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The mass-metallicity relation for high-redshift damped Lyα galaxies

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Abstract. We used our database of ESO VLT-UVES spectra of quasars to build up a sample of 67 damped Lyman-α (DLA) systems with redshifts $1.7 < z_{\rm abs} < 3.7$. For each system, we measured average metallicities relative to Solar, [X/H] (with either X = Zn, S, or Si), and the velocity widths of low-ionisation line profiles, W_1. We find that there is a tight correlation between the two quantities, detected at the 5σ significance level. The existence of such a correlation, over more than two orders of magnitude spread in metallicity, is likely to be the consequence of an underlying mass-metallicity relation for the galaxies responsible for DLA absorption lines. The best-fit linear relation is $[{\rm X/H}] = (91.35 \pm 0.11) \log W_1 - (3.69 \pm 0.18)$ with W_1 expressed in km s^{-1}. While the slope of this velocity-metallicity relation is the same within uncertainties between the higher and the lower redshift bins of our sample, there is a hint of an increase in the intercept point of the relation with decreasing redshift. This suggests that galaxy halos of a given mass tend to become more metal-rich with time. Moreover, the slope of this relation is consistent with that of the luminosity-metallicity relation for local galaxies. The DLA systems having the lowest metallicities among the DLA population would therefore, on average, correspond to the galaxies having the lowest masses. In turn, these galaxies should have the lowest luminosities among the DLA galaxy population. This may explain the recent result that the few DLA systems with detected Lyα emission have higher than average metallicities.

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1. Observations

Most of the DLA systems in our sample (with total neutral hydrogen column densities $\log N(\mbox{H\,{\sc i}}) \geqslant 20$) were observed at the ESO Very Large Telescope (VLT) with UVES between 2000 and 2003 to search for H_2 molecules at $z_{\rm abs} > 1.8$ (Petitjean *et al.* 2000; Ledoux *et al.* 2003). The absorption line analysis was homogeneously performed using standard Voigt-profile fitting techniques. Average DLA metallicities relative to Solar, $[{\rm X/H}] \equiv \log[N({\rm X})/N({\rm H})] - \log[N({\rm X})/N({\rm H})]_\odot$, were calculated as the sum of the column densities measured in individual components of the absorption profiles, with X=Zn as the reference element when Zn II is detected, or else either S or Si. One notable characteristic of this large dataset is that it samples well both the low and the high ends of the DLA metallicity distribution, from $[{\rm X/H}] \approx -2.6$ up to about half of Solar.

For each DLA system, we also measured the velocity widths of the metal absorption line profiles. Low-ionisation transition lines that are not strongly saturated were selected (see Prochaska & Wolfe 1997; Wolfe & Prochaska 1998). For high-ionisation lines, the velocity width could be dominated by extended galaxy halos and galactic winds. We calculated

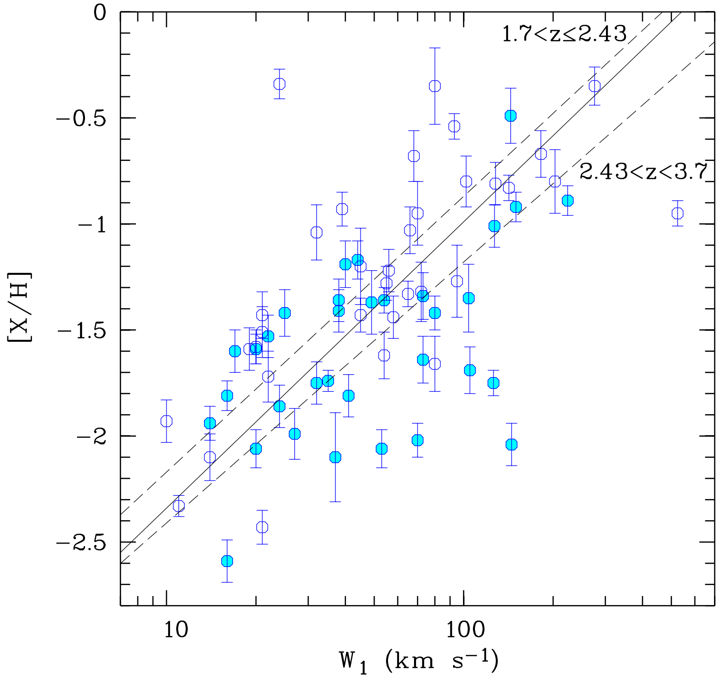

Figure 1. Average metallicity of each DLA system in our sample, [X/H], vs. W_1 on a logarithmic scale (empty circles: $1.7 < z_{\rm abs} \leqslant 2.43$; shaded circles: $2.43 < z_{\rm abs} < 3.7$). A correlation between the two quantities is detected at the 5σ significance level. The linear least-squares bisector fit to the total sample is shown by a solid line, and the $z_{\rm abs} \leqslant 2.43$ and $z_{\rm abs} > 2.43$ sub-samples with long-dashed lines.

the velocity width of the selected profiles as the second moment of the distribution of apparent optical depth along these profiles.

2. DLA velocity-metallicity correlation

The correlation between DLA low-ionisation metal line width and average metallicity, as observed in Fig. 1, over more than two orders of magnitude spread in metallicity, can be understood as the consequence of an underlying mass-metallicity relation for the galaxies responsible for DLA absorption lines. We fitted the data using the linear least-squares bisector method. For DLA systems with redshifts larger than the median redshift of our sample, we find $[{\rm X/H}] = (1.23 \pm 0.14) \log W_1 - (3.64 \pm 0.24)$ at $2.43 < z_{\rm abs} < 3.7$, and $[{\rm X/H}] = (1.30 \pm 0.16) \log W_1 - (3.47 \pm 0.26)$ at $1.7 < z_{\rm abs} \leqslant 2.43$.

While the slope of the DLA velocity-metallicity relation is the same within uncertainties between the higher and the lower redshift bins of our sample, there is a hint of an increase of the intercept point of the relation with decreasing redshift. This is linked to an increase of the mean DLA metallicity with decreasing redshift, with $[{\rm X/H}] = -1.58$ (resp. $[{\rm X/H}] = -1.22$) in the higher (resp. lower) redshift bin of our sample (see also Prochaska *et al.* 2003). *This suggests that galaxy halos of a given mass (resp. a given metallicity) tend to become more metal-rich (resp. less massive) with time*. This is consistent with the recent result by Savaglio *et al.* (2004) for $0.4 < z < 1$ galaxies selected from the Gemini Deep Deep Survey and the Canada-France Redshift Survey.

The above results are also in agreement with those of Nestor *et al.* (2003) who found larger metallicities in Sloan Digital Sky Survey (SDSS) $0.9 < z_{\rm abs} < 2.2$ DLA composites

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with larger Mg IIλ2796 equivalent widths. In addition, these authors showed that, within the large equivalent width regime, the metallicity is larger at lower redshift.

3. Implications and prospects

Haehnelt *et al.* (1998) performed similar line velocity width measurements on low-ionisation lines from DLA systems in simulations and compared them directly to the virial velocities of the underlying dark matter halos ($v_{\rm vir} = (GM/r)^{1/2}$ in a sphere over-dense by a factor of 200 compared to the mean cosmic density). They found $W_1 = 0.4 v_{\rm vir}$. According to Haehnelt *et al.* (2000), the luminosity function of $z \sim 3$ galaxies can be reproduced if a simple linear scaling of the luminosity with the mass of the dark matter halos is assumed, i.e. $m_B = -7.5 \log(v_{\rm vir}/200 \text{ km s}^{-1}) + m_B^0$, where m_B is the galaxy apparent B-band magnitude and $m_B^0 \simeq m_R^0 = 26.6$. Using our linear best-fit to the velocity-metallicity relation for $1.7 < z_{\rm abs} < 3.7$ DLA systems ($z_{\rm med} = 2.43$), we get:

$$[\text{X/H}] = -0.18(\pm 0.02) M_B - 4.70(\pm 0.18) - 0.18 K_B, \qquad (3.1)$$

where K_B is the K-correction in the B-band, which should be positive. The slope of this DLA luminosity-metallicity relation is consistent with that derived by Tremonti *et al.* (2004) for the luminosity-metallicity relation for $z \sim 0.1$ galaxies selected from the SDSS, $[\text{O/H}] = -0.185(\pm 0.001) M_B - 3.452(\pm 0.018)$. However, the zero points of the two relations are different *implying that galaxies of a given luminosity (resp. a given metallicity) are becoming more metal-rich (resp. fainter) with time.*

Eq. 3.1 implies that the more than two orders of magnitude spread in DLA metallicity reflects a more than ten magnitudes spread in DLA galaxy luminosity. In other words, a low metallicity should on average imply a small stellar mass and thus a low luminosity. Even though low-mass galaxies, i.e. gas-rich dwarf galaxies, can undergo periods of intense star formation activity, they show, on average, lower star-formation rates than more massive galaxies (Brinchmann *et al.* 2004; see also Okoshi *et al.* 2004). The existence of a DLA mass-metallicity relation may thus explain the fact that the few DLA systems with detected Lyα emission have higher than average metallicities (Møller *et al.* 2004; Christensen *et al.*, in prep.). This should be confirmed by additional deep imaging of the fields of QSOs with selected DLA absorbers.

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