Interstellar UV radiation field in high redshift galaxies probed by Damped Lyman Alpha systems: measurements based on the excitation of H_2 rotational levels

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Abstract

We present measurements of the physical parameters of ISM, namely - gas density and intensity of the interstellar ultraviolet (UV) radiation field in the H_2 absorption systems at high redshifts (z=2-4). These H_2 absorptions systems are corresponded to the cold phase of the neutral interstellar medium (ISM) in the early Universe and are detected in the quasar spectra (associated with the Damped Ly-α systems (DLAs)). We have used the populations of rotational levels of the ground vibrational state of H_2 and populations of fine structure levels of neutral carbon (CI) in the known H_2 absorption systems at high redshifts to measure the physical state of the ISM. It is widely known that higher excited rotational levels of molecular hydrogen are populated mainly by the mechanism of radiative pumping, especially in diffuse ISM, while the population of lower rotational levels of H_2 are determined by thermal balance of the medium, therefore the analysis of H_2 rotational level populations gives accurate estimates of the intensity of the incident radiation field and number density of a gas. We present measurements of UV intensity and gas density in 21 H_2 absorption systems. We found that H_2-bearing medium in strong H_2-bearing DLAs have typical values for the kinetic temperature, hydrogen density and UV radiation field of, respectively, T~100 K, n~100 cm^{-3}, and I_{UV} about 3 times of the intensity of the Draine field.

Introduction

Interstellar UV radiation field (ISRF) make a strong impact on the interstellar medium in course of the evolution of the Universe. Ultraviolet photons heat the ISM, ionize atoms, disassociate molecules and destroy dust. ISRF is very important feedback mechanism between star formation and ISM and consequently, UV ISRF plays a crucial role in formation and evolution of galaxies. The properties of the local UV ISRF are fairly well known, but we still know a little about the properties of the UV ISRF in the early Universe. At the same time, the star formation rate at z ~ 2 was an order of magnitude higher than at z=0. Since the intensity of UV ISRF is integrated over all stars in the galaxy, it is proportional to the star formation rate in the galaxy. Therefore, the intensity of UV ISRF in galaxies at z ~ 2 is expected to be much higher than in the local Universe. This is partially confirmed by several observations of DLAs (Wolfe et al. 2003, Noterdaeme et al. 2007, 2015, Klimenko et al. 2016, Balashev et al. 2017).

Damped Lyman Alpha systems detected in the spectra of Quasars and Gamma ray burst afterglow. DLAs are identified by a broad absorption lines with a prominent Lorentzian wings. HI column densities in DLAs exceed $10^{20.3}$ cm^{-2} and it was shown that DLAs are the main reservoir of the neutral gas at high redshifts (Prochaska et al. 2009, Noterdaeme et al. 2012). It is believed that these systems are associated with disks of galaxies or their close vicinity with impact parameter less than 20 kpc (Krogager et al. 2012).

In some case the cold phase of ISM of DLAs can be examined. These realize by an identification and analysis of H_2 absorption systems, that are found in < 5% of DLAs (Balashev et al. 2018). To date about 40 H_2 absorption systems were accurately analysed and only half of them has a high fraction of H_2 about >0.01 of HI.

In the present work we propose a method for determining of physical conditions in diffuse ISM (gas number density and intensity of interstellar radiation filed) based on an analysis of the distribution of H_2 molecules over the rotational levels of the ground electronic state. We show that this technique together with analysis of population of CI fine structure levels (Silva et al. 2000) allows for joint estimate of physical parameters. We found that intensity of interstellar UV field in high redshift DLAs is on average three times higher than intensity of the Draine field (Draine 1978).

Method

The population of the H_2 rotational levels were previously used to estimate the physical conditions in a few high-z H_2-bearing DLAs, e.g. Klimenko et al. 2016, Shaw et al. 2016, Noterdaeme et al. 2017, Rawlins et al 2018. Here we used it to analyse whole sample of H_2-saturated absorption systems at high redshifts.

In case of saturated H_2 absorption systems (log N(H_2)/cm^{-2} > 17), when most of H_2 is self-shielded from incident UV field, the levels of J=0,1,2 are predominantly thermalized and their excitation is typically close to thermal temperature (Le Petit et al. 2006) which is set by the thermal balance, itself being a function of the **density** and **UV field**. Otherwise UV pumping plays a direct role in the excitation of high rotational levels J>=3, therefore H_2 excitation diagram occurs sensitive to the main physical parameters of the ISM.

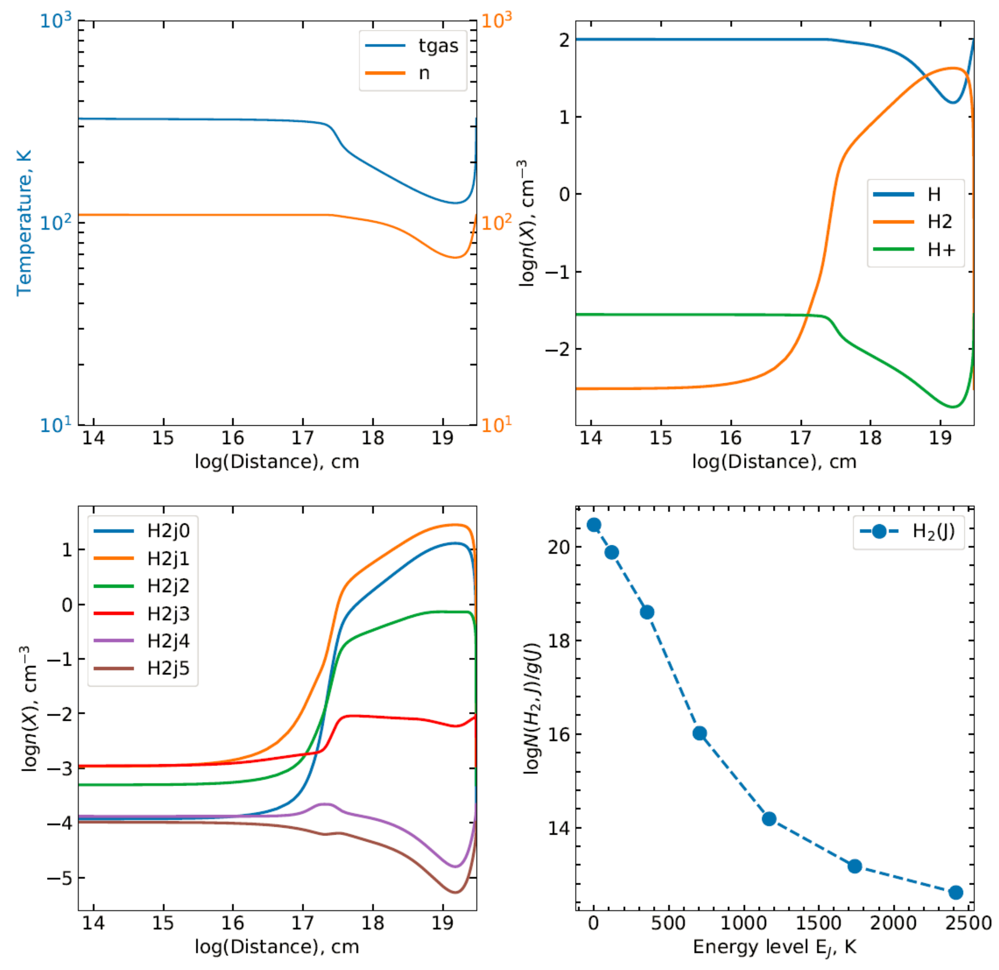
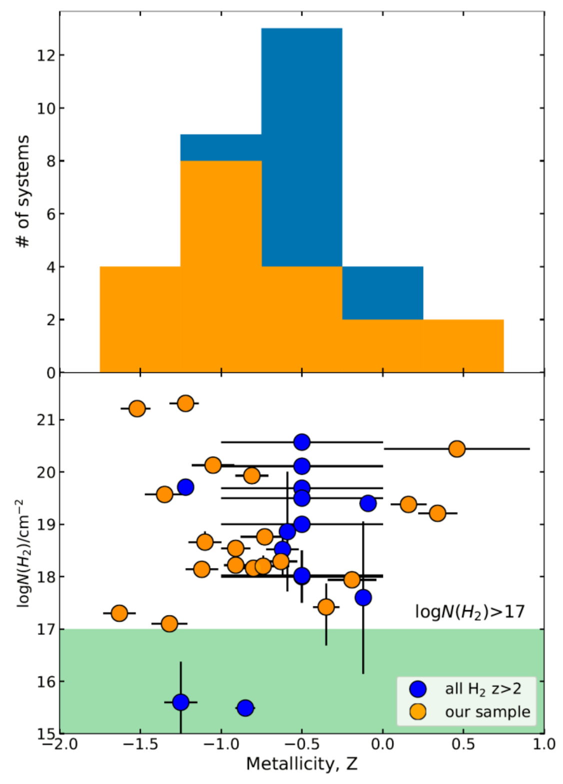


Fig. 1 Example of PDR Meudon simulation of a molecular cloud beamed by UV radiation from both side

- We therefore used the **PDR Meudon code** (Le Petit et al 2006) which performs full radiative transfer calculation in H_2 lines.
- We used a grids of pseudo-spherical **constant density** models with only parameters being the **metallicity** (dust scales to metallicity), **density** and **intensity of UV field**.
- The temperature profile was calculated from the solution of thermal balance.
- The grid covered the ranges
  0< log n_H/cm^{-3} < 4
  -2< log I_{UV} < 3
- We interpolated the calculated H_2 excitation on a denser grid in the n_H-I_{UV} parameter space.

Sample



We selected H_2 absorption systems with z>1.7 and log N(H_2)> 17 in all available H_2 absorption systems at a high redshift detected in quasar spectra, which were obtained with high spectral resolution spectrographs, VLT-UVES, KECK-HIRES, HST-STIS.

The column density of molecular hydrogen is sufficient for self-shielding of most of the H_2 from the incident ultraviolet field and the gas in such a system is associated with the cold phase of the interstellar medium. All systems are shown in Fig. 1 by circles. Orange circles represent H_2 systems in our sample.

Fig. 2 Column density of H_2 versus average metallicity of DLAs in the interstellar clouds at high redshifts.

Results

We derive the temperature and number density of the H_2-bearing gas in our sample as well as the intensity of UV irradiation onto the cloud. In order to constrain parameters we used relative population on CI fine structure levels and H2 rotational levels (se Fig.3). H_2 and CI estimates have the opposite dependence on parameters in the n-UV plane, that it remove the degeneracy between parameters. That allow us to reliably determine the parameters of the medium.

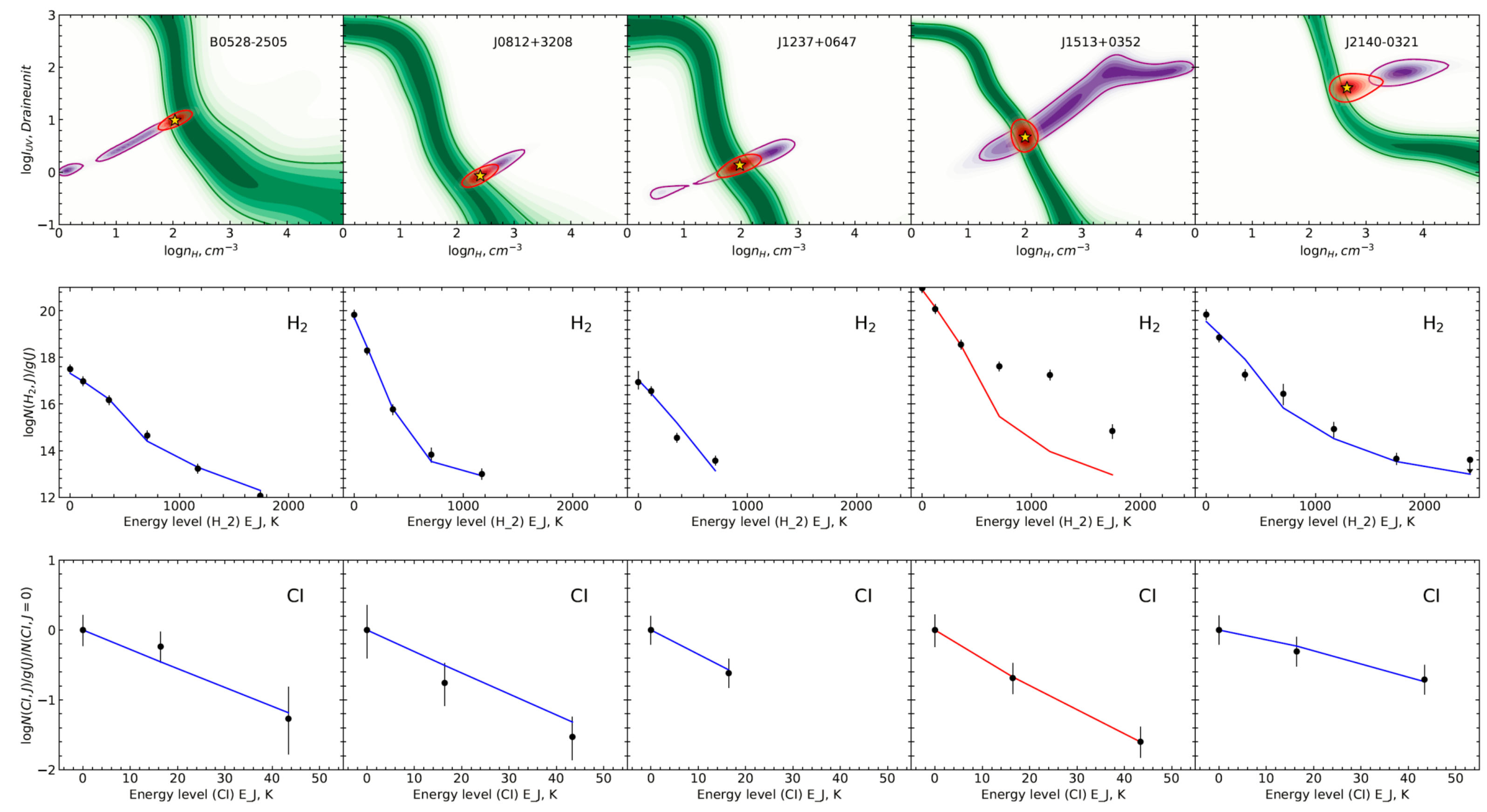


Fig. 3 Top: The green and violet color gradients represent the obtained probability density function (with the contour lines encompassing 68.3% of fit) for 5 systems in sample. Medium: H2 excitation diagram, circles correspond to measurements, lines are the best fit. Bottom: Fit to the relative population of fine structure levels of CI.

In Fig. 4 we show our estimates of UV intensity versus the total hydrogen density. We found that in our sample the intensity of UV field is from 1 to 30 of the Drain field. The mean value of **log I_{UV} = 0.5±0.5** in Draine unit and **log n_H = 1.7±0.6** in cm^{-3}. We did not found any trend with a gas metallicity.

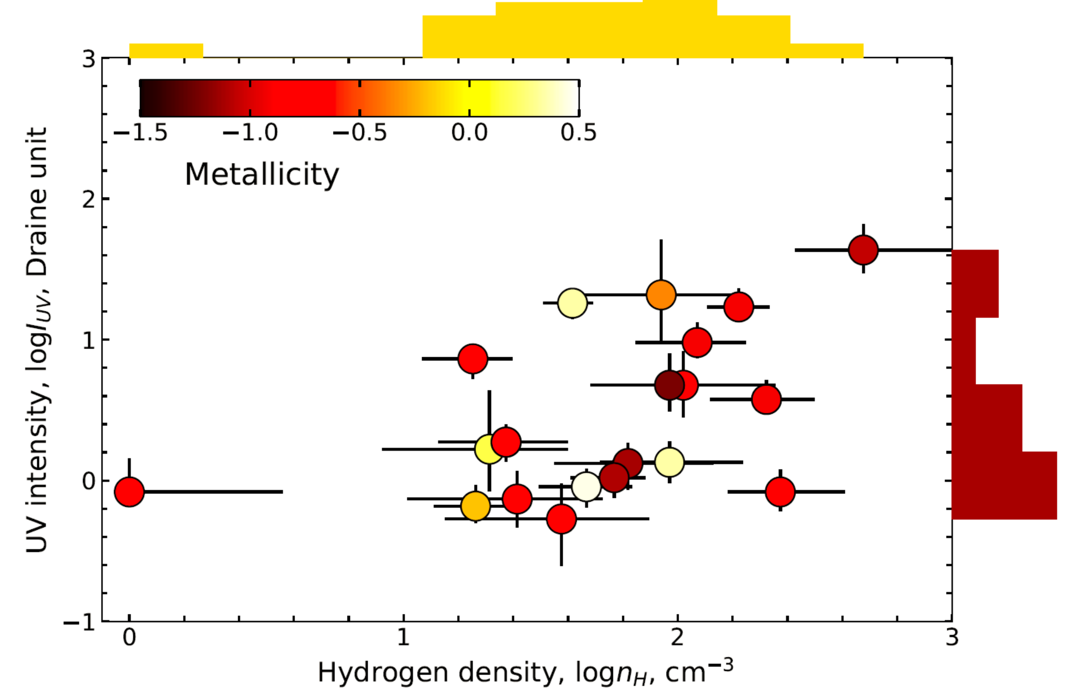
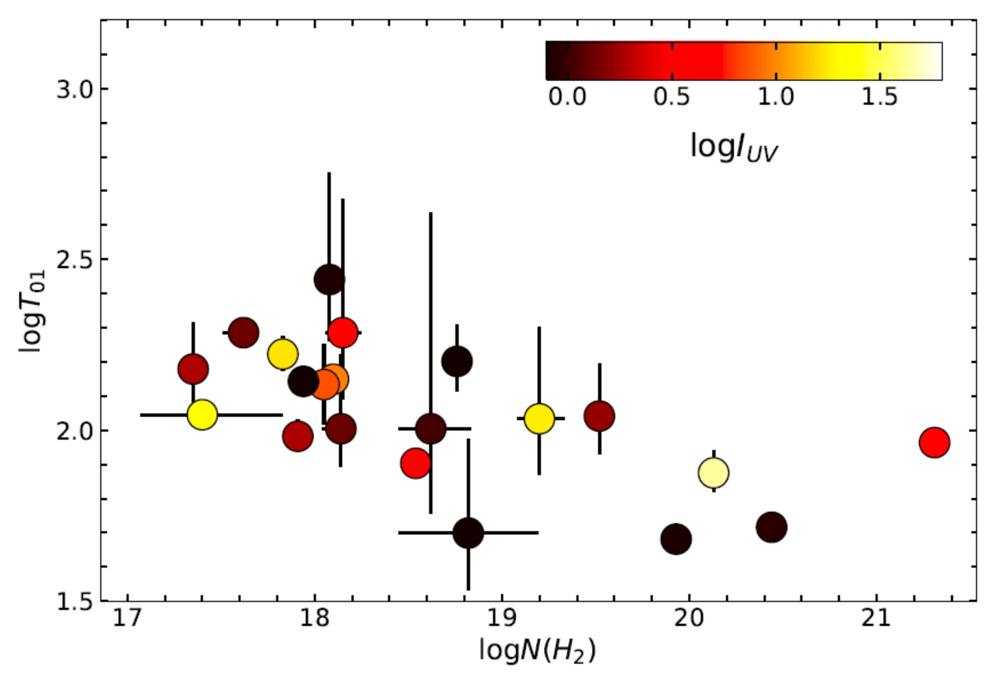


Fig. 4 The UV intensity as a function of the hydrogen density measured in strong H2-bearing DLAs at high redshifts. The color gradient represents the metallicity of the gas. Histograms on the top and right show n_H and I_{UV} distributions.



The statistic sample is small and our measurements are still within the dispersion of T_{01} and we do not see any trend. However, it seems that the higher N(H_2), the lower T_{01}. For one system with the highest N(H_2) we found a higher T_{01} and a higher I_{UV}.

Fig. 5 We show the dependence of the H_2 excitation temperature T_{01} on the total column density of H_2. The color gradient represent the intensity of UV field

Conclusions

- We presented measurements of the intensity UV filed and number density in DLAs at high redshifts based on the simulations by the PDR Meudon
- On average H_2 clouds in DLAs at high redshifts are characterized by a **higher** value of the intensity of interstellar **UV field** compared to the Draine field
- The gas in strong **H_2-bearing** systems indeed refers to **cold** and **dense** phase of the interstellar medium

References: Le Petit et al. A&A 164, 506 2006; Draine AJSS, 36, 595, 1978, Krogager et al. MNRAS 424, L1, 2012, Noterdaeme et al. A&A 547,1,2012, Wolfe et al. ApJ, 593, 215, 2003, Noterdaeme et al. A&A 474,16, 2007, Noterdaeme et al. A&A, 577, A24, 2015, Klimenko et al. AstrL 42, 161, 2016, Balashev et al. MNRAS 470, 2890, 2017, Balashev et ak. MNRAS, 478,7,2018, Shaw et al. MNRAS, 459, 3234, 2016, Noterdaeme et al. A&A, 597, 82, 2017, Rawlins et al MNRAS, 481, 2083, 2018