO's Science Archive Facility[1].

The spectrum was analyzed using the FITLYMAN program (Fontana & Ballester 1995) implemented in the ESO-MIDAS software package. The routine uses a χ^2-minimization algorithm for multi-component Voigt-profile fitting. Simultaneous line fitting of the high-resolution spectrum allows us to determine the column density, N, and the Doppler parameter, b, with high accuracy. The b values of the DLA system toward Q0913+072 are assumed to be composed of a thermal component, $b_{\rm th}$, and a non-thermal component, $b_{\rm non-th}$, in the way that

$$b = \sqrt{b_{\rm th}^2 + b_{\rm non-th}^2}. \quad (1)$$

The non-thermal component may include processes like macroscopic turbulence, unresolved velocity components, and others. Note that in our case $b_{\rm th}^2 \ll b_{\rm non-th}^2$.

Due to the low overall metallicity of this system, metal absorption is detected only in the strong lines of C II, N I, O I, Al II, Si II, and Fe II. No other low ion or other element could be identified. Upper limits for elements like sulfur or zinc can be derived but they are of no further use. Fitting the detected low-ionization lines we can identify two dominant velocity components at −1 km s^{-1} and +11 km s^{-1} in the $z_{\rm abs} = 2.6183$

[1] http://archive.eso.org

restframe (Fig. 1), as well as three satellite components at +114, +152, and +181 km s^{-1}, respectively. For the study presented in this paper we will concentrate on the two dominant components. Due to the large neutral hydrogen column density the H I Ly α absorption spans several Å, so that all subcomponents are superposed in one big Lyman trough (Fig. 2). Therefore, it is impossible to decompose the HI absorption line profile into the various velocity subcomponents. From a simultaneous single-component fit of the Ly α and Ly β absorption we obtain a total neutral hydrogen column density of $\log N(\mathrm{H\,I}) = 20.36 \pm 0.05$. This value, together with the total column densities derived for the species listed above, is used to determine metal abundances $[\mathrm{X/H}] = \log (N(\mathrm{X})/N(\mathrm{H})) - \log (N(\mathrm{X})/N(\mathrm{H}))_{\odot}$. These range from −3.84 (nitrogen) to −2.47 (oxygen), implying that the overall metal abundance ([M/H] = [O/H] = −2.47 or $Z = 0.0034$) of the gas is very low. All individual column densities and abundances in the $z = 2.6183$ absorber are summarized in Table 1. The errors in this paper represent the 1σ fitting errors given by the FITLYMAN program. Additional uncertainties arise from to the continuum placement (on the order of 0.1 dex) and the fixing of the line centers and b values. Note that these additional error sources are not included in the error estimates listed.

Our measurements confirm the previous abundance estimates from Ledoux et al. (1998). However, due to the higher resolution of the UVES data, the system is now resolved into two major and three satellite components for the low ions (instead of one), and five components for the high ions (instead of two). The new detection of Al II and upper limits for Fe III and Ni II provide additional information about the chemical composition of the gas. With [M/H] = −2.47 ($\sim 1/300$ solar) this absorber has one of the lowest metallicities ever measured in DLA systems. More precisely, it is among the four lowest in the sample of 100 DLA systems from Prochaska et al. (2003) and the system with the lowest metallicity in the redshift range $2 < z < 3$. Also, this DLA system is (to our knowledge) the only system for which an accurate carbon abundance can be determined. Due to the low metallicity the strong C II absorption is not heavily saturated (or very mildly at most) in contrast to all other known DLA systems.

Note while the two-component structure is clearly seen in the N I λ 1199 line, the observed absorption profile slightly deviates from the expected shape. The reason for this is unclear, but possibly related to noise features that are present in this wavelength range (see Fig. 1). The detection significance exceeds 3σ and 4σ for the blue and the red component, respectively. However, the main source of uncertainty for the column density derived from the N I λ 1199 line is related to the choice of the continuum level.

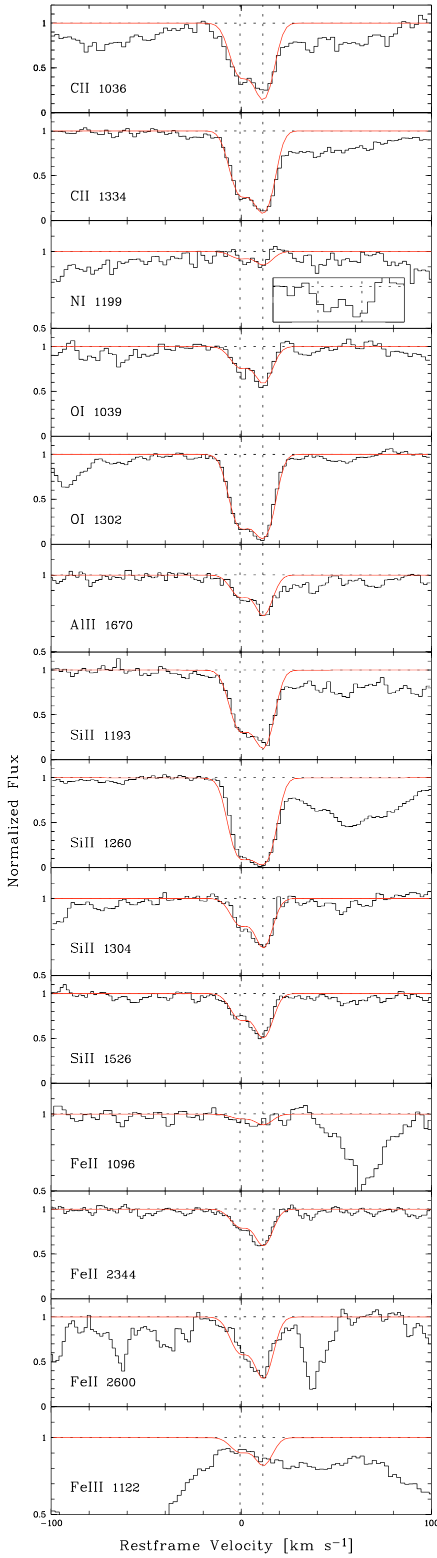

Fig. 1. Absorption profiles of various ions are plotted against the restframe velocity. Two dominant absorption components are identified at −1 km s^{-1} and +11 km s^{-1} (vertical dashed lines).

4. Results and discussion

4.1. Metal abundance pattern

The redshift of $z_{\mathrm{abs}} = 2.6183$ of this system corresponds to a lookback time of 11.1 Gyr (i.e., to an age of the Universe of 2.5 Gyr at that redshift)[2]. Given the very low overall abundance level and the observed abundance pattern, the chemical evolution of this system is lagging behind the evolution of other DLA systems at similar redshifts. The DLA system toward Q0913+072 can be compared with the nearby dwarf galaxy

[2] Using $H_0 = 71$ km s^{-1}, $\Omega_{\mathrm{m}} = 0.27$, and $\Omega_{\mathrm{tot}} = 1$.

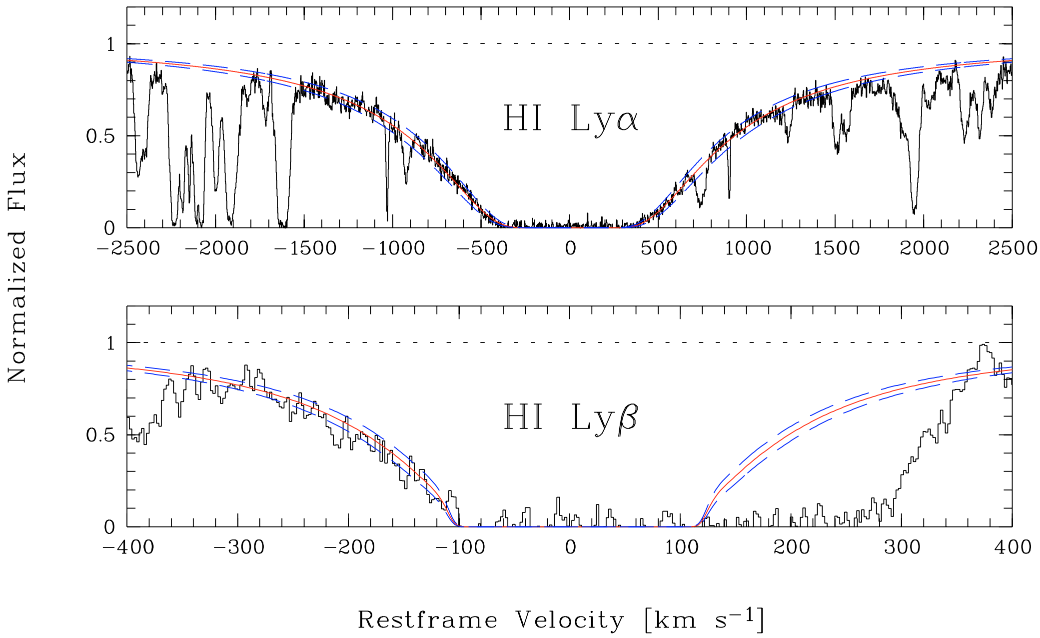

Fig. 2. The Ly α and Ly β absorption profiles of the DLA system at $z_{\rm abs} = 2.6183$ toward the quasar Q0913+072 are shown, plotted on a restframe velocity scale. The solid line shows the optimum single-component fit with $\log N$(H I) = 20.36, the dashed lines indicate the 1σ error range of ± 0.05 dex.

Table 1. Summary of chemical abundances using the common notation [X/H] = $\log(N(\rm X)/N(\rm H)) - \log(N(\rm X)/N(\rm H))_\odot$. The column densities represent the sum over the two main absorption components at -1 km s^{-1} and $+11$ km s^{-1}, as derived from simultaneous multi-component Voigt-profile fits. The total neutral hydrogen column density is $\log N$(H I) = 20.36 ± 0.05. Oscillator strengths are taken from Morton (2003). Solar reference abundances are listed in Table 2.

Species	Transition lines used	$\log N(\rm X) \pm \sigma_{\log N}$	[X/H] $\pm \sigma_{\rm [X/H]}$
H I	1025, 1215	20.36 ± 0.05	
C II	1036, 1334	14.05 ± 0.01	−2.83 ± 0.05
N I	1199	12.47 ± 0.10	−3.84 ± 0.11
O I	1039, 1302	14.58 ± 0.02	−2.47 ± 0.05
Al II	1670	11.84 ± 0.01	−3.01 ± 0.05
Si II	1304, 1526	13.35 ± 0.01	−2.57 ± 0.05
Fe II	1096, 2344, 2600	13.09 ± 0.01	−2.77 ± 0.05
Fe III	1122	≤13.33	
Ni II	1370	≤12.17	≤−2.44

Table 2. Solar abundances as listed in Morton (2003), based on data from Grevesse & Sauval (2002), except for oxygen, for which we adopt the value given in Allende Prieto et al. (2001).

Element	$\log N((\rm X)/N(\rm H))_\odot + 12.00$
Carbon	8.52
Nitrogen	7.95
Oxygen	8.69
Aluminum	6.49
Silicon	7.56
Iron	7.50
Nickel	6.25

I Zwicky 18 (at a distance of ∼15 Mpc), which contains no stars older than 500 Myr (Izotov & Thuan 2004). Either these kinds of galaxies have formed just recently, or they have been existing as protogalactic structures for several Gyr. An alternative explanation for the poor enrichment we observe in the DLA system toward Q0913+072 would be that an initial violent starburst might have disrupted the integrity of the protogalactic structure and consequently would have prevented further starformation activity. This would bring the nucleosynthesis processes to a halt and the chemical composition of the gas would reflect the enrichment pattern produced by the initial starburst.

In the following we focus on the abundances of individual elements that could shed light on the chemical evolution history of this system.

Nitrogen – Comparing our results with a database of 66 DLA systems (Centurión et al. 2003; and Lanfranchi et al. 2003), the nitrogen abundance is among the lowest ever measured (see also Richter et al. 2005). There is general consensus that oxygen is almost entirely produced by (massive) SNe, the contribution from low- and intermediate-mass stars is practically irrelevant. Carbon, on the other hand, is produced in stars of nearly all masses (essentially by helium burning). In contrast to oxygen and carbon, however, the initial formation of nitrogen is still not well understood. If nitrogen is formed directly from helium it is called *primary*. If the nitrogen production is dependent on pre-existing carbon seed nuclei, it is called *secondary* and is obviously dependant on the star's initial metallicity. While all stars which reach the CNO cycle (nitrogen is formed at the expense of carbon and oxygen) produce secondary nitrogen, it cannot be decided at present whether primary nitrogen is produced mostly in massive stars (exploding as SNe) or in intermediate-mass stars (∼4–8 $M_\odot$) during their AGB phase, or both (Spite et al. 2005). The role of low-mass stars ($<4\ M_{\odot}$) for the nitrogen enrichment at high z is not well understood yet, but needs to be explored in future studies (see, e.g., Pettini et al. 2002). Pettini et al. suggest that a significant fraction of DLA systems with oxygen abundances between $\sim^1/_{10}$ and $\sim^1/_{100}$ solar have not yet attained the full primary level of nitrogen enrichment (i.e., $\log\,[\mathrm{N/O}] < -1.5$) and may represent protogalactic structures that just recently have formed out of the IGM.

For the α-elements, the enrichment depends critically on the star formation rate (SFR). Different absorber systems have different star formation histories, which means that they can reach the same amount of α-enrichment at different epochs. However, the nitrogen production depends more critically on the lifetime of the progenitor stars rather than on the SFR. Intermediate-mass stars dominate the nitrogen production and will follow the massive stars ($M > 8\ M_{\odot}$), which are the main production sites for carbon, with a typical lag time of ~250 Myr (Henry et al. 2000). The two plateaus in a [N/Si, O] versus [N, O/H] plot for DLA systems nicely reflect this bimodal nitrogen production scenario (see Prochaska et al. 2002). The observed range in the [N/O] ratio at low [O/H] then is a natural consequence of the delayed release of nitrogen into the ISM relative to the oxygen produced by SNe. In the DLA system towards Q0913+072 we measure $[\mathrm{N/O}] = -1.37 \pm 0.10$, i.e., primary nitrogen. This is what we would expect when observing a chemically young system that just has recently condensed out of the IGM.

Our value of $[\mathrm{N/O}] = -1.37 \pm 0.10$ does not favor a very small dispersion in low-N DLA systems, i.e., $[\mathrm{N}/\alpha] = -1.45 \pm 0.05$, as suggested earlier by Centurión et al. (2003). Matteucci & Calura (2005) argue that Pop III stars alone cannot be responsible for the abundance ratios in low-metallicity DLA systems. They conclude that the intermediate-mass Pop II stars must have played an important role for the early nitrogen enrichment in the Universe, even at redshift of $z = 5$. However, the redshift alone is not a good indicator for the evolutionary state of a galaxy. The very low abundances measured in the DLA system toward Q0913+072 together with the very low nitrogen content, when compared with yields from explosive nucleosynthesis model calculations, indeed speak against a major contribution from intermediate mass Pop II stars to the nitrogen enrichment in this DLA system.

Carbon – Reliable carbon measurements in QAL systems are very sparse, since in most cases the C II absorption in DLA systems, sub-DLA systems, and Lyman-Limit Systems (LLS)[3] is heavily saturated. Levshakov et al. (2003a) have measured C II absorption in a LLS at $z_{\mathrm{abs}} = 2.917$[4]. D'Odorico & Molaro (2004) also reported a carbon measurement in a DLA system at $z_{\mathrm{abs}} = 4.383$, but their C II and O I lines presumably are mildly saturated. Although the results of the LLS depend on photo-ionization calculations, all cases seem to have $[\mathrm{C/Fe}] \sim 0.0$ and $[\mathrm{C}/\alpha] < 0$ in common. For the DLA system toward Q0913+072 we derive $[\mathrm{C/Fe}] = -0.06 \pm 0.01$, $[\mathrm{C/O}] = -0.36 \pm 0.02$, and $[\mathrm{C/Si}] = -0.26 \pm 0.01$, thus very similar to what has been derived for the other systems. In all four cases, carbon appears to be underabundant compared to the α elements. Although LLSs and DLA systems are expected to trace different cosmological objects (at least in general), the observed underabundance of carbon may provide information about the early metal enrichment in the Universe. Clearly, more carbon measurements in DLA systems and LLSs are desired to investigate this interesting behavior in detail.

Oxygen – Oxygen is the best element to infer the α-element abundance in interstellar and intergalactic gas, as O I and H I have similar ionization potentials and both elements are coupled by a strong charge-exchange reaction. In the most widely cited set of solar abundances from Grevesse & Anders (1991), the solar oxygen abundance was reported to be $\log\,(N(\mathrm{O})/N(\mathrm{H}))_{\odot} + 12 = 8.93$. However, recent estimates lead to significant revisions of the Sun's oxygen abundance. In this work we adopted the value of $\log\,(N(\mathrm{O})/N(\mathrm{H}))_{\odot} + 12 = 8.69$ from Allende Prieto et al. (2001). Further, uncertainties in stellar nucleosynthesis inputs such as the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate, convection, fall back and mass loss could alter these and previous results, which therefore have to be viewed with caution.

Dust depletion – No trace of molecular hydrogen was found the DLA system toward Q0913+072. The logarithmic ratio of hydrogen nuclei in molecules to the total hydrogen nuclei is $\log f_{\mathrm{H}_2} = \log 2N(\mathrm{H}_2) - \log N(\mathrm{H}) \leq -6.9$, where $\log N(\mathrm{H}_2) \leq 13.2$, i.e., the total upper limits of the rotational ground states $J = 0$ and $J = 1$ in the Werner band of molecular hydrogen. Because of the lack of H_2 (which predominantly forms on dust grains) and the extremely low overall metallicity we do not expect dust depletion to alter significantly the abundance pattern in this absorption system (Ledoux et al. 2003; Vladilo 2002).

Photoionization corrections – Given the large neutral hydrogen column density in this absorber, it is not expected that photoionization has any significance on the abundances listed in Table 1. This is supported by our photoionization model for a DLA system at $z = 2.5$ based on CLOUDY (Ferland et al. 1998). In the case that photoionization should nonetheless be relevant, i.e., in view of the observed two-component structure, the fact that the ionization potential (IP) of H I is lower than the IPs of C II, N I, Al II, Si II, and Fe II, means that correcting for ionization effects would further decrease these abundances.

Comparison with metal-poor stars – It is legitimate to compare very metal-poor DLA systems to very metal-deficient stars which are believed to retain information of a preceding single SN event or at most a few (McWilliam et al. 1995). Comparing the abundances from this DLA system with a sample of 9 (unmixed) extremely metal-poor (EMP) Galactic halo giants ($-4.0 \leq [\mathrm{Fe/H}] \leq -2.0$) from Spite et al. (2005), we find a very good agreement for carbon, a reasonable agreement for oxygen and iron (typically ±0.2 dex), but clearly higher

[3] $10^{17.2}\ \mathrm{cm}^{-2} \leq N(\mathrm{H\,I}) \leq 10^{19}\ \mathrm{cm}^{-2}$.

[4] All previous measurements of metal abundances in LLS lie in the range of $[\mathrm{M/H}] \geq -2.4$ (Fan 1995; Songaila & Cowie 1996; Levshakov et al. 2002, 2003b).

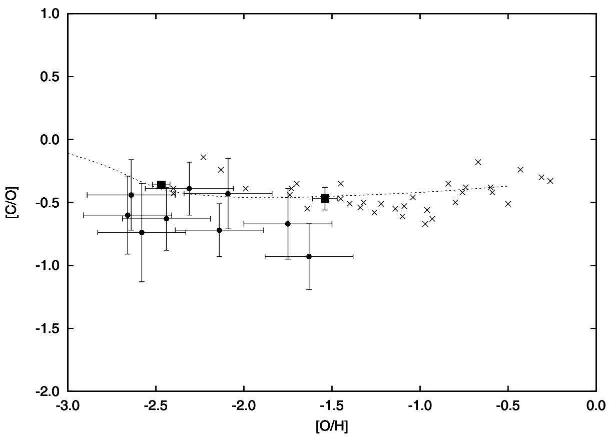

Fig. 3. We compare the only two existing carbon abundance measurements in DLA systems (squares; from this study and from D'Odorico & Molaro 2004) with extremely metal-poor halo stars (crosses) from Akerman et al. (2004), and (circles) from Spite et al. (2005). The dashed line shows predictions from Pop III star yields from Chieffi & Limongi (2002) for the case of an IMF with $M_{\rm ms} \geq 10\ M_{\odot}$.

values for nitrogen (in average of ~1 dex) in the EMP stars. In Fig. 3, we include a sample of 34 F and G dwarf and subgiant stars belonging to the halo population ($-3.2 \leq$ [Fe/H] ≤ -0.7) from Akerman et al. (2004). Although their mean values for [C/H] and [O/H] are higher by more than 1 dex, their lowest values for carbon and oxygen are very similar to our observations.

An interesting aspect is to compare the two existing carbon measurements in DLA systems (this paper and D'Odorico & Molaro 2004) with these halo stars (Fig. 3). We find a reasonable agreement for the carbon evolution in the DLA systems and the halo stars. When comparing with predictions from yields from Pop III stars (Chieffi & Limongi 2002) for the case of an IMF with $M_{\rm ms} \geq 10\ M_{\odot}$ (Fig. 3, dashed line), we notice that the carbon abundances in the two DLA systems match these theoretical predictions extremely well.

Ultra-metal-poor giants with high [O/Fe] ratios, such as presented by Israelian et al. (2004), seem to predict a new type of SNe (Aoki et al. 2002) where most of the matter was absorbed by the iron core. Smaller [O/Fe] ratios possibly indicate that a significant fraction of iron was incorporated in the SN ejecta, leading to a smaller mass cut and thus less compact remnants, possibly neutron stars. Stars with very low metallicities and DLA systems obviously are extremely important objects to derive constraints on Pop III stars. The nitrogen production mechanism clearly plays a key role but yet requires more detailed work.

4.2. Additional constraints from numerical models

The DLA system toward Q0913+072 is a chemically very young DLA system, enriched by one or at most a few stellar generations that have left their typical abundance signature in the gas. We now want to compare the abundance pattern of this system with predictions from recent model calculations to learn more about the origin of this absorber.

SNe Ia vs. SNe II – The absence of a clear-cut [α/Fe] ratio leaves the possibility open that SNe Ia might have contributed to the metal enrichment of the observed DLA system, especially to the iron-peak elements. On the other hand, there are arguments against any significant contribution from SNe Ia: (1) based on results from the *Hubble Higher z Supernova Search*, Strolger et al. (2004) constrain the delay times for SNe Ia, i.e., the time from the formation of the progenitor stars to the explosion, in the range of 2–4 Gyr, where the lower barrier of 2 Gyr distinctly exceeds the age of the DLA system toward Q0913+072, recalling that the age of the Universe at $z_{\rm abs} = 2.6183$ was only 2.5 Gyr. (2) Metallicity effects influence the SNe Ia rate. This kind of low-metallicity inhibition of SNe Ia could occur if the iron abundance of the accreted matter from the companion is as low as [Fe/H] $\lesssim -1$ (Kobayashi et al. 1998, and references therein). The companion star in a single-degenerated scenario is typically a red-giant (RG) with an initial mass of $M_{\rm RG} \sim 1\ M_{\odot}$ or a near main-sequence star with an initial mass of $M_{\rm ms} \sim 2$–$3\ M_{\odot}$. Both stars are not massive enough to ignite silicon burning. Consequently, an iron abundance, as low as measured in our case, must inhibit the occurrence of SNe Ia. The observed low [O/Fe] ratios (more generally: the [α/Fe] ratios) thus should reflect the enrichment pattern of the first generations of stars that have enriched this protogalaxy, most likely by SNe II and probably HNe as well. We observe [O/Fe] = $+0.30 \pm 0.02$ and [O/Si] = $+0.10 \pm 0.02$ which is consistent with the yield ratios of SNe II from massive stars from Kobayashi et al. (2005). Furthermore, the ratios of [Si/H] = -2.57 ± 0.05 and [Fe/H] = -2.77 ± 0.05 are roughly consistent with numerical investigations from Kawata et al. (2001), which predict that a typical SN II is producing more silicon (~5:1) and slightly less iron (~0.8:1) than a typical SN Ia.

Very Massive Stars (VMS) – VMS with $M_{\rm ms} \approx 130$–$300\ M_{\odot}$, exploding as PISNe, show a tendency to produce too much silicon, but not enough carbon and oxygen when compared to this DLA system. The observed [Si/C] = $+0.26 \pm 0.01$ or [C/O] = -0.36 ± 0.02, and [Si/Al] = $+0.44 \pm 0.01$ ratios imply an IMF in which the first stars cannot have been very massive (Tumlinson et al. 2004).

Yields from explosive nucleosynthesis models – The metallicity of the DLA system we probe is only slightly higher than what cosmological models predict for the IGM at this redshift. We speculate that this primeval metal enrichment we observe originates from only one single star generation, i.e., from Pop III stars. If there was only one enrichment cycle, or at most a few, then the ISM will carry the imprint from these stars and their typical enrichment pattern. As mentioned earlier, only stars in the range of $M_{\rm ms} \sim 10$–$50\ M_{\odot}$ and $M_{\rm ms} \sim 140$–$260\ M_{\odot}$ will contribute to the enrichment on galactic scales. In other words, the questions we ask is: were the first stars massive (~ 10–$50\ M_{\odot}$) or super-massive (~ 140–$260\ M_{\odot}$), i.e., were they core-collapse S/HNe or PISNe?

We make use of the latest yield calculations from explosive nucleosynthesis models from Kobayashi et al. (2005) for the case of "ordinary" (core-collapse) SNe, the typical SNe II, with an explosion energy of $E = 1 \times 10^{51}$ erg $= E_{51}$, hyper-energetic (i.e., $E > E_{51}$) core-collapse HNe, and PISNe. Two mass-energy relations were set: a constant $E_{51} = 1$ for SNe with 13, 15, 18, 20, 25, 30, and 40 $M_\odot$, and $E_{51} = 10$, 10, 20, and 30 for HNe with 20, 25, 30, and 40 $M_\odot$, respectively. The yields for PISNe with 150, 170, 200, and 270 $M_\odot$ were taken from Umeda & Nomoto (2002).

The metal abundance pattern of this DLA system was then compared with these yields for metallicities of $Z = 0$, 0.0001, and 0.004. We assumed a simple power-law IMF, i.e., $\xi(M_\star) = (M_\star/M_\odot)^\gamma$, varying γ from −5 to +2 ($\gamma = -2.35$ corresponds to the Salpeter IMF). We found that there is no significant difference between a scenario of SNe combined with HNe and a scenario of SNe only. On the other hand, Z and γ are very sensible indicators. We find that zero-metallicity stars produce the most accurate abundance pattern in the case of a steep IMF ($\gamma \lesssim \gamma_{\rm Salpeter}$). This and the fact that yields from PISNe do not match the abundance pattern observed in the DLA system toward Q0913+072 (see Fig. 4) excludes any significant contribution of PISNe, yet puts a question mark on their existence. Considering the case of an initially enriched ISM, we compared as well with yields from SNe and HNe with progenitors stars having $Z = 0.0001$ and $Z = 0.004$. For these second-generation stars (exploding as S/HNe), the abundance pattern is generally reproduced with less accuracy but we notice that a top-heavy IMF partially can reduce these inaccuracies.

The reader should not take this analysis as a proof of the inexistence of PISNe but rather as a strong indication that PISNe events must have been – at most – very rare. We also have to recall that the explosion energy, as well as the mass cut (i.e., the limiting radius between the remnant and the ejecta) for the core-collapse scenario are still two important parameters which are not very well understood, yet could lead to noticeable errors.

Kobayashi et al. (2005) are using basically the same code as Umeda & Nomoto (2001, 2002) but with a different treatment of the mixing-fallback mechanism in order to explain the chemical evolution of the solar neighborhood. Umeda & Nomoto, on the other hand, focus on iron peak elements, and, in particular, try to reproduce the large [Zn/Fe] observed in EMP stars. Using the yields from Umeda & Nomoto we find that the IMF should peak around stars with 25 $M_\odot$ and 10 E_{51} in order to reproduce the abundance pattern we observe in this DLA system. When using the results from Kobayashi et al. we find that the IMF should peak around stars with typically 15 $M_\odot$ and 1 E_{51}.

Galactic and cosmic chemical evolution – In a recent paper Daigne et al. (2004) have modeled the chemical evolution of condensed cosmic structures (galaxies) and the IGM as a function of redshift including the process of reionization. They consider various different SFRs and IMFs for the progenitor stars that drive the metal enrichment in the early Universe. Following their calculations, a bimodal (or top-heavy) IMF with a moderate mass range of 40−100 $M_\odot$ yields both, the required number of ionizing photons to reionize the Universe at $z = 17$, and the correct chemical composition of nucleosynthesis products of these stars to match the observations of metal

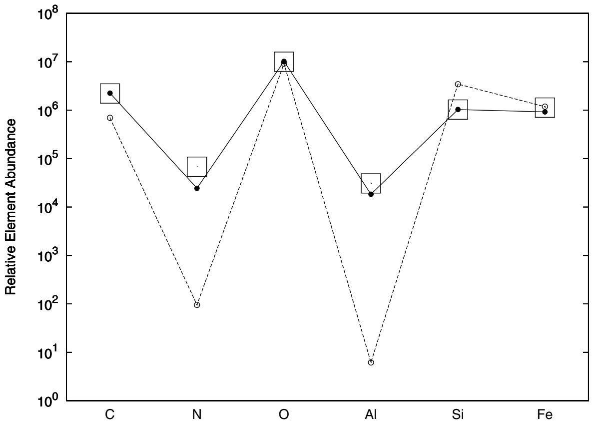

Fig. 4. Comparison of relative element abundances from the DLA system toward Q0913+072 and model calculations for explosive nucleosynthesis. The open boxes show the measured abundances in the DLA system toward Q0913+072 where the box size corresponds to an assumed *total* error of ±0.2 dex. Yields from numerical model calculations of a core-collapse SN with 15 $M_\odot$ and 1 E_{51} are indicated with filled circles and continuous lines, and yields of a PISN with 200 $M_\odot$ are shown as open circles with dashed lines. The reader should note that *relative* abundances are compared. For this the sum of the abundances for C, N, O, Al, Si, and Fe of each set was normalized to unity and then shifted arbitrarily (oxygen$_{\rm DLA}$ = 10^7) to the scale shown on the y axis to indicate the full range of the measured and predicted element abundances.

abundances in metal-poor halos stars and in the IGM. When comparing the mass fractions of C, N, O, Si, and Fe presented in their models with those derived for the DLA system toward Q0913+072 we find that the abundances of these elements in the DLA system are slightly (<1 dex, typically) above the values predicted for the IGM at $z = 2.6$, but substantially lower than what is expected for the ISM in galaxies at that redshift. This implies that the DLA system toward Q0913+072 represents a protogalactic structure that has just recently formed, so that local star formation activity in this system had not enough time to significantly enhance the abundance level above that of the surrounding IGM.

5. Summary and conclusions

The DLA system at $z = 2.6183$ toward Q0913+072 is characterized by a very low overall metal abundance ([M/H] = [O/H] = −2.47 or $Z = 0.0034$), a pronounced deficiency of nitrogen ([N/H] = −3.84), and a mild underabundance of carbon ([C/H] = −2.83). These values mark this system as the most metal-poor DLA system observed at $z < 3$. We further report this absorber to be the first DLA system at present date with a reliable carbon measurement. The low nitrogen abundance implies that this system has not yet attained the full level of primary nitrogen enrichment. This, and the fact that the overall abundance level is only slightly above that of the IGM at that redshift, point toward a protogalaxy that has just recently condensed out of the IGM.

The comparison of the abundances in this DLA system with a sample of extremely metal-poor halo giants shows a very good agreement for carbon, and a reasonable agreement for oxygen and iron. Predictions from yields from Pop III stars (Chieffi & Limongi 2002) for the case of an IMF with $M_{\rm ms} \geq 10\ M_{\odot}$ match the carbon measurements of the two available DLA systems extremely well.

Stars with main-sequence masses below ∼10 $M_{\odot}$ do not essentially contribute to the metal budget in the gas on galactic scales, and primordial stars in the range of $M_{\rm ms} \sim 50-140\ M_{\odot}$ and above ∼260 $M_{\odot}$ are believed to collapse without being able to eject any enriched gas. The only stars with a chemical feedback must therefore be stars with $M_{\rm ms} \sim 10-50\ M_{\odot}$, exploding as core-collapse S/HNe, or stars with progenitors in the mass range ∼140−260 $M_{\odot}$, exploding as PISNe. Scenarios of progenitor stars with a non-zero metallicity, a top-heavy IMF, other explosion mechanism like SNe Ia or PISNe, or a combination of the foregoing, cannot satisfactorily explain the observed chemical abundance pattern. Comparing the metal abundance pattern of the DLA system at $z_{\rm abs} = 2.6183$ toward Q0913+072 with yields from explosive nucleosynthesis model calculations, we conclude that the most likely scenario for the observed abundance pattern is massive (but not super-massive) Pop III stars with $M_{\rm ms} \approx 10-50\ M_{\odot}$, exploding as core-collapse S/HNe.

Acknowledgements. The authors are grateful to the referee Giovanni Vladilo for his helpful report and insightful comments. We also wish to thank ESO for the use of the UVES spectrum of Q0913+072 (ProgId 68.B-0115(A), 01 Oct. 2001, VLT-Kueyen, Paranal, Chile). P.E. and P.R. acknowledge financial support by the German *Deutsche Forschungsgemeinschaft*, DFG, through Emmy-Noether grant Ri 1124/3-1.

References

Akerman, C. J., Carigi, L., Nissen, P. E., Pettini, M., & Asplund, M. 2004, A&A, 414, 931
Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, 63
Aoki, W., Norris, J., Ryan, S., Beers, T., & Ando, H. 2002, PASJ, 54, 933
Bromm, V., Kudritzki, R. P., & Loeb, A. 2001, ApJ, 552, 464
Centurión, M., Molaro, P., Vladilo, G., et al. 2003, A&A, 403, 55
Chieffi, A., & Limongi, M. 2002, ApJ, 577, 281
Christlieb, N., Bessell, M. S., Beers, T. C., et al. 2002, Nature, 419, 904
Ciardi, B., & Ferrara, A. 2005, Space Sci. Rev., 116, 625
Daigne, F., Olive, K. A., Vangioni-Flam, E., Silk, J., & Audouze, J. 2004, ApJ, 617, 693
Fan, X. M. 1995, Ph.D. Thesis, University of California, San Diego
Ferland, G. J., Korista, K. T., Verner, et al. 1998, PASP, 110, 761
Fontana, A., & Ballester, P. 1995, ESO Messenger, 80, 37
Frebel, A., Aoki, W., & Christlieb, N. 2005, Nature, 434, 871
Grevesse, N., & Anders, E. 1991, in Solar Interior and Atmosphere (University of Arizona Press), 1227
Grevesse, N., & Sauval, A. J. 2002, Adv. Space Res., 30, 3
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Henry, R. B. C., Edmunds, M. G., & Köppen, J. 2000, ApJ, 541, 660
Israelian, G., Shchukina, N., Rebolo, R., et al. 2004, A&A, 419, 1095
Kobayashi, C., Tsujimoto, T., Nomoto, K., Hachisu, I., & Kato, M. 1998, ApJ, 503, 155
Kobayashi, C., Umeda, H., Nomoto, K., Tominaga, N., & Ohkubo, T. 2005, ApJ, submitted
Kawata, D. 2001, ApJ, 558, 598
Izotov, Y. I., & Thuan, T. X. 2004, ApJ, 616, 768
Lanfranchi, G. A., & Friaça, A. C. S. 2003, MNRAS, 334, 481
Lanzetta, K. M., Wolfe, A. M., & Turnshek, D. A. 1995, ApJ, 440, 435
Ledoux, C., Petitjean, P., Bergeron, J., Wampler, E. J., & Srianand, R. 1998, A&A, 337, 51
Ledoux, C., Petitjean, P., & Srianand, R. 2003, MNRAS, 346, 209
Levshakov, S. A., Agafonova, I. I., Centurión, M., & Mazets, I. E. 2002, A&A, 383, 813
Levshakov, S. A., Agafonova, I. I., Centurión, M., & Molaro, P. 2003a, A&A, 397, 851
Levshakov, S. A., Agafonova, I. I., D'Odorico, S., Wolfe, A. M., & Dessauges-Zavadsky, M. 2003b, ApJ, 582, 596
Matteucci, F., & Calura, F. 2005, MNRAS, 360, 447
McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Morton, D. C. 2003, ApJ, 149, 205
Nakamura, F., & Umemura, M. 2001, ApJ, 548, 19
D'Odorico, V., & Molaro, P. 2004, A&A, 415, 879
Oh, S. P., Nollett, K. M., Madau, P., & Wasserburg, G. J. 2001, ApJ, 562, L1
Omukai, K., & Palla, F. 2003, ApJ, 589, 677
Omukai, K., & Yoshii, Y. 2003, ApJ, 599, 746
Péroux, C., Dessauges-Zavadsky, M., Kim, T. S., D'Odorico, S., & McMahon, R. G. 2003, MSAIS, 3, 261
Pettini, M., Ellison, S. L., Bergeron, J., & Petitjean, P. 2002, A&A, 391, 21
Prochaska, J., Henry, R. B. C., O'Meara, J. M., et al. 2002, PASP, 114, 993
Prochaska, J., Gawiser, E., Wolfe, A. M., Castro, S., & Djorgovski, S. G. 2003, ApJ, 595, L9
Rao, S., & Turnshek, D. A. 2000, ApJS, 130, 1
Richter, P., Ledoux, C., Petitjean, P., & Bergeron, J. 2005, A&A, 440, 819
Schneider, R., Ferrara, A., Natara, P., & Omukai, K. 2002, ApJ, 571, 30
Songaila, A., & Cowie, L. L. 1996, AJ, 112, 335
Spite, M., Cayrel, R., Plez, B., et al. 2005, A&A, 430, 655
Storrie-Lombardi, L. J., & Wolfe, A. M. 2000, ApJ, 543, 552
Strolger, L. G., Riess, A. G., & Dahlen, T. 2004, ApJ, 613, 200
Tumlinson, J., Venkatesan, A., & Shull, J. M. 2004, ApJ, 612, 602
Umeda, H., & Nomoto, K. 2001, in Birth and Evolution of the Universe, ed. K. Sato, & M. Kawasaki, Universal Academy Press, 257
Umeda, H., & Nomoto, K. 2002, ApJ, 565, 385
Vladilo, G. 2002, A&A, 391, 407
Wolfe, A. M., Lanzetta, K. M., Flotz, C. B., & Chaffee, F. H. 1995, ApJ, 454, 698