The cold neutral phase of the interstellar medium in high redshift galaxies

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Abstract. We present the results of spectroscopic analysis of seven new H$_2$-bearing damped Ly-$\alpha$ systems in redshift range $z=2.5 - 3$. These systems were originally selected from SDSS catalog using a direct search for H$_2$ and followed up with X-SHOOTER spectrograph at 8-m Very Large Telescope observatory. We measured the column densities of H$_i$, H$_2$ on various rotational levels, and metals species in different ionization stages and excitation levels. We used the rotational excitation of H$_2$ molecules together with the fine-structure levels of neutral carbon to constrain the physical conditions in the associated medium. We found typical values for the kinetic temperature $T \sim 80 - 120$ K, hydrogen density $n_H \sim 30 - 400$ cm$^{-3}$ and UV radiation field $\xi_{UV} \sim 0.4 - 5$ times of the Draine field. These values along with estimated thermal pressure are in agreement with expected values from the theoretical calculation of the cold neutral interstellar medium.

1. Introduction

Molecular hydrogen, H$_2$, is the most abundant molecule in the Universe and predominantly resides in the cold neutral phase of interstellar medium (ISM). This phase is tightly linked with the onset of star-formation (SF) due to Jeans instability. The association between SF and molecular gas is well established for normal galaxies in the local Universe using the observation of CO emission (e.g. [1]). However, in the distant Universe, such observations in emission are limited to the bright-end of the galaxy population [2]. The SF process can be studied not only by emission (where the relation between SF and gas is derived globally over kpc scales), but also through absorption line analysis, where medium is probed on the scales of typical cloud sizes. An additional advantage of absorption line spectroscopy is that the absorption detection is independent on the luminosity of the probed galaxy. The neutral gas in or around high redshift galaxies is studied via so-called damped Lyman-$\alpha$ systems (DLA) – the absorption systems of H I and associated metals. The H I column densities in DLAs reach log $N$(H I) $\gtrsim 20$, ensuring the gas to be predominantly neutral. Statistical studies have showed that DLAs: (i) contain the bulk of the neutral atomic gas in the Universe (e.g. [3]); (ii) show significant metallicity evolution with redshift (e.g. [4], which represents the smoking gun of star formation); (iii) may be detected in emission lines (although it remains technically challenging, see [5] and references therein).
However, DLAs are mostly associated with the warm neutral and circumgalactic medium of high-z galaxies. The cold ISM, probed by molecular hydrogen, is found in a small fraction of high-z DLAs (~ 4%, [6]), meaning that cross section of the molecular gas is ~ 30 times lower than the neutral one. Therefore, a blind search of H₂-bearing DLAs is very ineffective and in spite of large number of studied and detected DLAs, only ~ 30 confirmed intervening H₂-bearing DLAs were detected at redshifts z > 2 (see [7] and references therein). However, with advent of the Sloan Digital Sky Survey (SDSS), a few effective techniques were proposed to preselect H₂-bearing DLAs from the SDSS low resolution spectra [8, 9, 10, 11]. One of this technique – is the direct detection of H₂ absorption lines in SDSS spectra. It is actually a quite challenging task due to insufficient quality of SDSS spectra and presence of the Ly-α forest. Nevertheless, we showed that such a detection is possible for a small fraction of the SDSS spectra [9] which multiplied on the large number of known DLAs in SDSS (~ 20000 in Data Release 11, DR11) resulted to ~ 50 confident candidates.

In this work we present the results of follow up studies of the seven H₂-bearing DLAs preselected from SDSS. The presented sample increases the number of known high column density H₂-bearing DLAs at high redshifts by 30 per cent and shows the effectiveness of the SDSS preselection. Using observations with X-SHOOTER spectrograph mounted at VLT we measured main characteristic of these DLAs (including H₁, H₂ and metal column densities) and constrain the physical conditions in the cold phase of the associated galaxies.

2. Observations and Analysis

The targeted quasars (J013644.02+044039.00, J085859.67+174925.32, J090609.46+054818.72, J094649.47+121628.56, J114638.95+074311.28, J123602.11+001024.60, J234730.76−005131.68) were preselected as candidates to H₂ absorbers in the SDSS DR11 with the lower false detection probability [9] that observable from the Paranal. The observation have been done with X-SHOOTER spectrograph [12] mounted at the Very Large Telescope in the service mode under program ID 094.A-0362 (PI: Balashev) between the end of 2014 and beginning of 2015. We have obtained all targets twice with 1 h exposure, except J234730.76−005131.68, which was observed only once. The details on the observation and spectral reduction are presented in [13].

To measure the parameters of absorption systems we used Voigt profile fitting (see [7] for the detailed description of the method and routine that was used). For each DLA we fit Lyα line, H₂ Lyman and Werner bands and metal lines to derive H₁, H₂ and metals column densities, respectively. In each DLAs we detected H₂ absorption lines correspond to the several first rotational levels. We fit H₂ lines independently from low ionization metal lines, since the latter usually indicate more components in the velocity structure. We tied Doppler parameters of different rotational levels of H₂, since the X-SHOOTER resolution is not enough to detect the effect of velocity distribution broadening of H₂ levels (see e.g. [14]). For all DLAs we detected associated C₁ absorption lines and found them correspond to the position of H₂ components.

This is in agreement with what is usually seen for H₂-bearing DLA [11] and it indicates the cold medium on the line of sight associated with H₂/C₁-bearing components. Therefore, we fit C₁ lines, separately, from other metals, to derive column densities on the C₁ fine-structure levels of the ground electronic state.

An example of fitted H₂ absorption lines is given in figure 1. The detailed fit profiles for all species and component by component results are presented in [13].

3. Properties of the H₂-bearing DLA sample

In table 1 we summarize the total column densities of H₁, H₂, C₁, the average molecular fraction, metallicity, and Fe depletion. Additionally we present the physical parameters (temperature, number density, and UV flux) that we derived in H₂-bearing medium of DLAs (below in Sect. 4) using measured column densities.
Figure 1. Fit to H$_2$ absorption lines in DLA at z=2.625 in the quasar spectrum J085859.67+174925.32. The black and red lines show the observed spectrum and profiles of H$_2$ absorption lines, respectively. The blue lines indicate the Lyman and Werner bands of molecular hydrogen.

Table 1. Measured parameters and physical conditions in H$_2$-bearing DLAs

| QSO     | J0136 | J0858 | J0906 | J0946 | J1146 | J1236 | J2347 |
|---------|-------|-------|-------|-------|-------|-------|-------|
| z       | 2.779 | 2.625 | 2.567 | 2.607 | 2.840 | 3.033 | 2.588 |
| log N(H$_2$) | 18.65$^{+0.06}_{-0.04}$ | 19.72$^{+0.04}_{-0.02}$ | 18.88$^{+0.02}_{-0.02}$ | 19.97$^{+0.01}_{-0.02}$ | 18.82$^{+0.03}_{-0.02}$ | 19.76$^{+0.01}_{-0.01}$ | 19.44$^{+0.01}_{-0.01}$ |
| log N(H)   | 20.74$^{+0.01}_{-0.01}$ | 20.55$^{+0.01}_{-0.01}$ | 20.18$^{+0.01}_{-0.01}$ | 21.20$^{+0.02}_{-0.01}$ | 21.54$^{+0.01}_{-0.01}$ | 20.86$^{+0.01}_{-0.01}$ | 20.54$^{+0.01}_{-0.01}$ |
| log f      | -1.79$^{+0.06}_{-0.06}$ | -1.53$^{+0.01}_{-0.01}$ | -1.00$^{+0.02}_{-0.02}$ | -0.93$^{+0.02}_{-0.02}$ | -2.42$^{+0.03}_{-0.03}$ | -0.80$^{+0.01}_{-0.01}$ | -0.80$^{+0.01}_{-0.01}$ |
| [X/H]     | -0.58$^{+0.03}_{-0.03}$ | -0.63$^{+0.02}_{-0.02}$ | -0.18$^{+0.00}_{-0.08}$ | -0.48$^{+0.01}_{-0.01}$ | -0.57$^{+0.02}_{-0.02}$ | -0.58$^{+0.04}_{-0.04}$ | -0.60$^{+0.06}_{-0.06}$ |
| [Fe/X]    | -0.70$^{+0.04}_{-0.03}$ | -1.70$^{+0.03}_{-0.03}$ | -1.26$^{+0.08}_{-0.06}$ | -0.77$^{+0.01}_{-0.01}$ | -0.67$^{+0.02}_{-0.02}$ | -1.09$^{+0.04}_{-0.04}$ | -0.92$^{+0.09}_{-0.09}$ |
| log N(C I) | 14.67$^{+0.15}_{-0.17}$ | 14.34$^{+0.04}_{-0.04}$ | 13.86$^{+0.05}_{-0.05}$ | 14.43$^{+0.05}_{-0.05}$ | 13.91$^{+0.07}_{-0.07}$ | 14.11$^{+0.07}_{-0.07}$ | 14.05$^{+0.25}_{-0.25}$ |
| $T_{01}$, K | 77$^{+7}_{-6}$ | 102$^{+2}_{-2}$ | 116$^{+26}_{-8}$ | 118$^{+9}_{-8}$ | 101$^{+12}_{-9}$ | 118$^{+7}_{-3}$ | 76$^{+2}_{-2}$ |
| log $n_H$ | 2.3$^{+0.1}_{-0.1}$ | 1.8$^{+0.1}_{-0.1}$ | 2.6$^{+0.1}_{-0.1}$ | 2.3$^{+0.1}_{-0.1}$ | 2.6$^{+0.2}_{-0.2}$ | 1.5$^{+0.6}_{-0.6}$ | 2.0$^{+0.4}_{-0.4}$ |
| log $I_{UV}$ | -0.2$^{+0.1}_{-0.1}$ | 0.1$^{+0.1}_{-0.1}$ | 0.7$^{+0.1}_{-0.1}$ | 0.5$^{+0.2}_{-0.2}$ | 0.6$^{+0.2}_{-0.2}$ | 0.4$^{+0.1}_{-0.1}$ | -0.4$^{+0.3}_{-0.3}$ |

† for all the systems the metallicity and depletion of Fe are given based on S abundance, except J1146+0743 where we used Zn since S is not well fitted.

‡ $n_H$ is measured in cm$^{-3}$ and $I_{UV}$ in the Draine field [15].
Figure 2. H$_2$ column density as a function of molecular fraction in local galaxies [16, 17, 18, 19] and at high redshift DLAs ([7, 11] and references therein). Green circles, yellow squares and blue triangles indicate H$_2$-bearing DLAs found by a blind search, C$\text{I}$ selection, and extremely saturated DLA selection techniques, respectively. The red stars represent the sample studied in this work.

In figure 2 we plot the dependence of H$_2$ column density of the average molecular fraction, $f$, measured in the local Galaxies and at high redshifts in H$_2$-bearing DLAs. We additionally separate the measurement at high redshift into 4 samples, based on the selection: blindly, C$\text{I}$ [11], H$\text{I}$ (i.e. using extremely saturated DLA, [10]) and the direct H$_2$ (this work) selected samples are shown by green, yellow, blue, and red symbols, respectively. Our sample located in similar region of the H$_2$-log $f$ plane, than C$\text{I}$ selected systems for H$_2$ column densities log $N$(H$_2$) > 19. However, it is worth to mention, that the direct H$_2$ selected technique probes the high end of the H$_2$ column density distribution (note that H$_2$-bearing DLA at J0843+0221, with the second highest H$_2$ column density was selected by both H$\text{I}$ and direct H$_2$ technique, see [9]), which is necessary to study H$\text{I}$/H$_2$ transition in the ISM of high z galaxies.

4. Physical conditions in associated ISM

We used relative population of H$_2$ rotational and C$\text{I}$ fine structure levels to estimate the physical conditions in the cold ISM associated with H$_2$-bearing DLAs. To infer the temperature in the medium we used the observed relative population of $J = 1/J = 0$ H$_2$ rotational levels (see figure 3). Note that this value provides only the measurement of the temperature of H$_2$-bearing medium and do not for the whole DLA, which presumably corresponds to the warm neutral medium with $T \gtrsim$ several 10$^3$ K. The number density and UV flux in the H$_2$-bearing medium was constrained using measured population of C$\text{I}$ fine structure levels, H$_2$ rotational levels, since these levels are predominantly populated by UV pumping and collisions. For the measurement from C$\text{I}$ we used the same calculations in the assumption of homogeneous medium and a code as in [7, 20]. For each DLA the temperature was fixed to be measured $T_{01}$. For H$_2$ rotational levels we use the PDR Meudon code [21] that calculate the full radiative transfer in H$_2$ lines to compare.
modeled excitation of H$_2$ rotational levels with observed ones. Since we are not confident that $J > 3$ rotational levels are well constrained we compare excitation only for $J = 0, 1, 2$ levels. We run a grid of models for two main parameters both number density and UV field, which was varied in ranges $\log n_H = 0.4$ and $\log UV = -1.5 \ldots 2.5$. An example of the estimate of $n_H$ and UV using C1 and H$_2$ is shown in figure 4. The results are given in table 1 and details of the calculation are presented in [13]. We found typical values for the kinetic temperature, hydrogen density and UV radiation field of, respectively $T \sim 80 \ldots 120$ K, $n_H \sim 30 \ldots 400$ cm$^{-3}$ and $\xi_{UV} \sim 0.4 \ldots 5$ times the Draine field.

![Figure 3.](image1.png)

**Figure 3.** The excitation diagram of H$_2$ in the DLA at $z=2.625$ in J0858+1749. The blue points show observed column densities of H$_2$ on different rotational levels as a function of the excitation energy. The black dotted lines indicate the best fit $T_{01}$ temperature constrained from the relative population of $J=0$ and $J=1$ levels. One can see that population of J=2 level is also consistent with $T_{01}$.

![Figure 4.](image2.png)

**Figure 4.** The estimation of hydrogen number density, $n_H$, and UV field (in Draine field units) in H$_2$-bearing medium of the DLA in J0858+1749 using C1 fine-structure and H$_2$ rotational levels excitation. The green, violet, and red contour plots show the constraints obtained from C1, H$_2$ and joint C1 and H$_2$ fit of levels excitation, respectively. The red lines on the top and right axis indicate marginalized distribution from the joint fit. The black line show the constraint from the H$_1$/H$_2$ transition in the medium (see e.g. [20]).

Figure 5 shows the dependence of the measured $T_{01}$ temperature on the H$_2$ column densities at high redshifts DLAs and in the local Universe [16, 18, 19]. We found that $T_{01}$ estimates at high redshift are $\sim 100$ K and in a well agreement with local measurements and following the trend of decreasing temperature with H$_2$ column density increase.

In figure 6 we compare observed values of the thermal pressure, $P = nT$, and number density in the cold ISM of local and high z galaxies with the theoretical calculations [22]. We see that our new measurements are well agree with the expected dependence for the gas that is thermally stable to isobaric perturbations. However, some systems at high z indicate marginally higher values of the thermal pressure, which can be due to either typical lower metallicity in the ISM or an additional source of the pressure from thermal and hydrodynamical instabilities.
Figure 5. The dependence of $T_{01}$ on $\log N(H_2)$ measured in DLAs and the local galaxies. The gray point shows the measurement in the local galaxies. The circles indicate the known measurements at high redshifts (for data see, [7]), where the red stars show the sample presented in this paper. The color saturation indicates the metallicity of the associated DLAs.

Figure 6. The dependence of the thermal pressure, $P$, on number density, $n$, measured in DLAs (red start and green circles) and the local galaxies (blue squares and triangles). The black curve shows the theoretical calculation for cold ISM from [22]. The sizes of circles and stars correspond to the $H_2$ column densities shown in the legend.

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