

# Molecular hydrogen and the nature of damped Lyman- $\alpha$ systems <sup>\*</sup>

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the date of receipt and acceptance should be inserted later

**Abstract.** We report results from our mini-survey for molecular hydrogen in eight high-redshift damped Lyman- $\alpha$  (DLA) systems using the ESO Ultra-violet and Visible Spectrograph on the VLT. In addition, we investigate two systems using ESO public data. We include in the sample the only system where H<sub>2</sub> was previously detected and studied at high-spectral resolution. Altogether our sample consists of eleven absorbers with  $1.85 < z_{\text{abs}} < 3.4$ .

We confirm the presence of H<sub>2</sub> in the  $z_{\text{abs}} = 2.3377$ , metal-poor ( $[\text{Si}/\text{H}] = -1.20$ ), system toward PKS 1232+082. The derived molecular fraction,  $f = 2N(\text{H}_2)/(2N(\text{H}_2)+N(\text{H I})) = 4 \times 10^{-4}$ , is two orders of magnitude less than what has been claimed previously from low-resolution data. The physical conditions within the cloud can be constrained directly from observation. The kinetic temperature and particle density are in the ranges, respectively,  $100 < T < 300$  K and  $30 < n_{\text{H}} < 50$  cm<sup>-3</sup>. In addition, UV pumping is of the same order of magnitude than in our Galaxy.

The upper limits on the molecular fraction derived in nine of the systems are in the range  $1.2 \times 10^{-7} - 1.6 \times 10^{-5}$ . There is no evidence in this sample for any correlation between H<sub>2</sub> abundance and relative heavy element depletion into dust grains. This should be investigated using a larger sample however. The molecular abundance in a few DLA systems (and in particular in the two systems where H<sub>2</sub> is detected) is consistent with what is seen in the Magellanic clouds. But most of the DLA measurements are well below these values. This is probably partly due to small amounts of dust and/or high UV flux. We argue however that the lack of molecules is a direct consequence of high kinetic temperature ( $T > 3000$  K) implying a low formation rate of H<sub>2</sub> onto dust grains. Therefore, most of the DLA systems arise in warm and diffuse neutral gas.

## 1. Introduction

Damped Lyman- $\alpha$  systems observed in QSO spectra are characterized by large neutral hydrogen column densities. The systems at high redshift have been claimed to arise through large disks, progenitors of present-day galaxies (e.g. Wolfe 1995), but this is a matter of debate. Earlier searches for associated H<sub>2</sub> molecules, though not systematic, have led to small values or upper limits on the molecular fraction (Black et al. 1987; Chaffee et al. 1988; Levshakov et al. 1992). This is intriguing as, in the disk of our Galaxy, all clouds with  $\log N(\text{H I}) > 21$  have  $\log N(\text{H}_2) > 19$  (e.g. Jenkins & Shaya 1979).

More recently, Ge & Bechtold (1999), have searched eight DLA systems for molecular hydrogen using the MMT moderate resolution spectrograph ( $FWHM = 1$  Å). They detect molecular hydrogen in two of them with surprisingly large molecular fractions ( $f = 0.22$  at  $z_{\text{abs}} = 1.97$  toward Q 0013–004, see also Ge & Bechtold 1997, Ge et al. 1997; and  $f = 0.07$  at  $z_{\text{abs}} = 2.34$  toward Q 1232+082). For other systems, they find upper limits on  $f$  ranging between  $10^{-6}$  and  $10^{-4}$ . Reliable measurement of H<sub>2</sub> column densities is achieved only from high spectral resolution data however. For the  $z_{\text{abs}} = 2.8112$  DLA system toward PKS 0528–250, Srianand & Petitjean (1998) have estimated, from high-resolution data,  $N(\text{H}_2) \sim 6 \times 10^{16}$  cm<sup>-2</sup> and  $f = 5.4 \times 10^{-5}$ , which is a factor of fifteen smaller than what had been claimed from low-resolution data (Foltz et al. 1988; see however Levshakov & Varshalovitch 1985).

Formation of H<sub>2</sub> is expected on the surface of dust grains if the gas is cool, dense and mostly neutral, and from the formation of negative hydrogen if the gas is warm and dust free (see e.g. Jenkins & Peimbert 1997). Destruction is mainly due to UV photons. The effective photo-dissociation of H<sub>2</sub> takes place in the energy range 11.1 – 13.6 eV through Lyman-Werner band line absorption. Constraints on the kinetic and rotational excitation temperatures, the particle density and the radiation field can be derived from H<sub>2</sub> absorption. A direct determination of the local radiation field could have important im-

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<sup>\*</sup> Based on observations collected during ESO programmes 65.P-0038 and ESO 65.O-0063 at the European Southern Observatory with UVES on the 8.2m KUEYEN telescope operated on Cerro Paranal, Chile

plications for our understanding of the link between DLA systems and star formation activity at high redshift. We present here a high-resolution mini-survey of DLA systems focussed on the search for  $\text{H}_2$  molecules. Section 2 describes the data, Section 3 details the sample, while results are given and discussed in Sections 4 and 5.

## 2. Observations

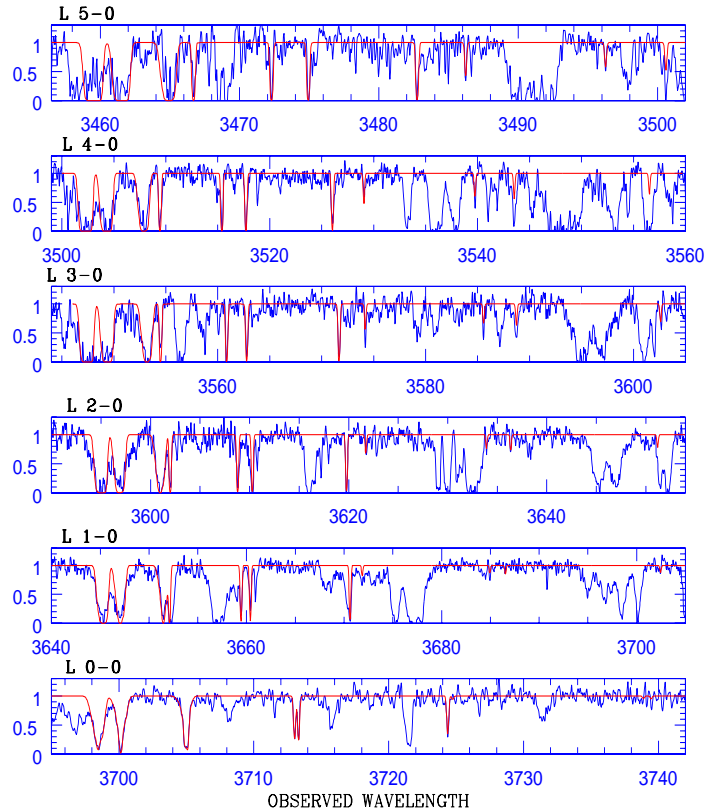
The Ultra-violet and Visible Echelle Spectrograph (D’Odorico et al. 2000) mounted on the ESO Kueyen 8.2 m telescope at the Paranal observatory has been used on April 5 to 8 and 29, 2000 to obtain high-spectral resolution spectra of eight previously known DLA systems at  $z_{\text{abs}} > 1.8$ . Settings have been adjusted in both arms to cover the  $\text{H}_2$  Werner and Lyman series absorption range together with several important metal absorption lines. The slit width was 1 arcsec (the seeing  $FWHM$  was most of the time better than 0.8 arcsec) and the CCDs were binned  $2 \times 2$  resulting in a resolution of  $\sim 45000$ . The exposure time  $\sim 2$  hours was split into two exposures. The data was reduced using the UVES pipeline, a set of procedures implemented in a dedicated context of MIDAS, the ESO data reduction package. The main characteristics of the pipeline is to perform a precise inter-order background subtraction for science frames and master flat-fields, and an optimal extraction of the object signal rejecting cosmic ray impacts and subtracting the sky at the same time. Wavelengths were corrected to vacuum-heliocentric values and individual 1D spectra were combined together. The resulting S/N ratio per pixel is of the order of 10 at  $\sim 3500 \text{ \AA}$  and 20 at  $\sim 6000 \text{ \AA}$ .

## 3. Comments on individual objects and sample

Results are summarized in Table 1. In addition to the eight DLA systems observed during our mini-survey, we have used ESO public data on two QSOs: Q 0000–263 and Q 1101–264 have been observed during, respectively, UVES commissioning and science verification. We have included in our sample the system at  $z_{\text{abs}} = 1.839$  toward Q 1101–264 although it does not qualify as a DLA system following the conventional definition,  $\log N(\text{H I}) > 20.3$ . Indeed, the former definition has no physical grounds. For  $\log N(\text{H I}) > 19.5$ , damped wings are conspicuous and although care should be exercised when discussing ionization corrections, in most cases, these corrections are small (e.g. Petitjean et al. 1992; Viegas 1995). We use the standard definition  $[\text{X}/\text{H}] = \log Z(\text{X}) - \log Z(\text{X})_{\odot}$  where  $Z$  is the metallicity of species X relative to hydrogen. Solar metallicities are from Savage & Sembach (1996).

### 3.1. $\text{H}_2$ at $z_{\text{abs}} = 2.3377$ towards PKS 1232+082

Our data confirms the presence of  $\text{H}_2$  absorption at  $z_{\text{abs}} = 2.3377$  toward PKS 1232+082 (Fig. 1), previously



**Fig. 1.** Portions of the PKS 1232+082 normalized spectra. Fit models for  $\text{H}_2$  absorption lines at  $z_{\text{abs}} = 2.3377$  are over-plotted.

detected by Ge & Bechtold (1999). We summarize and complement here the results presented elsewhere (Sri-anand et al. 2000). The metallicity in the corresponding  $\log N(\text{H I}) = 20.9 \pm 0.1$  DLA system, estimated from lines of Mg II, S II and Si II is  $6.3 \pm 0.7 \times 10^{-2}$  solar. Iron is depleted by a factor of  $\sim 5$  compared to this; the depletion factor is therefore reduced compared to previous measurements. The molecular fraction  $f = 4 \times 10^{-4}$  is two orders of magnitude smaller than what has been claimed previously from low-resolution data.

Absorption profiles corresponding to transitions from  $J > 1$  rotational levels are consistent with a single component at the same redshift as C I absorption. Lines from the  $J = 0$  and 1 levels are broader and are well fitted with four components at  $z_{\text{abs}} = 2.3372, 2.3374, 2.3377$  and  $2.3378$ . The respective excitation temperatures between the levels  $J = 0$  and  $J = 1$  are  $67_{-10}^{+12}$ ,  $78_{-13}^{+15}$ ,  $170_{-130}^{+40}$  and  $67_{-4}^{+3}$  K. The physical conditions within the cloud at  $z_{\text{abs}} = 2.3377$  can be constrained directly from the observation of  $\text{H}_2$ , C I, C I\*, C I\*\* and C II\*. The kinetic temperature is defined by the  $J = 0-1$   $\text{H}_2$  excitation temperature,  $100 < T < 300$  K; the particle density is then constrained using the  $N(\text{C II}^*)/N(\text{C II})$  column density ratio,

$30 < n_{\text{H}} < 50 \text{ cm}^{-3}$ ; and UV pumping is estimated, from the  $J = 4$  and  $5 \text{ H}_2$  populations, to be of the same order as in our Galaxy (see Srianand et al. 2000 and Srianand & Petitjean 1998 for the derivation of these numbers).

This shows that molecules are present even in gas with low metallicity and low depletion into dust grains. This is a consequence of moderately high local UV flux and low ( $T < 300 \text{ K}$ ) temperature.

### 3.2. Other systems

Two systems are at redshift close to the emission redshift of the quasar. They are real DLA systems (see Wolfe & Briggs 1981, Briggs et al. 1984 for Q 1157+014 and Leibundgut & Robertson 1999 for Q 2059–360). Note that when peculiar velocity is taken into account, the systems with  $z_{\text{abs}} \sim z_{\text{em}}$  can be located far away from the quasar. Moreover, out of the three systems where  $\text{H}_2$  is detected so far, one, toward Q 0528–250, has a redshift larger than the QSO emission redshift. It is included in our sample because the measurement has been obtained from high spectral resolution data (Srianand & Petitjean 1998).

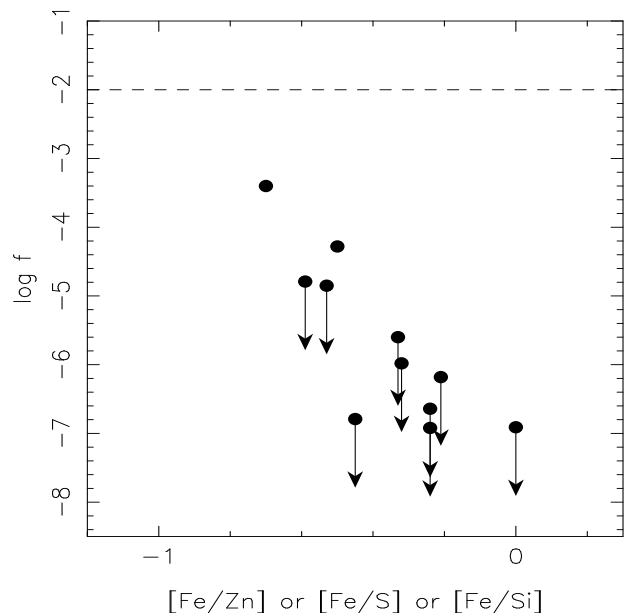
We have searched the spectra for lines from the  $J = 0$  and  $J = 1$  rotational levels. We detect absorption from the  $J = 1$  level in none of the systems. We thus consider as an upper limit on the total  $\text{H}_2$  column density the sum of the (tentative) detection or upper limit for the  $J = 0$  level and the upper limit on the  $J = 1$  level. Although, for typical physical conditions prevailing in such gas, the first two levels are the most populated, in principle, the higher  $J$  levels can be populated as well. This implies an uncertainty on the upper limits of about a factor of two. Recently, Levshakov et al. (2000) have claimed the presence of  $\text{H}_2$  molecules in the  $z_{\text{abs}} = 3.3901$  DLA system toward Q 0000–263 from the detection of a weak feature they identified as  $\text{H}_2 \text{ L}(4-0)\text{R}(1)$ . No other line is detected however and the probability that the feature be associated with another metal or Lyman- $\alpha$  line is high. We have therefore considered the measurement as an upper limit,  $N(\text{H}_2) < 10^{14.2} \text{ cm}^{-2}$  for  $T_{01} = 50 \text{ K}$ .

We detect weak but consistent features at the redshifted positions of  $\text{L}(4-0)\text{R}0$  and  $\text{L}(2-0)\text{R}0$  at  $z_{\text{abs}} = 2.374$  toward Q 0841+129. Other detectable lines are blended. We tentatively derive  $N(\text{H}_2)(J=0) = 3.66 \pm 0.9 \times 10^{14} \text{ cm}^{-2}$ .

Due to incomplete wavelength coverage, we do not observe the Lyman- $\alpha$  line at  $z_{\text{abs}} = 3.171$  toward Q 1451+123. Lyman- $\alpha$  damping wings are clearly seen in the intermediate resolution spectrum of Bechtold (1994). We use their equivalent width and derive  $\log N(\text{H I}) \sim 19.7$  which is consistent with other lines of the Lyman series present in our spectrum.

## 4. Results

Ge & Bechtold (1999) tentatively claimed a correlation between  $\text{H}_2$  abundance and relative heavy element deple-



**Fig. 2.**

Molecular fraction,  $f = 2N(\text{H}_2)/(2N(\text{H}_2)+N(\text{H I}))$ , versus depletion into dust grains as indicated by the relative abundance of iron compared to either zinc, sulfur or silicon (Table 1). DLA systems observed at high spectral resolution are indicated by filled circles.

tion into dust grains as indicated by  $[\text{Zn}/\text{Cr}]$  (zinc and chromium are assumed, respectively, undepleted and heavily depleted into dust grains as in our Galaxy). The claim was based on two detections done at low-resolution. One of the latter at  $z_{\text{abs}} = 2.337$  toward Q 1232+082 was overestimated by two orders of magnitude however (see Section 3.1). It can be seen on Fig. 2 that no correlation can be claimed. Conversely, it is apparent that the  $\text{H}_2$  fraction in DLA systems is fairly small. Note also that, even when  $\text{H}_2$  is detected, the depletion factor is small,  $> -0.7$ , while metallicity relative to solar ranges between  $-2.0$  and  $-0.9$ . To investigate this further, we have plotted on Fig. 3 the molecular fraction versus the  $\text{H I}$  column density. Over-plotted are measurements in the Magellanic clouds (Richter 2000) and measurements along lines of sight perpendicular to the disk of the Galaxy (Shull et al. 2000; none of the measurements shown on this figure are from a line of sight in the plane of our Galaxy). Part of the  $f$  measurements in DLA systems, and in particular the two detections, are consistent with what is seen in the Magellanic gas. But most of the DLA points are well below what is observed for the Magellanic clouds. It is interesting to note that these  $f$  values are consistent with what is seen in the nearby metal-poor dwarf galaxy I Zw 18 (Vidal-Madjar et al. 2000). However, it would be hazardous to conclude from this that DLA systems are associated with dwarf galaxies. More likely this shows that the physical conditions must be similar in the gas associated to DLA systems and to I Zw 18.

**Table 1.** The sample of damped Lyman- $\alpha$  systems

Quasar	$z_{\text{em}}$	$z_{\text{abs}}$	$\log N(\text{H I})^{\text{k}}$	$\log N(\text{H}_2)^{\text{k}}$		$\log f^{\text{j}}$	[Fe/H]	Metallicity <sup>1</sup>
				J = 0	J = 1			
0000–263	4.11	3.390	21.41±0.08 <sup>a</sup>	<14.2		<−6.91	−2.05±0.09 <sup>b</sup>	−2.05±0.09 <sup>b</sup>
0528–250	2.80	2.811	21.35±0.10	16.77±0.09 <sup>h</sup>		−4.28	−1.41±0.13 <sup>h</sup>	−0.91±0.12 <sup>a</sup>
0841+129	2.50	2.374	20.95±0.09 <sup>c</sup>	14.56±0.10::	<14.0	<−5.98	−1.74±0.09	−1.42±0.11
0841+129	2.50	2.476	20.78±0.10 <sup>c</sup>	<14.0	<14.0	<−6.18	−1.73±0.10	−1.52±0.10
1101–264	2.14	1.839	19.45±0.04	<14.0	<14.0	<−4.85	−1.47±0.05	−0.94±0.16
1157+014	1.99	1.944	21.80±0.10 <sup>e</sup>	<14.3	<14.5	<−6.79	−1.81±0.12	−1.36±0.13
1223+178	2.94	2.466	21.52±0.10	<14.0	<14.0	<−6.92	−1.98±0.12	−1.74±0.12
1232+082	2.57	2.338	20.90±0.10 <sup>g</sup>	16.78±0.10 <sup>g</sup>		−3.40	−1.90±0.13 <sup>g</sup>	−1.20±0.20 <sup>g</sup>
1451+123	3.25	2.469	20.39±0.10	<15.0:	<15.0:	<−4.79	−2.54±0.12	−1.95±0.16
1451+123	3.25	3.171	~19.7 <sup>i</sup>	<13.5	<13.5	<−5.60	−1.88±0.30	−1.55±0.30
2059–360	3.09	3.083	20.85±0.10 <sup>f</sup>	<13.5	<13.7	<−6.64	−1.84±0.12	−1.60±0.15

Measurements are from this work except when indicated.

<sup>a</sup> Lu et al. (1996); <sup>b</sup> Molaro et al. (2000); <sup>c</sup> Prochaska & Wolfe (1999); <sup>e</sup> Wolfe et al. (1981);

<sup>f</sup> Leibundgut & Robertson (1999); <sup>g</sup> Srianand et al. (2000); <sup>h</sup> Srianand & Petitjean (1998); <sup>i</sup> Bechtold (1994).

<sup>j</sup>  $f = 2N(\text{H}_2)/(2N(\text{H}_2)+N(\text{H I}))$ ; <sup>k</sup>  $\text{cm}^{-2}$ ; <sup>1</sup> [Zn/H] except: [S/H] for Q1101–264 Q2059–360 and Q0841+129  $z_{\text{abs}} = 2.476$ ; [Si/H] for Q1451+123 and Q1232+082

The lack of  $\text{H}_2$  molecules seems to be related *only partly* to the lack of dust in these systems as shown by Fig. 4 where we have calculated an artificial color excess for the DLA systems by scaling the value for the SMC with metallicity:  $E_{\text{B-V}}(\text{damp}) = E_{\text{B-V}}(\text{SMC}) \times Z(\text{damp})/0.1$  with  $N(\text{H I})/E_{\text{B-V}}(\text{SMC}) = 4.5 \times 10^{22}$  (Bouchet et al. 1985) and  $Z(\text{damp})$  the metallicity of the DLA (see Table 1). Most of the upper limits are measured along lines of sight with  $E_{\text{B-V}}(\text{damp}) < 0.01$ . However, the presence or absence of  $\text{H}_2$  is *not* strictly related to the presence or absence of dust. Indeed,  $\text{H}_2$  is present along one line of sight (toward PKS 1232+082) with  $\log E_{\text{B-V}}(\text{damp})$  as low as  $-2$  and, for  $\log E_{\text{B-V}}(\text{damp}) > -2$ , two out of the three systems have no detection.

## 5. Discussion

The idea that high-redshift DLA systems arise in large rotating proto-galactic disks (e.g. Wolfe 1995, Prochaska & Wolfe 1997) is a matter of debate. Indeed, simulations have shown that high-redshift progenitors of present-day disks of galaxy could look like an aggregate of well-separated dense clumps. The kinematics could be explained by relative motions of the clumps with little rotation (Haehnelt et al. 1998; Ledoux et al. 1998).

The presence of heavy elements ( $Z \sim 1/13 Z_{\odot}$ ; Pettini et al. 1997) suggests that the gas associated with DLA systems is located in over-dense regions close to sites where star formation is favored. However, at high redshift, emission counterparts of DLA systems are difficult to detect, implying low star-formation rates (e.g. Kulkarni et al. 2000). Moreover, the ambient UV flux derived from the analysis of the  $\text{H}_2$  lines in PKS 1232+082 is found to be similar to that in our Galaxy.

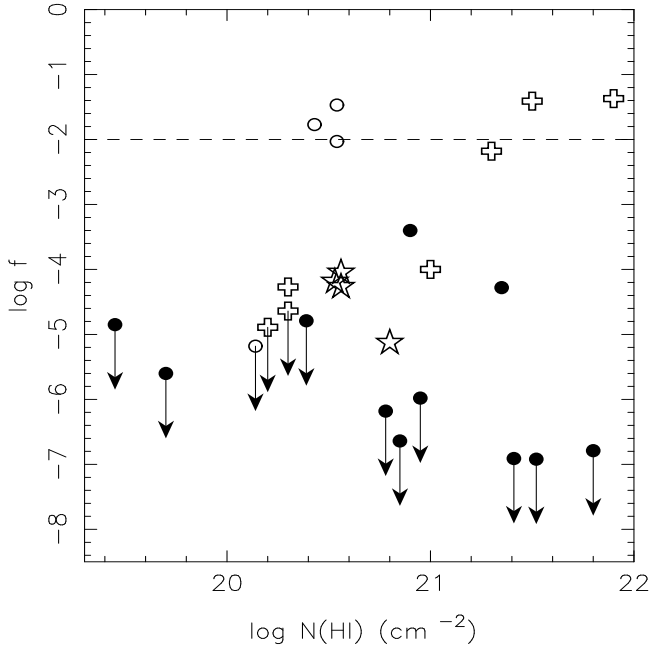
All this suggests that the lack of  $\text{H}_2$  detection in most DLA systems is not only a consequence of high ambient UV flux.

The physical conditions in the gas probably prevent the formation of  $\text{H}_2$ . However,  $\text{H}_2$  formation onto dust grains is efficient even in gas with low metallicity (and therefore low dust content) providing the dust temperature and the kinetic temperature are low enough ( $T_{\text{kin}} < 300$  K). Therefore, in order to prevent the formation of  $\text{H}_2$ , the gas temperature must be high. To illustrate this, we used CLOUDY (Ferland 1993) to compute the molecular fraction through a plane parallel slab with  $\log N(\text{H I}) = 21$ , metallicity 0.03 solar, dust-to-metal ratios 0.3, 0.1 and 0.03 that in our Galaxy, illuminated by a starburst-like spectrum. The results are plotted versus the ionization parameter ( $U = n_{\text{phot}}/n_{\text{H}}$ ) in Fig. 5. It can be seen that models with  $\log f < -6$  have  $\log U > -3.2$  and  $T > 3000$  K. We therefore conjecture that most of the DLA systems arise in diffuse and warm gas, typically  $T > 3000$  K, consistent with measurements of H I spin temperatures (Lane et al. 1999, Chengalur & Kanekar 2000). A picture where small (a few parsec), dense ( $n_{\text{H}} \sim 20 \text{ cm}^{-3}$ ) and cold ( $T \sim 100$  K) clumps are embedded in a pervasive, lower density ( $n < 1 \text{ cm}^{-3}$ ) and warm ( $T > 3000$  K) medium is probably adequate to describe the structure of DLA systems (see Petitjean et al. 1992, Petitjean et al. 2000).

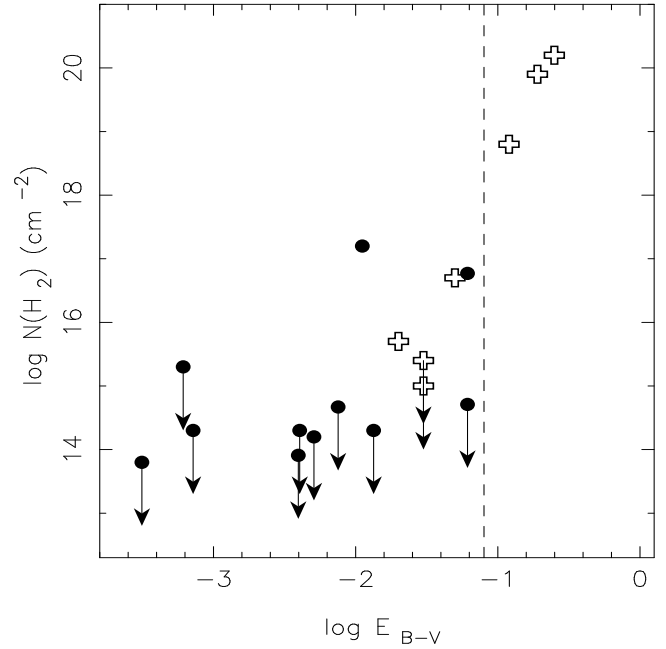
*Acknowledgements.* We gratefully acknowledge support from the Indo-French Centre for the Promotion of Advanced Research (Centre Franco-Indien pour la Promotion de la Recherche Avancée) under contract No. 1710-1. PPJ thanks IUCAA for hospitality during the time this work was completed.

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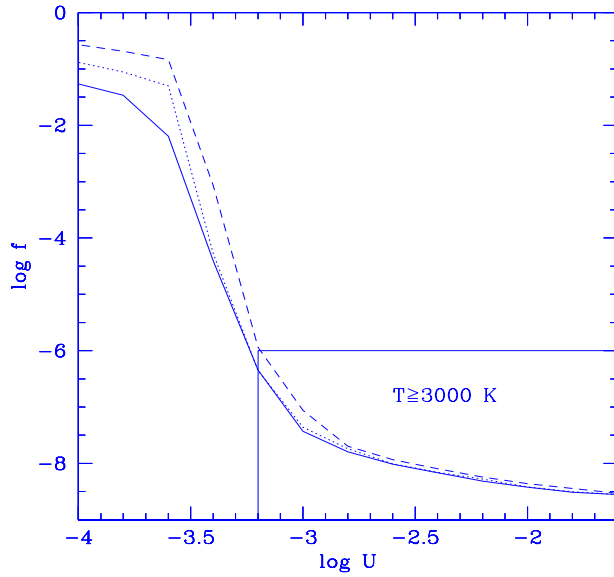
**Fig. 3.** Molecular fraction,  $f = 2N(\text{H}_2)/(2N(\text{H}_2)+N(\text{H I}))$ , versus H I column density. Damped Lyman- $\alpha$  systems observed at high spectral resolution are indicated by filled circles (verticle arrows are for upper limits). Measurements in the Magellanic clouds by Richter (2000) are indicated by open crosses. Open circles and open stars are for, respectively, lines of sight perpendicular to the disk of our Galaxy and lines of sight toward the Magellanic clouds (Shull et al. 2000). The horizontal dashed line marks the transition from low to high molecular fraction in the local Galactic gas ( $f = 0.01$ ; Savage et al. 1977).



**Fig. 4.**  $\text{H}_2$  column density versus color index. For DLA systems we define  $E_{B-V}(\text{damp}) = E_{B-V}(\text{SMC}) \times Z(\text{damp})/0.1$  with  $N(\text{H I})/E_{B-V}(\text{SMC}) = 4.5 \times 10^{22}$  (Bouchet et al. 1985) and  $Z(\text{damp})$  the metallicity of the DLA (see Table 1). DLA systems observed at high spectral resolution are indicated by filled circles (verticle arrows are for upper limits). Measurements in the Magellanic clouds by Richter (2000) are indicated by open crosses. The vertical dashed line marks the transition from low to high molecular fraction in the local Galactic gas ( $E_{B-V} = 0.08$ ; Savage et al. 1977).

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**Fig. 5.** Molecular fraction versus ionization parameter ( $U = n_{\text{phot}}/n_{\text{H}}$ ) through a plane parallel slab with  $\log N(\text{H I}) = 21$ , metallicity 0.03 solar, dust to metal ratios 0.3 (dashed), 0.1 (dotted) and 0.03 (solid) that in our Galaxy, illuminated by a starburst-like spectrum. The models with  $\log f < -6$  have  $\log U > -3.2$  and  $T > 3000$  K.

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