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Molecular hydrogen at high redshift

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Abstract. Absorption lines of molecular hydrogen provide a most sensitive and powerful tool to understand the early evolution of galaxies and the intergalactic medium (IGM). In addition these lines are useful to investigate the space and time variations of the ratio of electron to proton mass. In this presentation I review the status of the search for H_2 at high z. High resolution spectrograph on ELTs will allow us to detect H_2 in the Lyman Break Galaxies (LBGs) and CO and HD in DLAs that already show H_2. This will allow us to investigate the astrochemistry at early epochs and study the physics of interstellar medium (ISM) at high redshifts.

Keywords. quasar:absorption lines, Galaxies: Intergalactic medium, Galaxies: high-redshift

1. Introduction

H_2 is the first neutral molecule to be formed in the universe and is an important coolant for the first generation of stars. In the local universe H_2 is ubiquitous in star-forming giant molecular clouds, the diffuse interstellar medium (ISM) and in the atmospheres of Jovian planets. In the diffuse ISM, H_2 molecules are mainly formed on grain surfaces and destroyed by the UV photons with typical energy ~10 eV (called Lyman-Werner band photons). Thus equilibrium abundance and the population of H_2 in different rotational levels together with excitation of fine-structure states C^0 are used to get a handle on physical conditions such as gas pressure, ambient radiation field and chemical history etc (Savage *et al.* 1977, Shull & Beckwith 1982, Black & van Dishoeck 1987, Jenkins & Tripp 2000, Tumlinson *et al.* 2002). These conditions are believed to be driven by the injection of energy and momentum through various dynamical and radiative processes associated with star formation activity. Thus detecting H_2 molecule at high z is an important step to understand the evolution of normal galaxies. In addition to this detection of HD and CO in the systems with H_2 detections will allow us to find CO/H_2 in different environments and HD/H_2 can potentially be used to measure $\Omega_{\rm b}$. Also H_2 lines in a good s/n spectrum will allow us to constrain the variation of, $\mu = m_e/m_p$, as a function of time (see for example Ivanchik *et al.* 2005). Beyond the local universe H_2 is detected only in damped Ly-α (DLA) systems seen in the spectra of high z QSOs. These systems are characterized by very large neutral hydrogen column densities: $N(\mathrm{H\,I}) \geqslant 10^{20}$ cm^{-2}. Here, I summarize the details of H_2 surveys at high z, compare the properties of DLAs with those of the Galaxy, the LMC and the SMC, and provide possible issues that can be addressed with ELTs.

2. Molecular Hydrogen in DLAs

We have searched for H_2 in DLA and sub-DLA systems at high redshift ($z_{\rm abs} > 1.8$), using UVES at the VLT, down to a detection limit of typically $N(H_2) \sim 2 \times 10^{14}$ cm^{-2}. Out of the 65 systems in our sample, ~15% of the systems have tentative detections of associated H_2 absorption lines. Results for the first part of the survey (33 systems) are published in Ledoux *et al.* (2003) and rest will be published soon. CO is not detected

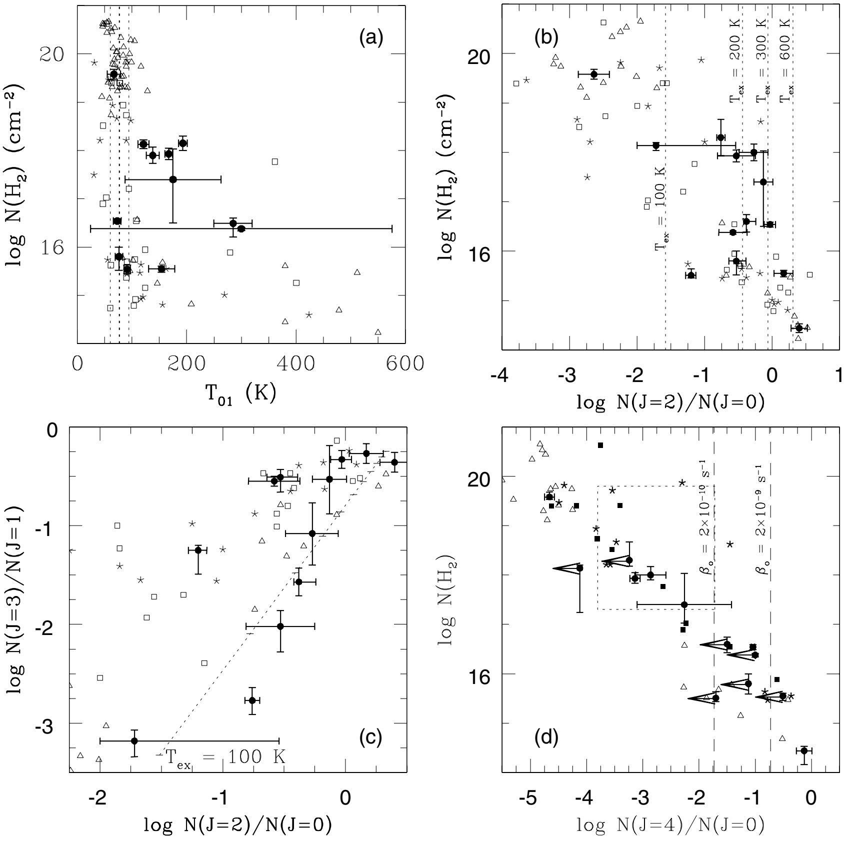

Figure 1. Filled circles with error-bars are our measurements in DLA components, other data points are from Savage *et al.* (1977), Spitzer, Cochran & Hirshfelf (1974) for the Galactic ISM (triangles), and Tumlinson *et al.* (2002) for the LMC (squares) and SMC (asterisks). The vertical short-dashed lines in panel (a) show the mean and 1σ range of T_{01} measured by Savage *et al.* (1977) in the Galactic ISM. Vertical dashed lines in panels (b) give the expected ratio for different excitation temperatures. In panel (c) the dotted line gives the expected relation under LTE with temperatures ranging from 100 to 600 K (horizontal tick-marks show the values for different temperatures with 50 K steps). In panel (d) the vertical dashed lines give the predicted ratio for different values of photo-absorption rate β_0.

in any of the systems with a typical N(CO)$\leqslant 10^{13}$ cm^{-2}. HD is detected in one system (Varshalovich *et al.* 2001). The systems where H$_2$ is detected are usually amongst those with the highest metallicities and depletion factors. This directly demonstrates that a large amount of dust is present in the components where H$_2$ is detected. The mean H$_2$ molecular fraction, $f = 2N(\mathrm{H_2})/[2N(\mathrm{H_2}) + N(\mathrm{H\,I})]$, in DLA systems is typically $\log f < -1$ and similar to what is observed in the Magellanic Clouds. There is no correlation between f and N(H I). Approximately 50 percent of the systems have $\log f < -6$. The details of the survey and data used can be found from (Srianand & Petitjean, 1998; Petitjean *et al.* 2000; Srianand *et al.* 2000; Petitjean *et al.* 2002; Ledoux *et al.* 2002; Ledoux *et al.* 2003; Srianand *et al.* 2005). Now let us compare the physical conditions in DLAs with those seen in the local universe.

Rotational excitation of H_2: It is a standard procedure in ISM studies to use the T_{01} obtained from,

$$\mathrm{OPR_{LTE}} \sim \frac{\mathrm{N(J=1)}}{\mathrm{N(J=0)}} = 9 \times \exp(-170.5/\mathrm{T_{01}}). \tag{2.1}$$

to infer the kinetic temperature of the gas assuming LTE. Panel (a) in Fig. 1 shows T_{01} measured in DLAs, Galaxy, LMC and SMC as a function of $N(H_2)$. The observed mean T_{01} in DLAs (153±78 K) is higher than that measured in ISM (77 ± 17) and from the Magellanic clouds (82 ± 21 K). Under the LTE assumption this will mean the kinetic temperature of the H_2 components in DLAs in the range 100 to 200 K.

The collisional excitation plays a significant role in populating the low-J levels and $J \geqslant 3$ levels are usually populated by formation processes and UV pumping. In DLAs where H_2 is optically thick, the $N(\mathrm{J}=2)/N(\mathrm{J}=0)$ ratio is larger than that seen in similar gas within the Galactic ISM, or that of the LMC and SMC (panel b in Fig. 1). We notice that T_{02} and T_{03} are consistent with one another (see panel (c) in Fig. 1), but higher than T_{01}. This means $J \geqslant 2$ levels are influenced by UV pumping and/or formation pumping. Following the analytic prescription by Jura (1975) we can write,

$$p_{4,0}\beta(0)n(H_2, J=0) + 0.24Rn(H)n = A(4 \rightarrow 2)n(H_2, J=4) \tag{2.2}$$

Here, $\beta(0)$, $p_{4,0}$ are, respectively, the photo-absorption rate in the Lyman and Werner bands and the pumping efficiency from $J = 0$ to $J = 4$; $A(4 \rightarrow 2)$ is the spontaneous transition probability between $J = 4$ and $J = 2$ and R is the formation rate of H_2. Neglecting the second term on the left hand side of Eq. 2.2 leads to a conservative upper limit on the UV radiation field. For log $N(H_2) \leqslant 16.5$ the $N(\mathrm{J}=4)/N(\mathrm{J}=0)$ ratio in DLAs is of the order of or slightly higher than that seen in the ISM of our Galaxy. This probably means the optically thin H_2 components without detectable H_2 absorption from the $J = 4$ state arise in gas embedded in a UV field with intensity similar to (or slightly higher than) that of the mean ISM field. This together with the 15% detection rate of H_2 in DLAs can be used to conclude that DLAs at $z \geqslant 1.9$ could contribute as much as half of the global star-formation rate contributed by Lyman break galaxies.

C I and C II* absorption: C I and C II* absorption lines are usually detected in systems with H_2 absorption. No clear trend is seen between $N(H_2)$ and N(C I). We notice detectability of C I absorption is highly probable in systems with high dust depletion and metallicity (Srianand *et al.*, 2005). We show, using N(S II) as a proxy for N(C II), that the DLA components with C I detections have an ionization state consistent with them originating from the cold neutral medium (CNM) (see Fig. 2). The distribution of N(S II) is somewhat similar for components with both H_2 and C I absorptions (filled circles), and for components with C I but no H_2 absorptions (open circles). However, N(C I) in components without H_2 is typically lower. Most of the upper limits on C I are consistent with N(C I)/N(C II) $\leqslant -3$. This can mean most of the DLA systems originate from warm neutral medium (WNM) or warm ionized medium (WIM) where the above ratio can be as low as 10^{-4}. The CMBR field expected from the Big-Bang is not sufficient to explain the observed N(C I*)/N(C I) and an extra contribution is required from collisional processes and/or the UV flux (right panel in Fig. 2). For the temperature range seen in H_2 components from T_{01} and UV radiation field like that seen in Galactic ISM the observed N(C I*)/N(C I) is consistent with $20 \leqslant n_H$ (cm^{-3}) $\leqslant 250$. All the systems with H_2 detections show C II* absorption. C II* absorption is also detected in a considerable fraction of DLAs that do not show H_2 or C I absorption. However, 50% of the DLAs do not show detectable C II* absorption (see also Wolfe *et al.* 2003). In the case of systems with H_2 detections N(C II*)/N(C II) is consistent with that expected

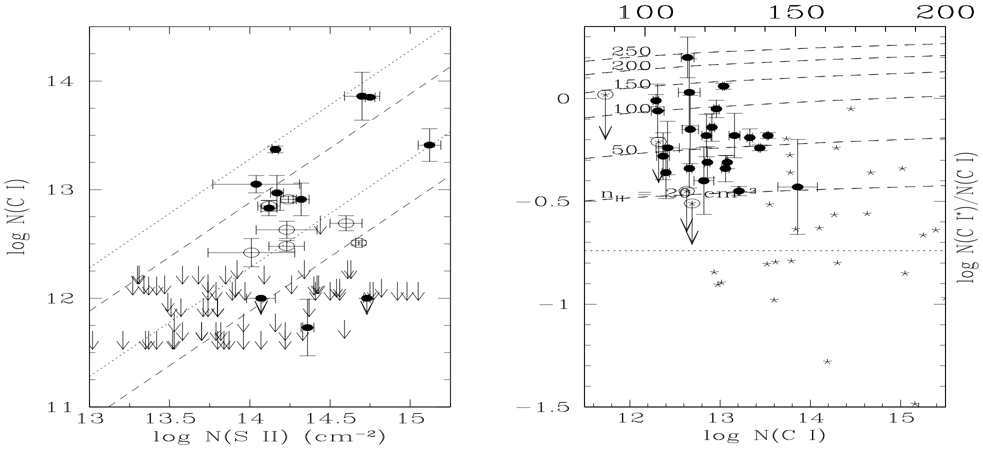

Figure 2. *Left panel*: N(C I) measured in individual components of DLAs (filled and open circles are for the component with and without H_2 detection respectively) as a function N(S II). The arrows are the upper limits from systems where there is no H_2 or C I absorption. The two dotted lines give the expected correlation for log $N(\text{C I})/N(\text{C II}) = -3$ (lower line) and -2 (upper line) respectively, when solar relative abundances are used. The short-dashed lines give the same correlations when C is depleted with respect to S by 0.4 dex. The C I detections are consistent with what one expects in the case of the CNM. *Right panel*: The ratio $N(\text{C I}^*)/N(\text{C I})$ is plotted as a function of $N(\text{C I})$. The points with error bars are our measurements in individual DLA components. The stars are data measurements in the ISM of the Milky way drawn from Jenkins & Tripp (2001) and Jenkins, Jura & Loewenstein (1983). The horizontal dotted line gives the expected value of the ratio if it is assumed that C I is excited by the CMBR only with $T_{\text{CMBR}} = 8.1$ K as expected at $z = 2$. The short dashed lines give the expected ratio for different n_{H} as a function of temperature (top portion of the x-axis).

in CNM. C II* is detected in all the systems with log $N(\text{H I}) \geqslant 21.0$. Most the systems with log $N(\text{H I}) \geqslant 21.0$ have $N(\text{C II}^*)/N(\text{C II})$ consistent with what is expected in CNM. On the contrary, the measured values of $N(\text{C II}^*)/N(\text{C II})$ in systems with lower $N(\text{H I})$ spread over more than an order of magnitude covering the expected ranges for WNM and CNM. In the whole sample the number of systems with C II* without H_2 detections that are consistent with CNM and WNM are approximately equal. Clearly detections of absorption lines of fine-structure allow us to study the ISM physics in greater detail even at very high z.

Time variation of μ: The possible cosmological variation of the proton-to-electron mass ratio, $\mu = m_p/m_e$, can be investigated using wavelengths of H_2 lines of Lyman and Werner bands. As the rest wavelengths of the H_2 lines are not precisely known the uncertainties in the analysis could be very large (see for example Ivanchik *et al.* 2005). Also the requirement of high s/n and high resolution is possible for only two systems till now. ELTs will allow us to perform detailed investigations using statistically significant number of systems.

3. Discussion

It is clear from the above presentation that detecting the absorption lines of H_2 and atomic fine-structure levels at high z is very useful. Bright LBGs and GRB host galaxies are the potential sites where one can in principle detect H_2. As the Lyman Werner band absorption line of H_2 are expected in the Ly α forest it is important to have high resolution and signal-to-noise in the blue spectrum. As can be demonstrated from our study, a signal to noise of 20 and R = 20 000 may be sufficient to detect H_2. However, with 8m-class telescopes this is possible only for bright sources. ELTs with blue sensitive spectrographs will allow us to search for H_2 towards fainter QSOs, GRBs and brighter LBGs. However in the case of GRBs H_2 may be in non-equilibrium and it is important to target the source as quickly as possible to be able to detect the H_2 lines. Indeed the time variation of H_2 column density will give important clues about the GRB hosts.

C I is mainly detected in high density regions in DLAs. Spectroscopy with 10 times more sensitivity will allow us to detect C I even from the WNM. At $z > 2$ the cosmic microwave background is an important source of pumping of the excited fine-structure states. Thus the ratio of N(C I*)/N(C I) will directly track the T(CMBR).

Detecting other molecules in systems with H_2 detections is also important for the understanding of astrochemistry in low metallicity gas in the early universe. CO is not detected in DLAs and the achieved limits are close to the lowest column measured in Milky Way. As the metallicities in DLAs are low, to test N(H_2) vs. N(CO) relation we need to push this limit by roughly a factor 50. HD is detected in one case (Varshalovich *et al.* 2001) and there are two candidate systems. At present N(HD) limits for DLAs are around 10^{14} cm^{-2}. For D/H from BBNS things become interesting only when N(HD) $\simeq 10^{12}$ cm^{-2}. In short S/N $\simeq$ 500 spectrum of the known DLAs with H_2 will allow us to investigate astrochemistry at very early universe.

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Discussion

ROMERO COLMENERO: What kind of S/N would you require to detect H_2 in a GRB host at $2 < z < 4.5$?

SRIANDAND: For a detection limit of N(H_2) $\sim 10^{14}$ cm^{-2}, a S/N of 30 and R $\sim$ 40 000 will be good enough. However, for lower thresholds one may need higher S/N.