# **PAPER • OPEN ACCESS**

# HD/H<sub>2</sub> absorption systems at high redshifts

To cite this article: D N Kosenko and S A Balashev 2018 J. Phys.: Conf. Ser. 1135 012009

View the article online for updates and enhancements.

You may also like

- Extragalactic astronomy (Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 28 October 2009)
- <u>Sensitivity of the negative ion beam</u> <u>extraction to initial plasma parameters by</u> <u>3D particle modelling</u> Max Lindqvist, Dirk Wünderlich, Alessandro Mimo et al.
- <u>PRODUCT BRANCHING RATIOS OF</u> <u>THE REACTION OF CO WITH  $H^+_3$  AND</u> <u> $H_2D^+_3$ </u> Hua-Gen Yu





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 18.220.212.186 on 11/05/2024 at 10:43

**IOP** Publishing

# $HD/H_2$ absorption systems at high redshifts

# D N Kosenko<sup>1,2</sup>, S A Balashev<sup>1</sup>

<sup>1</sup> Ioffe Institute, 26 Politeknicheskaya st., St. Petersburg, 194021, Russia <sup>2</sup> Peter the Great St. Petersburg Polytechnic University, 29 Politeknicheskaya st., St. Petersburg, 195251, Russia

E-mail: kosenkodn@yandex.ru, s.balashev@gmail.com

Abstract. We present new measurements of HD/H<sub>2</sub> in absorption systems at redshift  $z \sim 2$ in quasar spectrum J0812+3208 and J2340-0053. In J0812+3208 we detect and measure column density of H<sub>2</sub> at  $z \sim 2.07$  for the first time and place upper limit on HD column density. In  $J_{2340-0043}$  we identify HD in already known multicomponent H<sub>2</sub> absorption system at  $z \sim 2.05$ . In this system we obtain relative abundance of HD/H<sub>2</sub> molecules close to isotopic ratio, suggesting the similar molecular fraction of deuterium and hydrogen. We discuss possible explanation of measured  $HD/H_2$  abundance.

#### 1. Introduction

It is well established that interstellar medium (ISM) consists of several phases – the sufficient part of mass of ISM can be in cold and dense clouds that are embedded in the volume dominated mixture of neutral and ionized phase. The volume and mass fractions of these phases are in intimate connection with galactic properties, such as mass, star-formation activity and environment. These phases are well studied in the local universe, but their description is still limited for high redshifts. However, absorption line spectroscopy of high redshift quasars provides a unique way to do it. Galaxies at high redshifts are detected in the quasar spectra via so called Damped Lyman alpha system (DLA) [1] – absorption line systems of damped Lyman series HI lines and associated metal lines. High resolution studies of the relatively large samples of DLAs indicate that they mostly represent the warm neutral phase of ISM [2]. The cold phase of the ISM is detected in DLA only rarely in  $\sim 5\%$  [3]. In all of the cases (where it is assessable) the cold phase of ISM indicates the presence the detectable amount of molecular hydrogen, H<sub>2</sub>. The relative population of orto-para low rotational levels of detected  $H_2$  is a good thermometer of the gas and gives that the kinetic temperature in H<sub>2</sub>-bearing medium is typically  $\sim 100 \,\mathrm{K}$ [4]. This indicates that the corresponding line of sights probed the diffuse atomic and molecular medium.

If the column of cold gas is large enough the less abundant (than  $H_2$ ) HD [5] molecules can be detected. Detection of HD molecules are interesting due to several reasons. Firstly, It is known that  $HD/H_2$  at high redshifts is systematically higher than in our Galaxy [6], but this discrepancy can not be solely explained by the astration of deuterium in the course of galaxy evolution [7]. So the most probable explanation is the difference in physical conditions. Also, the models of ISM chemistry show that HD/H<sub>2</sub> relative abundance is a very sensitive to the number density, UV flux and cosmic ray ionization rate [8]. Therefore relative abundance  $HD/H_2$  can be possibly used to constrain the physical conditions in the medium. Secondly, In limiting

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1

IOP Conf. Series: Journal of Physics: Conf. Series 1135 (2018) 012009 doi:10.1088/1742-6596/1135/1/012009

"fully molecularized" case (i.e. all D in HD and most of H in H<sub>2</sub>) the ratio  $N(\text{HD})/2N(\text{H}_2)$ is equal D/H isotopic ratio. It was shown that in detected HD/H<sub>2</sub> systems at high z with log N(HD) > 15 (here and in following N is the column density measured in cm<sup>-2</sup>) are well agree with the primordial D/H value derived by atomic D/H as well as the anisotropy of cosmic microwave background [9], [10], [11]. Thridly, HD can be very useful when lines from the first excited rotational level, J=1, of HD are detected, since the measured relative population of J=1/J=0 can be used to estimate the number density in the cold ISM [6], [4].

The studies concerned with HD are still limited due to very low HD/H<sub>2</sub> statistics at high redshift. Only 11 HD/H<sub>2</sub> systems have been detected at z > 2 ([12], [6], [4], [13], [14], [9], [15], [16], [17]) This is mostly due to two factors. Firstly, the detection and analysis of H<sub>2</sub> and HD lines can be done only in high resolution quasar spectra. Secondly, the incidence rate of cold ISM in DLAs at high z is low. Therefore, the blind search of HD/H<sub>2</sub> is very inefficient. Fortunately, several efficient preselection routines were proposed for the detection of cold ISM bearing DLAs in the intermediate resolution spectra of Sloan Digital Sky Survey [18], [19], [20]. Most probably such techniques allow us to sufficiently increase HD/H<sub>2</sub> detection at high z in the near future. However, the obtained archival data of high resolution quasar spectra at the VLT and Keck telescopes are still not exhaustively explored. In this work we present two new estimates of HD/H<sub>2</sub> in high-z H<sub>2</sub>-bearing Damped Lyman Alpha (DLA) systems using archival high resolution spectra.

#### 2. Data and analysis

We searched for the HD/H<sub>2</sub> absorption systems in high resolution spectra already obtained at VLT and Keck telescopes. To do this we selected already published DLAs containing either H<sub>2</sub> or associated CI. Latter is found to be excellent proxy of H<sub>2</sub> [20]. We made new detection of HD in DLAs at z = 2.05 and H<sub>2</sub> in DLA atz = 2.05 in spectra of J2340-0053 and J0812+3208, respectively, using spectra with resolution R ~ 50000 obtained at High Resolution Echelle Spectrograph (HIRES) at Keck telescope.

Absorption lines of  $H_2$  and HD have been fitted with Voigt profiles using Monte Carlo Markov Chain technique to estimate posterior probability distribution of the fit parameters. The best fit values reported in this paper are maximum a posteriory value of derived probability distributions. Uncertainties correspond to 0.683 confidence intervals.



 $J0812+3208, z_{abs} = 2.07$ 

Figure 1: Fit to H<sub>2</sub> absorption lines in DLA at z = 2.066780 in J0812+3208. The lower right panel show the HD L0-0R0 line used to place upper limit on HD column density in the DLA.

Jorgenson et al. [21] detected CI fine-structure levels in spectrum towards J0812+3208 at z=2.626491 and z=2.066779. Corresponding HD/H<sub>2</sub>-bearing DLA at z=2.626491 was studied in

details by several authors [22], [6], [23], however no attention was payed for DLA at z=2.06678. Several of H<sub>2</sub> lines from L0-0 and L1-0 Lyman bands associated with this DLA are clearly detected at the very blue end of the spectrum. To fit H<sub>2</sub> and HD lines we used already reduced spectrum by one of us [6]. We selected  $H_2$  lines without evident blend and fit them using onecomponent model. Usually, rotational levels of  $H_2$  indicate different Doppler parameters, due to various radiative transfer effects [24]. However, we tied Doppler parameter to be the same for all H<sub>2</sub> levels, since only a few lines from each rotational level of H<sub>2</sub> is detected. The fit results are given in the table 1. The excitation diagram of  $H_2$  rotation levels and the profiles of  $H_2$  and HD lines are shown in figure 2 and 1, respectively. The relative population of J = 0, J = 1 and J = 2 levels of H<sub>2</sub> suggest the single excitation temperature  $T_{01} = 66 \pm 1$  K which is used to be good proxy of the kinetic temperature in the cloud. This temperature is typical for diffuse molecular clouds probed by saturated H<sub>2</sub> absorption systems [4]. The column density on J = 2level agrees with  $T_{01}$  excitation temperature, suggesting that this level is populated by collisions, which can be due to low UV field, or relatively high number density.



z = 2.066780(1) in J 0812+3208

Table 1: Fit results of  $H_2$  and HD in DLA at Figure 2: Excitation diagram of  $H_2$  in DLA at z = 2.066780(1) in J 0812+3208

Unfortunately, only the weakest L0-0R0 line of HD from the DLA at z = 2.0668 is not blended in the spectrum. Therefore, we place only the upper limit on the HD column density using fixed redshift and Doppler parameter measured from  $H_2$ .

# $J2340 - 0053, z_{abs} = 2.05$

CI and H<sub>2</sub> associated with DLA at  $z \sim 2.05$  were previously detected in this spectrum [21]. To fit HD and H<sub>2</sub> lines we use spectrum of  $J_{2340}-0053$  from KODIAQ DR2 database [25]. We fit the HD/H<sub>2</sub> absorption system using 8 component model, suggested from the separate fit of CI fine-structure lines. Most  $H_2$  and HD lines from four central components are significantly blended with each other and in saturated regime. Therefore we used redshifts and Doppler parameters obtained from fit of CI as priors for HD fit. The detailed description of the fit will be present in Kosenko et al. in prep. In comparison with Jorgenson et al. (they fit  $H_2$  lines with six component model, while they reported CI in nine) we found higher column density of  $H_2$ . We tentatively detect HD absorption lines in five central major components, seen in  $H_2$  profiles. The measured total column densities of  $H_2$  and HD in each component are given in table 2 and profiles of HD lines are shown in figure 3.

# 3. Results and discussion

We summarize our measurements of HD and  $H_2$  column densities and relative abundance  $N(\text{HD})/2H(\text{H}_2)$  for J 0812+3208 and J 2340-0052 in Table 2. Previously, it was found that

IOP Conf. Series: Journal of Physics: Conf. Series 1135 (2018) 012009 doi:10.1088/1742-6596/1135/1/012009



Figure 3: Fit to HD absorption lines in DLA at z = 2.055 in J 2340-0053. The top panels show the fit to CI lines, that parameters used as a prior for b and z to fit HD lines.

Quasar	$z^{\dagger}$	$b^{\dagger},\mathrm{km/s}$	$\log N({\rm H_2})$	$\log N(\mathrm{HD})$	$rac{N(\mathrm{HD})}{2N(\mathrm{H_2})}$
J 0812+3208	2.066780(1)	$3.8^{+0.1}_{-0.1}$	$19.28\substack{+0.01 \\ -0.01}$	< 14.78	$<1.58\times10^{-5}$
$J2340{-}0053$	$2.054156(^{+4}_{-7})$	$0.6^{+2.1}_{-0.1}$	$16.85_{-0.62}^{+0.13}$	< 13.4	$< 3.3 \times 10^{-4}$
	$2.054286(^{+6}_{-4})$	$0.6^{+1.8}_{-0.1}$	$15.19^{+0.07}_{-0.07}$	< 12.9	$< 2.6  imes 10^{-3}$
	$2.0545255(^{+\bar{1}1}_{-15})$	$1.6^{+0.1}_{-0.1}$	$17.97_{-0.03}^{+0.03}$	$13.62^{+0.11}_{-0.08}$	$(2.2^{+0.7}_{-0.4}) \times 10^{-5}$
	$2.054597(^{+3}_{-7})$	$1.2^{+0.2}_{-0.7}$	$17.85_{-0.14}^{+0.08}$	$13.18_{-0.68}^{+0.30}$	$(1.1^{+1.2}_{-0.8}) \times 10^{-5}$
	$2.054660(^{+10}_{-38})$	$4.6_{-1.5}^{+0.4}$	$17.67^{+0.18}_{-0.23}$	$13.52_{-0.14}^{+0.15}$	$(3.5^{+3.1}_{-1.4}) \times 10^{-5}$
	$2.0547212(^{+32}_{-19})$	$1.6_{-0.3}^{+0.3}$	$18.28_{-0.03}^{+0.02}$	$13.67_{-0.14}^{+0.11}$	$(1.2^{+0.4}_{-0.3}) \times 10^{-5}$
	$2.054996(^{+24}_{-13})$	$5.3^{+5.7}_{-1.1}$	$16.56\substack{+0.08\\-0.07}$	< 13.2	$< 2.2 \times 10^{-4}$
	$2.055125(^{+5}_{-4})$	$2.4^{+0.8}_{-1.5}$	$17.30^{+0.06}_{-0.12}$	$13.16^{+0.22}_{-0.36}$	$(3.6^{+2.8}_{-2.1}) \times 10^{-5}$
total		1.0	$18.62_{-0.01}^{+0.02}$	$14.18_{-0.05}^{+0.05}$	$(1.8^{+0.2}_{-0.2}) \times 10^{-5}$

**Table 2:** New measurements of  $HD/H_2$  molecules at high redshifts.

<sup> $\dagger$ </sup> For J 2340–0053 *b* and *z* are from CI absorption lines fit and was used as a prior on these parameters during the fit of HD lines.

relative abundance of HD/H<sub>2</sub> measured at high redshifts [6,9] is systematically higher than what is measured in the diffuse clouds of our Galaxy [28]. This difference is higher than expected astration of deuterium (on average high redshift DLAs have lower gas-phase metallicity than local measurements) and therefore much probably it is attributed to difference of the physical conditions between the diffuse ISM of DLAs and our Galaxy. Moreover, some of the measurements at high redshifts consistent with the D/H isotopic ratio, which indicates that deuterium and hydrogen have the same molecular fraction. At the high end of H<sub>2</sub> and HD column density distributions, the observed systems are in self-shielding regime and therefore both molecular fraction should approach one [29]. This was the reason why these high H<sub>2</sub> IOP Conf. Series: Journal of Physics: Conf. Series 1135 (2018) 012009 doi:10.1088/1742-6596/1135/1/012009



Figure 4: The relative abundance of HD and H<sub>2</sub> molecules. Triangles and circles correspond to measurements in Milky Way and high redshifts (see [4, 6, 9, 12–17] with one point at  $z \approx 0.18$  from [26]), respectively. The measurements in this paper shown by red circles. The solid black line is D/H ratio derived from power spectrum of CMB anisotropies [27].

column density DLAs were used to estimate D/H isotopic ratio [6, 14]. One can think that at lower  $H_2$  and HD column densities expected  $HD/2H_2$  abundance should be lower, since HD is much easily photodissociated by UV radiation than H<sub>2</sub>, due to typically 4 order less column densities. However, in contrast with H<sub>2</sub>, HD have the very rapid formation channel, via ion exchange reaction. Therefore in case of relatively high ionization fraction in the medium the deuterium molecular fraction can be similar or even higher than hydrogen one even in at low HD column densities [6, 8, 13, 17]. In addition, ionization fraction which determine the rate of the main formation channel of HD in diffuse ISM usually governs by cosmic rays. The high cosmic ray ionization rate can result that molecular fraction of  $H_2$  is less 1 even for totally shielded parts of the medium [17]. Therefore we expect, that  $HD/H_2$  systems measured at high redshift can show  $HD/2H_2$  abundance higher than isotopic one at any typically measured HD column densities, since these systems probe wide range of the physical conditions. All this explain our new measurements correspond to the lower end of  $H_2$  distribution of DLAs, where we found that  $HD/2H_2$  abundance consistent with isotopic ratio of D/H. However, note that  $\log N(\text{HD}) \sim 13.5$  is about the detection limit of HD via Lyman and Werner UV lines for typical quasar high resolution spectra with  $S/N \sim 20$ , therefore any statistical conclusion on the sample should take this into consideration. To summarize, it was found that relative  $HD/H_2$ abundance is very sensitive to physical conditions if the medium [8], therefore with proper modeling the relative abundance of  $HD/2H_2$  molecules can be very important indicator of the physical conditions in the diffuse ISM. Our knowledge of the latter will be greatly benefit from the additional measurements of  $HD/H_2$  in various environments over evolution of the Universe.

IOP Conf. Series: Journal of Physics: Conf. Series 1135 (2018) 012009 doi:10.1088/1742-6596/1135/1/012009

### 4. Acknowledgements

This work is supported by Russia Science Foundation grant number 18-12-00301.

#### References

- [1] Wolfe A M, Gawiser E and Prochaska J X 2005 Ann. Rev. Astron. Astroph. 43 861–918 (Preprint astro-ph/0509481)
- [2] Neeleman M, Prochaska J X and Wolfe A M 2015 Astroph. J. 800 7 (Preprint 1411.5027)
- [3] Balashev S A and Noterdaeme P 2018 MNRAS (Preprint 1804.04611)
- [4] Balashev S A, Noterdaeme P, Rahmani H, Klimenko V V, Ledoux C, Petitjean P, Srianand R, Ivanchik A V and Varshalovich D A 2017 MNRAS 470 2890-2910 (Preprint 1705.10283)
- [5] Varshalovich D A, Ivanchik A V, Petitjean P, Srianand R and Ledoux C 2001 Astronomy Letters 27 683-685 (*Preprint* astro-ph/0107310)
- [6] Balashev S A, Ivanchik A V and Varshalovich D A 2010 Astronomy Letters 36 761–772 (Preprint 1009.4186)
- [7] Dvorkin I, Vangioni E, Silk J, Petitjean P and Olive K A 2016 MNRAS 458 L104-L108 (Preprint 1602.04831) [8] Liszt H S 2015 Astroph. J. 799 66 (Preprint 1411.5055)
- [9] Ivanchik A V, Balashev S A, Varshalovich D A and Klimenko V V 2015 Astronomy Reports 59 100-117
- [10] Balashev S A, Zavarygin E O, Ivanchik A V, Telikova K N and Varshalovich D A 2016 MNRAS 458 2188-2198 (Preprint 1511.01797)
- [11] Cooke R J, Pettini M, Nollett K M and Jorgenson R 2016 Astroph. J. 830 148 (Preprint 1607.03900)
- [12] Klimenko V V, Balashev S A, Ivanchik A V, Ledoux C, Noterdaeme P, Petitjean P, Srianand R and Varshalovich D A 2015 MNRAS 448 280-298 (Preprint 1501.07210)
- [13] Klimenko V V, Balashev S A, Ivanchik A V and Varshalovich D A 2016 Astronomy Letters 42 137-162 (*Preprint* 1603.01531)
- [14] Ivanchik A V, Petitjean P, Balashev S A, Srianand R, Varshalovich D A, Ledoux C and Noterdaeme P 2010 MNRAS 404 1583-1590 (Preprint 1002.2107)
- [15] Noterdaeme P, Petitjean P, Ledoux C, Srianand R and Ivanchik A 2008 Astron. Astroph. 491 397-400 (*Preprint* 0809.3785)
- [16] Noterdaeme P, Petitjean P, Ledoux C, López S, Srianand R and Vergani S D 2010 Astron. Astroph. 523 A80 (*Preprint* 1008.0637)
- [17] Noterdaeme P, Krogager J K, Balashev S, Ge J, Gupta N, Krühler T, Ledoux C, Murphy M T, Pâris I, Petitjean P, Rahmani H, Srianand R and Ubachs W 2017 Astron. Astroph. 597 A82 (Preprint 1609.01422)
- [18] Balashev S A, Klimenko V V, Ivanchik A V, Varshalovich D A, Petitjean P and Noterdaeme P 2014 MNRAS **440** 225–239 (*Preprint* **1402.2672**)
- [19] Noterdaeme P, Srianand R, Rahmani H, Petitjean P, Pâris I, Ledoux C, Gupta N and López S 2015 Astron. Astroph. 577 A24 (Preprint 1502.03921)
- [20] Noterdaeme P, Ledoux C, Zou S, Petitjean P, Srianand R, Balashev S and López S 2018 Astron. Astroph. 612 A58 (Preprint 1801.08357)
- [21] Jorgenson R A, Wolfe A M and Prochaska J X 2010 Astroph. J. 722 460-490 (Preprint 1008.4676)
- [22] Jorgenson R A, Wolfe A M, Prochaska J X and Carswell R F 2009 Astroph. J. 704 247-254 (Preprint 0908.3485)
- [23] Tumlinson J, Malec A L, Carswell R F, Murphy M T, Buning R, Milutinovic N, Ellison S L, Prochaska J X, Jorgenson R A, Ubachs W and Wolfe A M 2010 Astroph. J. Lett. 718 L156-L160 (Preprint 1007.0030)
- [24] Balashev S A, Varshalovich D A and Ivanchik A V 2009 Astronomy Letters 35 150–166 (Preprint 0908.2919) [25] O'Meara J M, Lehner N, Howk J C, Prochaska J X, Fox A J, Peeples M S, Tumlinson J and O'Shea B W
- 2017 Astron. J. 154 114 (Preprint 1707.07905)
- [26] Oliveira C M, Sembach K R, Tumlinson J, O'Meara J and Thom C 2014 Astroph. J. 783 22 (Preprint 1401.4199)
- [27] Planck Collaboration, Ade P A R, Aghanim N, Arnaud M, Ashdown M, Aumont J, Baccigalupi C, Banday A J, Barreiro R B, Bartlett J G and et al 2016 Astron. Astroph. 594 A13 (Preprint 1502.01589)
- [28] Snow T P, Ross T L, Destree J D, Drosback M M, Jensen A G, Rachford B L, Sonnentrucker P and Ferlet R 2008 Astroph. J. 688 1124–1136 (Preprint 0808.0926)
- [29] Le Petit F, Roueff E and Le Bourlot J 2002 Astron. Astroph. 390 369-381