The elusive H$_i$→H$_2$ transition in high-\(z\) damped Lyman-\(\alpha\) systems

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ABSTRACT

We study the H$_2$ molecular content in high redshift damped Lyman-\(\alpha\) systems (DLAs) as a function of the H$_i$ column density. We find a significant increase of the H$_2$ molecular content around log\(N(\text{H}i)\) (cm$^{-2}$) $\sim$ 21.5 - 22, a regime unprobed until now in intervening DLAs, beyond which the majority of systems have log\(N(\text{H}i)\) $>$ 17. This is in contrast with lines of sight towards nearby stars, where such H$_2$ column densities are always detected as soon as log\(N(\text{H}i)\) $>$ 20.7. This can qualitatively be explained by the lower average metallicity and possibly higher surrounding UV radiation in DLAs. However, unlike in the Milky Way, the overall molecular fractions remain modest, showing that even at a large N(\(\text{H}i\)) only a small fraction of overall H$_i$ is actually associated with the self-shielded H$_2$ gas. Damped Lyman-\(\alpha\) systems with very high-N(\(\text{H}i\)) probably arise along quasar lines of sight passing closer to the centre of the host galaxy where the gas pressure is higher. We show that the colour changes induced on the background quasar by continuum (dust) and line absorption (H$_i$Lyman and H$_i$ Lyman and Werner bands) in DLAs with log\(N(\text{H}i)\) $>$ 22 and metallicity $\sim$1/10 solar is significant, but not responsible for the long-discussed lack of such systems in optically selected samples. Instead, these systems are likely to be found towards intrinsically fainter quasars that dominate the quasar luminosity function. Colour biasing should in turn be severe at higher metallicities.

Key words. Quasars: absorption lines – ISM: molecules

1. Introduction

The atomic to molecular hydrogen transition is a prerequisite process for star formation through the collapse of molecular clouds and therefore has important implications for the evolution of galaxies (e.g. Kennicutt & Evans 2012). The relative amount of dense molecular and diffuse atomic gas in nearby galaxies is found to be correlated with the hydrostatic pressure at the galactic mid-plane (Blitz & Rosolowsky 2006), which is driven by the gravity of gas and stars. This is a natural consequence of thermal equilibrium of the gas, leading to multiple phases under an external pressure (e.g. Wolfire et al 1995). The transition between H$_i$ and H$_2$ can then be linked to a critical gas surface mass density above which star formation is triggered, inducing a Schmidt-Kennicutt relation (e.g. Schaye 2001). The local abundance of H$_2$ in the interstellar medium (ISM) depends on the balance between its formation, primarily on the surface of dust grains (e.g. Lada 1974, but also in the gas phase through the H$^+$→H$^+$→e$^+$ reaction, Black et al. 1987), and its dissociation by UV photons. Because the dissociation occurs through Lyman and Werner band line transitions (e.g. Dalgarno & Stephens 1970), self-shielding becomes very efficient when H$_2$ absorption lines from several rotational levels become saturated (e.g. Draine & Bertoldi 1996). Dust grains also absorb Lyman and Werner band photons further contributing to decreasing the photo-dissociation rate. Theoretical microphysics models that include detailed treatment of the formation of H$_2$ onto dust grains and the dust- and self-shielding of H$_2$ show that the conversion from atomic to molecular occurs above a N(\text{H}i)-threshold that increases with decreasing metallicity (e.g. Krumholz et al. 2009; McKee & Krumholz 2010; Gnedin & Kravtsov 2011; Sternberg et al. 2014).

A sharp increase in the H$_2$ column densities has been first noticed above log\(N(\text{H}i)\) $>$ 20.7 in the local Galactic ISM by Savage et al. (1977). In turn, the first studies of the Magellanic clouds by Tumlinson et al. (2002) did not reveal any dependence of the H$_2$ content on the H$_i$ column density. This was explained by a high average UV radiation due to intense local star formation activity together with lower metallicities. At high redshift, H$_2$ is generally detected in about 10% of damped Lyman-\(\alpha\) systems (DLAs) or less (Petitjean et al. 2001; Ledoux et al. 2003; Noterdaeme et al. 2008). Physical conditions in these sub-solar metallicity systems indicate densities of the order of $n \sim 50$ cm$^{-3}$ in the cold neutral medium, and ambient radiation field a few times the Draine field (e.g. Srianand et al. 2005; Neeleman et al. 2008). In turn, the first studies of the Magellanic clouds by Tumlinson et al. (2002) did not reveal any dependence of the H$_2$ content on the H$_i$ column density. This was explained by a high average UV radiation due to intense local star formation activity together with lower metallicities. At high redshift, H$_2$ is generally detected in about 10% of damped Lyman-\(\alpha\) systems (DLAs) or less (Petitjean et al. 2001; Ledoux et al. 2003; Noterdaeme et al. 2008). In turn, the first studies of the Magellanic clouds by Tumlinson et al. (2002) did not reveal any dependence of the H$_2$ content on the H$_i$ column density. This was explained by a high average UV radiation due to intense local star formation activity together with lower metallicities. At high redshift, H$_2$ is generally detected in about 10% of damped Lyman-\(\alpha\) systems (DLAs) or less (Petitjean et al. 2001; Ledoux et al. 2003; Noterdaeme et al. 2008). We have recently searched for H$_2$ in four extremely strong DLAs (ESDLAs, defined as log\(N(\text{H}i)\) $> 21.7$) (Noterdaeme et al. 2012) and high-resolution spectroscopic follow-up.

2. The atomic to molecular hydrogen transition

We have recently searched for H$_2$ in four extremely strong DLAs (ESDLAs, defined as log\(N(\text{H}i)\) $> 21.7$) (Noterdaeme et al. 2012) and high-resolution spectroscopic follow-up. This brings the number of ESDLAs with H$_2$ searches (all with VLT/UVES) to seven. Details of H$_i$ and H$_2$ measurements in these ESDLAs are summarised in Table 1. Combining this with other measurements we
Right: Frequency of H$_2$ detection as a function of the H$_1$ column density. For each N(H$_1$) bin, systems with log N(H$_2$) ≥ 17 are coded in colour, and systems with log N(H$_2$) < 17 are shown in white. Systems with upper limits that are not stringent (i.e. above log N(H$_2$) = 17) are not taken into account. The numbers in each box indicate the total number of systems contributing to the bin. Crossed boxes have no statistics.

### Table 1. H$_2$ in ESDLAs with log N(H$_1$)≥17.1

| Quasar | z$_{abs}$ | log N(H$_1$) | log N(H$_2$) | Ref. |
|--------|----------|-------------|-------------|------|
| HE0027−1836 | 2.402 | 21.75±0.10 | 17.43±0.02 | 1 |
| QJ0154+1935 | 2.251 | 21.75±0.15 | 17.10±0.02 | 2 |
| Q0458−0203 | 2.040 | 21.70±0.10 | 14.60 | 3 |
| QJ0816+1446 | 3.287 | 22.00±0.10 | 18.66±0.30 | 4 |
| Q1157+0128 | 1.944 | 21.80±0.10 | 14.50 | 1 |
| Q11456+1609 | 3.352 | 21.70±0.10 | 17.10±0.09 | 2 |
| Q12140−0321 | 2.346 | 22.40±0.10 | 20.13±0.07 | 2 |

**References.** (1) Rahmani et al. (2013); (2) Noterdaeme et al. (2015); (3) Noterdaeme et al. (2008); (4) Guimarães et al. (2012).

Explore the H$_2$ content as a function of N(H$_1$) in DLAs while refraining from drawing any conclusion on the overall H$_2$ detection rate. We can do so since the DLAs used for this study were selected only on the basis of their neutral hydrogen content. For this reason, we do not include recent H$_2$ detections obtained by directly targeting systems based on the presence of cold gas.$^1$

In the left panel of Fig. 1 we compare the total H$_2$ column density versus that of H$_1$ in our extended high-z DLA sample (Noterdaeme et al. 2008) and the new ESDLAs with values in the local Galactic ISM (Savage et al. 1977), in the SMC (Welty et al. 2012), and in DLAs associated with γ-ray burst afterglows (GRB-DLAs). In the overall population, we clearly see a bimodality in the distribution of N(H$_2$): most detections have log N(H$_2$) > 17, far above the typical detection limits (a few times 10$^{14}$ cm$^{-2}$). In the following, we denote as “strong” (resp. “weak”) the systems with log N(H$_2$) > 17 (resp. < 17). The right panel shows the distribution of systems in each of these populations as a function of the H$_1$ column density.$^2$

We find that H$_2$ is detected with column densities higher than 10$^{17}$ cm$^{-2}$ in four (five if we include the possible H$_2$ detection in the DLA towards J0154+1935) ESDLAs out of seven. This is significantly higher than the value seen in the ‘the overall DLA population (∼ 10%’. Noterdaeme et al. 2008; Balashev et al. 2014 or possibly less, Jorgenson et al. 2014). The increase in the fraction of strong H$_2$ systems is significant but not as sharp as is seen in the Milky Way or in the Small Magellanic Cloud. In addition, the overall molecular fractions remain modest (∼ 1% or less).

To explain this, it must be noted that the multi-phase nature of the neutral gas is not equivalently probed by the different samples. The values corresponding to the Milky Way come from lines of sight towards nearby stars that are located only within ~100 pc. These should therefore probe a single cloud that produces most of the total observed column density (in which the N(H$_1$) and N(H$_2$) can be directly related by microphysics. The situation is already different towards stars in the Magellanic clouds for which the observed column densities may include gas from different clouds or phases along the same line of sight. Welty et al. 2012 also argued that previous N(H$_1$) determinations in the SMC were overestimated because they were derived from 21 cm emission, which averages structures in the ISM at scales smaller than the radio beams. Indeed, once the N(H$_1$)-values are more accurately determined using Ly-α-absorption (i.e. along the same pencil-beam line of sight as Srianand et al. 2008; Noterdaeme et al. 2010), the presence of 21 cm absorption Srianand et al. 2012, or direct evidence of H$_2$ lines Balashev et al. 2014).

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1. Either because of the detection of C$_1$ absorption Srianand et al. 2008; Noterdaeme et al. 2010, the presence of 21 cm absorption Srianand et al. 2012, or direct evidence of H$_2$ lines Balashev et al. 2014.

2. For simplicity only the total H$_1$ column density is used for a given DLA. In spite of this, the total N(H$_2$) is dominated in all cases by a few components that individually also have log N(H$_2$) > 17.
used for H2 measurements) higher molecular fractions are found in the SMC, revealing a clearer segregation between the strong and weak H2 populations around log N(H2) ∼ 21. In DLAs, the H1 and H2 column densities are measured through UV absorption along the same line of sight. However, a single quasar sight line likely samples multiple gas components having different physical conditions, as seen from the excitation of different species (e.g. Srianand et al. 2003, Liszt 2015, Noterdaeme et al. 2015). In addition, at a given redshift, different DLAs probe different galaxies with their own sets of physical conditions, which may contribute to smoothing the observation of any underlying transition. Recently, Balashev et al. (2015) have used chlorine to show that the local metallicity and molecular fraction in the H2 components could be much higher than the line-of-sight averaged value, although this does not tell us whether the remaining H1 is located in outer layers or in unrelated interloping clouds.

Our results show that a large amount of H1 in ESDLAs could indeed be unrelated to H2. This is also supported by the similar H2 column densities seen in several much lower N(H1) systems. The large N(H1) probably results from a low impact parameter of the line of sight relative to the galactic centre (Noterdaeme et al. 2014) where the covering factor of H1-bearing gas would be higher owing to higher ISM pressure (Blitz & Rosolowsky 2006).

The situation could be similar along the lines of sight towards afterglows of long-duration γ-ray bursts (GRBs) where DLAs are often seen with log N(H1) > 22 (e.g. Jakobsson et al. 2006). As these GRBs are linked to the death of a massive star (Bloom et al. 1999), they are probably related to star forming regions that are typically denser and closer to the centre of the host galaxy than quasar-DLAs (Pontzen et al. 2010). Because GRB-DLAs may be subject to a very intense UV radiation field (Tumlinson et al. 2007) one has to exercise caution when comparing them with quasar-DLAs. Nevertheless, although the sample is still small it appears that the detection rate is consistent with that seen in quasar-DLAs albeit with larger molecular fractions. This further supports the idea that most high column density lines of sight likely probe the central regions of a galaxy.

ESDLAs are very rare and huge surveys are needed to find them (Noterdaeme et al. 2009, 2012). However, one could question the fact that the H1 to H2 transition may induce a bias in the selection of the quasars against the detection of the corresponding systems.

3. The effect of ESDLAs on the colours of the background quasar.

In Fig. we identify the H2-bearing DLAs in the (N(H1)) metallicity plane. Interestingly three quasar-DLAs and four GRB-DLAs are now known beyond the limit for significant dust obscuration by Boissé et al. (1998) and long discussed in the literature (e.g. Neeliman et al. 2013). Six of these DLAs show self-shielded H2. As observed by Petitjean et al. (2006) and as predicted by some models (e.g. Krumholz et al. 2009, Sternberg et al. 2014), the H2 detection rate is higher at high metallicity. However, the metallicity at which H2 is found increases with decreasing N(H1). The presence of H2 could be more closely related to the column density of dust grains (Noterdaeme et al. 2008), using the column density of undepleted elements as a first-order proxy for that of dust (Vladilo & Péroux 2005), we can see that 10 of the 15 systems above a line of constant log N(Zn ii) = 12.5 have log N(H2) ≥ 17, while this fraction is only 4/6 below.

Continuum absorption by dust and the absorption from lines in the Lyman series of H1 and Lyman and Werner bands of H2 can significantly affect the quasar transmitted flux in the different bands when column densities become very large. We quantify these effects by calculating the transmission for different H1 and H2 column densities and different reddening. For each absorption situation, the induced colour changes depend on the absorption redshift, the filter responses, and the input spectrum (quasar continuum plus Ly α forest). For simplicity, we fixed zabs = 2.35 (i.e. the redshift of our strongest ESDLA towards J2140–0321), used the filter responses of the Sloan Digital Sky Survey (SDSS, York et al. 2000), and considered a flat quasar spectrum. Our results are shown in Fig. We empirically checked that assuming a flat spectrum has little effect on the results. To this end, we introduced fake absorbers with known properties (N(H1), N(H2), and dust) in real non-BAL quasar spectra (with emission redshift close to that of J2140–0321) and derived the colour changes. We find very good agreement (∼ 0.01 mag for i, z and 0.05 mag in g) with our simple model.

In the case of J2140–0321, we find that the damped Ly α line alone severely affects the g-band (by 0.18 mag). Similarly, the strong H2 absorption lines raise the u-band magnitude by ∼ 0.26 mag. The importance of these line absorption is similar to that of the continuum absorption owing to the presence of dust (for E(B−V) ∼ 0.05, estimated through SED profile fitting, see Noterdaeme et al. 2014) in these two bands. While the overall colour excesses estimated for J2140–0321 are likely not large enough to push the quasar out of typical colour-settings, it is still significant. We note that a DLA with the same characteristics as those of the DLA associated with GRB 080607 would in
samples of absorbers selected for their high molecular content. Also consistent with the skewed so is the probability of intercepting a molecular cloud. This is the threshold for additive and so are the colour vectors. The red arrow shows the estimated colour excess of J2140−0321 (circled red) due to the intervening ESDLAs. For comparison, the colour excess that would produce a DLA with same column densities and reddening as those associated with GRB080807 would reach the full ranges covered by both axes.

4. Conclusions

We have extended the study of H\textsubscript{2} in DLAs to the very high H\textsubscript{1} column density end, allowing us to uncover a significant increase in the fraction of strong H\textsubscript{2} systems (that we define as having log(N(H\textsubscript{2}) > 17) at log(N(H\textsubscript{1}) > 21.5. While the high N(H\textsubscript{1})-threshold is qualitatively consistent with expectations from theoretical models describing H\textsubscript{2} microphysics, the mean molecular fraction in these systems remains relatively low. This can be explained by the quasar lines of sight having long path lengths through galaxies. In this picture, most of the H\textsubscript{1} is due to clouds unrelated to the molecular phase probed by H\textsubscript{2}. The threshold for local H\textsubscript{1} to H\textsubscript{2} conversion in high-z DLAs could actually occur at N(H\textsubscript{1}) and metallicities similar to those in the Milky Way disc. The large H\textsubscript{2} column densities observed in EDLAs (with log(N(H\textsubscript{2}) > 21.7) could simply be due to the line of sight passing closer to the galaxy centre as shown by Noterdaeme et al. (2014), where the ISM pressure is higher and so is the probability of intercepting a molecular cloud. This is also consistent with the skewed N(H\textsubscript{1})-distributions observed in samples of absorbers selected for their high molecular content.

The N(H\textsubscript{2})-distribution of ~20 strong H\textsubscript{2} absorbers directly selected from the SDSS (Balashev et al. 2014) is indeed biased towards high N(H\textsubscript{1}) systems. Similarly, Ledoux et al. (2015) observe an excess of strong N(H\textsubscript{1})-systems among C\textsubscript{i}-selected absorbers, which appear to harbour high molecular content. We note that high molecular content is also found in some low N(H\textsubscript{1}) absorbers (e.g. Srianand et al. 2008, Noterdaeme et al. 2010), which shows that the conversion from atomic to molecular hydrogen due to microphysics (which occurs on pc-scales, e.g. Srianand et al. 2013) does not require very high N(H\textsubscript{1}) (see also Muzahid et al. 2015).

We have investigated the impact on the quasar colours by the presence of systems beyond the neutral to molecular transition and showed that selection of quasars with NIR photometry would be important in order to avoid biasing against the detection of systems with high molecular content.

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