Zinc and chromium abundances
in a third damped Lyman α system at intermediate redshift

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Abstract. We have determined the metallicity of the $z_{\mathrm{abs}} = 1.0093$ damped Lyman α system in the bright QSO EX $0302-223$; this is only the third such measurement at redshifts $z \lesssim 1$. Unlike the previous two cases, we find that the abundance of Zn is only a factor of ~ 2 lower than in the Galactic interstellar medium today and is entirely compatible with the typical metallicity of stars in the Milky Way disk at a look-back time of 9.5 Gyrs. Although the galaxy responsible for producing the absorption system has yet to be positively identified, our observations show that galaxies on a chemical evolution path similar to that of the Milky Way do contribute to the damped Lyman α population at intermediate redshifts. Cr is 2.5 times less abundant than Zn, presumably because of depletion onto dust; however, the degree of depletion is less severe than in diffuse interstellar clouds in the disk of our Galaxy and in the Magellanic Clouds. Evidently, the interstellar environment in damped Lyman α galaxies is less conducive to the formation and survival of dust grains (and molecular hydrogen), but the physical processes at the root of this effect have yet to be clarified.

Key words: galaxies: abundances – galaxies: ISM – quasar: absorption lines – quasar: individual: EX $0302-223$

1. Introduction

Damped Lyman α systems (DLAs) are commonly considered to be the high redshift progenitors of present-day luminous galaxies (e.g. Wolfe 1990). If this is the case, they present us with some of the best opportunities for studying in detail the physical conditions of galaxies at early stages of evolution, including kinematics, chemical abundances, dust content, temperature, and densities of both particles and radiation (e.g. Prochaska & Wolfe 1997; Lu et al. 1996; Pettini et al. 1997a,b; Ge, Bechtold, & Black 1996; Ge & Bechtold 1997). In the past few years there has been much emphasis in particular on measuring element abundances in the interstellar gas of DLA absorbers with

the long term aim of tracing the chemical evolution of the universe from redshift $z \approx 4$ to the present time. Zinc is an especially useful tracer of metallicity because: *(a)* it shows little affinity for interstellar dust and is found in the gas-phase of the Milky Way ISM in near-solar proportions, and *(b)* it tracks closely the abundance of iron in stars of all metallicities (Pettini et al. 1990, 1997a and references therein). The large survey recently completed by Pettini et al. (1997b) has shown that at redshifts $z \simeq 1.5 - 3$ the typical abundance of Zn in DLAs is $[\langle \mathrm{Zn/H} \rangle]_{\mathrm{DLA}} \simeq -1.1$, or approximately 1/13 of solar[1], reflecting a generally low degree of chemical enrichment in the universe at look-back times of $\approx 11 - 14$ Gyr ($H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.01$ adopted throughout the paper). There are indications that $[\langle \mathrm{Zn/H} \rangle]_{\mathrm{DLA}}$ is even lower at higher redshifts; this led Pettini et al. (1995) to propose that $z \simeq 3$ may have been the period when the first major episodes of star formation took place in galaxies. Such a conclusion is supported by the results of deep imaging surveys in the rest frame ultraviolet which also indicate a marked increase in the comoving star formation rate from $z \simeq 4$ to $\simeq 2.75$ (Steidel et al. 1996; Madau et al. 1996).

In this picture the typical metallicity of DLAs should rise to near-solar values at redshifts $z \lesssim 1$, when the cosmic star formation rate was near its peak (Lilly et al. 1995; Madau 1996) and when stars forming in the disk of our Galaxy had [Fe/H] $\gtrsim -0.5$ (Edvardsson et al. 1993; Friel 1995). Verifying whether this is indeed the case is a crucial element in making the connection between DLA absorbers and the population of normal galaxies; yet this seemingly simple test has proved difficult up to now. The main problem is the paucity of known DLAs at intermediate and low redshifts (e.g. Bahcall et al. 1996), due to the combination of three effects: the reduced redshift path, the general consumption of H I gas into stars in the universe (Lanzetta, Wolfe & Turnshek 1995), and the need for space observations to identify a damped Lyman α line at $z \lesssim 1.5$.

To date measurements of metallicity have been published for only two damped systems at $z < 1$: at $z_{\mathrm{abs}} = 0.6922$ in Q1328+307 (3C 286–Meyer & York 1992) and at $z_{\mathrm{abs}} = 0.8596$

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[1] In this paper we use the conventional notation where $[\mathrm{X/Y}] = \log (\mathrm{X/Y}) - \log (\mathrm{X/Y})_\odot$

in Q0454+039 (Steidel et al. 1995). The fields of both QSOs have been imaged from the ground (Steidel et al. 1994, 1995) and with the *Hubble Space Telescope* (Le Brun et al. 1997), and plausible candidates for the absorbing galaxies have been identified. However, in neither case is a Milky Way-type galaxy indicated. The former appears to be an extended object of low surface brightness and low metallicity ([Zn/H] = -1.21), consistent with the reduced star formation efficiencies typical of such galaxies (McGaugh 1994). The latter also has a relatively low abundance, [Zn/H] = -0.85, and a rest frame B-band absolute magnitude, $M_B \simeq -19.5$, corresponding to $\approx 0.25L^*$. The finding that the only two abundance measurements available at $z < 1$ are both well below solar – and quite typical of the sample at $z > 1.5$ – has caused concerns as to whether DLAs are really unbiased tracers of the chemical evolution history of the universe.

Here we report measurements of the abundances of Zn and Cr in a third DLA at intermediate redshift, the $z_{abs} = 1.0093$ system in the QSO EX 0302$-$223. This absorber turns out to have a metallicity more in line with that of the Milky Way at a look-back time of 9.5 Gyr. While it is reassuring to confirm that galaxies with a chemical enrichment similar to that of the Galactic disk do indeed contribute to the cross-section for damped Lyman α absorption at these redshifts, the new data also stress the importance of building a reasonably large sample of such measurements before drawing conclusions on the nature of the DLA population.

2. The $z_{abs} = 1.0093$ DLA absorber in EX 0302$-$223

The serendipitous *Einstein* X-ray source EX 0302$-$223 was identified by Chanan, Margon, & Downes (1981) with an optically bright ($V = 16.0$) $z_{em} = 1.400$ QSO. Lanzetta et al. (1995) drew attention to three possible damped Lyman α lines in low resolution *IUE* spectra of the QSO, at $z_{abs} = 0.9690, 0.9874$ and 1.0140. An *HST* spectrum, which we have retrieved from the HST Data Archive, confirms that the third system is indeed damped. EX 0302$-$223 was observed with *HST* on 1995 December 7; using the G270H grating and red detector of the Faint Object Spectrograph (FOS), a 2390 s exposure was recorded through the 0.43 arcsec circular aperture. The spectrum covers the wavelength interval 2225–3275 Å; a portion centred on the damped Lyman α absorption line is shown in the top panel of Fig. 1. In producing this spectrum, we resampled the pipeline calibrated data to the original dispersion of 0.51 Å pix^{-1}, and found it necessary to apply a small correction for scattered light ($\sim 2\%$ of the continuum) to bring the core of the absorption line to zero flux.

The profile of the damped Lyman α line is well fitted by a column density of neutral hydrogen $N(H^0) = (2.15 \pm 0.35) \times 10^{20}$ cm^{-2} at $z_{abs} = 1.0099$. The difference between this redshift and $z_{abs} = 1.0093$, measured by Petitjean & Bergeron (1990) from the centroids of the Mg II and Fe II absorption lines, corresponds to approximately one third of a diode on the FOS detector and is typical of the accuracy with which the zero point of the FOS wavelength scale can be determined.
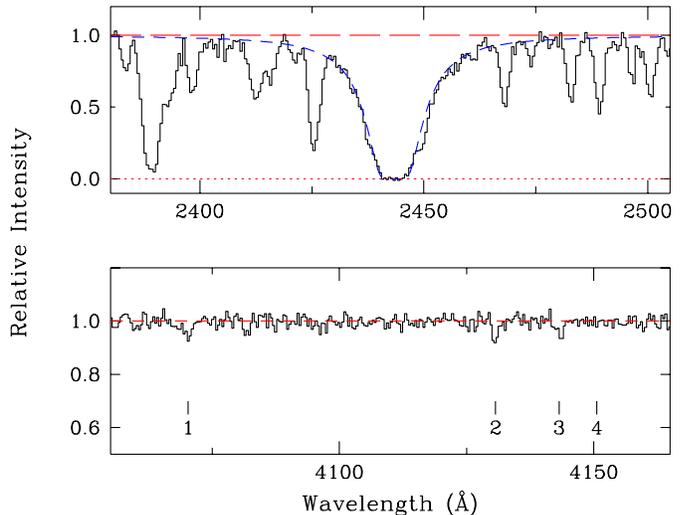

Fig. 1. *Upper Panel:* Portion of the G270H FOS spectrum of EX 0302$-$223 encompassing the damped Lyman α line in the $z_{abs} = 1.0093$ system. The resolution is 1.8 Å FWHM and S/N $\simeq 20$. The short-dash line shows the theoretical damping profile for a column density $N(H^0) = 2.15 \times 10^{20}$ cm^{-2}. *Lower Panel:* Portion of the WHT spectrum covering the region of the Zn II and Cr II absorption lines in the DLA system. The resolution is 0.88 Å and S/N = 50. The vertical tick marks indicate the expected positions of the lines, as follows (vacuum wavelengths): 1: Zn II $\lambda2026.136$; 2: Cr II $\lambda2056.254$; 3: Cr II $\lambda2062.234$ + Zn II $\lambda2062.664$ (blended); and 4: Cr II $\lambda2066.161$. Both spectra have been normalised to the underlying continua; the spectrum in the lower panel is shown on an expanded vertical scale.

Le Brun et al. (1997) have obtained images of the QSO field through the F702W (2400 s integration) and F450W (2000 s integration) filters of WFPC2 on the *HST*. After subtracting the instrumental point spread function, they suggest that the two galaxies closest to the QSO sight-line (objects 2 and 3 in their Fig. 3, respectively 1.1 and 2.5 arcsec from the QSO) are promising candidates for the damped absorber. However, a positive identification will have to wait until spectra, or at least broad-band colours, are available.

If the two galaxies are indeed at $z \simeq 1.0093$, the corresponding impact parameters are 12 h_{50}^{-1} and 27 h_{50}^{-1} kpc respectively. Le Brun et al. measured magnitudes $m_{702} = 25.4$ and 23.8 (on a Vega-based photometric system); at $z = 1.0093$ these values would correspond to $M_B = -19.3$ and -20.9 for galaxy 2 and 3 respectively, adopting a k-correction appropriate to an Sbc spectral template (we used the template by Coleman et al. 1980 for consistency with Le Brun et al.). Thus, if at $z = 1.0093$, then galaxy 2 has a luminosity $L_B \approx 0.2L_B^*$, while object 3 is more luminous with $L_B \approx L_B^*$. Both galaxies appear compact with approximate dimensions 4×3 and 1×2 kpc respectively; presumably we are seeing predominantly their bulges at the exposure levels attained in the WFPC2 images. If *both* galaxies are at $z = 1.0093$ their projected separation from each other is only 22 h_{50}^{-1} kpc, and they may well be interacting. Thus the galaxies may be intrinsically fainter than their luminosities sug-

Table 1. Journal of observations

UT Date	Exp. Time (s)	Resolution (Å)	S/N
1997 Jan 08	2000	0.88	33
1997 Jan 09	2000	0.88	28
1997 Jan 17	2000	0.90	16
1997 Jan 17	2000	0.90	14

Table 2. Zn II and Cr II absorption lines

Line	Ion	$\lambda_0^{a,b}$ (Å)	$\lambda_{\text{obs}}^{a,c}$ (Å)	z_{abs}^a	W_0^d (mÅ)
1	Zn II	2026.136	4071.09	1.0093	53 ± 10
2	Cr II	2056.254	4131.55	1.0093	51 ± 10
3	Cr II+	2062.234+	4144.01	blend	48 ± 10
	Zn II	2062.664			
4	Cr II	2066.161	. . .	. . .	≤ 30

[a] All wavelengths are in vacuum
[b] Rest wavelength
[c] Observed wavelength (heliocentric)
[d] Rest frame equivalent width

gest, if we are observing them during a period of enhanced star formation triggered by the interaction, and the absorbing gas in front of the QSO may be tidally disrupted material. There is clearly a strong incentive to determine the redshifts of galaxies 2 and 3 and clarify the nature of this damped Lyman α system.

At least one object in the field of EX 0302−223 is at a redshift close to that of the DLA. Le Brun et al. refer to unpublished observations of object 7 by Guillemin & Bergeron showing that it is at redshift $z = 1.000$; at a separation of 84 h_{50}^{-1} kpc from the QSO sight-line, however, this galaxy is unlikely to be the absorber.

3. Zn and Cr abundances

We observed EX 0302−223 in service mode during the nights of 8–9 and 17–18 January 1997 with the double spectrograph at the cassegrain focus of the William Herschel telescope on the island of la Palma, Canary Islands. Table 1 gives the journal of observations.

A detailed description of the procedures used in acquiring and reducing the data can be found in Pettini et al. (1994). Briefly, we used a 1200 grooves mm^{-1} grating, blazed near 4100 Å, and a thinned 1024×1024 pixel Tektronix CCD to record a ≈ 400 Å wide portion of the spectrum centred at 4121 Å and encompassing the wavelengths of the Zn II $\lambda\lambda 2026.136, 2062.664$ and Cr II $\lambda\lambda 2056.254, 2062.234, 2066.161$ multiplets in the damped Lyman α system. A total of four exposures, each 2000 s long, was secured. The QSO was moved by a few arcseconds along the slit between each exposure, so as to use different rows of the detector to record the spectrum. Using standard IRAF routines, the individual spectra were optimally extracted and wavelength calibrated by reference to the emission lines of Cu-Ar and Cu-Ne hollow cathode lamps; they were then mapped onto a common, vacuum heliocentric wavelength scale before being co-added. The QSO was observed at large zenith distances (ZD $\simeq 55 - 65$ degrees); the bright of moon and poor seeing on 17 January account for the lower S/N of those data (see Table 1). The final spectrum has S/N = 50 and a resolution of 0.88 Å, sampled with 2.2 wavelength bins. The corresponding 3σ limit for the rest-frame equivalent width of an unresolved absorption line is $W_0(3\sigma) = 26$ mÅ. The lower panel of Fig. 1 shows the wavelength region of interest after division by the underlying QSO continuum; the wavelengths and rest-frame equivalent widths of the Zn II and Cr II lines are listed in Table 2. We detect fea-

tures 1, 2 and 3 at the $\sim 5\sigma$ level, while feature 4 is below our detection limit. The weakness of the absorption lines and their equivalent width ratios indicate that saturation effects are probably not important.

Assuming that Zn II $\lambda 2026.136$ and Cr II $\lambda 2056.254$ are on the linear part of the curve of growth and adopting the f-values measured by Bergeson & Lawler (1993), we deduce the values of column density of Zn$^+$ and Cr$^+$ listed in columns 2 and 5 of Table 3 respectively. Dividing by $N(\text{H}^0)$ and comparing with the solar abundances of Zn and Cr (Anders & Grevesse 1989)[2] we reach the conclusion that Zn and Cr are less abundant in the $z_{\text{abs}} = 1.0093$ DLA than in the Sun by factors of 3 and 8 respectively.

4. Discussion

4.1. Chemical evolution

The Zn abundance deduced is in good agreement with expectations for a galaxy like the Milky Way at this redshift. In the present day interstellar medium [Zn/H]$_{\text{gas}} = -0.19$ which may imply that $\approx 35\%$ of Zn is locked up in dust grains (Roth & Blades 1995; Sembach et al. 1995). The finding that [Zn/H]$_{\text{DLA}}$ is only a factor of ~ 2 lower than this value at a lookback time of 9.5 Gyrs is consistent with the mild increase with time of the average [Fe/H] of Galactic disk stars over this period (see Fig. 14 of Edvardsson et al. 1993). While it would be of great interest to relate the metallicity we have determined to other properties of the galaxy producing the DLA – such as mass, morphology and impact parameter – it is difficult to proceed further pending a positive identification of the absorber. Nevertheless, the observations presented here do demonstrate that galaxies which are on a chemical evolution path similar to that of the Milky Way disk do contribute to the DLA population at intermediate redshifts.

The three measurements of [Zn/H]$_{\text{DLA}}$ at $z \lesssim 1$ available at present span a factor of ~ 5, from 1/3 solar found here to 1/16 solar at $z_{\text{abs}} = 0.6922$ in 3C 286 (Meyer & York 1992, corrected for the more recent f-values used in the present analysis). Such

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[2] $\log (\text{Zn/H})_\odot = -7.35$, $\log (\text{Cr/H})_\odot = -6.32$

Table 3. Column densities and abundances in the z_{abs} = 1.0093 DLA system

$N(H^0)$ (10^{20} cm^{-2})	$N(Zn^+)$ (10^{12} cm^{-2})	$N(Zn^+)/N(H^0)$ (10^{-8} cm^{-2})	[Zn/H]	$N(Cr^+)$ (10^{12} cm^{-2})	$N(Cr^+)/N(H^0)$ (10^{-8} cm^{-2})	[Cr/H]	[Cr/Zn]
2.15 ± 0.35	3.0 ± 0.6	1.4 ± 0.4	$-0.51^{+0.11}_{-0.14}$	13.0 ± 2.5	6.0 ± 1.5	$-0.90^{+0.09}_{-0.13}$	$-0.39^{+0.11}_{-0.14}$

a range in the degree of chemical enrichment is in line with indications from the imaging survey by Le Brun et al. (1997) that DLAs at these redshifts arise in a diverse population of galaxies, which includes amorphous low-surface brightness objects and compact galaxies, as well as apparently normal spirals of various sizes and luminosities. The same presumably applies at $z \gtrsim 1.5$ where values of [Zn/H]$_{DLA}$ span more than one order of magnitude (Pettini et al. 1997b).

The challenge for the future, then, is to assess whether there are significant changes with redshift in the relative contributions of different galaxies to the cross-section for DLA absorption. It is possible, for example, that typical spiral galaxies like the Milky Way become progressively under-represented with decreasing redshift, if much of the gas has been turned into stars by $z \simeq 1$, or if the build-up of dust which goes hand in hand with production of metals introduces significant selection effects (e.g. Pei & Fall 1995). Given the wide range of values of Zn abundance encountered at all redshifts, it is clear that tracing the global chemical evolution of the DLA population from high redshifts to $z < 1.5$ will only be possible with a moderately large sample of data. The availability of STIS on the *HST* has now brought within reach Zn and Cr absorption lines at redshifts $z \lesssim 0.65$; this new opportunity should double the number of measurements in the next two years. Looking further ahead, the 2dF and Sloan surveys will lead to major advances by increasing by one order of magnitude existing samples of damped Lyman α systems.

4.2. Dust depletion of chromium

As can be seen from the last column of Table 3, Cr is less abundant than Zn by a factor of ~ 2.5; as discussed by Pettini et al. (1997a) the most straightforward interpretation of this abundance difference is the selective depletion of Cr – and presumably other refractory elements – onto dust grains. The value [Cr/Zn] = -0.39 when [Zn/H] = -0.51 fits in well with the broad trend of increasing depletion with increasing metallicity found in the analysis of 18 such measurements by Pettini et al. (1997a–see their Fig. 1). In agreement with that study, we find that the depletion of Cr in the z_{abs} = 1.0093 damped system is less severe than in diffuse interstellar clouds in the Galactic disk, where typically [Cr/Zn] $\lesssim -1$, and closer to values encountered in halo clouds located at distances of more than 300 pc from the plane (Savage & Sembach 1996).

This could be simply an indication that the line of sight to EX 0302$-$223 does not intersect interstellar clouds of sufficiently high density to maintain a large fraction of Cr in solid

form, as is the case in the disk of the Milky Way. Indeed, we do not know whether the z_{abs} = 1.0093 DLA arises in a galactic disk at all. On the other hand, it is intriguing that *none* of the 19 cases in which [Cr/Zn] has now been measured exhibit the degree of Cr depletion typical of local disk clouds. Even along sightlines to stars in the Magellanic Clouds, which probe long pathlengths through both the disk and halo of the Milky Way in a geometry presumed to be similar to that of damped Lyman α systems, it is found that [Cr/Zn] $\lesssim -1$, and there is essentially no overlap with the values measured in DLAs (Roth & Blades 1997).

The lower depletions of refractory elements in halo clouds are commonly interpreted as an indication that grain processing in interstellar shocks is either more efficient or more frequent in the low density regions away from the Galactic plane (e.g. Savage & Sembach 1996). Possibly the interstellar medium of DLA galaxies is a more hostile environment to interstellar grains, particularly if the galaxies are forming stars at a higher rate than the Milky Way today and consequently experience more frequent supernova explosions. Ge & Bechtold (1997) used the relative populations of the rotationally excited levels of molecular hydrogen to measure the interstellar radiation field density near 1000 Å in the z_{abs} = 1.9730 DLA system in Q0013$-$004 and indeed found it to be a few times higher than the ambient value in the solar vicinity. Even so, given that the DLA population probably encompasses a wide range of galaxy types at different evolutionary stages, it is implausible that all galaxies are observed during periods of enhanced star formation.

Possibly several factors are at play. Clarifying the physical reasons at the root of the lower depletions of refractory elements in damped Lyman α systems–and the undoubtedly related lower concentrations of molecular hydrogen–remains an important goal for our understanding of the interstellar medium of distant galaxies.

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