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LETTER TO THE EDITOR

Metallicity as a criterion to select H₂-bearing damped Lyman-α systems[⋆]

P. Petitjean[1,2], C. Ledoux[3], P. Noterdaeme[3], and R. Srianand[4]

[1] Institut d'Astrophysique de Paris, CNRS – Université Pierre et Marie Curie, 98bis boulevard Arago, 75014 Paris, France
e-mail: petitjean@iap.fr
[2] LERMA, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France
[3] European Southern Observatory, Alonso de Córdova 3107, Casilla 19001, Vitacura, Santiago, Chile
[4] IUCAA, Post Bag 4, Ganesh Khind, Pune 411 007, India

ABSTRACT

Aims. We characterize the importance of metallicity on the presence of molecular hydrogen in damped Lyman-α (DLA) systems.
Methods. We constructed a representative sample of 18 DLA/sub-DLA systems with $\log N(\text{H I}) > 19.5$ at high redshift ($z_{\text{abs}} > 1.8$) and with metallicities relative to solar [X/H] > −1.3 (with [X/H] = $\log N(\text{X})/N(\text{H}) - \log(\text{X/H})_\odot$ and X either Zn, S or Si). We gathered data covering the expected wavelength range of redshifted H₂ absorption lines on all systems in the sample from either the literature (10 DLAs), the UVES-archive, or new VLT-UVES observations for four of them. The sample is large enough to allow us to discuss for the first time the importance of metallicity as a criterion for the presence of molecular hydrogen in the neutral phase at high-z.
Results. From the new observations, we report two new detections of molecular hydrogen in the systems at $z_{\text{abs}} = 2.431$ toward Q 2343+125 and at $z_{\text{abs}} = 2.426$ toward Q 2348−011. Q 2348−011, From a comparison of the H2 detection fraction in the high-metallicity sample with earlier results, we find that the fraction of DLA systems with $\log f = \log 2N(\text{H}_2)/(2N(\text{H}_2) + N(\text{H I})) > -4$ is as large as 50% for [X/H] > −0.7, when it is only ∼5% for [X/H] < −1.3 and ∼15% in the overall sample (with −2.5 < [X/H] < −0.3). This demonstrates that the presence of molecular hydrogen at high redshift is strongly correlated with metallicity.

Key words. galaxies: high-redshift – galaxies quasars: absorption lines – galaxies quasars: individual: Q 2343+125 – galaxies quasars: individual: Q 2348−011

1. Introduction

Early searches for molecular hydrogen in DLAs, though not systematic, have led to either low values of or upper limits to the molecular fraction of the gas. For a long time, only the DLA at $z_{\text{abs}} = 2.811$ toward Q 0528−250 was known to contain H₂ molecules (Levshakov & Varshalovich 1985; Foltz et al. 1988). Ge & Bechtold (1999) searched for H₂ in a sample of eight DLAs using the MMT moderate-resolution spectrograph (*FWHM* = 1 Å). Apart from the detection of molecular hydrogen at $z_{\text{abs}} = 1.973$ and 2.338 toward Q 0013−004 and Q 1232+082, respectively, they measured upper limits on f in the range 10^{-6}–10^{-4} in the other systems.

A major step forward in understanding the nature of DLAs through their molecular hydrogen content has recently been made possible by the unique high-resolution and blue-sensitivity capabilities of UVES at the VLT. In the course of the first large and systematic survey for H₂ at high redshift, we searched for H₂ in DLAs down to a detection limit of typically $N(\text{H}_2) = 2 \times 10^{14}$ cm^{-2} (Petitjean et al. 2000; Ledoux et al. 2003). Out of the 33 surveyed systems, eight had firm detections of associated H₂ absorption lines. Considering that three detections had

been already known from past searches, H₂ was detected in ∼15% of the surveyed systems. The existence of a correlation between metallicity and depletion factor, measured as [X/Fe] (with X = Zn, S or Si) was demonstrated (see also Ledoux et al. 2002a) and the DLA and sub-DLA systems where H₂ was detected were usually among those with the highest metallicities.

However, the high metallicity end of the Ledoux's sample was biased by the presence of already known detections. Therefore, to further investigate this possible dependence with metallicity and derive the actual molecular content of the high-redshift gas with highest metallicity, we searched a representative sample of high metallicity DLAs for H₂. The number of H₂ measurements in systems with [X/H] > −1.3 is twice larger in our sample compared to previous surveys. We describe the sample and the observations in Sect. 2, present two new detections of H₂ in Sect. 3 and the results of the survey and our conclusions in Sect. 4.

2. Sample and observations

We have selected from the literature all $z > 1.8$ DLAs and sub-DLAs systems ($\log N(\text{H I}) \geq 19.5$) with previously measured elemental abundances (e.g. Prochaska & Wolfe 2001; Kulkarni & Fall 2002) larger than [X/H] > −1.3 and accessible to UVES. The inclusion of sub-DLAs is justified by the fact that for $\log N(\text{H I}) > 19.5$ most of the hydrogen is neutral (Viegas 1995). In addition, Ledoux et al. (2003) have shown that for

Table 1. Metal and molecular content of high-metallicity DLA/sub-DLA systems at $z_{abs} > 1.8$.

QSO	z_{em}	z_{abs}	$\log N(\text{H\,I})$ [1]	[X/H] [1]	X	$\log N(\text{H}_2)$ [2] $J = 0$	$J = 1$	$\log f$ [3]	References
Q 0013−004	2.09	1.973	20.83 ± 0.05	−0.59 ± 0.05	Zn	17.72–20.00		$-1.68^{+1.07}_{-1.18}$	a
Q 0112−306	2.99	2.702	20.30 ± 0.10	−0.49 ± 0.11	Si	<14.1	<14.0	<−5.55	b
Q 0216+080	2.99	2.293	20.50 ± 0.10	−0.70 ± 0.11	Zn	<14.3	<14.5	<−5.39	c
Q 0347−383	3.22	3.025	20.73 ± 0.05	−1.17 ± 0.07	Zn	$14.53^{+0.06}_{-0.06}$		$-5.90^{+0.11}_{-0.11}$	b
Q 0405−443	3.02	2.595	21.05 ± 0.10	−1.12 ± 0.10	Zn	$18.14^{+0.07}_{-0.10}$		$-2.61^{+0.17}_{-0.20}$	b, d
Q 0458−020	2.29	2.040	21.70 ± 0.10	−1.22 ± 0.10	Zn	<14.6	<14.6	<−6.40	e
Q 0528−250	2.77	2.811	21.35 ± 0.07	−0.91 ± 0.07	Zn	$18.22^{+0.11}_{-0.12}$		$-2.83^{+0.18}_{-0.19}$	b, d
Q 0551−366	2.32	1.962	20.70 ± 0.08	−0.35 ± 0.08	Zn	$17.42^{+0.45}_{-0.73}$		$-2.98^{+0.53}_{-0.81}$	f
Q 1037−270	2.23	2.139	19.70 ± 0.05	−0.31 ± 0.05	Zn	<14.0	<14.1	<−5.05	g
Q 1209+093	3.30	2.584	21.40 ± 0.10	−1.01 ± 0.10	Zn	<14.9	<15.1	<−5.69	c
Q 1441+276	4.42	4.224	20.95 ± 0.10	−0.63 ± 0.10	S	$18.28^{+0.08}_{-0.07}$		$-2.38^{+0.18}_{-0.17}$	h
Q 1444+014	2.21	2.087	20.25 ± 0.07	−0.80 ± 0.09	Zn	$18.16^{+0.14}_{-0.12}$		$-1.80^{+0.21}_{-0.19}$	b
Q 2116−358	2.34	1.996	20.10 ± 0.07	−0.34 ± 0.11	Zn	<14.5	<14.8	<−4.75	c
Q 2206−199	2.56	1.921	20.67 ± 0.05	−0.54 ± 0.05	Zn	<14.4	<14.7	<−5.44	c
Q 2230+025	2.15	1.864	20.90 ± 0.10	−0.81 ± 0.10	S	<15.4	<15.4	<−4.80	c
Q 2243−605	3.01	2.331	20.65 ± 0.05	−0.85 ± 0.05	Zn	<13.8	<13.9	<−6.15	c
Q 2343+125	2.51	2.431	20.40 ± 0.07	−0.89 ± 0.08	Zn	$13.69^{+0.09}_{-0.09}$		$-6.41^{+0.16}_{-0.16}$	c
Q 2348−011	3.01	2.426	20.50 ± 0.10	−0.60 ± 0.11	S	$18.45^{+0.27}_{-0.26}$		$-1.76^{+0.37}_{-0.36}$	c

[1] Neutral-hydrogen column densities and metallicities relative to Solar, [X/H] ≡ $\log[N(X)/N(H)] - \log[N(X)/N(H)]_\odot$ (with X = Zn as the reference element when Zn II is detected, or else either S or Si) are from Ledoux et al. (2006a).
[2] Molecular-hydrogen column densities are summed up over all J levels in case of detection and upper limits for $J = 0$ and $J = 1$ are given in case of non-detection.
[3] Molecular fraction, $f = 2N(\text{H}_2)/(2N(\text{H}_2) + N(\text{H\,I}))$.
a Petitjean et al. (2002), b Ledoux et al. (2003), c this work, d Srianand et al. (2005), e Heinmüller et al. (2006), f Ledoux et al. (2002b), g Srianand & Petitjean (2001), h Ledoux et al. (2006b).

$\log N(\text{H\,I}) > 19.5$, there is no correlation between the presence of H$_2$ and the H I column density. That we include ALL known systems with these criteria guarantees that the sample is representative of the population of DLA-subDLA.

We ended up with a sample of 15 DLAs and 3 sub-DLAs (with $\log N(\text{H\,I})$ = 19.7, 20.10 and 20.25) as presented in Table 1. The H$_2$ content of ten of these systems has already been published (Srianand & Petitjean 2001; Petitjean et al. 2002; Ledoux et al. 2002b, 2003, 2006b; Srianand et al. 2005 and Heinmüller et al. 2006). Five of the eight remaining systems have data in the UVES archive (Q 1209+093: Prog. 67.A-0146 P.I. Vladilo; Q 2116−358: Prog. 65.O-0158 P.I. Pettini; Q 2230+025: Prog. 70.B-0258, P.I. Dessauges-Zavadsky; Q 2243−605: Prog. 65.O-0411 P.I. Lopez; Q 2343+125: Prog. 69.A-0204 and 67.A-0022, P.I. D'Odorico). New observations of Q 0216+080, Q 2206−199, Q 2343+125, and Q 2348−011 have been performed with the Ultraviolet and Visible Echelle Spectrograph (UVES, Dekker et al. 2000) mounted on the ESO Kueyen VLT-UT2 8.2 m telescope on Cerro Paranal in Chile. These new observations resulted in two new detections described in the next section.

The data for each of the eight QSOs were reduced using the UVES pipeline, which is available as a package (a so-called context) of the ESO MIDAS data reduction system (see e.g. Ledoux et al. 2003 for details). Standard Voigt-profile fitting methods were used to analyze metal lines and molecular lines, when detected, to determine column densities using the oscillator strengths compiled in Ledoux et al. (2003) for metal species and by Morton & Dinerstein (1976) for H$_2$. We adopted the Solar abundances from Morton (2003) based on meteoritic data from Grevesse & Sauval (2002).

The characteristics of the sample are summarized in Table 1. The H I column densities and most of metallicities are from the compilation by Ledoux et al. (2006a). Slight differences with previously published values, e.g. Ledoux et al. (2003), are due to the use of different damping coefficients for H I. The only known $z > 1.8$ H$_2$ bearing DLA system out of this sample is the system at z_{abs} = 2.337 toward Q 1232+082 (Srianand et al. 2000).

3. Two new detections

We report two new detections of H$_2$ in DLAs from our new observations. Detail analysis and interpretation of the physical conditions in these two DLAs are beyond the scope of the present work and will be described in a subsequent paper.

3.1. Q 2343+125, $z_{abs} = 2.431$

This DLA system was first studied by Sargent et al. (1988). High resolution data have been described by Lu et al. (1996), D'Odorico et al. (2002), and Dessauges-Zavadsky et al. (2004). The profile of the metal lines is spread over more than 250 km s^{-1} from z_{abs} = 2.4283 to 2.4313, but the strongest component is centered at z_{abs} = 2.43127 corresponding to the red edge of the above redshift range. From Voigt-profile fitting to the H I Lyman-α, β, and γ lines, we find that the damped Lyman-α line is centered at z_{abs} = 2.431, and the column density is $\log N(\text{H\,I})$ = 20.40 ± 0.07, consistent with previous measurement by D'Odorico et al. (2002; $\log N(\text{H\,I})$ = 20.35 ± 0.05). We use Zn as the reference species for metallicity measurement and find [Zn/H] = −0.89 ± 0.08. This is consistent with

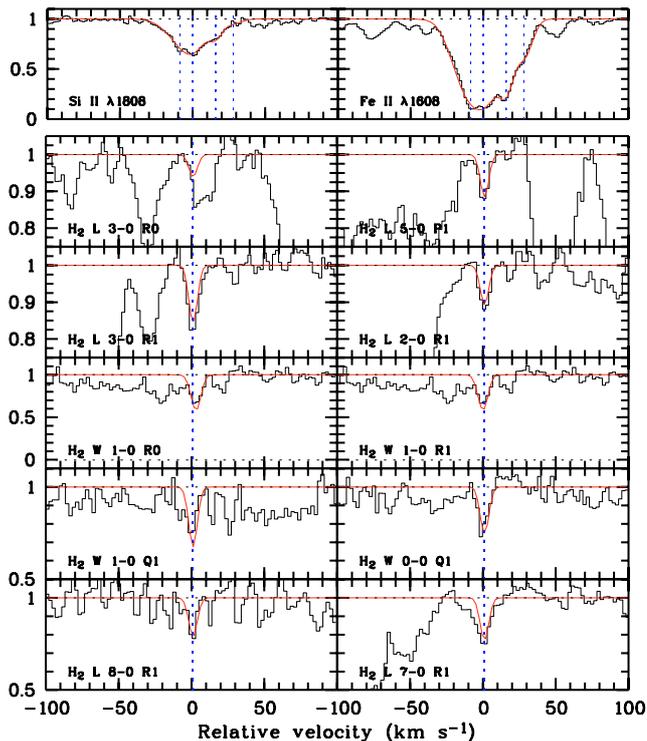**Fig. 1.** Velocity plots of observed H$_2$ absorption lines from the $J = 0$ and $J = 1$ rotational levels at $z_{abs} = 2.43127$ toward Q 2343+125. Profiles of associated Si II and Fe II absorptions are shown in the upper panels. The best-fitting model to the system is overplotted; the location of Voigt-profile sub-components are shown as vertical dashed lines.

previous findings. Absorption from the $J = 1$ and probably from the $J = 0$ rotational levels of H$_2$ is detected in this system at $z_{abs} = 2.43127$ (see Fig. 1). The optically-thin H$_2$ absorption lines are very weak, i.e. close to, but above, the 3σ detection limit. A very careful normalization of the spectrum was performed by adjusting the continuum while fitting the lines. The best-fitting consistent model for H$_2$ is shown in Fig. 1. The total H$_2$ column density, integrated over the $J = 0$ and 1 levels, is estimated to be $\log N(H_2) = 13.69 \pm 0.09$ (12.97 ± 0.04 and 13.60 ± 0.10 for $J = 0$ and 1, respectively). This leads to the lowest molecular fraction observed up to now, $\log f = -6.41^{+0.16}_{-0.16}$. We also derive an upper limit on the detection of absorption from the $J = 2$ level, $\log N(H_2-J = 2) < 13.1$ at the 3σ level.

3.2. Q 2348−011, $z_{abs} = 2.426$

There are two DLA systems at $z_{abs} = 2.426$ and $z_{abs} = 2.615$ toward Q 2348−011, with total neutral hydrogen column densities of $\log N(H I) = 20.50 \pm 0.10$ and $\log N(H I) = 21.30 \pm 0.08$, respectively. Conspicuous H$_2$ absorptions are detected in the $z_{abs} \simeq 2.426$ DLA system, the only system to be considered here as displaying a high metallicity (see Fig. 2). The molecular lines are very numerous and strong, but the spectral resolution of our data is high enough to allow unambiguous detection and accurate determination of the line parameters. Seven H$_2$ components spread over about 300 km s^{-1} were used for the H$_2$ fit. It is interesting to note that the strongest metal component (at $V = 0$ km s^{-1} in Fig. 2) has no associated H$_2$ absorption. Strong H$_2$ absorption is seen at $V \sim -150$ and $+50$ km s^{-1}. All seven molecular components have associated C I absorption. However, additional components are needed to fit the metal absorption
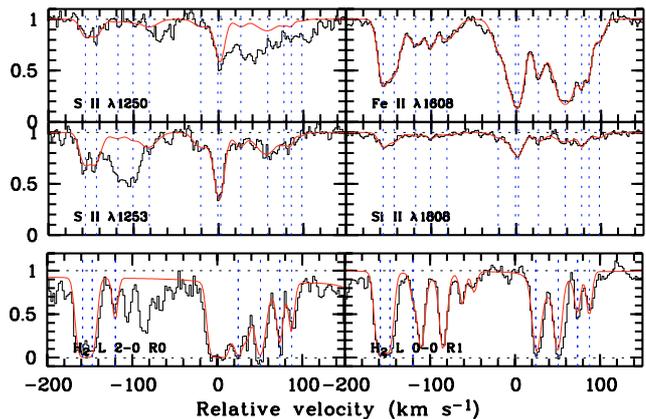

Fig. 2. Absorption profiles at $z_{abs} = 2.4263$ (taken as zero of the velocity scale) toward Q 2348−011. The positions of the seven (respectively, 13) components needed to fit the H$_2$ (respectively, metal line) profiles are indicated by vertical dashed lines. The resulting best-fitting model to the system is overplotted.

lines: 9 components for C I and 13 components for the singly ionized species. H$_2$ absorption from the rotational levels $J = 0$ to 5 are unambiguously detected. The total H$_2$ column density integrated over all rotational levels is $\log N(H_2) = 18.45^{+0.27}_{-0.26}$, corresponding to a molecular fraction $\log f = -1.76^{+0.37}_{-0.36}$. We also derive an upper limit on the column density of HD molecules, leading to $\log N(HD)/N(H_2) < -3.3$.

4. Metallicity as a criterion for the presence of molecular hydrogen

From Table 1, it can be seen that H$_2$ is detected in nine high-metallicity systems out of 18. However, for two of the detections, the corresponding value of $\log f$ is lower than most of the upper limits derived for other systems. All upper limits are lower than −4.5 and all detections higher than these upper limits are higher than −3. We therefore define a system with large (respectively small) H$_2$ content if $\log f$ is higher (respectively lower) than −4.

In Fig. 3 we plot the molecular fraction, $\log f$, versus metallicity, [X/H], for our representative sample of DLAs with [X/H] > −1.3 (18 measurements summarized in Table 1) and measurements by Ledoux et al. (2003) for [X/H] < −1.3 (23 measurements). The $\log f$ distribution is bimodal with an apparent gap in the range $-5 < \log f < -3.5$ justifying the above classification of systems. Note that this jump in $\log f$ was already noticed by Ledoux et al. (2003) and is similar to what is seen in our Galaxy (Savage et al. 1977; see also Srianand et al. 2005). It is apparent that the fraction of systems with molecular fraction $\log f > -4$ increases with increasing metallicity. It is only ∼5% for [X/H] < −1.3 when it is ∼39% for [X/H] > −1.3. This fraction is even higher, 50%, for [X/H] > −0.7 which is the median metallicity for systems with [X/H] > −1.3. In addition, all systems with [X/H] < −1.5 have $\log f < -4.5$.

We conclude that metallicity is an important criterion for the presence of molecular hydrogen in DLAs. This may not be surprising as the correlation between metallicity, and the depletion of metals onto dust grains (Ledoux et al. 2003) implies that higher metallicity means higher dust content and therefore higher H$_2$ formation rate. In addition, the presence of dust implies a greater absorption of UV photons that usually dissociate the molecule. More generally, Ledoux et al. (2006a)
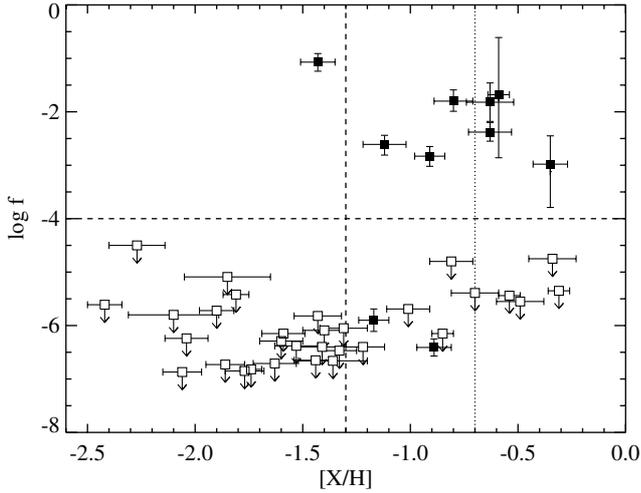
Fig. 3. Logarithm of the molecular fraction, $f = 2N(\text{H}_2)/(2N(\text{H}_2) + N(\text{H I}))$, versus metallicities, $[\text{X/H}] = \log N(\text{X})/N(\text{H}) - \log(\text{X/H})_\odot$ with X either Zn, S or Si, in DLAs from the sample described in this paper ([X/H] > −1.3, see Table 1) and the sample of Ledoux et al. (2003, [X/H] < −1.3). Filled squares indicate systems in which H$_2$ is detected. Dashed lines indicate the limits used in the text (log f = −4; [X/H] = −1.3). The dotted line shows the median of the high-metallicity sample ([X/H] = −0.7).

have shown that a correlation exists between metallicity and velocity width in DLAs. If the latter kinematic parameter is interpreted as reflecting the mass of the dark-matter halo associated with the absorbing object, then DLAs with higher metallicity are associated with objects of higher mass where star formation could be enhanced. All this makes it arguable that, in DLAs, star-formation activity is probably correlated with the molecular fraction (Hirashita & Ferrara 2005). It is therefore of prime importance to survey a large number of DLA systems to define their molecular content better and use this information to derive the

physical properties of the gas and the amount of star-formation occurring in the associated objects.

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