Molecules in the interstellar medium at high redshift

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Abstract:

We present the current status of ongoing searches for molecules in high redshift Damped Lyman-α systems (DLAs) with the Ultraviolet and Visual Echelle Spectrograph mounted on the Very Large Telescope of the European Southern Observatory. To study the incidence of H_2, we built a sample of 77 DLAs/strong sub-DLAs, with $N(\mathrm{H\,I}) \geq 10^{20}$ cm^{-2} and $z_{\rm abs} > 1.8$, which have data that include redshifted Lyman- and/or Werner-band absorption lines. This sample of H I, H_2, and metal line measurements, performed in an homogeneous manner, is more than twice as large as our previous survey (Ledoux et al. 2003). We detect H_2 in 13 of these systems and measure upper limits of $N(\mathrm{H_2}) \sim 2\times10^{14}$ cm^{-2} for the remaining ones. The molecular fractions are found to be in the range $f \simeq 5\times10^{-7}$ to $f \simeq 0.1$ where $f = 2N(\mathrm{H_2})/(2N(\mathrm{H_2}) + N(\mathrm{H\,I}))$. We found a clear dependence of $N(\mathrm{H_2})$ with the column density of iron in dust. The overall detection rate in $\log N(\mathrm{H\,I}) \geq 20$ DLAs is found to be 10% (considering only $\log f > -4.5$ detections) after correction for a slight bias toward large $N(\mathrm{H\,I})$.

We also present recent high resolution observations of a fourteenth H_2-bearing system, selected from an automated search for and analysis of DLAs in $\sim$ 10 000 low resolution quasar spectra from the Sloan Digital Sky Survey. This unique system has the largest molecular fraction measured till date in a DLA ($f = 0.27$) and also features carbon monoxide (CO) and deuterated molecular hydrogen (HD) absorption lines. This is only the second detection of HD while the very first detection of CO in a high-z DLA. From the population in different rotational levels of CO, we are able to measure at an unprecedent accuracy the temperature of the Cosmic Microwave Background Radiation when the Universe was less than 3 Gyr old. From HD/2H$_2$, we obtain a very low upper limit on the astration factor (1.7), contrasting with the high chemical enrichment of the system. This probably result from a scenario where star formation is coupled with an infall of primordial gas onto the associated galaxy.

DLAs: The high-z interstellar medium imprinted in quasar spectra

Damped Lyman-α systems (DLAs) are the highest column densities absorbers seen in the spectra of background QSOs, with $N(\mathrm{H\,I}) \geq 2\times10^{20}$ atoms cm^{-2}. They probably arise in the interstellar medium of protogalaxies, progenitors of present-day galaxies (see, e.g. Wolfe & Prochaska 2000; Haehnelt et al. 2000; Wolfe et al. 2005).

Our understanding of DLAs is mainly based on the study of:
- low-ionization metal absorptions (e.g. Prochaska & Wolfe 2002)
- high-ionization metal absorptions (e.g. Fox et al. 2007)
- molecular absorptions (e.g. Ledoux et al. 2003, Noterdaeme et al. 2008).

Constraints on the physical conditions such as kinetic temperature, particle density, and UV radiation field (e.g. Srianand et al. 2005, Hirashita & Ferrara 2005, Noterdaeme et al. 2007a,b) in the neutral ISM at high redshift can be derived from H_2 absorptions and suggest this sub-class of DLAs is associated with regions of star-formation.

New discoveries and detailed studies of H_2-bearing DLAs are possible thanks to the Ultraviolet and Visual Echelle Spectrograph (UVES) at the Very Large Telescope (VLT), see Petitjean et al. (2000). We recently showed that selecting high-metallicity DLAs is an effective way to find H_2-bearing systems (Petitjean et al. 2006), and present here the full UVES survey for H_2-bearing DLAs (first part published by Ledoux et al. 2003).

Molecular hydrogen

Our sample consists in 68 DLAs and 9 sub-DLAs toward 65 quasars, all observed with UVES and selected with the criteria:
- $N(\mathrm{H\,I}) \geq 10^{20}$ cm^{-2}. At these column densities, most of the hydrogen is neutral (Viegas 1995).
- $z_{\rm abs} > 1.8$, so that redshifted UV lines of H_2 are observable from the ground.

Most of the systems in our sample were selected from Ledoux et al.(2006a). We also consider 13 systems from the Hamburg-ESO DLA survey (Smette et al. 2005), 7 from the CORALS survey (Akermann et al. 2005), and 4 from additional observing runs.

$\Longrightarrow$ By now, 14 high-z H_2 systems are known from which 9 have been discovered in the course of our survey, while one is associated to our recent discovery of a CO-bearing DLA.

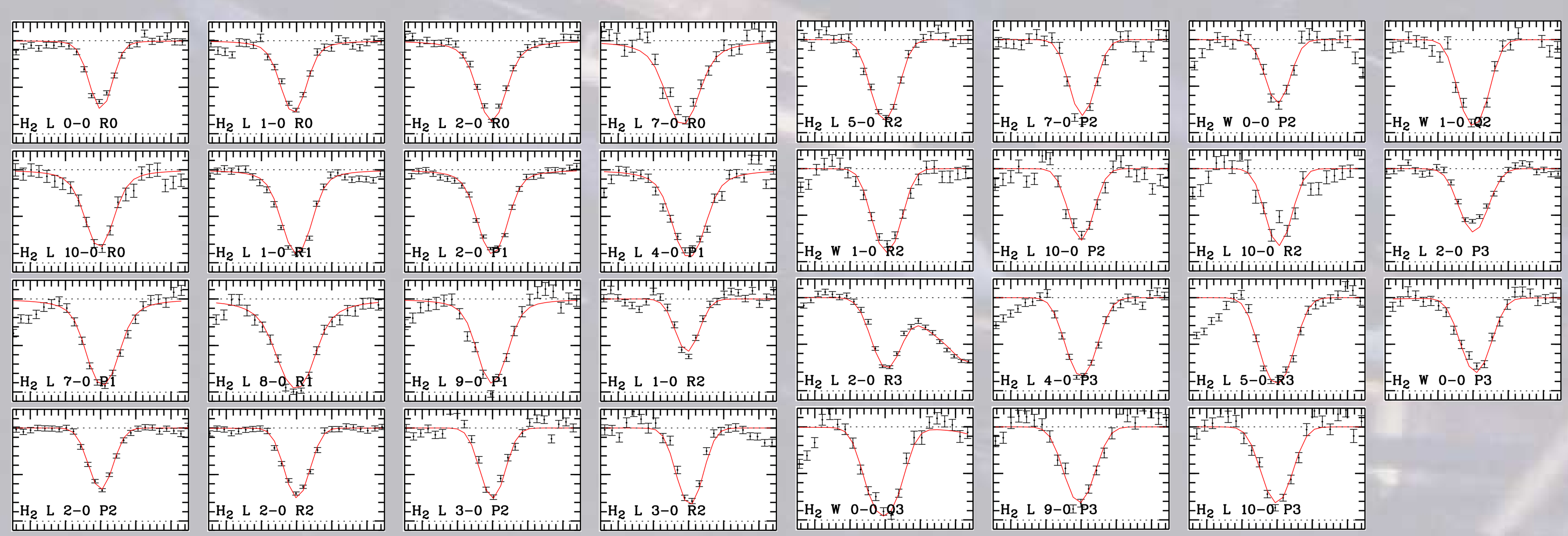


Fig. 1: VLT/UVES spectrum showing a selection of H_2 absorption lines in rotational levels J = 0 to J = 3 at $z_{\rm abs} = 2.4$. Each box is 50 km s^{-1} wide.

Dust and physical conditions

We plot in Fig. 2. the column density of H_2, as a function of the column density of iron in dust (see Vladilo 2002). There is a clear gap in the H_2 column densities between the upper limits and firm detections of about four orders of magnitude, whereas H_2 detections span a small range (only one order of magnitude) on $N(\mathrm{Fe})_{\rm dust}$. This is a measure of the total column density of dust in the DLA. There is no H_2 detected in DLAs with $N(\mathrm{Fe})_{\rm dust} < 5\times10^{14}$ cm^{-2}. This shows the presence of dust is necessary to the presence of H_2. On the other hand, there are three non-detection of H_2 at $N(\mathrm{Fe})_{\rm dust} > 3\times10^{15}$ cm^{-2}. This is probably due to the large neutral hydrogen column density in these systems ($\log N(\mathrm{H\,I})$= 21.70; 21.80; 21.40), together with a low volumic density.

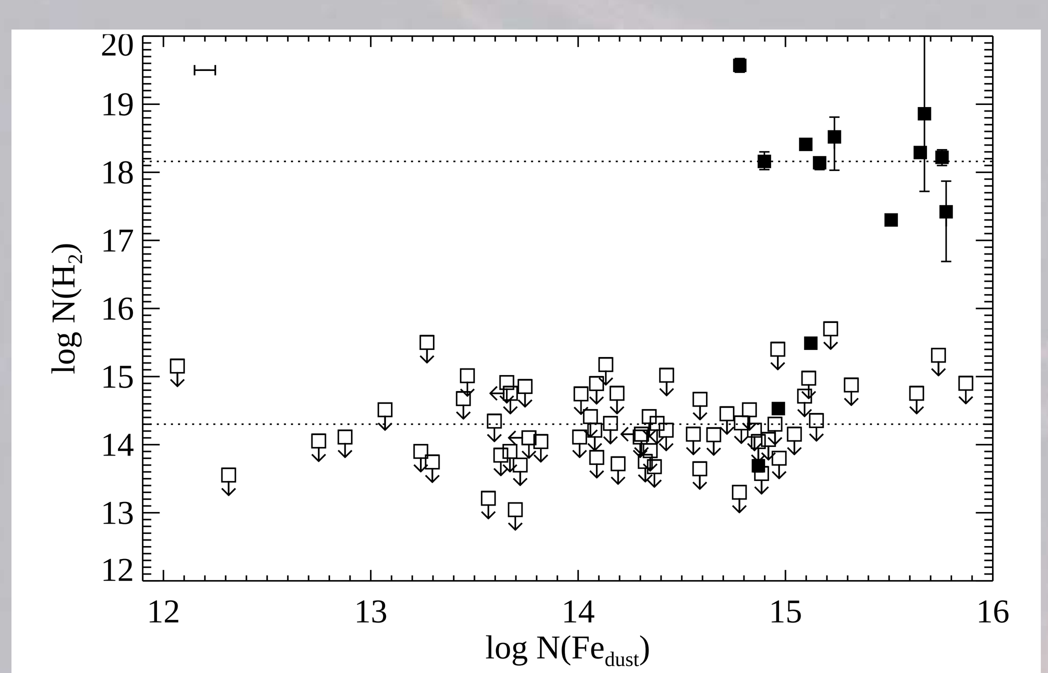


Fig. 2. The column density of H_2 versus the column density of iron in dust, $N(\mathrm{Fe})_{\rm dust} = (1-10^{-[\mathrm{X/Fe}]})N(\mathrm{X})\,(\mathrm{Fe/X})_{\rm dla}$. The two dotted lines show the median of $N(\mathrm{H_2})$ (resp. upper limit on $N(\mathrm{H_2})$) for the H_2-detected DLAs and the non H_2-detected ones. The 4 orders of magnitude range for a same $N(\mathrm{Fe})_{\rm dust}$ is due to differences in the physical conditions.

From the observed column densities in the different rotational levels together with the excitation of C I we discuss the physical conditions in the gas (e.g., Srianand et al. 2005, Noterdaeme et al. 2007a,b). The gas is found to be cold (typically 100-150 K) but still hotter than similar gas in our Galaxy. Densities are found to be about $n \sim 10-200$ cm^{-3} and UV fluxes range between 1 to 100 times Galactic.

Carbon Monoxide: MEASURING THE CMB TEMPERATURE AT $z \simeq 2.4$

The results from the H_2 survey show that molecules are preferably found in cold and dusty clouds, that can be identified as high-metallicity (Petitjean et al. 2006) and CI-bearing (Srianand et al. 2005) systems. We therefore searched for DLAs with such properties in $\sim 10\,000$ QSOs from the SDSS. High-resolution observations of the best candidate resulted in the first detection of CO in a DLA.

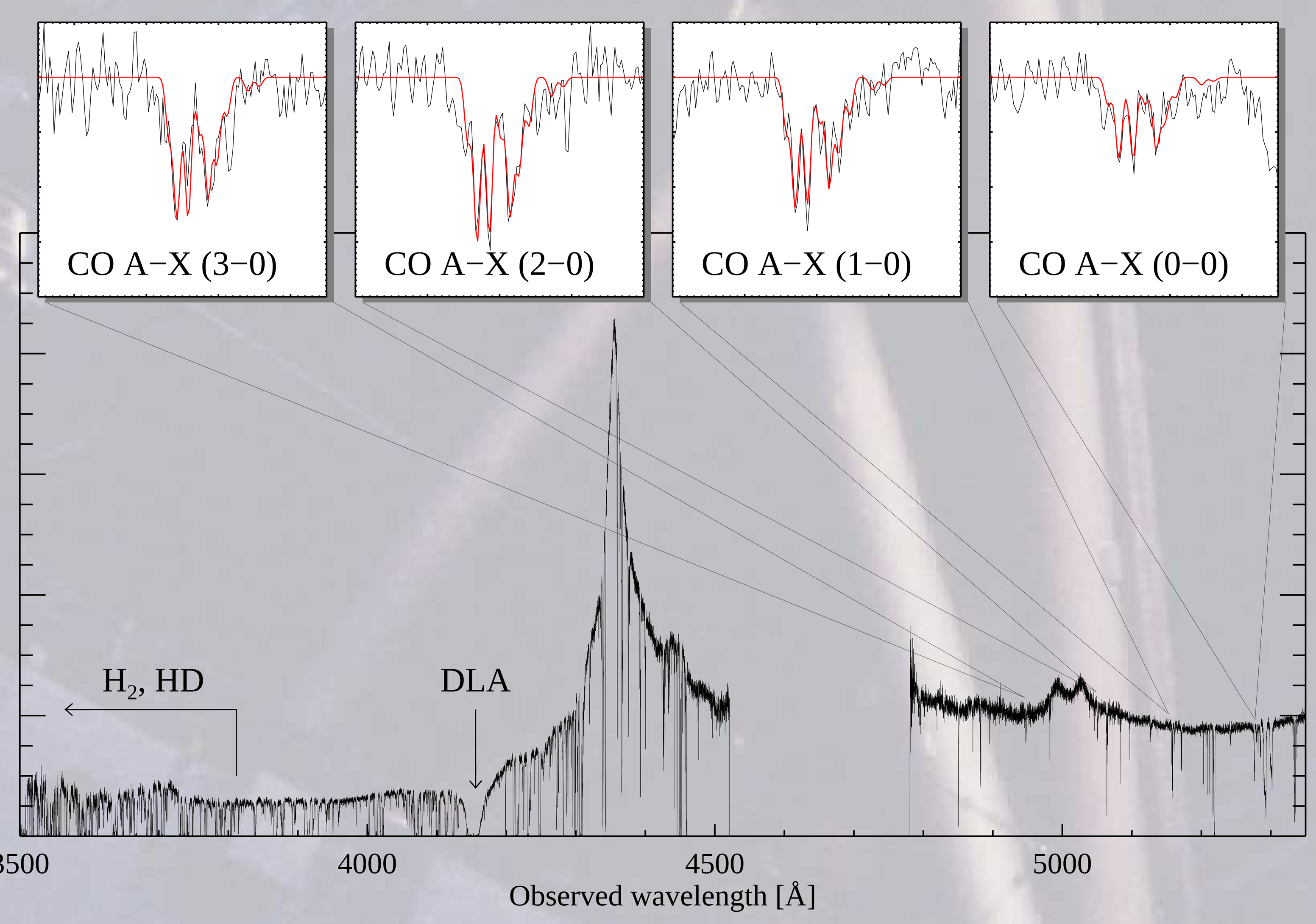
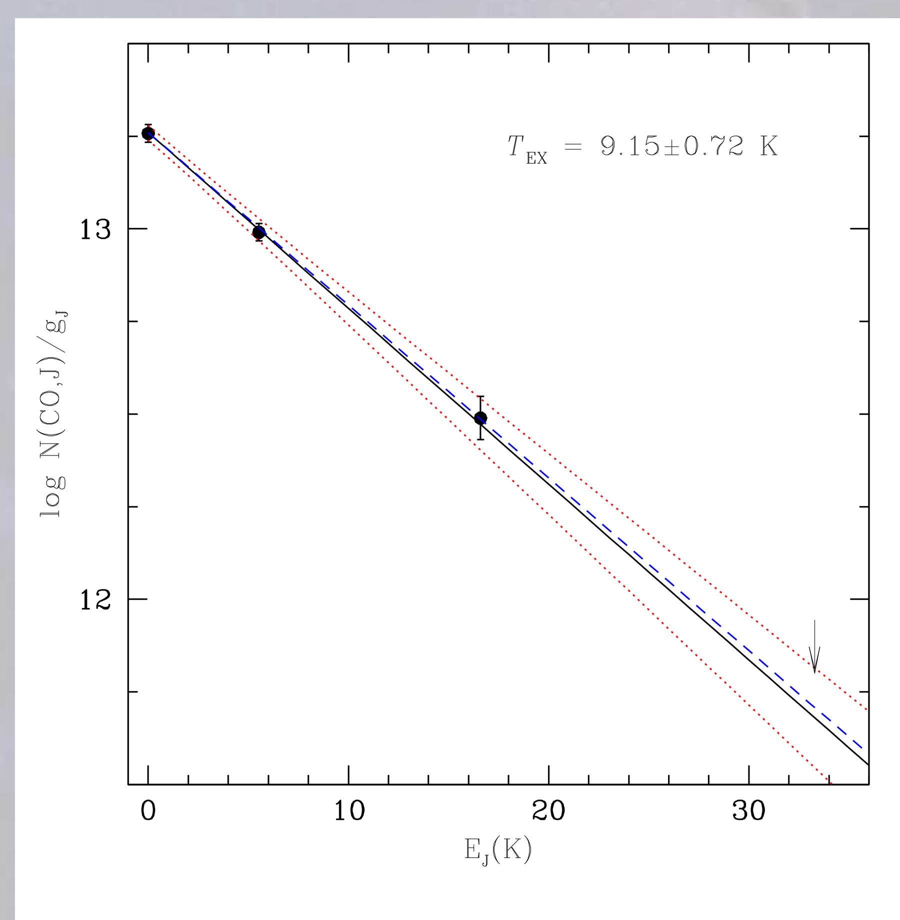


Fig. 3. UVES spectrum of quasar SDSS J143912.04+111740.5 which features strong H_2, HD and CO absorption lines at redshift $z \simeq 2.42$.

Using the fine-structure excitations of neutral carbon, detected from the same gas, we show the rotational excitation of CO is dominated by Cosmic Microwave Background Radiation (CMBR). We measure $T_{CMBR} = 9.15 \pm 0.72$ K when 9.315 ± 0.007 K is expected. *This is the most accurate confirmation of the prediction of the Big-Bang theory at high redshift.*

Fig. 4: The CO excitation diagram. A straight line with slope $1/(T_{\rm ex}\ln 10)$ indicates thermalization of the levels. The diagram is given for the main CO component at $z_{\rm abs} = 2.41837$. The three lines give the mean and 1σ range on the measured temperatures. The diagram is compatible with thermalization by a black-body radiation of temperature 9.15 ± 0.72 K when $T_{\rm CMBR} = 9.315 \pm 0.007$ K (long dashed line) is expected at this redshift from the hot Big-Bang theory.



HD: Evidence for intense infall of primordial gas onto galaxies

From the column density of HD in the system toward SDSS J143912+111740, we derive $N(\mathrm{HD})/2N(\mathrm{H_2}) = 1.5\times10^{-5}$, consistent with an astration factor of deuterium less than 1.7. This constrasts with the high chemical enrichment (Solar metallicity) and is best explained by a scenario in which the gas that goes through star formation is replenished by continous infall of ambient primordial gas.

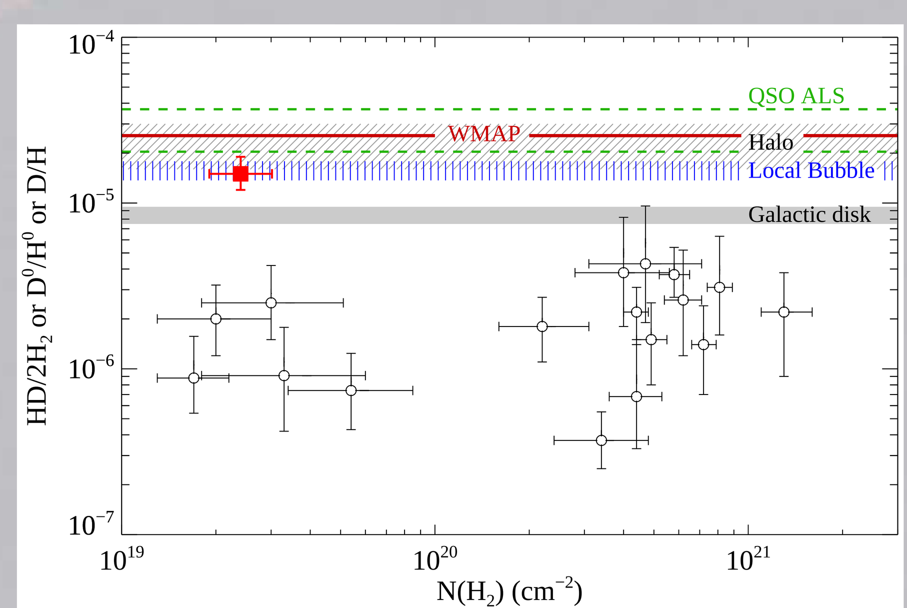


Fig. 5: The D/H ratio vs the H_2 column density. The red filled square is the new measurement at $z_{\rm abs} = 2.42$. The empty circles are FUSE and COPERNICUS measurements in the Galactic ISM (Lacour 2005). D/H ratio obtained in different environments are also indicated. The primordial ratio from WMAP is represented by the solid line.