A new estimation of HD/2H$_2$ at high redshift using the spectrum of the quasar J 2123−0050

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Abstract. We present a new analysis of the quasar spectrum J 2123−0050 obtained using VLT/UVES. The H$_2$/HD absorption system at $z = 2.059$ was analysed. This system consists of two subsystems with $z_A = 2.05933$ and $z_B = 2.05955$. The HD lines have been detected only in subsystem A with the column density of $\log N = 13.87 \pm 0.06$. We have determined the column density of H$_2$ in this subsystem, $\log N = 17.93 \pm 0.01$, which is about three times larger than estimation derived early from analyses of quasar spectrum obtained using KECK/HIRES [1]. The derived ratio $\text{HD}/2\text{H}_2 = (4.28 \pm 0.60) \times 10^{-5}$ is the largest in quasar spectra, nevertheless it coincides with the primordial deuterium abundance within 2σ error. Additionally, we have found some evidence in the partial covering effect for the H$_2$ system.

1. Introduction

The physical conditions in the cold dense phase of the neutral interstellar medium (ISM) can be examined by analysis of molecular absorptions in spectra of background sources (e.g. stars in local galaxies or quasars and gamma-ray bursts at high redshift). H$_2$ and HD are widespread molecules in the ISM. The populations of different rotational levels of H$_2$ and HD molecules and the relative abundance of HD molecules (HD/2H$_2$) are sensitive to physical conditions of the medium: kinetic temperature, volume density, intensity of UV background radiation, cosmic ray ionization rate, dust and metal content and others (e.g. [2]).

Firstly, H$_2$ and HD molecules have been detected in the diffuse Galactic ISM in UV absorption ($\lambda \sim 1000$ Å) [3]. Due to atmospheric extinction, these absorption lines can be detected only on spacecraft observatories (such as Copernicus, FUSE, HST). However, because of the cosmological redshift, H$_2$ and HD molecules in galaxies at high redshift ($z > 2$) can be studied in visible-band observations with ground-based telescopes (such as the 8.2-metre Very Large Telescope (VLT) and 10-metre KECK telescope).

To date, since the first detection in 1985 [4], only 27 H$_2$ absorption systems at high redshift have been identified in quasar spectra, because it is difficult task even for large telescopes. Since the first detection of HD molecules in 2001 [5], HD molecules have been detected in 9 out of 27 systems (e.g. [6]). The result of the analysis of the H$_2$/HD system at $z = 2.06$ in the quasar spectrum J 2123−005 obtained using the High Resolution Echelle Spectrometer (HIRES) at KECK [1] stands out among other measurements for clouds at high redshift. The measured ratio, $\text{HD}/2\text{H}_2 = (7.94^{+2.32}_{-1.46}) \times 10^{-5}$ [1], is more than two times larger than the primordial...
deuterium abundance \((D/H)_P = (3.05 \pm 0.22) \times 10^{-5}\) (e.g. \([7]\)), whereas all other measurements are consistent or less than the primordial value.

Additionally, this \(H_2\) system has been investigated by \([8]\) to test possible cosmological variation of the proton-to-electron mass ratio, \(\mu = m_p/m_e\). However, the results of the analyses are different in the number of the \(H_2\) components and the derived total column densities.

Here we present a new independent analysis of this \(H_2/HD\) system at \(z_{abs} = 2.059\) in the spectrum of the quasar J2123–0050 obtained using the Ultraviolet and Visible Echelle Spectrograph (UVES) at VLT (Program ID 081.A-0242, PI: Ubachs). The signal-to-noise ratio in this spectrum is nearly twice as large as one in the spectrum obtained using KECK/HIRES, that allows us to measure \(H_2\) and HD column densities with higher accuracy.

2. Observational Data

The spectrum of J 2123-0050 was obtained using UVES/VLT. This quasar was observed in the wavelength 3024-3884 \(\AA\) and 4584-9645 \(\AA\) in 2008 (Program ID 081.A-0242, PI: Ubachs). The data are in free access from the UVES archive. 1D spectra of individual exposure was taken from the Advanced UVES archive. All the spectra are corrected for the motion of the observatory around the barycenter of the solar system and converted to vacuum wavelengths. We interpolate these spectra into an common wavelength array and generate the weighted mean combined spectrum using the inverse square of error as the weight. The total exposure time is 11.3-h, which allowed a signal-to-noise ratio to be achieved about 30 at the resolution of 49600 for the part of the spectrum containing \(H_2\) and HD absorption lines.

3. The analysis of the \(H_2/HD\) system

Molecular hydrogen is detected in several rotational levels, up to \(J = 5\), in two components at \(z_A = 2.05932(5)\) and \(z_B = 2.05955(2)\). Since the velocity shift between A and B components \((\sim 22 \text{ km/s})\) almost three times exceeds the full width half maximum of UVES instrumental function \((\text{FWHM} \sim 6 \text{ km/s})\) and Doppler parameters of \(H_2\) lines \((b \sim 1 - 5 \text{ km/s})\), therefore the individual components are resolved even for saturated \(H_2\) lines of the low \(J = 0, 1\) levels. We use a single-component model for the analysis of each of the subsystems A and B.

3.1. Partial coverage of the \(H_2\) absorption lines

It is known that, when not taking into account the partial coverage effects, the column density of an absorber can be underestimated by a factor up to two orders of magnitude \([9, 10]\). To date, the partial coverage effect has been detected in three of 27 known \(H_2\) systems in quasar spectra \([10, 11, 12]\). The detail discussion and manifestation of the partial coverage effect are presented in \([10, 11]\). Here we present the fourth case of the partial coverage effect.

We demonstrate that the \(H_2\) cloud does not cover the emission region of QSO J 2123–0050 completely. A residual flux at the bottom of saturated \(H_2\) absorption lines is detected at the level 1-3 per cent of the continuum. The comparison of the residual fluxes at the bottom of \(H_2\) lines and saturated Ly\(\alpha\) forest lines \((\Delta \lambda > 0.5 \text{ Å}, \ i.e. \ \delta v > 40 \text{ km/s})\) is shown in Fig.1. The residual flux was calculated as the median value of the flux in pixels at the bottom of a line, which have the fluxes within \(f_c \pm 1\sigma_i\) (where \(f_c\) is the flux at the centre of the line).

A non-zero residual flux can be also the result of a convolution saturated \(H_2\) lines with instrumental function of the UVES. In order to find out the cause of the detected residual flux we use the following procedure. We fit the saturated \(H_2\) lines at \(J = 0\) and \(J = 1\) using four model: (i) without a source of a residual flux, (ii) with a source of a residual flux in continuum, (iii) with a source of a residual flux in the emission lines (Ly\(\beta\) and O\(\text{vi}\)), and (iv) with two sources of a residual flux in continuum and in emission lines simultaneously. For each model we have determined a value of the corrected Akaike Information Criterion (AICC, \([13]\)), which allows for selecting a preferred model. Note, that the difference of criteria, \(\Delta \text{AICC} = 10\), implies...
Figure 1. Top panel: A part of J2123−0050 quasar spectrum (VLT/UVES) containing H$_2$ absorption lines. Emission lines are named. Bottom panel: The residual fluxes at the bottom of H$_2$ (open circles) and Ly$\alpha$ forest (black squares) absorption lines. The dashed line shows the mean error for pixels at the bottom of the absorption lines.

Table 1. Best-fitting results of the analyses for different models of the H$_2$ system. The columns present statistical estimations, residual fluxes (RF) and logarithm of column densities.

| Model | $\chi^2_{red}$ | AICC | $\Delta$AICC | $\text{RF}_{\text{Cont}}$ (%) | $\text{RF}_{\text{Emiss}}$ (%) | log $N(J = 0)$ | log $N(J = 1)$ |
|-------|----------------|------|---------------|-----------------|-----------------|---------------|---------------|
| i     | 1.11           | 374.7| 0             | no              | no              | 17.36 ± 0.02  | 17.79 ± 0.01  |
| ii    | 1.05           | 363.9| -10.8         | 1.1 ± 0.4       | no              | 17.38 ± 0.02  | 17.80 ± 0.01  |
| iii   | 0.94           | 330.0| -44.7         | no              | 2.7 ± 0.5       | 17.35 ± 0.02  | 17.78 ± 0.01  |
| iv    | 0.91           | 321.3| -53.4         | 1.1 ± 0.3       | 3.4 ± 0.5       | 17.37 ± 0.02  | 17.79 ± 0.01  |

strong evidence for the model with the lower value of the criterion. The results of the analysis are shown in Table 1. Following the above discussion we used model IV to describe the H$_2$ absorption system in the spectrum of J2123−0050.

3.2. H$_2$ column densities

We have performed a Voigt-profile fitting of the H$_2$ system using model IV with two additional sources of the residual flux. The flux detected by an observer is divided into three parts. The main source is covered by both H$_2$ clouds (A and B). Two additional sources are not covered by H$_2$ clouds and produce a non-zero residual flux at the bottom of the H$_2$ lines. One additional source produces the uniform residual flux in all H$_2$ lines, another one produces only in the H$_2$ absorption lines located on top of the quasar emission lines (Ly$\beta$ and O vi). The best-fitting
parameters are present in Table 2. The best fit of the H$_2$ lines at J = 0, 1 are shown in Fig. 2. The total H$_2$ column densities are log $N_{H2}^{A}$ = 17.93 ± 0.01 and log $N_{H2}^{B}$ = 17.16 ± 0.01. Using the H$_2$ ortho-to-para ratio for the component A we determine the kinetic temperature of cloud A, T$_A$ = 138.6 ± 2.5 K. As the result of lower H$_2$ column density in cloud B, the H$_2$ lines are optically-thin, and the populations of the H$_2$ rotational levels are mainly caused by UV pumping.

4. HD column density
In subsystem A, we have detected HD lines, corresponding to J = 0 level. The laboratory wavelengths of HD transitions were taken from [14], the oscillator strengths were taken from the calculations by [15]. For estimating parameters we use the Markov Chain Monte Carlo (MCMC) method. We have determined the HD column density, log $N$(HD) = 13.87 ± 0.05 taking into account the partial coverage effect. But it should be note that for lines with a small value of optical depths the partial coverage does not affect on column densities determination. The best fitting profiles of HD lines are shown in Fig. 3. The derived HD/2H$_2$ ratio in subsystem A, (4.28 ± 0.60) $\times$ 10$^{-5}$, is the largest of such values obtained in quasar spectra. Nevertheless, it coincides (within 2σ) with the value of the primordial deuterium abundance $\langle D/H \rangle_{P_{T}}$ = (3.05 ± 0.22) $\times$ 10$^{-5}$ (e.g. [7]).

5. Conclusion
The comparison of our result with the result obtained in the work [1] is present in Table 3. Since the signal-to-noise ratio of the spectrum obtained using UVES/VLT about three times larger than ones in the spectrum obtained using HIRE/SKECK, our estimates of H$_2$ and HD column densities have the higher accuracy. We have found that the HD/2H$_2$ ratio in subsystem A is

| J   | log $N_A$ | $b_A$, km/s | J   | log $N_B$ | $b_B$, km/s |
|-----|----------|-------------|-----|----------|-------------|
| H$_2$ 0 | 17.37 ± 0.02 | 1.71 ± 0.04 | H$_2$ 0 | 14.00 ± 0.02 | 5.18 ± 0.51 |
| 1    | 17.79 ± 0.01 | 2.07 ± 0.05 | 1    | 14.84 ± 0.01 | 5.24 ± 0.11 |
| 2    | 15.99 ± 0.03 | 2.97 ± 0.05 | 2    | 14.41 ± 0.01 | 5.02 ± 0.18 |
| 3    | 15.54 ± 0.02 | 3.56 ± 0.06 | 3    | 14.50 ± 0.01 | 4.71 ± 0.30 |
| 4    | 14.16 ± 0.01 | 4.64 ± 0.23 | 4    | 13.84 ± 0.03 | 7.86 ± 0.57 |
| 5    | 13.75 ± 0.03 | 5.10 ± 0.51 | 5    | 13.50 ± 0.06 | 7.36 ± 0.80 |
| HD   0 | 13.87 ± 0.06 | 2.0 ± 0.6   | HD   0 | undetected  |

Table 2. Best fitting results of the analysis of the H$_2$ system at z = 2.06 towards J2123–005.

| J   | log $N$ | $b$, km/s |
|-----|---------|-----------|
| H$_2$ 0 | 17.37 ± 0.02 | 1.71 ± 0.04 |
| 1    | 17.79 ± 0.01 | 2.07 ± 0.05 |
| HD   0 | 13.87 ± 0.06 | 2.0 ± 0.6 |

Table 3. Comparison of the results of the H$_2$/HD system analyses.

| J   | log $N$ | $b$, km/s |
|-----|---------|-----------|
| H$_2$ 0 | 16.86 ± 0.24 | 1.5 ± 0.2 |
| 1    | 17.55 ± 0.10 | 1.5 ± 0.2 |
| HD   0 | 13.84 ± 0.20 | 1.9 ± 0.5 |

| J   | log $N$ | $b$, km/s |
|-----|---------|-----------|
| HD/2H$_2$ = (4.28 ± 0.60) $\times$ 10$^{-5}$ | | |
| HD/2H$_2$ = (7.94±1.36$^{+1.25}_{-1.46}$) $\times$ 10$^{-5}$ | | |
Figure 2. The synthetic spectrum of the H$_2$ absorption lines at $z_{abs} = 2.059$ (solid line) in the observed quasar spectrum of J 2123−0050 (UVES/VLT). The H$_2$ lines associated with J = 0 and J = 1 levels are shown in the top and bottom panels, respectively.

more than twice as lower as the value obtained by [1]. This is caused mainly by quite different estimates of the H$_2$ column densities at J = 0. Probably, it might be explained by complexity of the analysis of the H$_2$ lines for J = 0. All these lines in the spectrum of J 2123−005 are blended by the Ly$\alpha$ forest lines (except for the
Figure 3. The synthetic spectrum of the HD absorption lines at $z_{abs} = 2.059$ (solid line) in the observed spectrum of J2123−0050 (UVES/VLT).

L0R0 line, see Fig.2). Therefore, to determine the H$_2$ column density from J = 0 level, it is necessary to correct continuum level near H$_2$ lines by the inclusion of the Ly$\alpha$ forest lines. We have found that, in some cases the Ly$\alpha$ forest lines located at the wings of the H$_2$ lines, but sometimes the Ly$\alpha$ forest line located near the center of the H$_2$ lines. Insufficient or excessive use of the Ly$\alpha$ blends in the H$_2$ system analysis might cause over- or underestimation of the determined column density of H$_2$, respectively, especially for moderate signal-to-noise ratios.

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