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The VLT-UVES survey for molecular hydrogen in high-redshift damped Lyman-α systems

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Abstract. We report the current results of our on-going search for molecular hydrogen (H_2) in damped Lyman-α (DLA) and sub-DLA systems at $1.8 < z_{\rm abs} < 3.4$ using the Ultraviolet and Visible Echelle Spectrograph (UVES) installed at the ESO's Very Large Telescope (VLT), Unit Kueyen.

1. Introduction

High-redshift DLA and sub-DLA systems observed in absorption against QSO spectra are characterised by their large neutral hydrogen column densities, $\log N(\rm H\,I) \geqslant 20.3$ and $19.4 \leqslant \log N(\rm H\,I) < 20.3$, respectively. Formation of H_2 molecules is expected on the surface of dust grains if the gas is cool, dense, and mostly neutral; and from the formation of negative hydrogen ions if the gas is warm and dust-free (see e.g. Jenkins & Peimbert 1997; Cazaux & Tielens 2002). As the former process is most likely dominant in the neutral gas associated with DLA systems, it is possible to obtain an indirect indication of the amount of dust in DLA systems without depending on extinction and/or heavy element dust depletion effects. Moreover, from determining the relative populations of different rotational levels of H_2, one can constrain the kinetic and rotational excitation temperatures, and the particle densities. The effective photo-dissociation of H_2 takes place in the energy range $11.1 - 13.6$ eV through Lyman- and Werner-band absorption lines and, therefore, the intensity of the local UV radiation field can be derived from the observed molecular fractions.

2. Evidence for dust in DLA systems

Out of 33 systems in the sample of the first part of our survey (Ledoux, Petitjean & Srianand 2003), eight have firm and two have tentative detections of associated H_2 absorption lines down to a detection limit of typically $\log N(H_2) = 14.3$. Considering that three detections were already known from past searches, molecular hydrogen is detected in 13 to 20% of the newly-surveyed systems. We reported new H_2 detections at $z_{\rm abs} = 1.962$ toward Q 0551−366 (Ledoux, Srianand & Petitjean 2002b), $z_{\rm abs} = 1.968$ and $z_{\rm abs} = 1.973$ toward Q 0013−004 (Petitjean, Srianand & Ledoux 2002), $z_{\rm abs} = 2.087$ and 2.595 toward

Q 1444+014 and Q 0405−443 respectively, and reanalysed the system at $z_{\rm abs} = 3.025$ toward Q 0347−383 using higher quality data (Ledoux *et al.* 2003).

In all of the DLA and sub-DLA systems in our sample, we measured metallicities relative to Solar, [X/H] (with either X=Zn, or S, or Si), and depletion factors of Fe, [X/Fe], supposedly onto dust grains, and compared the characteristics of our sample with those of the global population of DLA systems (60 systems in total). We found that there is a correlation at the 4σ significance level between metallicity and depletion factor in both our sample and also the global population of DLA systems (see Fig. 1, lower right panel). Moreover, the DLA and sub-DLA systems where H_2 is detected are usually amongst those having the highest metallicities and the largest depletion factors (Fig. 1, left panels).

The individual profile components where H_2 is detected have depletion factors systematically larger than other components in the same profiles. In two different systems, one of the H_2-detected components even has $[\mathrm{Zn/Fe}] \geqslant 1.4$. These are the largest depletion factors seen to date in DLA systems. All this clearly demonstrates the presence of dust in a large fraction of the DLA systems. This also strongly favours the fact that the correlation between metallicity and depletion factor is a consequence of dust depletion effects.

3. Physical conditions in the DLA systems

The mean H_2 molecular fraction, $f = 2N(\mathrm{H_2})/[2N(\mathrm{H_2}) + N(\mathrm{H\,I})]$, is generally small in DLA systems (typically $\log f < -1$). There is no correlation between the observed amount of H_2 and the total H I column density. In fact, two of the systems where H_2 is detected have $\log N(\mathrm{H\,I}) < 20.3$, i.e. they are sub-DLA systems.

We found that there is a trend for the H_2 molecular fraction to be related to the dust-to-gas ratio. However, several orders of magnitude spread in H_2 molecular fraction for a given dust content among the detected cases suggests that in addition to the amount of dust, the physical conditions of the gas (temperature, density, and UV flux) play an important role in governing the formation of molecules in DLA systems (Ledoux *et al.* 2002b, 2003).

The derived kinetic temperatures in DLA systems that show H_2 absorption lines (153 ± 78 K), based on the ortho-to-para ratio, are higher than those measured in the Galactic ISM and the Magellanic Clouds (Srianand *et al.* 2005). The typical pressure in the H_2 components ($\mathrm{T} = 100-300$ K and $n_{\rm H} = 10-200$ cm^{-3}), measured using C I fine-structure excitation lines, is also higher than what is measured along Galactic sight-lines. Based on the observed high J excitation, we conclude that the typical radiation field in the H_2-bearing DLA clouds is of the order of or slightly higher than the mean UV field in the Galactic ISM (Srianand *et al.* 2005).

From 58 to 75% of the DLA systems have extremely low H_2 molecular fractions, $\log f < -6$. The non-detection of H_2 in these systems is consistent with them having low densities (i.e. $n_{\rm H} \leqslant 1$ cm^{-3}) for a radiation field similar to the mean Galactic UV field.

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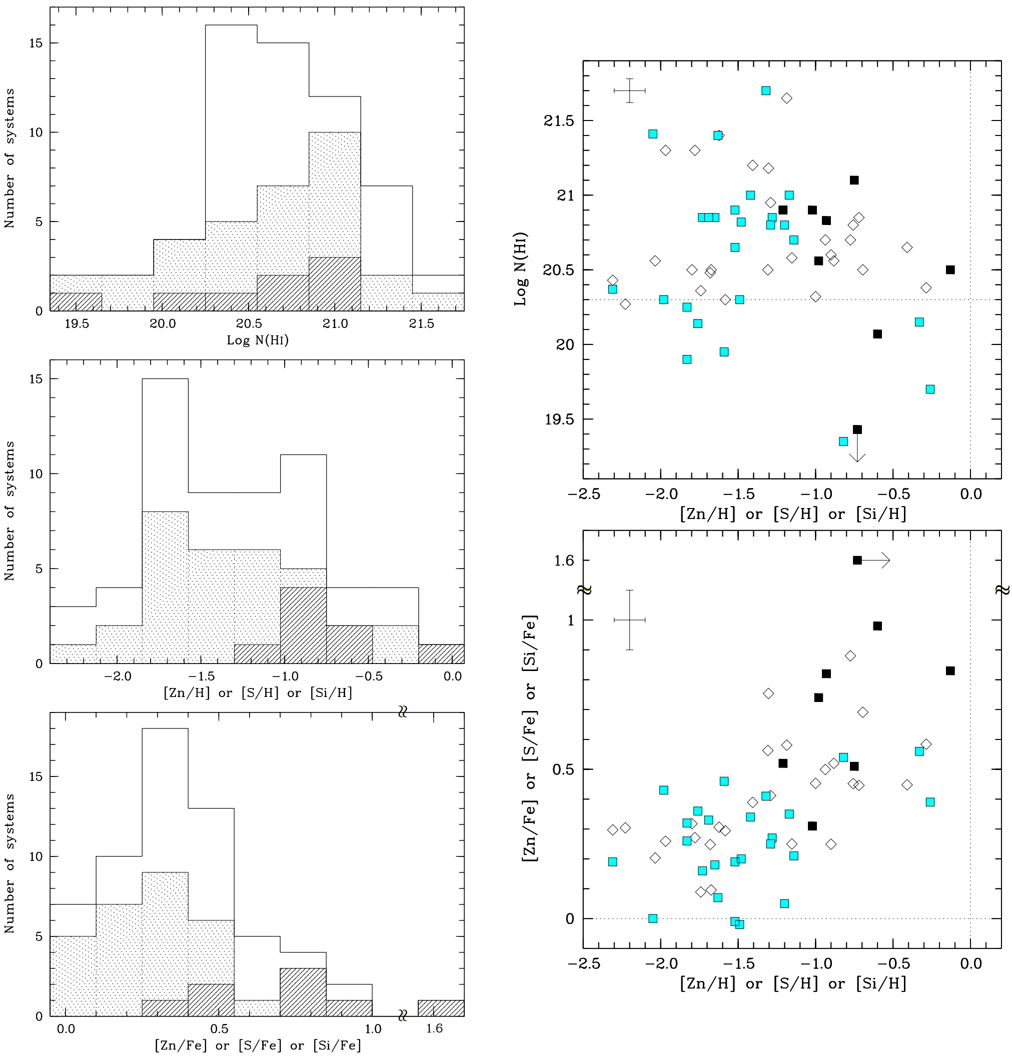

Figure 1. *Left panels:* Distributions of total neutral hydrogen column densities (*upper panel*), average metallicities (*middle panel*; measured from either [Zn/H], [S/H], or [Si/H]) and depletion factors (*lower panel*; measured from either [Zn/Fe], [S/Fe], or [Si/Fe]) in respectively the global population of DLA/sub-DLA systems (overall distribution), the H_2-survey sample (dotted histogram), and the sub-sample of H_2-detected systems (hashed histogram).
Right panels: Total neutral hydrogen column density (*upper plot*) and depletion factor (*lower plot*) versus average metallicity in, respectively, the global population of DLA/sub-DLA systems (all symbols), the H_2-survey sample (all squares) and the sub-sample of H_2-detected systems (dark squares). The typical error bars are shown in the upper-left part of each plot. A correlation between metallicity and depletion factor is present at the 4σ significance level, confirming the trend previously detected by Ledoux, Bergeron & Petitjean (2002a).

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