Molecular hydrogen abundance in the dust-free damped Ly- α galaxy at z = 3.4

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Abstract. New results from the search for H₂ absorption in the damped Ly α galaxy at redshift z = 3.4 toward QSO 0000–2620 ($z_{\rm em} = 4.1$) are reported. The high-resolution ($\lambda/\Delta\lambda = 48,000$) spectra of Q0000–2620 were obtained using the Ultraviolet - Visual Echelle Spectrograph (UVES) on the 8.2m *ESO* Kueyen telescope. The ortho-H₂ column density is found to be $N(J = 1) = (5.55 \pm 1.35) \times 10^{13}$ cm⁻² (2σ C.L.). The combination of N(J = 1) with the limits available for other low rotational levels restricts the excitation temperature $T_{\rm ex}$ in the range (290–540) K. This gives the total H₂ column density of $N({\rm H}_2) = (8.75 \pm 1.25) \times 10^{13}$ cm⁻² and the corresponding fraction of hydrogen atoms bound in molecules of $f({\rm H}_2) = (6.8 \pm 2.0) \times 10^{-8}$.

1 Introduction

It has long been recognized that H₂ (and HD) molecules play a central role in the formation of gas condensations in the post-recombination era since they provide the cooling necessary for the collapse on all scales of the first objects. In the primordial gas at redshift $z \leq 50$, the fractional abundance of H₂ is calculated to be $f(H_2) = 10^{-5} - 10^{-6}$ (e.g. [1]). The H₂ absorption lines from the Lyman and Werner bands may be observable at lower redshift $z \sim 2 - 4$ in QSO absorption systems with high neutral hydrogen column densities, $N(\text{HI}) = 10^{21} - 10^{22} \text{ cm}^{-2}$ (so-called Damped Lyman α systems, DLA). It has been suggested that these systems are most closely related to the progenitors of normal galaxies [2]. So far, absorption from H₂ has been detected in a few DLA systems which show, in general, a small amount of molecular gas [3]. In contrast to DLAs, observations in our Galaxy reveal the presence of H₂ in nearly all lines of sight in the disk and halo [4]. It was also found that the ISM diffuse clouds with the neutral hydrogen column densities $N(\text{HI}) \gtrsim 3 \times 10^{20} \text{ cm}^{-2}$ show $f(\text{H}_2) \gtrsim 10^{-5}$.

Absorption from H₂ in the z = 3.4 DLA system toward Q0000–2620 was not detected in the 1 Å resolution spectrum obtained with the Multiple Mirror Telescope (MMT) and only an upper limit of $f(H_2) < 3 \times 10^{-6}$ has been reported previously [5]. New observations with the UVES/VLT, having approximately 11 times higher resolution, revealed H₂ absorption in this DLA.

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Fig. 1. Best fit to H₂ lines associated with the z = 3.4 DLA system toward Q0000–2620. (**a**, **b**, **c**, **d**) Simultaneous fit to the Lyman L(4-0)R(1), L(1-0)R(2) and Werner W(2-0)Q(1), W(2-0)R(0) lines with $N(J = 0) = 8.4 \times 10^{12}$ cm⁻² (1 σ upper limit), $N(J = 1) = (5.5 \pm 0.7) \times 10^{13}$ cm⁻², $N(J = 2) = 1.2 \times 10^{13}$ cm⁻² (1 σ upper limit), and $b \simeq 10.07$ km s⁻¹. The velocities shown are related to z = 3.390127. (**e**) Confidence regions for the ortho-H₂ column density calculated from the simultaneous fit of the L(4-0)R(1) + W(2-0)Q(1) lines and all low-ion lines located redward the Ly α emission. (**f**, **g**) The corresponding deviations of the local continuum level. (**h**) The corresponding Doppler parameter variations. The grey areas restrict the $\Delta C/C$ and b values at 1 σ level in accordance with panel **e**

Exactly at the expected position of the L(4-0)R(1) line where the MMT gave the limit $W_{\text{rest}} < 114 \text{ mÅ} (3\sigma)$, an absorption line with the equivalent width $W_{\text{rest}} \simeq 6 \text{ mÅ}$ was detected [6]. The chance identification of this line in the Ly α forest at $z \sim 3$ has a probability $\lesssim 10^{-3}$ (cf. [7]).

Below we report on new identifications of H_2 lines in this DLA system and give improved values of molecular hydrogen column density and excitation temperature.

2 Data analysis and results

Spectroscopic observations of Q0000–2620 are described in detail in [8]. The spectrum was obtained with the rms uncertainty of the wavelength calibration $\delta\lambda \leq 0.6 \text{ km s}^{-1}$, the velocity resolution of FWHM $\simeq 6 \text{ km s}^{-1}$ (the corresponding bin size equals 2.4 km s⁻¹) and the signal-to-noise ratio of S/N $\simeq 40$ (per pixel) in the range $\lambda\lambda = 4605 - 4615$ Å allowing us to detect the L(4-0)R(1) line ($\lambda_0 = 1049.9596$ Å and the oscillator strength f = 0.016 are from [9]) at the expected position, $\lambda_{obs} = 4609.4$ Å. The line shows excellent redshift agreement with the low-ion lines and the same Doppler parameter, $b \simeq 10 \text{ km s}^{-1}$. The corresponding H₂ lines from the Lyman and Werner bands are badly blended with Ly α forest absorption, but the L(4-0)R(1) line is relatively clean of contamination from forest absorption.

The analysis of absorption lines occurring in the Ly α forest may have large intrinsic errors due to uncertainties in the local continuum level determinations. Therefore to control solutions, theoretical L(4-0)R(1) profiles were fitted to the observed intensities simultaneously with the fitting of all metal lines located redward the QSO Ly α emission (ZnII λ 2026, CrII λ 2062, CrII λ 2056, FeII λ 1611, SiII λ 1808, and NiII λ 1709), assuming that *b* is the same for H₂ and low-ion lines and leaving all the elemental column densities as well as the local continuum deviations ($\Delta C/C$) around the L(4-0)R(1) line free to vary (the computational procedure is described in [10]).

Analyzing the obtained UVES spectrum, we have identified a new line W(2-0)Q(1) from the Werner band, and have set a more stringent upper limit to the para-H₂ abundance through the W(2-0)R(0) line. The fits are shown in Fig. 1 (**a**, **b**, **c**, **d**) by solid lines superimposed on the observed (re-normalized) intensities, which are marked by dots with 1σ error bars. A simultaneous treatment of the L(4-0)R(1) and W(2-0)Q(1) lines yields the ortho-H₂ column density of $N(J = 1) = (5.5\pm0.7)\times10^{13}$ cm⁻². Right column of Fig. 1 shows the confidence levels for N(J = 1) (panel **e**), the corresponding variations for $\Delta C/C$ (panels **f** and **g**), and the Doppler broadening (panel **h**). From panels **f** and **g** it is seen that the local continuum is shifted with respect to the general continuum level (determined over the whole region of the Q0000-2620 spectrum) to about + 1.0% for the L(4-0)R(1) line and to - 30.5% for the W(2-0)Q(1) line, respectively. The shifts at the position of the W(2-0)R(0) line (panel **c**) and at the position of the L(1-0)R(2) line

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(panel **d**) are found to be negligible. The combination of the N(J = 1) value with the limits $N(J = 0) \leq 8.4 \times 10^{12} \text{ cm}^{-2}$ and $N(J = 2) \leq 1.2 \times 10^{13} \text{ cm}^{-2}$ restricts the excitation temperature T_{ex} in the range (290 - 540) K. This gives the total H₂ column density of $N(\text{H}_2) = (8.75 \pm 1.25) \times 10^{13} \text{ cm}^{-2}$ and the corresponding fraction of hydrogen atoms bound in molecules of $f(\text{H}_2) = (6.8 \pm 2.0) \times 10^{-8}$ [11].

The obtained result has an interesting connection to a local DLA system – the metal-deficient $(Z/Z_{\odot} \sim 1/50)$ starburst galaxy I Zw 18 with $N(\text{HI}) \simeq 3 \times 10^{21} \text{ cm}^{-2}$ where recent FUSE observations set a limit $f(\text{H}_2) \ll 10^{-6}$ [12].

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