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Molecular Hydrogen in the High Redshift Damped Ly-α Systems:

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Abstract. This review talk summarizes the main results obtained from the just completed survey of molecular hydrogen in damped Lyman-α systems (DLAs). Preliminary results based on modeling ionization conditions and chemical network is also presented. The presence of H_2 and fine-structure lines of C I in 13-20% of DLAs allow one to investigate the physical conditions using the techniques that are commonly used in the studies of the Galactic ISM. It is shown that the DLAs with H_2 trace regions with higher density, lower temperature, moderate to high dust depletion, and local star-formation. Absence of H_2 in DLAs with moderate dust depletion could just be a simple consequence of lower densities in the systems.

1. Introduction

DLAs are believed to originate in gas associated with protogalaxies that lie along our line of sight to background quasars. The physical conditions within DLAs can reveal the star formation history, determine the chemical composition of the associated ISM, and hence document the first steps in the formation of present day galaxies. At H I column densities typically measured in DLAs, molecular hydrogen (H_2) are conspicuous in our galaxy (Savage et al., 1977). It is known that H_2 is a very useful tracer of radiation field and dust content in the photodissociation regions. Thus detecting H_2 is the first major step toward a complete understanding of physical condition in DLAs. This was the aim of our survey using UVES installed at the ESO VLT 8.2m telescope. The survey details and notes on the observations can be seen from (Ledoux et al., 2002, 2003; Petitjean et al., 2000, 2002 and Srianand et al., 2000). Here we just summarize the main results.

2. Physical conditions in DLAs derived from the observations

Molecular hydrogen is detected in 13-20% of the newly-surveyed systems. Typical upper limits on the molecular fraction obtained in the case of non-detections is log f $\leq$ -6. Absence of H_2 in 80% of the systems can be explained if the formation rate of H_2 on to dust grains is reduced and/or the ionizing flux is enhanced relative to what is observed in our galaxy.

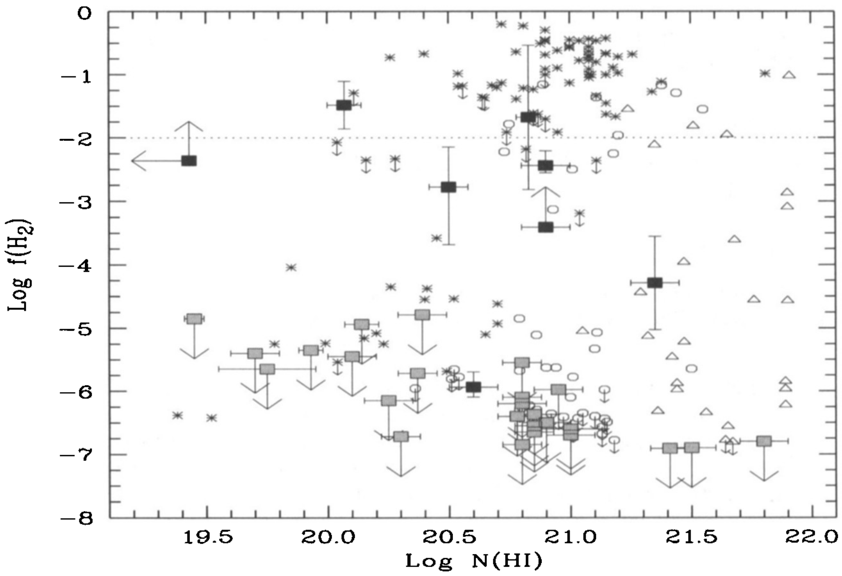

Figure 1. Mean H_2 molecular fraction, f =2N(H_2)/(2N(H_2)+N(H I)), versus neutral hydrogen column density. Measurements in DLAs are indicated by dark squares for H_2 detections and shaded ones for upper limits. Observations along lines of sight in the Galaxy (Savage et al 1977) and LMC and SMC (Tumlinson et al 2002) are indicated by, respectively, asterisks, circles and triangles.

In what follows we will concentrate on physical conditions in the systems that show H_2. It is known in the case of Galactic ISM that H_2 becomes optically thick at log N(H I cm^{-2}) = 20.7. However no such critical N(H I) is defined in the case of LMC and SMC. This seems to be the case with DLAs as well (Fig. 1). The lack of this characteristic self-shielding scale is either because the DLAs span a wide range of physical conditions or the formation rate of H_2 onto dust grains is reduced and the ionizing flux is enhanced relative to what is seen in our Galaxy (i.e the characteristic N(H I) is pushed to a much higher value). Presence of dust is an important factor in the formation of H_2 in DLAs (see Fig. 2). The systems with larger molecular fractions (i.e log f ≥ -4) are always found to have large depletion (i.e., $\kappa \geq -1.5$). Few non-detections with high κ seen in the figure could just be the consequence of enhanced radiation field in these systems.

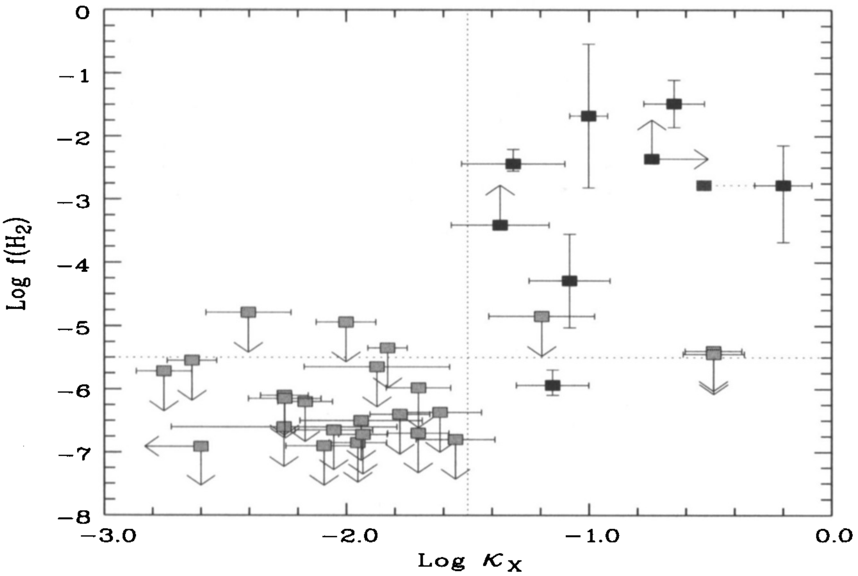

Figure 2. H_2 molecular fraction versus the amount of dust, $\kappa_X = 10^{[X/H]}(1 - 10^{[Fe/X]})$, with either X=Zn or S or Si. A weak trend between κ and f is apparent; however, several orders of magnitude spread in $f(H_2)$ for a given κ, among the detected cases, suggests that in addition to the amount of dust the physical conditions of the gas (density, temperature, and UV flux) play an important role in governing the formation of H_2 in DLAs.

Absorption lines of C I are invariably detected in systems that show H_2 absorption. The observed fine-structure excitations of C I in DLAs are much higher than that seen in our ISM (Fig. 3). This difference can not be explained by the CMB pumping alone and higher gas densities are favored (≥ 20 cm^{-3} for a temperature of 100 K) in the molecular gas. Rotational excitations of H_2 can as well give a handle on the physical conditions. The ortho-para ratio (OPR) measured in individual components is distributed between 1 and 3 (see Fig. 4). This is higher than what is seen in galactic ISM, LMC, and SMC for similar H_2 content. If we assume LTE then the observed range in OPR corresponds to the kinetic temperatures in the range 100 to 300 K. This is consistent with the usually preferred T_{01} measured in all these systems. The ratio N(J=2)/N(J=0) is very sensitive to the collisional excitations. We notice that this ratio is higher in the case of DLAs compared to what is measured in the local universe for similar H_2 column densities (see Fig. 4). This is consistent with the higher densities derived based on C I absorption lines. As the excitational energy is large the ratio N(J=4)/N(J=0) is very sensitive to the formation pumping and UV pumping. The distribution of this ratio in DLAs is similar to that seen ISM, LMC, and SMC (see Fig. 4). The meta-galactic UV background is not good enough to pump the high J levels to the extent that is observed in DLAs. Thus local radiation field and hence in situ star formation is most likely in these systems.

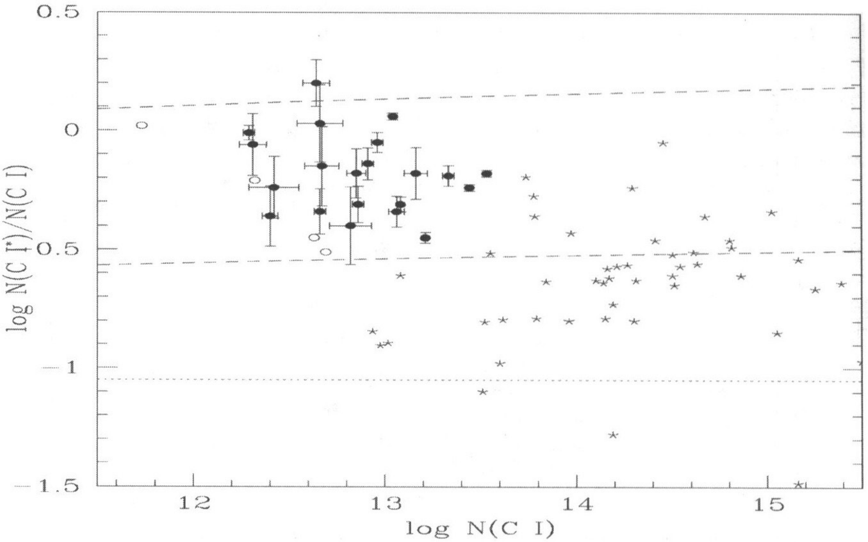

Figure 3. The filled circles and stars are measured values in DLAs and the Galactic ISM respectively (Jenkins & Tripp (2001)). The expected value from the CMB pumping at z = 2 is given by the dotted line. The expected range of the ratios when we consider CMB pumping and collisional excitation (in a gas of density 20 and 80 cm^{-3} and temperature $T = 100$ K) is marked by the dashed lines.

3. Preliminary results from the models

We consider the case of a cloud irradiated by the QSO dominated meta-galactic UV radiation field (BGR) (Haardt & Madau (1996)) and cosmic microwave background radiation (CMBR) at z = 2. We model the ionization state, chemical history, and temperature of the gas using version 96 of Cloudy. For simplicity we consider the absorbing gas to be a plane parallel slab of uniform density. The details of the improved grain physics (dust mediated molecular formation, heating, and radiative transport etc.,) and molecular network (formation, interaction with UV photons etc.,) used here are described in van Hoof et al (2001) and Ferland et al. (1994; 2002). Results are summarized in Fig. 5. It is clear from the figure that our models produce detectable amounts of H_2 (with $N(H_2) \geq 10^{14}$ cm^{-2}) only when n(H I)$\geq$ 0.1 cm^{-3}. The presence of an additional radiation field, turbulent motions, lower dust content or a lower N(H I) will move this limit toward higher n_H owing to greater photo-dissociation and less shielding. For the range of parameters directly measured in DLAs, the absence of detectable H_2 absorption lines could just be a direct consequence of lower densities. This argument is supported by the fact that models with lower densities, $n_H \leq 0.1$ cm^{-3}, show the spin temperature (T_s) in excess of 1000 K consistent with the available observations. It is clear from Fig. 5 that, for a randomly chosen DLA without any local source of radiation, either there will be no H_2 or most of the H will be in H_2. For the derived value of density and κ

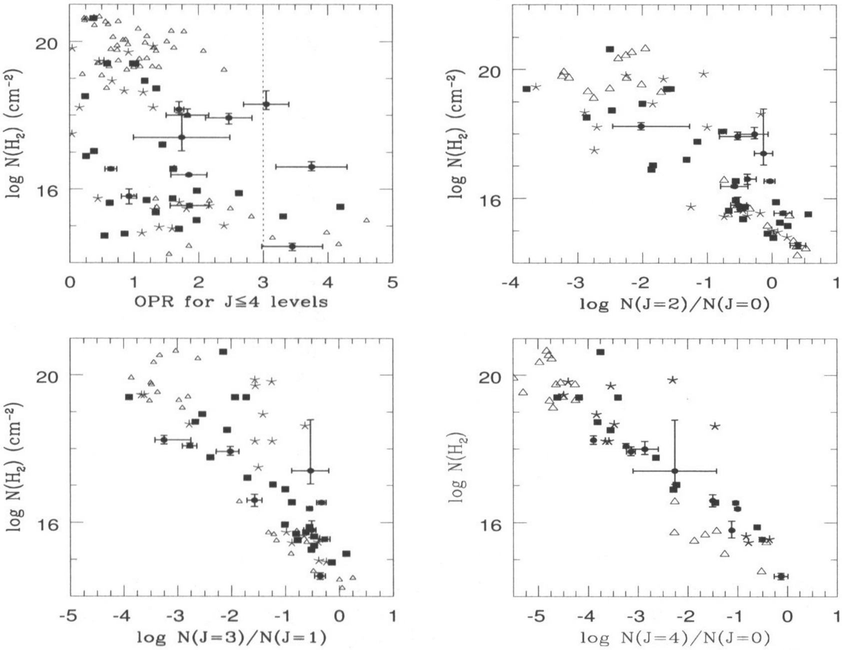

Figure 4. The column density ratios of different J levels observed in individual components in DLAs are plotted against N(H_2).Open triangles, stars and filled squares show the results obtained along the lines of sight through the Milkyway, LMC, and SMC from Tumlinson et al., (2002), Savage et al., (1977) and Spitzer, Cochran & Hirshfeld (1974).

(see the previous section) it is clear that if only the BGR is present then all the H will be in H_2. Thus the low molecular content seen in these systems require an extra additional radiation field probably due to local star-formation. This is consistent with what we infer from the high J excitations.

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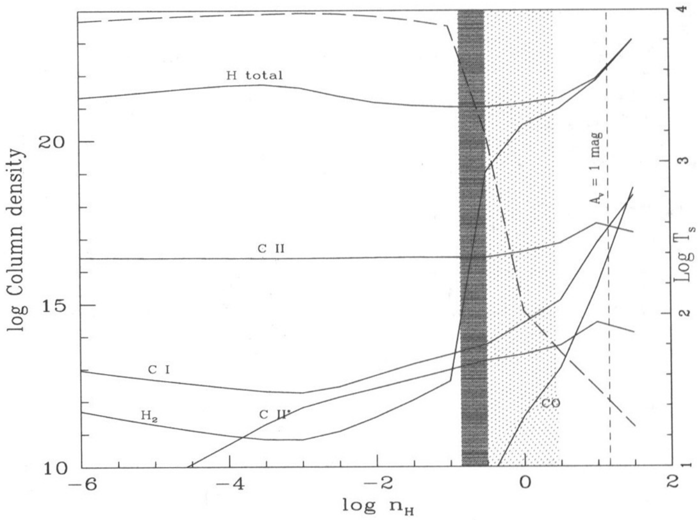

Figure 5. Column densities of different species as a function of density. The calculation uses the QSO dominated meta-galactic UV radiation field at z=2, N(H I) = 10^{21} cm^{-2}, metallicity, Z = 0.1, $\kappa = 0.1$. The long dashed line gives the spin-temperature, T_s (given in the right hand side ordinate), as a function of n_H. The light shadow region gives the range of n_H where H_2 is detectable (i.e., N(H_2) $\geq 10^{14}$ cm^{-2}) and less than H I (i.e., N(H_2) $\leq 10^{21}$ cm^{-2}). The dark shadow region shows the n_H range that reproduces the observed range in N(H_2). The long dashed vertical line gives the n_H at which the visual extinction A_V is unity.

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