A high molecular fraction in a subdamped absorber at $z = 0.56$


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ABSTRACT
Measuring rest-frame ultraviolet rotational transitions from the Lyman and Werner bands in absorption against a bright background continuum is one of the few ways to directly measure molecular hydrogen ($H_2$). Here, we report the detection of absorption from $H_2$ at $z = 0.56$ in a subdamped Lyα system with neutral hydrogen column density $N_{HI} = 10^{19.5\pm0.2}$ cm$^{-2}$. This is the first $H_2$ system analysed at a redshift of <1.5 beyond the Milky Way halo. It has a surprisingly high molecular fraction: $\log_{10} f_{H2} > -1.93 \pm 0.36$ based on modelling the line profiles, with a robust model-independent lower limit of $f_{H2} > 10^{-3}$. This is higher than $f_{H2}$ values seen along sightlines with similar $N_{HI}$ through the Milky Way disc and the Magellanic Clouds. The metallicity of the absorber is $0.19_{-0.10}^{+0.21}$ solar, with a dust-to-gas ratio of <0.36 of the velocity in the solar neighbourhood. Absorption from associated low-ionization metal transitions such as O I and Fe II is observed in addition to O VI. Using CLOUDY models, we show that there are three phases present; a $\sim 100$ K phase giving rise to $H_2$, a $\sim 10^4$ K phase where most of the low-ionization metal absorption is produced; and a hotter phase associated with O VI. Based on similarities to high-velocity clouds in the Milky Way halo showing $H_2$, and the presence of two nearby galaxy candidates with impact parameters of $\sim 10$ kpc, we suggest that the absorber may be produced by a tidally stripped structure similar to the Magellanic Stream.

Key words: ISM: molecules – galaxies: haloes – quasars: absorption lines.

1 INTRODUCTION
Molecular hydrogen ($H_2$) is the most abundant molecule in the Universe and is closely linked to star formation via the star formation surface density rate–molecular gas surface density relation (Bigiel et al. 2008). Measuring rest-frame ultraviolet (UV) rotational transitions from the Lyman and Werner bands in absorption against a bright background continuum is one of the few ways to directly measure $H_2$ (see e.g. Draine 2011). This technique probes diffuse gas with molecular fractions, $f_{H2}$, of $\sim 10^{-6}$ to $\sim 0.1$ – denser molecular clouds are both dusty, and thus likely to extinguish UV light from a background source, and compact, such that there is a low probability of intersection with a sightline to a background light source (Hirashita et al. 2003; Zwaan & Prochaska 2006). However, the lower molecular fraction systems that are detected give valuable insights into the environments and physical mechanisms necessary for the formation of $H_2$. With this technique, we can measure the physical properties of cool, dense gas over a large fraction of the age of the Universe, from the interstellar medium (ISM) in the solar neighbourhood to protogalaxies a few Gyr after the big bang. Since the initial detection towards the UV bright star $\xi$ Persei (Carruthers 1970), a large sample of sightlines exhibiting $H_2$ in absorption from the Milky Way (MW) and its halo has been assembled. These observations have characterized $H_2$ in diffuse molecular gas in the MW plane (Savage et al. 1977), the Magellanic

* All of the data and much of code used in this paper are available at https://github.com/nhmc/H2.
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Clouds (Tumlinson et al. 2002; Welty, Xue & Wong 2012), high latitude sightlines out of the MW plane (Gillmon et al. 2006; Wakker 2006), in intermediate- and high-velocity clouds (IVCs and HVCs; Richter et al. 1999; Richter, Sembach & Howk 2003), and in the Magellanic Clouds (Richter et al. 2001; Sembach et al. 2001). A physical picture where H$_2$ formation occurs predominantly on the surface of dust grains (Shull & Beckwith 1982) in clouds with total densities of $n \sim 10$–$100$ cm$^{-3}$ illuminated by the local UV radiation has been successful in reproducing both the observed H$_2$ rotational population levels and molecular fractions in the MW (e.g., Spitzer, Cochran & Hirshfield 1974; Jura 1975a,b) and the Magellanic Clouds (Tumlinson et al. 2002).

H$_2$ has also been measured at redshifts 1.5–4.5, corresponding to lookback times of $\sim$9–12 Gyr, in damped Ly{$\alpha$} ($N_{\text{HI}} > 10^{20.5}$ cm$^{-2}$, DLA) and subdamped Ly{$\alpha$} ($10^{17} \lesssim N_{\text{HI}} \lesssim 10^{20.3}$ cm$^{-2}$, sub-DLA) absorption systems seen towards bright background QSOs. In this redshift range, absorption features from HI and sometimes H$_2$ are redshifted into the optical range, making them relatively easy to detect with large ground-based telescopes. The first unambiguous detection in a redshifted absorber was made by Foltz, Chaffee & Black (1988, see also Levshakov & Varshalovich 1985), and since then at least 16 further such systems have been discovered (e.g., Ge & Bechtold 1997; Ge, Bechtold & Kulkarni 2001; Levshakov et al. 2002; Cui et al. 2005; Ledoux, Petitjean & Srianand 2006; Noterdaeme et al. 2007). Approximately 10 per cent of DLAs have a molecular fraction $f_{H_2} > 10^{-4.5}$, and these tend to be more metal rich and dustier (Ledoux, Petitjean & Srianand 2003), and have higher velocity widths (Noterdaeme et al. 2008) than DLAs without detectable H$_2$. Several physical diagnostics are available to measure the properties of the H$_2$ absorbing gas. Some H$_2$ systems also show absorption from the CO molecule, revealing the presence of a cold, dense core of gas with excitation temperatures consistent with those expected from the cosmic microwave background (e.g., Srianand et al. 2008; Noterdaeme et al. 2009). The H$_2$ rotational level populations and CI fine structure transitions can also be used to measure particle densities. They are generally found to be similar to those measured along local sightlines in the MW ($\sim$10–100 cm$^{-3}$), but the ambient UV field, gas temperatures and gas pressures tend to be higher (Hirashita & Ferrara 2005; Srianand et al. 2005).

No studies currently exist of H$_2$ at lower redshifts, $z < 1.5$, outside the MW halo. Until recently, the low number of DLAs and sub-DLA systems known at low redshifts, together with the smaller light gathering power of spaced-based UV telescopes compared to large aperture ground-based optical telescopes, have made observing the Lyman–Werner bands in this redshift range impractical. However, with the availability of the far-ultraviolet (FUV) sensitive Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (HST), molecular absorption can now be effectively detected for $0.1 \lesssim z \lesssim 0.8$.

In this paper, we report the serendipitous detection of H$_2$ in a sub-DLA at $z = 0.56$, the first such system analysed at a redshift below 1.5 beyond the MW halo. It has a high molecular fraction given the total cloud neutral hydrogen column density, and we show that the associated metal absorption features seen require the presence of three phases: a cold $T \sim 100$ K phase analogous to the cold neutral medium observed in the MW’s ISM; a partially ionized $T \sim 10^6$ K phase, similar to the warm neutral medium in the ISM; and a warmer, probably collisionally ionized phase. Based on the cloud properties, we argue that the absorber is likely caused by a tidally stripped absorbing structure similar to the Magellanic Stream embedded in a warm halo $\sim 10$ kpc from a nearby galaxy.

### Table 1. Properties of the background QSO towards which the sub-DLA is seen. Columns show the coordinates, emission redshift (measured from Mg~$\lambda$ 2296, 2803 emission in the HIRES spectrum) and $R$-band magnitude.

<table>
<thead>
<tr>
<th>Name</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>$z_{\text{em}}$</th>
<th>$R$ mag</th>
</tr>
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<tr>
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<td>01$^h$10$^m$14.43</td>
<td>$-02^\circ16^\prime57^\prime6$</td>
<td>0.728</td>
<td>18.4</td>
</tr>
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</table>

The layout of the paper is as follows. Section 2 describes the data used; Section 3 describes how we identified lines and measured the absorption line properties; and Section 4 describes the properties of the H$_2$ absorption and the sub-DLA. We compare to theoretical models and discuss our results in Section 5, and summarize the main results of the paper in Section 6. When not explicitly shown logarithms are to base 10, and we use a 7-year Wilkinson Microwave Anisotropy Probe cosmology ($H_0 = 70.4$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.272$, $\Omega_L = 0.728$; Komatsu et al. 2011) where necessary. We use transition wavelengths and oscillator strengths given by Morton & Dinerstein (1976), Morton (2003) and Verner, Barthe & Tyler (1994), and H$_2$ transition wavelengths from Bailly et al. (2010).

### 2 DATA

Transitions from the sub-DLA are measured in absorption against the continuum from the background QSO, Q 0107–0232, at $z_{\text{em}} = 0.728$ (see Table 1). This was discovered by the Large Bright Quasar survey (Hewett, Foltz & Chaffee 1995) and is one of a group of three bright QSOs with small angular separations on the sky. Spectra of these QSOs taken using the Faint Object Spectrograph (FOS) on the HST have been used to measure correlations in neutral hydrogen absorption (Young, Impey & Foltz 2001; Petry et al. 2006) and in absorption with galaxy positions (Crighton et al. 2010) across the three sightlines.

Here, we present higher resolution FUV spectra of Q 0107–0232 taken with the COS on the HST, and an optical spectrum taken with the High Resolution echelle Spectrograph (HIRES) on Keck I. In our analysis, we also make use of $K$-band imaging of the QSO and archival UV FOS spectra. The FOS spectra were originally published by Young et al. (2001). We employ the combined spectrum used by Crighton et al. (2010), covering a wavelength range of 1572–2311 Å at a typical signal-to-noise ratio (S/N) of 31 per 4 Å resolution full width at half-maximum (FWHM) intensity.

### 2.1 COS spectra reduction

The COS spectra were obtained over a period from 2010 November 6 to December 7, as part of the Cycle 17 proposal 11585. They represent a total exposure time of 23 h across 30 orbits. Two central wavelength settings were taken with the G160M grating, each using four FP-POS positions to enable complete wavelength coverage from 1380 to 1850 Å. Details of the exposures are given in Table 2.

We used the CALCOS pipeline to perform background subtraction, wavelength calibration and extraction. The default background extraction smoothing scale of 100 pixels resulted in poor background subtraction for our spectra, presumably because the pipeline was optimized for brighter targets. We found that changing BWIDTH in the XTRACTAB calibration table from the default value of 100
Wavelength shifts are expected between visits and different wavelength settings due to temperature differences and uncertainty in the telescope pointing. The S/N in individual exposures is generally too low (∼2 per pixel) to reliably measure the centres of absorption features. Therefore, we combined subsets of exposures grouping by FP-POS position, by visit (corresponding to a single data set name in Table 2), by grating central wavelength and by FUV segment to search for any shifts. Wavelength solutions were consistent across different visits and FP-POS values, but there are significant wavelength-dependent shifts between different central wavelength settings. To correct these, we measured the centroid for common narrow absorption features where two wavelength settings overlapped, and used these centres to calculate a wavelength offset as a function of position. We fitted these offsets with a linear dependence on wavelength, and then corrected for them such that FUV segment A matched the FUV segment A, FUV segment B matched the FUV segment B, and the largest shifts applied in this way were 0.1 Å, corresponding to 20 km s$^{-1}$, but they could result in an ∼40 km s$^{-1}$ internal shift between the shortest and longest wavelengths of an exposure. These shifts are given in Table A1.

The scores of H$\alpha$ absorption features distributed across the full spectral range enable a further check of the internal consistency of the wavelength solution. By measuring the centroid of these features and comparing to a single-component model of H$\alpha$ absorption, we discovered an additional wavelength-dependent shift (shown in Table A2). The magnitude of this shift is smaller (∼5 km s$^{-1}$) than that applied above, but still significant when fitting an absorption system with transitions spread across a large wavelength range. We removed this shift by subtracting a cubic spline fitted to the offsets as a function of wavelength position from the wavelength scale.

To match the zero-points of the COS and HIRES wavelength scales, we compared the N$\text{ii}$1084 and C$\text{i}$945 features from the same system measured in the HIRES spectrum. The wavelength zero-point of the HIRES spectrum is known to better than 1 km s$^{-1}$, ensuring Nyquist sampling. The resulting combined spectrum has an S/N of 10 per ∼20 km s$^{-1}$ resolution element at the continuum and covers a wavelength range from 1380 to 1850 Å.

### 2.2 HIRES spectra reduction

The HIRES observations were performed on the night of 2011 August 4. Four 1800 s exposures were taken using the red cross-disperser and a 0.861 arcsec width slit. Two wavelength settings were used to cover gaps in the detector. We used MAKEE to process each exposure, which subtracts the bias level and the sky background, corrects for the echelle blaze, generates a wavelength solution by identifying arc lines to yield a mapping from pixel number to wavelength for each echelle order, and extracts one-dimensional spectra for each echelle order. We then used custom-written PYTHON code to co-add the individual orders for each exposure into a combined spectrum, and to infer the unabsorbed continuum level by fitting spline segments to regions free from absorption. The final combined spectrum has an S/N at 5000 Å of 33 per 6.67 km s$^{-1}$ FWHM, and covers a wavelength range of 3890 to 8330 Å.

### 2.3 Imaging

We acquired K-band imaging of a 7 arcmin × 7 arcmin field around Q 0107−0232 using the High Acuity Wide field K-band Imager (HAWK-I) on the Very Large Telescope during programme 383.A-0402. Five 180 s exposures were taken at four offset positions on 2009 September 15. We used the HAWK-I pipeline recipes to process each exposure to remove the bias level and correct for sensitivity variations using a flat-field. An astrometric solution was measured for each exposure using SCAMP (Bertin 2006), then re-sampled to a common world coordinate system and co-added all the exposures with SWARP (Bertin et al. 2002). We determined the conversion between the measured counts and the magnitude by comparison to Two Micron All Sky Survey magnitudes for objects in the field. The limiting magnitude reached is ∼23.5 mag (AB) for a 3σ detection of a point source.
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3 ANALYSIS

3.1 Line identification

Most of the transitions associated with the sub-DLA fall inside the Ly$\alpha$ forest of the background QSO, and many are blended with absorption at different redshifts. We identified each absorption feature in the COS and FOS spectra in the following way. We first searched for Galactic absorption at the wavelengths of transitions typically seen in the Galactic ISM (Si ii $\lambda 1526$, C iv $\lambda \lambda 1548, 1550$, Fe ii $\lambda 1608$, C i $\lambda 1657$, and Mg i $\lambda 2026$; Zn ii $\lambda 2026$ were present$^2$). Then we identified systems by the presence of either C iv ($\lambda \lambda 1548, 1550$), O vi ($\lambda \lambda 1032, 1038$) or H i Ly$\alpha$ and Ly$\beta$, starting at the emission redshift to the QSO and moving down in redshift to $z = 0$. Once these systems were identified, we searched for any further associated metal transitions such as Si iv, Si iii, Si ii, C iii and C ii. We found that it was necessary to iterate this process several times, each time including line IDs from previous runs. The $z = 0.56$ sub-DLA was previously identified by Crighton et al. (2010) by its many associated strong metal transitions in the FOS spectrum. Once we had made plausible identifications for lines at redshifts other than the $z = 0.56$ sub-DLA, we identified metals and molecular absorption lines from the Lyman and Werner bands for this system. Finally, we assumed that any remaining unidentified absorption features were Ly$\alpha$. For this paper, we focus on absorption features associated with the $z = 0.56$ system. Absorbers at different redshifts are used only to identify blends with transitions from the sub-DLA.

3.2 Kinematics and velocity structure of the sub-DLA

H$_2$ is expected to be found in gas with temperatures less than $\sim 5000$ K – at higher temperatures molecules are destroyed through collisional excitation (Shull & Beckwith 1982). Therefore, we expect the H$_2$ absorption features to be narrow, $< 10$ km s$^{-1}$, and the COS spectra will not resolve the H$_2$-bearing components. H$_2$ components do not necessarily coincide with the strongest H i or metal line positions (e.g. Petitjean, Srianand & Ledoux 2002; Noterdaeme et al. 2010). However, we use transitions covered by the higher resolution HIRES spectrum to inform us about the velocity structure of the absorbing gas, and apply this to H$_2$ and other transitions only present in the UV spectra.

Fig. 1 shows the transitions at $z = 0.56$ detected in the HIRES spectrum: Mg ii ($\lambda \lambda 2796, 2803$), Mg i ($\lambda 2853$), Ca ii ($\lambda \lambda 3934, 3969$) and Fe ii ($\lambda \lambda 2586, 2600$). We also measure upper limits on Al i, Fe i, Ca i, Na i, Ti ii and Mn ii. We fitted velocity components and column densities to these transitions using VPFIT. The best-fitting values are given in Table 3. A single common velocity structure spanning $\sim 200$ km s$^{-1}$ provides a good fit to all of these transitions, assuming that line broadening is dominated by Gaussian turbulent motions rather than the gas temperature. The best-fitting model is shown in Fig. 1. Ca ii and Mg i have the lowest ionization energies (11.87 and 7.65 eV, respectively), and so a priori we might expect them to be associated with the cold environment where H$_2$ is found. However, the photoionization analysis in Section 4.5 indicates that most of the Mg ii and much of the Ca ii probably arises in diffuse, photoionized gas distinct from H$_2$.

Component 6 has a Doppler width $b$ ($= \sqrt{2} \sigma$) of 20 km s$^{-1}$, larger than is usually observed in low-ionization metal transitions. This, together with the suggestion of correlated residuals in Mg ii near the position of this component suggests that it is in fact a molecular transition.

$^2$ There is also absorption at the expected position of Zn i $\lambda 2139$, redwards of the QSO Ly$\alpha$ emission. However, since this line is only observed in sightlines with $N_{HI} \gtrsim 10^{21}$ cm$^{-2}$ in the MW ISM (Welty, private communication), we identify it as N v $\lambda 1238$ near the QSO redshift.

http://www.ast.cam.ac.uk/~rfc/vpfit.html
Table 3. Best-fitting Voigt profile parameters for each component in transitions for the $z = 0.56$ system that are covered by the HIRES spectrum.

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<th>$b$ (km s$^{-1}$)</th>
<th>$\sigma_b$ (km s$^{-1}$)</th>
<th>$z$</th>
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</table>

3.3 UV transitions for the sub-DLA

We apply the Mg II velocity structure to models fitted to transitions observed in the lower resolution COS and FOS spectra. Using this velocity structure we were able to match the N II, Si II and O I profiles by varying the component line widths and column densities. Several of the COS transitions that have measurable absorption and are not saturated or heavily blended with unrelated systems are shown in Fig. 2. When fitting the COS spectra we use the tabulated line spread function provided by Space Telescope Science Institute, linearly interpolated to the wavelength at the centre of each fitting region. We also measured column densities using the apparent optical depth (AOD) method (which assumes the transition is optically thin; Savage & Sembach 1991), including a 5 per cent uncertainty in the continuum level. As the individual components are not resolved by the COS spectra, we quote these AOD measurements and give the total column densities for all components in aggregate. For transitions C I, N II, O I and O VI we were able to directly compare column densities measured using both Voigt profile fitting and the AOD method. In each case, they are consistent with one another. C II, C III and Si III are saturated, and lower limits are measured using the AOD method. The FOS spectrum provides an upper limit on $N_{\text{Si IV}}$.

Table 4 gives measurements and uncertainties, lower and upper limits for all of the transitions in the UV spectra.

Figure 2. Transitions for the $z = 0.56$ sub-DLA in the COS and FOS UV spectra. The smooth red line shows Voigt profile models of the data. Absorption that is not due to the named transition in each panel (usually from H$_2$) is shown by the dashed lines. The tick marks show the component positions from Fig. 1, the dark ticks show components that have associated H$_2$ absorption. All transitions are covered by the COS spectra, apart from Si III, which is covered by the lower resolution FOS spectrum.

4 http://www.stsci.edu/hst/cos/performance/spectral_resolution/
We measure H₂ transitions from the J = 0–3 rotational levels, with upper limits on J = 4 and 5. The asymmetric profiles for many of the H₂ lines suggest that there is more than one absorbing component. We were also unable to successfully fit the equivalent widths of the transitions using a curve of growth analysis with a single component. Therefore, we fitted two H₂ components, with redshifts close to those of the two central strong metal components at −26 and 0 km s⁻¹ (components 5 and 6 in Table 3). These are clearly separated in the resolution ∼6 km s⁻¹ HIRES spectra, but blended at the instrumental line profile of COS. However, the large number of transitions over a range of oscillator strengths allow us to constrain velocity structure below the instrumental resolution. As it is not uncommon for H₂ to be significantly offset from the strongest metal absorption — indeed, in Section 5.4 we show that H₂ is probably produced in a different environment to most of the metal lines — we allow the redshifts of each H₂ component to vary in our fitting procedure.

We experimented with fitting the two components using vppfit, and found there were large degeneracies between the Doppler b parameter and column density. One way to robustly explore the b–N–z parameter space for the two components is to generate large grids of likelihood values as a function of the fitted parameters over plausible regions of parameter space. However, in our case this proved to be prohibitively expensive computationally. Instead, we used a Monte Carlo Markov chain (MCMC) technique to sample parameter space. This samples parameter values in proportion to the likelihood value at any point in parameter space. Thus, from a set of initial parameter positions, a ‘chain’ of parameter values is generated by a stochastic walk through parameter space with distributions approximating the Bayesian posterior probability for each parameter.

We generated posterior parameter distributions using the package emcee (the MCMC Hammer; Foreman-Mackey et al. 2013). We fitted for each component’s redshift and b parameter, and for the column density of each rotational level using the 56 transitions shown in Fig. 4. All transitions for a component were constrained to have the same b value, which is generally observed to be the case in local sites of H₂ absorption for at least J levels <3 (Spitzer et al. 1974). Fitting transitions from each rotational level individually also gives b parameters consistent with a single value. Even after correcting the wavelength scale, residual wavelength shifts of ∼1 km s⁻¹ remain, so we also allowed a small wavelength shift for each fitted region. Thus, we fit for eight column densities, two redshifts, two b parameters and one wavelength offset for each of the 56 regions resulting in a total of 68 parameters.

Table 5 gives the parameter estimates and 1σ errors for the velocity offsets (with respect to metal components 5 and 6), b parameters and H₂ column densities for each rotational level. The 1σ regions are determined by marginalizing over all other parameters and finding the narrowest region that encompasses 68.3 per cent of the samples. We choose the parameter estimates to be at the centre of these 1σ regions. The absorption model with the set of parameters that maximize the likelihood is shown in Fig. 4.

4 ABSORPTION SYSTEM PROPERTIES

4.1 Metallicity

The metallicity, Z, can be estimated from an element X using the log of the ratio of the abundance of element X in the absorber, Nₓ/NH₁, to the solar abundance

\[
\frac{\log_{10} N(X)_{\text{abs}}}{N(X)_{\odot}}
\]


\[\frac{\log_{10} N(X)_{\text{abs}}}{N(X)_{\odot}}\]

where N(X)_{\text{abs}} is the observed column density of element X in the absorber, N(X) is the solar abundance of element X, and N(H)_{\odot} is the solar abundance of hydrogen.

3.4 H₂ velocity structure

We measure H₂ transitions from the J = 0–3 rotational levels, with upper limits on J = 4 and 5. The asymmetric profiles for $N_{\text{H}_2}$ calculated using the AOD method. The NI and Si IV structures than that fitted to the HIRES transitions. but only by using a more complicated velocity structure.

The damping wings measured at Lyα in the FOS spectrum constrain $N_{\text{H}_2} = 10^{19.5} \pm 0.2 \text{ cm}^{-2}$, where the error is dominated by the systematic uncertainty in the continuum level (see Fig. 3).

The histogram shows the data, the dashed line the continuum and the lower green points the residuals as defined in Fig. 1. The thick red solid curve shows the best-fitting $N_{\text{H}_2}$, and the thinner upper and lower solid curves show $N_{\text{H}_2} = 10^{19.3}$ and $10^{19.7} \text{ cm}^{-2}$, respectively.

Table 4. Total column densities for transitions in the $z = 0.56$ system observed in the COS and FOS spectra. $N_{\text{H}_2}$ is calculated from the damping wings at Lyα in the FOS spectrum. C ii, C iii and Si iv are saturated, and lower limits are calculated using the AOD method. The NI and Si iv values are 3σ upper limits. The remaining values were calculated using the AOD of the transition with rest wavelength in the second column. Uncertainties given for these values are 1σ and include a 5 per cent uncertainty in the continuum level, which generally dominates the statistical uncertainty.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition (Å)</th>
<th>log10N (cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₁</td>
<td>1215</td>
<td>19.5</td>
</tr>
<tr>
<td>C i</td>
<td>945</td>
<td>13.5</td>
</tr>
<tr>
<td>C ii</td>
<td>1036</td>
<td>&gt;14.8</td>
</tr>
<tr>
<td>C iii</td>
<td>977</td>
<td>&gt;14.3</td>
</tr>
<tr>
<td>N i</td>
<td>1135</td>
<td>&lt;14.4</td>
</tr>
<tr>
<td>N ii</td>
<td>1084</td>
<td>14.7</td>
</tr>
<tr>
<td>O i</td>
<td>1039</td>
<td>15.5</td>
</tr>
<tr>
<td>O vi</td>
<td>1031</td>
<td>14.6</td>
</tr>
<tr>
<td>Si ii</td>
<td>1020</td>
<td>14.7</td>
</tr>
<tr>
<td>Si iii</td>
<td>1206</td>
<td>&gt;13.7</td>
</tr>
<tr>
<td>Si iv</td>
<td>1393</td>
<td>&lt;13.1</td>
</tr>
</tbody>
</table>

The damping wings measured at Lyα in the FOS spectrum constrain $N_{\text{H}_2} = 10^{19.5} \pm 0.2 \text{ cm}^{-2}$, where the error is dominated by the systematic uncertainty in the continuum level (see Fig. 3).

The damping wings measured at Lyα in the FOS spectrum constrain $N_{\text{H}_2} = 10^{19.5} \pm 0.2 \text{ cm}^{-2}$, where the error is dominated by the systematic uncertainty in the continuum level (see Fig. 3).
Due to a charge transfer between O and H we expect the ratio of the number densities \( n_{\text{O}} \)/\( n_{\text{O}} \) and \( n_{\text{H}} \)/\( n_{\text{H}} \) to be the same (Field & Steigman 1971), provided the majority of O is in the form of O I and O II. In the presence of many high-energy ionizing photons, this is no longer true due to different absorbing cross-sections of O I and H I (see Prochter et al. 2010), but the absence of Si IV argues against a hard radiation field for this system, and the best-fitting CLOUDY models do not predict significant amounts of O in higher ionization states (O VI is seen, but we argue that this occurs in a hotter, collisionally ionized phase). Oxygen also shows little depletion (<0.3 dex) on to dust grains across a range of environments in the ISM of the MW (Jenkins 2009), so should provide a good estimate of the metallicity.

We find \([\text{O}/\text{H}]=−0.72 \pm 0.32\), or \(\sim 0.19 \odot\). For the photoionization analysis in Section 4.5 we assume that the metallicity is the same across the entire complex. In one of the few cases where the metallicity has been measured for individual components in a single absorption system, metallicity differences of a factor of 10 have been observed (Prochter et al. 2010). However, given that the dispersion in \(N_{\text{Mg}/\text{Fe}}\) across the system is not excessively large (the largest log difference between components is 0.38), the assumption of a constant metallicity seems reasonable. In particular, the two components with \(\text{H}_2\) do not show significantly different ion abundance ratios compared to the entire system.

### 4.2 Dust

Noterdaeme et al. (2008) have found a correlation between the presence of dust and the likelihood of observing \(\text{H}_2\) in DLAs, consistent with the main formation mechanism for \(\text{H}_2\) being on the surface of dust grains. We can measure the dust content by comparing elements known to deplete strongly on to dust grains (Fe, Mg) to those with low depletion (O). We assume negligible ionization corrections, but applying corrections from the best-fitting CLOUDY model in Section 4.5 does not change our conclusions. We find \([\text{Fe}/\text{O}]=−0.25^{+0.21}_{−0.29}\) and \([\text{Mg}/\text{O}]=−0.38 \pm 0.28\) for the entire system, indicating mild dust depletion. If we also assume solar abundance ratios, then we
can estimate the dust-to-gas ratio normalized by the value in the solar neighbourhood as
\[
\kappa = 10^{2X/10}(1 - 10^{6Fe/NX}),
\]
where X is an element that does not deplete strongly on to dust (for a derivation of this expression see the appendix of Wolfe, Prochaska & Gawiser 2003). Using oxygen gives log_{10} \kappa < -0.44, compatible with values found in other higher redshift systems showing H2 (Ledoux et al. 2003).

### 4.3 Temperature constraints from line widths

The line widths of absorption components in the HIRES spectra can be used to constrain the temperature of the gas using the relation \( b = \sqrt{2\kappa T/m} \), where \( m \) is the mass of the ion and \( T \) is the temperature. This constraint is an upper limit, as there can be large-scale turbulent motions in addition to thermal broadening, or the line may not be resolved. Indeed, we fitted each component in Mg II, Fe II and Ca II with a single \( b \) parameter value across all three transitions, consistent with turbulent broadening dominating over thermal broadening. Due to the relatively large masses for these elements, only component 2 gives a constraining upper limit of 6000 K, typical of temperatures in the warm neutral medium in the MW ISM. The H2 line widths give upper limits to the temperature of 6500 and 5400 K for the blue and redder components, but we argue below that the physical conditions in the H2 gas are probably different to those of the gas where most of the metal lines arise. It is also possible that the H2 widths are substantially broadened due to turbulent motions.

In conclusion, there are no strong temperature constraints from the line widths. The relative column densities of the H2 rotational levels provide an independent measure of the temperature, discussed in the next section.

### 4.4 H2 excitation temperature

The ratios of H2 column densities in different rotational levels can be expressed as excitation temperatures, assuming a Boltzmann distribution across the levels (see Draine 2011):
\[
\frac{N_{J}}{N_{J=0}} = \frac{g_{J}}{g_{J=0}} \exp \left( \frac{-B_{J}(J+1)}{T_{0}} \right).
\]

Here, \( N_{J} \) is the column density for molecules in rotational state \( J \), and \( g_{J} \equiv (2J + 1)(2I + 1) \), where \( I = 0 \) if \( J \) is odd or 1 if \( J \) is even, is the statistical weight of \( J \). \( B_{J} = 85.36 \ \text{K} \) and \( T_{0} \) is the excitation temperature from level \( J = 0 \) to \( J = 0 \).

Fig. 5 shows an excitation diagram for the column densities of the \( J = 0–3 \) transitions for the two H2 components. If the collisional time-scale for the \( J = 0 \) and 1 transitions is much shorter than the photodissociation time-scale, which occurs above densities of \( \sim 100 \ \text{cm}^{-3} \) when H2 is sufficiently self-shielded from dissociating photons, then \( T_{10} \) represents the kinetic temperature of the gas (see e.g. Dalgarno, Black & Weisheit 1973). The \( z = 0.56 \) system is likely only partially self-shielded, but assuming that it satisfies these requirements we find a lower limit on \( T_{10} \) for each component at 1σ (2σ) limits of 123 K (64 K) for component 5 and 77 K (37 K) for component 6. Two illustrative temperatures corresponding to the populations for \( J = 0–3 \) in each component are shown in Fig. 5. However, different physical processes affect the populations of these levels (Jura 1975b), so it is not expected that a single temperature should match all four levels.

### 4.5 CLOUDY MODELLING

In this section, we attempt to generate a simple single-cloud model illuminated by a UV radiation field that can reproduce all the observed column densities. We compare to the total column densities for all components, since the individual component columns are not well constrained for the O I, C I and Si II transitions or the saturated transitions (C II, C III and Si III). Given the large range of transitions present with widely differing ionization energies, it is likely that there are several different phases present, and a single cloud model is unlikely to be able to reproduce all the observed species.
Below we find that a single model can reproduce the majority of the low-ionization metal transitions, but Section 5.4 shows that multiple phases with different densities and temperatures are required to explain all the absorption.

We use models generated with version 8.01 of CLOUDY, last described by Ferland et al. (1998), to estimate the physical conditions in the absorption system. All models assume solar abundance ratios, constant gas density and an absorbing geometry of a thin slab illuminated on one side by an incident radiation field perpendicular to the slab surface. The radiation field includes the cosmic microwave background at the redshift of the absorber. We then compare four scenarios: a cloud in an intergalactic medium (IGM)-like environment, an ISM-like environment, close to a starburst galaxy and illuminated by an active galactic nucleus (AGN)-dominated spectrum. We chose the AGN-dominated spectrum to estimate the effect of a nearby AGN that may be present in one of the galaxy candidates described in Section 5.3, and to see if a spectrum with more high-energy UV photons can produce the observed O VI column density in addition to that of the low-ionization transitions. The IGM-like model is free of dust with a radiation field given by the UV background spectrum from Haardt & Madau (2012), including contributions from quasars and star-forming galaxies at the redshift of the absorber. It has a radiation field strength at 912 Å, $J_{912}\,_{\text{IGM}} = 6.08 \times 10^{-22}$ erg cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$. The ISM-like models have a radiation field similar to the Galactic ISM ($J_{912} \sim 400 J_{912}\,_{\text{IGM}}$), which is dominated at UV wavelengths by the spectral shape of hot stars, and a dust grain composition similar to that measured in the ISM. Even though the ISM-like models use solar relative abundances, the gas phase abundance ratios are substantially different from solar due to differential depletion of metals to grains. The starburst CLOUDY models assume that the absorbing cloud is 10 kpc from the galaxy and an escape fraction for UV light of 3 per cent, in addition to the IGM-like radiation field described above, without dust grains. They have $J_{912} \sim 2700 J_{912}\,_{\text{IGM}}$. The starburst galaxy spectrum used was generated using STARBURST99 (Leitherer et al. 1999) for a star formation rate of 20 $M_{\odot}$ yr$^{-1}$. The AGN models use the default tabulated AGN spectrum from CLOUDY with a normalization $J_{912} \sim 3000 J_{912}\,_{\text{IGM}}$ and do not include dust grains.

For each scenario, we generate a grid of models for a range of ionization parameters, metallicities and total $N_{\text{H}}$. We estimate the ionization parameter $U$, defined as the ratio of the densities of ionizing photons to hydrogen atoms, using the observed total column density ratios $N_{\text{MgI}}/N_{\text{MgII}}, N_{\text{SiI}}/N_{\text{SiII}}, N_{\text{SiII}}/N_{\text{SiIII}}, N_{\text{FeII}}/N_{\text{FeIII}}$. Using ratios of ionization states for the same element avoids any effects that might alter the column densities of ions for different elements in different ways, such as non-solar abundance ratios or differential dust depletion. We generate the likelihood of each parameter ($U, Z$ and $N_{\text{H}}$) for the grid of models based on the observed ratios, and include a Gaussian prior on the metallicity centred on the $[O/H]$ metallicity measurement with width $\sigma$ equal to the 1$\sigma$ uncertainty on the metallicity. For all three scenarios, only a relatively narrow range of $U$ values correctly reproduces the observed ratios. The likelihoods are only weakly dependent on the total $N_{\text{H}}$; we assume $N_{\text{H}} = 10^{19.5}$ cm$^{-2}$, which results in models that best reproduce the observed metal column densities.

Once we have found the most likely $U$ value, we compare the predicted column densities to the observed transitions with measurements or limits, and assess which scenario reproduces the observations best. We first compare to the AGN models. These are the only models with a hard enough spectrum to produce sufficient $N_{\text{H}}$ vi to match the observed value. However, at the same time they overpredict the amount of Si IV, Fe II, Mg I and Mg II by one or more orders of magnitude. Thus, it is more likely that the O VI arises in a collisionally ionized phase separate from the low-ionization transitions, as is observed in other systems (e.g. Fox et al. 2007; Ribaudo et al. 2011), and we do not compare to the high-ionization species (Si IV, O VI) for the remaining models.

From the mild depletions measured in Section 4.2, we already expect that the ISM-like case will not match the observed abundances. The most likely model does indeed underpredict the Fe II abundance by more than an order of magnitude, and Ca II by many orders of magnitude, as both are expected to be heavily depleted on to dust grains. This confirms that the depletion pattern in the $z = 0.56$ sub-DLA is different from that in the MW ISM. This model also underpredicts C I. The starburst scenario fails to reproduce the observed $N_{\text{SiI}}/N_{\text{SiII}}$ and also severely underpredicts Ca II, Fe II and C I. The IGM-like model gives the best fit to the observed data, and its predictions along with observed column densities are shown in Figs 6 and 7. Fig. 6 shows that column densities for O I, Mg I, Mg II, Fe II, N I and N II are reasonably well matched. The remaining small deviations from the predictions could be due to a slightly different incident UV continuum from the one assumed, or enhanced or depleted elemental abundances relative to the solar values assumed. For example, 0.2 dex less $N_{\text{FeII}}$ is observed than is predicted. This may be due to a nitrogen underabundance, often observed in similar $N_{\text{H}}$ systems at low redshifts (e.g. Battisti et al. 2012) and in DLAs at higher redshifts (Pettini et al. 2002; Prochaska et al. 2002). Fig. 7 shows that Si II, Si III, C II and C III columns are reproduced well.
However, there is still 0.5 dex too little \( N_{\text{C} \parallel} \) and 1 dex too little \( N_{\text{C} \|} \) predicted. In all three scenarios, we also find that the \( N_{\text{H} \|} \) predicted is more than an order of magnitude below the observed value. In Section 5.4, we suggest a scenario to explain this discrepancy between the models and observations.

We also ran CLOUDY models using constant pressure clouds instead of constant density. The motivation for these was to simultaneously include cool, lower density gas at the edge of the cloud and higher density, cold \( \sim 100 \) K gas at the core of the cloud where \( \text{H}_2 \) can survive. In these models we also included contributions from cosmic rays, which can be important for cold molecular regions. Although significant amounts of \( \text{H}_2 \) can co-exist with many of the metal transitions observed for these models, they still cannot correctly reproduce the \( \text{Ca} \parallel \) or \( \text{C} \parallel \) columns.

### 4.6 \( \text{C} \parallel \) fine structure absorption

Singly ionized carbon (\( \text{C}^+ \)) has electronic structure \( 2s^22s^22p \), where the outer shell has a configuration \( ^3P \), and thus fine structure splitting occurs between the \( J = 1/2 \) and \( J = 3/2 \) levels. Transitions from these two ground-state levels produce \( \text{C} \parallel \) and \( \text{C}^+ \) absorption, respectively.

The ratio of \( \text{C} \parallel^* \) to \( \text{C} \parallel \) column densities has been used to estimate the star formation rate inferred from the cooling rate in DLAs at high redshift (Wolfe et al. 2003). We find an upper limit on \( \text{C} \parallel^* \) from \( \lambda 1036 \) of \( N_{\text{C} \parallel^*} < 10^{14.5} \) cm\(^{-2}\) and \( N_{\text{C} \parallel} > 10^{14.6} \) cm\(^{-2}\). Assuming constant \( n(\text{C}^+)/n(\text{C} \parallel) \) over the entire complex, we find the ratio \( N_{\text{C} \parallel^*}/N_{\text{C} \parallel} < 0.8 \), consistent with ratios measured in higher redshift DLAs (e.g. Srianand et al. 2005) and local environments. Following the assumptions described by Morris et al. (1986), we can estimate the electron density \( n_e \) in cm\(^{-3}\) using the expression

\[
N_{\text{C} \parallel^*}/N_{\text{C} \parallel} = 3.9 \times 10^{-2} n_e \left[ 1 + \left( 0.22 n_p/n_e \right) \right].
\]

We use \( n_p/n_e \) corresponding to the ionized H fraction of 0.70 from the best-fitting CLOUDY ionization model to find \( n_e \leq 10 \) cm\(^{-3}\). Using \( N_{\text{H} \|} \) we can estimate the thickness of the absorbing cloud as \( N_{\text{H} \|}/n_e \). This gives a lower limit on the cloud size of 3 pc. This limit is not necessarily related to the density or size of the \( \text{H}_2 \) gas, as we argue in the discussion that most of the \( \text{C} \parallel \) is due to a warm ionized phase separate from \( \text{H}_2 \).

### 4.7 Molecular fraction

The molecular mass fraction is estimated by

\[
f_{\text{H}_2} = 2N_{\text{H}_2}/(N_{\text{H} \|} + 2N_{\text{H}_2}),
\]

assuming that most of the hydrogen associated with \( \text{H}_2 \) is neutral. In this case, as for many other QSO absorption systems, it is not clear how to divide the total \( N_{\text{H} \|} \) measured from the damping wings between different absorbing components, and in principle each \( N_{\text{H} \|} \) component could have a different \( f_{\text{H}_2} \) value. To calculate \( f_{\text{H}_2} \), we use the total \( N_{\text{H} \|} \) from both components and conservatively assume that all \( N_{\text{H} \|} \) is associated with \( \text{H}_2 \), meaning \( f_{\text{H}_2} \) is effectively a lower limit. This gives a molecular fraction of \( f_{\text{H}_2} = 0.9 \pm 0.36 \). As we discuss in the next section, given the total \( N_{\text{H} \|} \), this is a usually high molecular fraction compared to most other high redshift systems and sightlines in the Local Group. Therefore, we may be concerned that a different velocity model to the one we have used permits a much lower \( f_{\text{H}_2} \). To calculate a lower limit on \( f_{\text{H}_2} \), independent of the velocity model, we measure the column density of the lowest oscillator strength transition available for each rotational level (\( J = 0, 1, 1108.1; J = 1, 11008.5; J = 2, 1934.1 \) and \( J = 3, 1952.3 \)) using the AOD method. This gives a lower limit of \( N_{\text{H} \|} = 10^{16.5} \) cm\(^{-2}\) or \( f_{\text{H}_2} > 10^{-3} \), again assuming all of the \( N_{\text{H} \|} \) is associated with the \( \text{H}_2 \). This is still a high value relative to local \( \text{H}_2 \) systems with similar \( N_{\text{H} \|} \).

### 5 DISCUSSION

#### 5.1 Physical conditions in the \( \text{H}_2 \) cloud

To consider this system in the context of other \( \text{H}_2 \) detections in absorption, we plot \( f_{\text{H}_2} \) for local and higher redshift \( \text{H}_2 \) sightlines as a function of the total hydrogen column density and \( N_{\text{H} \|} \) in Fig. 8. It is apparent that the \( z = 0.56 \) sub-DLA (the solid circle) has an unusually high \( f_{\text{H}_2} \), given its \( N_{\text{H} \|} \) compared to sightlines through the plane of the MW (the cyan inverted triangles), or through the Magellanic Clouds (the green squares and the red diamonds). Before we discuss the likely origin of the \( z = 0.56 \) sub-DLA, we examine the physics underlying the \( f_{\text{H}_2} \) distribution as a function of \( N_{\text{H} \|} \) and \( N_{\text{H} \|} \). The left-hand panel shows a clear bimodality in the \( f_{\text{H}_2} = N_{\text{H} \|} \) distribution between high \( N_{\text{H} \|} \), high \( f_{\text{H}_2} \) sightlines at the top right, and lower \( f_{\text{H}_2} \) sightlines, generally with much lower \( N_{\text{H} \|} \). The right-hand panel shows that this is actually a bimodality between \( N_{\text{H} \|} \) values \( \lesssim 10^{16} \) and \( \gtrsim 10^{18} \) cm\(^{-2}\). This can be understood as the onset of \( \text{H}_2 \) self-shielding against UV dissociating photons.
(e.g. Hirashita & Ferrara 2005; Gillmon et al. 2006). An analytic approximation from Draine & Bertoldi (1996) shows that $>97$ per cent of H$_2$-dissociating photons are blocked by self-shielding once $N_{\text{HI}} \sim 10^{16}$ cm$^{-2}$. Once H$_2$ becomes self-shielded,$^5$ the dissociation rate drops and H$_2$ accumulates rapidly to the formation–dissociation equilibrium value predicted by the models by McKee & Krumholz (2010). These models are shown at the top right in each panel for two metallicities; solar and $Z = 0.2 Z_\odot$, the metallicity of the Small Magellanic Cloud (SMC). They were calculated using equations 4, 5, 7 and 8 from Kuhlen et al. (2012) and assume that the ISM is in a two phase equilibrium between a cold neutral medium and a warm neutral medium (e.g. Wolfire et al. 1995). The solar metallicity model reproduces the mean $f_{\text{HI}}$ for the MW sightlines through the Magellanic Stream and McKee for two illustrative metallicities. The three thin lines at the lower left are the analytic models described in Section 5.1. H$_2$ detections in $z > 1.5$ QSO absorption systems (from the compilation by Noterdaeme et al. 2008 with additions from Petitjean et al. 2002; Reimers et al. 2003; Srianand et al. 2008, 2010, 2012; Jorgenson, Wolfe & Prochaska 2010; Noterdaeme et al. 2010; Tumlinson et al. 2010; Guimarães et al. 2012) are also shown.

Figure 8. The molecular fraction versus the total $N_{\text{HI}}$. Compared to measurements in the Magellanic Clouds (Tumlinson et al. 2002; Welty et al. 2012), along the disc of the MW (Savage et al. 1977) and in IVCs (Richter et al. 2003) and HVCs (Richter et al. 1999), the $z = 0.56$ H$_2$ system has an unusually large $f_{\text{HI}}$ for its total H column. The local systems that appear most similar to this absorber are seen along sightlines through the Magellanic Stream (Richter et al. 2001; Sembach et al. 2001). Error bars at the corner of each plot show the typical uncertainties on $N_{\text{HI}}, N_{\text{H}_2}$ and $N_{\text{HI},0}$. The thin lines at the top right in each panel show analytic models from Krumholz and McKee for two illustrative metallicities. The three thin lines at the lower left are the analytic models described in Section 5.1. H$_2$ detections in $z > 1.5$ QSO absorption systems (from the compilation by Noterdaeme et al. 2008 with additions from Petitjean et al. 2002; Reimers et al. 2003; Srianand et al. 2008, 2010, 2012; Jorgenson, Wolfe & Prochaska 2010; Noterdaeme et al. 2010; Tumlinson et al. 2010; Guimarães et al. 2012) are also shown.

$^5$ Dust shielding only becomes important at total H columns of $\sim 10^{21}$ cm$^{-2}$, assuming solar metallicity.
(2005), $R_{\text{def}}$, is equal to $\kappa R$. Rearranging these expressions, we can estimate the particle density in the cloud as

$$n_{\text{HI}} = 74 \text{ cm}^{-3} \kappa^{-1} \left( \frac{R}{R_{\text{SN}}} \right)^{-1} \left( \frac{f_{\text{HI}}}{0.01} \right) \left( \frac{j_{\text{EW}}^{\text{SN}}}{j_{\text{EW}}^{\text{LW}}} \right) \left( \frac{S_{\text{shield}}}{0.01} \right),$$

where $j_{\text{EW}}^{\text{SN}} = 3.2 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ and $R_{\text{SN}} = 3 \times 10^{-17} \text{ cm}^{3} \text{ s}^{-1}$ are typical values measured in the solar neighbourhood (Habing 1968; Jura 1974).

The three curves at the lower left of each panel in Fig. 8 show the molecular fractions estimated with equation (7) for illustrative combinations of $\kappa R n_{\text{HI}} / R_{\text{def}}$. The upper curve and middle curves each have $n_{\text{HI}} = 10 \text{ cm}^{-3}$ with $\kappa = 0.04, 0.1 R_{\text{SN}}, 10 J_{\text{EW}}^{\text{SN}}$ and $\kappa = 1, 0.33 R_{\text{SN}}, 2 J_{\text{EW}}^{\text{SN}}$, respectively. The lower curve has $\kappa = 0.04, n_{\text{HI}} = 5 \text{ cm}^{-3}, R_{\text{SN}}$ and 0.01 $J_{\text{EW}}^{\text{SN}}$. This lower curve has qualitatively different behaviour from the upper two curves, because at such low molecular fractions, dust shielding from dissociating photons becomes important for H$_2$ self-shielding. Therefore, the observed variation in $f_{\text{HI}}$ can be explained by reasonable variations in the combination of UV field strength, particle density and H$_2$ dust formation rate. If the $z = 0.56$ system is in H$_2$ formation–dissociation equilibrium, the combination of low $N_{\text{HI}}$ and high molecular fraction suggests that it is either in a weaker UV field, and has an increased H$_2$ formation rate, a higher molecular fraction suggests that it is either in a weaker UV field, but would result in extremely small cloud sizes.

The local low column density of the $z = 0.56$ system suggests that it does not pass through the ISM of a galaxy. Returning to Fig. 8, we see that local systems with similarly low total $N_{\text{HI}}$ and almost as high $f_{\text{HI}}$ are sightlines through a HVC (Richter et al. 1999) and the Magellanic Stream (Richter et al. 2001; Sembach et al. 2001). These clouds have subsolar metallicities ($0.3$–$0.5$ solar), and are most likely tidally stripped from the Magellanic Clouds (for the Magellanic Stream) or the MW. Sembach et al. (2001) estimate the density of the H$_2$-bearing cloud they observed in the Magellanic Stream to be $0.3$–$3 \text{ cm}^{-3}$ with a photoionization rate at least a factor of 10 smaller than the MW ISM value. The H$_2$ formation time-scale for these low densities is around 1 Gyr, a large fraction of the estimated lifetime of the Magellanic Stream (e.g. Besla et al. 2010). Therefore, they favour a scenario where H$_2$ is not formed in place, but has survived the tidal stripping process and persists due to a combination of self-shielding and the lower ambient UV field compared to the LMC ISM. Such a scenario could also be responsible for the $z = 0.56$ absorber.

5.2 Comparison to higher redshift H$_2$ absorbers

Unlike the local sightlines, there is no clear bimodality in the $f_{\text{HI}}$–$N_{\text{HI}}$ distribution for higher $z$ H$_2$ systems. This could be due to each higher $z$ absorber being comprised of several clouds, or to a much wider range of incident UV and H$_2$ formation rates, both of which may smooth away an underlying distribution.

The three high-$z$ systems with $f_{\text{HI}}$ and $N_{\text{HI}}$ most similar to this system are those described by Petigura et al. (2002) (at $z = 1.973$ towards Q0013–0029 with $N_{\text{HI}} \lesssim 10^{19.4} \text{ cm}^{-2}$, $f_{\text{HI}} = 10^{-3}$), Reimers et al. (2003) ($z = 1.51$ towards HE0515–4414 with $N_{\text{HI}} = 10^{19.88} \text{ cm}^{-2}$, $f_{\text{HI}} = 10^{-2.64}$), and Tumlinson et al. (2010) and Milutinovic et al. (2010) ($z = 2.059$ towards Q2123–0500 with $N_{\text{HI}} = 10^{19.18} \text{ cm}^{-2}$, $f_{\text{HI}} = 10^{-1.35}$). The $z = 1.973$ system is a sub-DLA component that is highly depleted to the same extent as is observed for cool gas in the MW. It has a solar metallicity and the gas pressure is even higher than is typically measured in MW ISM. The $z = 1.51$ system has a metallicity of 0.3 solar, and dust-to-gas ratio of 0.89 $\pm$ 0.19 relative to solar. It also shows evidence of a higher photodissociation rate than is seen locally. The final sub-DLA at $z = 2.059$ has a metallicity of 0.5 solar, and HD absorption is observed in addition to H$_2$. It exhibits a multiphase medium of cold and warm gas, similar to the system we have presented in this paper. Unfortunately, none of these absorbers have associated imaging to suggest a typical impact parameter of any nearby galaxy producing the absorption.

Therefore, the three higher redshift systems showing a similarly high $f_{\text{HI}}$, and low $N_{\text{HI}}$, tend to have larger metallicities and dust-to-gas ratios than the $z = 0.56$ absorber. However, it is possible that the components producing H$_2$ in the $z = 0.56$ system have a higher metallicity and dust-to-gas ratio than that averaged over the whole absorber.

5.3 Connection to galaxies

The K-band imaging around Q 0107–0232 has a seeing FWHM of 0.8 arcsec, and shows two possible galaxy candidates less than 1.2 arcsec from the QSO sightline. Fig. 9 shows a 5 arcsec x 5 arcsec region centred on the QSO. The QSO image has been subtracted using the point spread function of a nearby star. The two galaxy candidates are seen to the north-west (G1) and south-west (G2). Assuming they are at the redshift of the absorber, they have luminosities of $0.7L^{*}$ (G1) and $2L^{*}$ (G2), and impact parameters of 10 kpc (G1) and 11 kpc (G2), both smaller than the median impact parameter of 33 kpc for galaxies associated with sub-DLAs found by Rao et al. (2011). Therefore, it is likely that at least one is associated with the absorber, on scales typical of the separations between the MW and HVC (10–60 kpc; see Putman, Peek & Joung 2012, and the references therein).

5.4 Three different gas phases in the sub-DLA

Figs 6 and 7 show the total hydrogen particle density for the majority of metals observed in this system corresponding to the ionization parameter, assuming that the normalizations of the incident radiation fields are correct. The most likely model corresponds to hydrogen densities from $10^{-3}$ to $10^{-2} \text{ cm}^{-3}$. Even assuming a factor of 10 uncertainty in the radiation field strength, this is much lower than
the typical densities where H2 is seen in both our galaxy and in other H2-bearing DLAs ($n_{H_2} = 10^{13} - 100 \ cm^{-3}$). This is confirmed by our CLOUDY modelling, which shows that there is no single cloud model that can simultaneously reproduce both the C I and H2 column densities, in addition to those of the other low-ionization metal transitions. Therefore, the gas traced by most of the metal absorption is probably in a different environment to that in which H2 resides. This is also likely the cause of the excess $N_C$ over that predicted by the CLOUDY models. C I is often seen in dense components showing H2 (e.g. Srianand et al. 2005) and can have extremely narrow line widths corresponding to temperatures of $\sim 100 \ K$ (Jorgenson et al. 2009; Carswell et al. 2011), indicating that it occurs in the same environment as H2. Thus, most of the C I and some Ca II may be from a high-density region co-spatial with H2.

As discussed in Section 4.5, the presence of O vi is unlikely to be explained by photoionization by a hard UV field. At the metallicity of the absorber ($\sim 0.1 \ solar$), significant O vi is only produced via collisional ionization for temperatures larger than $10^5 \ K$, even in non-equilibrium cases (Gnat & Sternberg 2007). Thus, it is likely that a hotter medium than that producing the H2 and metal lines is also present.

We conclude that the absorption is due to gas in three phases: a photoionized medium at $\sim 10^4 \ K$ in which most of the metal transitions we see are produced, a cold neutral medium at $\sim 100 \ K$ where the H2 and C I absorption occurs and a hotter phase where O vi is produced. The H1 column is likely split between the two cooler phases. A similar multiphase environment is also seen in other higher redshift sub-DLAs that show molecular absorption (Milutinovic et al. 2010).6

6. The Magellanic Stream and many other HVCs comprise $10^4 \ K$ ionized gas that is seen in Hz emission, $T > 10^4 \ K$ hot gas producing O vi absorption and they can also contain cold neutral gas with H2 (Sembach et al. 2003; Fox et al. 2010). Taken together, the existence of these three phases, the high molecular fraction with a low total column density, and the proximity of a possible $\sim L^*$ galaxy suggest that the $z = 0.56$ absorber is due to a tidally stripped feature analogous to the Magellanic Stream.

5.5 Incidence rate of H2 in low-redshift sub-DLAs

Due to the need for bright targets observable with space-based UV spectroscopy and their low incidence rate, very few DLAs and sub-DLAs have been found at low redshift. Until recently only $\sim$10 DLAs at redshifts <1 were known, and only a handful of these have coverage of H2 Lyman–Werner bands. With the availability of COS, the number of such systems is being increased dramatically, and due to its FUV wavelength coverage the presence of H2 can be easily detected.

Battisti et al. (2012) present a sample of two DLAs and six sub-DLAs at $z < 0.35$, serendipitously discovered along sightlines as part of a large COS programme. Like the sub-DLA presented here, they were not pre-selected by the strength of their metal lines or other properties that might influence the likelihood of detecting molecules. Interestingly, they also discovered a subdamped system with H2 absorption at $z = 0.2477$. Taking this sample together with the system in this paper and assuming binomial statistics, we find the expected incidence rate of DLAs and sub-DLAs showing molecular hydrogen at $N_{H_2} \sim 10^{14} \ cm^{-2}$ at low redshift to be $2/9 = 22$ per cent (with a 95 per cent confidence level lower limit of 4 per cent), rising to 33 (5) per cent if we consider only the subdamped systems with $N_{H_2} < 10^{20} \ cm^{-2}$. This is a surprisingly large fraction given that sub-DLAs are often found to be highly ionized absorbers with $\lesssim 10$ per cent of their hydrogen in the form of H1.

If we think that the absorption cross-section for H2 is dominated by cold gas associated with Local Group-type systems (the Magellanic Stream for example), then this may be consistent with this high incidence rate. Richter (2012) shows that one can explain 30–100 per cent of the observed incidence rate of systems with $N_{H_2} > 10^{17.5} \ cm^{-2}$ as IVCs and HVCs distributed around galaxies with H1 masses between $10^{10}$ and $10^{11} \ M_\odot$ in a similar way as is seen around M31 and the MW. As discussed in the previous section, some HVCs also show relatively high molecular fractions, and in terms of $N_{H_2}$ and $f_{H_2}$, HVCs are the local systems most analogous to the system analysed in this paper.

It would be interesting to perform a systematic search for H2 in further $10^{19} \ cm^{-2} < N_{H_2} < 10^{20.3} \ cm^{-2}$ sub-DLAs at both high and low redshifts that have metal absorption consistent with a cool, dusty environment. Sub-DLAs tend to have both higher metallicities and larger velocity widths than DLAs, and H2 is more likely to be found in DLAs with both these characteristics (Noterdaeme et al. 2008).

5.6 Evolution in $f_{H_2}$

We plot the $f_{H_2}$ values as a function of cosmic time in Fig. 10. There is no evidence for evolution in $f_{H_2}$, though more measurements are needed, particularly at intermediate redshifts, given the large scatter in $f_{H_2}$ seen along both local sightlines in the MW halo and in higher $z$ DLAs.
two H$_2$ detections were found. A survey for H$_2$ in low-redshift subdamped systems could be a fruitful way to measure the physical conditions giving rise to these absorbers.

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The authors wish to recognize and acknowledge the significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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REFERENCES


6 SUMMARY

We have analysed a sub-DLA system with N$_{HI} = 10^{19.5} \pm 0.2$ cm$^{-2}$ at $z = 0.56$ that shows associated molecular hydrogen absorption in the Lyman and Werner bands. Using velocity components determined from a high-resolution spectrum covering metal transitions falling in the optical, we fit a two-component model to the H$_2$ absorption and find a lower limit to the molecular fraction of $\log_{10} f_{H_2} = -1.93 \pm 0.36$, and a lower limit independent of the assumed velocity structure of $f_{H_2} > 10^{-3}$. This is higher than other sightlines with similar N$_{HI}$, where H$_2$ has been measured in the MW halo. We find a metallicity for the cloud $\log_{10} Z = -0.72 \pm 0.32$, or 0.19$^{+0.21}_{-0.15}$ solar. The dust-to-gas ratio relative to the solar neighbourhood is $\log_{10} \kappa < -0.44$, or $\kappa < 0.36$.

We modelled the observed transitions using CLOUDY and were unable to find a single solution that can simultaneously reproduce all the observed transitions. However, a model for the absorber of a 10$^6$ K cloud illuminated by a radiation field dominated by the UV background can broadly reproduce all the observed column densities apart from those of H$_2$, C$_1$ and O$_1$. We conclude that there are three phases in the absorber: a $T \sim 100$ K phase where the C$_1$ and H$_2$ arise, a $T \sim 10^4$ K phase where the low-ionization metal absorption occurs, and a hotter, collisionally ionized phase associated with O$_1$.

Using simple models of H$_2$ formation–dissociation equilibrium, we calculate densities for the H$_2$ absorbing region from $\sim$1 to $\sim$70–480 cm$^{-3}$, depending on the incident strength of the radiation field. The lower density range corresponds to cloud thicknesses of $\sim$3–10 pc, the high density range to $\sim$0.002–0.15 pc. Given the N$_{HI}$, the presence of a three phase medium, the molecular fraction, metallicity and two galaxy candidates near the QSO sightline with impact parameters of $\sim$10 kpc, we conclude this system may be a tidally stripped feature similar to the Magellanic Stream.

Finally, we remark that of the seven sub-DLAs observed at $z < 0.7$ for which there is the possibility to detect $N_{HI} > 10^{14.5}$ cm$^{-2}$,
Table A1. Wavelength shifts required to bring COS G160M exposures with central wavelength settings into a common wavelength solution between exposures taken using the FUV A and FUVB segments.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Valid λ range (Å)</th>
<th>Apply to λ setting</th>
<th>α</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUV A</td>
<td>1600–1800</td>
<td>1627</td>
<td>1.233 × 10^{-3}</td>
<td>−2.115</td>
</tr>
<tr>
<td>FUV B</td>
<td>1425–1600</td>
<td>1589</td>
<td>−0.952 × 10^{-3}</td>
<td>1.468</td>
</tr>
</tbody>
</table>

Table A2. Wavelength shifts inferred from the H2 absorption as function of wavelength. Δλ should be added at each wavelength λ to correct the wavelength scale.

<table>
<thead>
<tr>
<th>λ (Å)</th>
<th>Δλ (Å)</th>
<th>λ</th>
<th>Δλ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1425</td>
<td>−0.1099</td>
<td>1625</td>
<td>−0.0062</td>
</tr>
<tr>
<td>1450</td>
<td>−0.0848</td>
<td>1650</td>
<td>−0.0033</td>
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<td>−0.0245</td>
<td>1750</td>
<td>0.0052</td>
</tr>
<tr>
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<td>−0.0160</td>
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</tr>
<tr>
<td>1600</td>
<td>−0.0101</td>
<td>1800</td>
<td>0.0116</td>
</tr>
</tbody>
</table>
ing different central wavelength settings. Table A1 gives the shifts that must be applied to bring our G160M exposures with central wavelength settings 1589 and 1627 Å to a common wavelength scale. Table A2 gives the further $\sim 10 \text{ km s}^{-1}$ shifts that were required to give an internally consistent wavelength solution based on the expected positions of $\text{H}_2$ absorption features.

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