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 $N_{\text{HI}} = 10^{19.5\pm 0.2} \text{ cm}^{-2}$. 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: $\log_{10}(f_{H_2}) > -1.93 \pm 0.36$ based on modelling the line profiles, with a robust model-independent lower limit of $f_{H_2} > 10^{-7}$. This is higher than $f_{H_2}$ values seen along sightlines with similar $N_{\text{HI}}$ through the Milky Way disc and the Magellanic Clouds. The metallicity of the absorber is $0.19^{+0.21}_{-0.10}$ solar, with a dust-to-gas ratio of < 0.36 of the value 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 $\sim 100 \text{ K}$ phase giving rise to $H_2$, a $\sim 10^4 \text{ K}$ 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 $\sim 10 \text{ kpc}$, 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, $f_{H_2}$, 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 ξ 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

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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 Stream (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 & Hirshfeld 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$\alpha$ ($N_{HI} > 10^{20.3}$ cm$^{-2}$, DLA) and subdamped Ly$\alpha$ ($10^{17} \lesssim N_{HI} \lesssim 10^{20.3}$ cm$^{-2}$, sub-DLA) absorption systems seen towards bright background QSOs. In this redshift range, absorption features from H$_2$ and sometimes H$_3^+$ 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 2003, 2006). The H$_2$ transition wavelengths from Bailly et al. (2010).

### Table 1. Properties of the background QSO towards which the sub-DLA is seen.

| Name     | RA (J2000)   | Dec. (J2000) | $z_{em}$ | $R$ mag |
|----------|--------------|--------------|----------|---------|
| Q 0107–0232 | 01$^h$10$^m$14$^s$3 | -02°16’57’’6 | 0.728 | 18.4 |

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$^{-1}$, $\Omega_M = 0.272$, $\Omega_\Lambda = 0.728$; Komatsu et al. 2011) where necessary. We use transition wavelengths and oscillator strengths given by Morton & Dinerstein (1976), Morton (2003) and Verner, Barthel & 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 $z_{em} = 0.728$ (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$^1$ 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

$^1$ Version 2.13.6, http://www.stsci.edu/hst/cos/pipeline/
to 20 significantly improved the background level such that the flux in strongly saturated features broader than the COS instrument line spread profile was consistent with zero.

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 \( \lambda_c = 1627 \) matched the FUV segment A \( \lambda_c = 1589 \) setting, and FUV segment B \( \lambda_c = 1589 \) matched the FUV segment B \( \lambda_c = 1627 \) setting. 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\(_2\) 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\(_2\) 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\(_{\text{II}}\)945 features from the \( z = 0.56 \) system in the combined COS spectrum to their expected positions from the redshifts of the Fe\(_{\text{II}}\) and Mg\(_{\text{II}}\) lines 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\(^{-1}\) relative to narrow Galactic Ca\(_{\text{II}}\) absorption features seen in the spectrum. Both the N\(_{\text{II}}\) and C\(_{\text{I}}\) appear at redshifts expected from the HIRES Fe\(_{\text{II}}\) and Mg\(_{\text{II}}\) redshifts, and N\(_{\text{II}}\) shows a similar component structure (albeit at the lower COS resolution). We conclude that no correction to the wavelength zero-point of the combined COS spectrum is necessary.

We also measured the redshift of Galactic absorption features in the COS spectrum to confirm that the zero-point of the wavelength solution was correct. These are all saturated and possibly contain multiple components, so do not provide a stringent constraint on the zero-point. However, they show no evidence of a systematic offset.

After correcting each exposure for these wavelength shifts we made a combined spectrum in the following way. First, we rebinned each exposure to a single wavelength scale with pixel width 0.0367 Å, ensuring Nyquist sampling. We used nearest-neighbour binning to preserve the spectra’s noise properties, and checked that this did not introduce any significant wavelength shifts. The 1σ uncertainty on each pixel was estimated empirically as the standard error on the mean of the contributing pixel fluxes. This is a slight overestimate of the true uncertainty, as the exposure times were not all identical. However, the uncertainties measured in this way are consistent with the standard deviation of the flux in regions free from absorption, and we believe this is a good estimate of the true uncertainty.

Since the background level of the COS spectra is low, at small source count rates the flux distribution may be better described by Poisson rather than Gaussian statistics. However, in practice we find that for regions of our spectra with the lowest number of counts – the cores of saturated profiles – uncertainties in the background levels from the many contributing exposures make a Gaussian flux distribution a good approximation.

Finally, we estimated the unabsorbed continuum level of the combined spectrum by fitting spline segments joining regions that appeared free from absorption. 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.

### Table 2. Observations of Q 0107–0232 with HST/COS. Columns show the HST archive data set name, the date observed, total exposure time, grating and central wavelength setting used.

| Data set   | Date obs.   | Exp. time (s) | Grating | \( \lambda_c \) (Å) |
|------------|-------------|---------------|---------|---------------------|
| LB5H12010  | 6 Nov 2010  | 13 905.728    | G160M   | 1589                |
| LB5H13010  | 18 Nov 2010 | 13 905.472    | G160M   | 1589                |
| LB5H11010  | 19 Nov 2010 | 13 905.376    | G160M   | 1589                |
| LB5H14010  | 24 Nov 2010 | 13 905.536    | G160M   | 1623                |
| LB5H15010  | 26 Nov 2010 | 13 905.504    | G160M   | 1623                |
| LB5H16010  | 7 Dec 2010  | 13 905.472    | G160M   | 1623                |

### 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\(^{-1}\) resolution FWHM, and covers a wavelength range of 3890 to 8330 Å.

### 2.3 Imaging

We acquired K-band imaging of a 7 arcmin \times 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 resampled 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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Figure 1. Observed transitions and upper limits at $z = 0.56$ in the HIRES spectrum. The thin smooth curve shows our best-fitting model using a single common velocity structure. The darker tick marks show components 5 and 6 that have associated H$_2$. Points distributed around $-0.25$ show the residuals, defined as $\frac{\text{flux} - \text{model}}{\sigma_{\text{error in flux}}}$. The two thin lines above and below this distribution mark the 1$\sigma$ deviation levels. Only upper limits are measured for Ca I and Fe I.

### 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 $\lambda\lambda$ 1526, C IV $\lambda\lambda$ 1548, 1550, Fe II $\lambda$ 1608, C I $\lambda\lambda$ 1657, and Mg II $\lambda$ 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 of 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.

$^2$ 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 $N_{\text{H}_1} \gtrsim 10^{21}$ cm$^{-2}$ in the MW ISM (Welty, private communication), we identify it as N v $\lambda$ 1238 near the QSO redshift.

#### 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 measured 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.$^3$ 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 I and much of the Ca II probably arises in diffuse, photoionized gas distinct from H$_2$.

Component 6 has a Doppler width $b = \sqrt{2\sigma} \approx 20$ 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

$^3$ 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.

| No. | Ion   | $\Delta \nu$ (km s$^{-1}$) | $\log N_{\text{HI}}$ | $\sigma_{\text{v}}$ (N in cm$^{-2}$) | $b$ | $\sigma_{b}$ (km s$^{-1}$) | $z$ | $\sigma_z \times 10^6$ |
|-----|-------|-----------------------------|----------------------|--------------------------------------|----|-----------------------------|----|------------------------|
| 1   | Fe II | $-110$                      | $<12.81$             | 6.98                                 | 1.20| 0.556 7157                 | 3.7 |                        |
|     | Mg I  | $10.72$                      | 0.25                  |                                      |     |                             |     |                        |
|     | Mg II | $12.02$                      | 0.05                  |                                      |     |                             |     |                        |
|     | Ca II | $<11.48$                     |                       |                                      |     |                             |     |                        |
| 2   | Fe II | $-93$                        | 12.18                 | 0.11                                 | 2.05| 0.70 0.556 8053             | 2.0 |                        |
|     | Mg I  | $10.27$                      | 0.54                  |                                      |     |                             |     |                        |
|     | Mg II | $12.25$                      | 0.08                  |                                      |     |                             |     |                        |
|     | Ca II | $<11.40$                     |                       |                                      |     |                             |     |                        |
| 3   | Fe II | $-72$                        | 12.84                 | 0.04                                 | 11.65| 0.86 0.556 9132             | 2.4 |                        |
|     | Mg I  | $11.08$                      | 0.14                  |                                      |     |                             |     |                        |
|     | Mg II | $13.02$                      | 0.02                  |                                      |     |                             |     |                        |
|     | Ca II | $11.32$                      | 0.12                  |                                      |     |                             |     |                        |
| 4   | Fe II | $-50$                        | 13.09                 | 0.03                                 | 6.94| 0.54 0.557 0298              | 1.5 |                        |
|     | Mg I  | $11.41$                      | 0.06                  |                                      |     |                             |     |                        |
|     | Mg II | $13.11$                      | 0.03                  |                                      |     |                             |     |                        |
|     | Ca II | $11.54$                      | 0.06                  |                                      |     |                             |     |                        |
| 5   | Fe II | $-26$                        | 12.94                 | 0.09                                 | 9.43| 1.04 0.557 1530              | 3.5 |                        |
|     | Mg I  | $11.39$                      | 0.09                  |                                      |     |                             |     |                        |
|     | Mg II | $13.16$                      | 0.06                  |                                      |     |                             |     |                        |
|     | Ca II | $11.22$                      | 0.18                  |                                      |     |                             |     |                        |
| 6   | Fe II | 0                            | 13.68                 | 0.02                                 | 19.81| 0.83 0.557 2885              | 4.6 |                        |
|     | Mg I  | $11.84$                      | 0.04                  |                                      |     |                             |     |                        |
|     | Mg II | $13.54$                      | 0.02                  |                                      |     |                             |     |                        |
|     | Ca II | $12.10$                      | 0.03                  |                                      |     |                             |     |                        |
| 7   | Fe II | $+44$                        | 12.81                 | 0.04                                 | 6.51| 0.40 0.557 5174              | 1.2 |                        |
|     | Mg I  | $11.24$                      | 0.08                  |                                      |     |                             |     |                        |
|     | Mg II | $12.72$                      | 0.02                  |                                      |     |                             |     |                        |
|     | Ca II | $11.05$                      | 0.17                  |                                      |     |                             |     |                        |
| 8   | Fe II | $+68$                        | 13.42                 | 0.02                                 | 8.41| 0.25 0.557 6435              | 0.8 |                        |
|     | Mg I  | $11.60$                      | 0.04                  |                                      |     |                             |     |                        |
|     | Mg II | $13.25$                      | 0.02                  |                                      |     |                             |     |                        |
|     | Ca II | $11.57$                      | 0.06                  |                                      |     |                             |     |                        |
| 9   | Fe II | $+100$                       | 12.20                 | 0.10                                 | 5.08| 0.76 0.557 8081              | 2.3 |                        |
|     | Mg I  | $10.74$                      | 0.25                  |                                      |     |                             |     |                        |
|     | Mg II | $12.13$                      | 0.02                  |                                      |     |                             |     |                        |
|     | Ca II | $<11.44$                     |                       |                                      |     |                             |     |                        |
| 10  | Fe II | $+124$                       | 12.51                 | 0.08                                 | 9.74| 0.56 0.557 9336             | 1.8 |                        |
|     | Mg I  | $10.15$                      | 1.03                  |                                      |     |                             |     |                        |
|     | Mg II | $12.57$                      | 0.02                  |                                      |     |                             |     |                        |
|     | Ca II | $<11.56$                     |                       |                                      |     |                             |     |                        |

blend of two or more narrower components. The quality of even the HIRES data is not sufficient to constrain the parameters of such heavily blended components. However, as long as the distribution of unresolved component widths is not strongly bimodal, the column density estimates for this component should be accurate (Jenkins 1986). We also measure $N_{\text{HI}}$ independently of the velocity model assumed for $H_2$ in Section 4.7 to ensure that the velocity model does not strongly bias our measurement of the molecular fraction.

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,

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.
Table 4. Total column densities for transitions in the $z = 0.56$ system observed in the COS and FOS spectra. $N_{H_2}$ 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 N I 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 percent uncertainty in the continuum level, which generally dominates the statistical uncertainty.

| Ion      | Transition $\lambda$ (Å) | $\log_{10} N$ (cm$^{-2}$) |
|----------|---------------------------|----------------------------|
| H I      | 1215                      | $19.50^{+0.20}_{-0.20}$    |
| C I      | 945                       | $13.53^{+0.24}_{-0.77}$    |
| C II     | 1036                      | $>14.8$                    |
| C III    | 977                       | $>14.3$                    |
| N I      | 1135                      | $<14.4$                    |
| N II     | 1084                      | $14.73^{+0.17}_{-0.19}$    |
| O I      | 1039                      | $15.53^{+0.24}_{-0.24}$    |
| O VI     | 1031                      | $14.60^{+0.16}_{-0.24}$    |
| Si II    | 1020                      | $14.79^{+0.23}_{-0.64}$    |
| Si III   | 1206                      | $>13.7$                    |
| Si IV    | 1393                      | $<13.1$                    |

Note: Velocity models for N II with a saturated central component allow higher column densities than this value and are still compatible with the data, but only by using a more complicated velocity structure than that fitted to the HIRES transitions.

Figure 3. Constraints on $N_{H_1}$ from the Lyα transition. The histogram shows the data, the dashed line the continuum and the lower green points the upper limits on $J = 4$ and 5. The asymmetric profiles for many of the H$_2$ 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 H$_2$ components, with redshifts close to those of the two central strong metal components at $-26$ and $0 \text{ km s}^{-1}$ (components 5 and 6 in Table 3). These are clearly separated in the resolution $\approx 6 \text{ km s}^{-1}$ HIRES spectra, but blended at the instrumental line profile of COS. However, the large number of transitions over a range of oscillator strengths allows us to constrain velocity structure below the instrumental resolution. As it is not uncommon for H$_2$ to be significantly offset from the strongest metal absorption — indeed, in Section 5.4 we show that H$_2$ is probably produced in a different environment to most of the metal lines — we allow the redshifts of each H$_2$ component to vary in our fitting procedure.

We experimented with fitting the two components using VPFIT, and found there were large degeneracies between the Doppler $\beta$ 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 EMDCEE (the MCMC Hammer; Foreman-Mackey et al. 2013). We fitted for each component’s redshift and $\beta$ 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 $\beta$ value, which is generally observed to be the case in local sites of H$_2$ absorption for at least $J$ levels $<3$ (Spitzer et al. 1974). Fitting transitions from each rotational level individually also gives $\beta$ parameters consistent with a single value. Even after correcting the wavelength scale, residual wavelength shifts of $\approx 1 \text{ km s}^{-1}$ remain, so we also allowed a small wavelength shift for each fitted region. Thus, we fit for eight column densities, two redshifts, two $\beta$ 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), $\beta$ parameters and H$_2$ 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% 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, $N_X/N_{H_1}$, to the solar abundance

$$\log_{10} \left( \frac{N_X/N_{H_1}}{N_X/N_{H_1}} \right) = [X/H]$$

(1)

The damping wings measured at Lyα in the FOS spectrum constrain $N_{H_1} = 10^{19.5} \pm 0.2$ cm$^{-2}$, where the error is dominated by the systematic uncertainty in the continuum level (see Fig. 3).

### 3.4 H$_2$ velocity structure

We measure H$_2$ transitions from the $J = 0$–3 rotational levels, with upper limits on $J = 4$ and 5. The asymmetric profiles for many of the H$_2$ 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 H$_2$ components, with redshifts close to those of the two central strong metal components at $-26$ and $0 \text{ km s}^{-1}$ (components 5 and 6 in Table 3). These are clearly separated in the resolution $\approx 6 \text{ km s}^{-1}$ HIRES spectra, but blended at the instrumental line profile of COS. However, the large number of transitions over a range of oscillator strengths allows us to constrain velocity structure below the instrumental resolution. As it is not uncommon for H$_2$ to be significantly offset from the strongest metal absorption — indeed, in Section 5.4 we show that H$_2$ is probably produced in a different environment to most of the metal lines — we allow the redshifts of each H$_2$ component to vary in our fitting procedure.

We experimented with fitting the two components using VPFIT, and found there were large degeneracies between the Doppler $\beta$ 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 EMDCEE (the MCMC Hammer; Foreman-Mackey et al. 2013). We fitted for each component’s redshift and $\beta$ 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 $\beta$ value, which is generally observed to be the case in local sites of H$_2$ absorption for at least $J$ levels $<3$ (Spitzer et al. 1974). Fitting transitions from each rotational level individually also gives $\beta$ parameters consistent with a single value. Even after correcting the wavelength scale, residual wavelength shifts of $\approx 1 \text{ km s}^{-1}$ remain, so we also allowed a small wavelength shift for each fitted region. Thus, we fit for eight column densities, two redshifts, two $\beta$ 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), $\beta$ parameters and H$_2$ 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% 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.
Due to a charge transfer between O and H we expect the ratio of the number densities \( n_{\text{O I}}/n_{\text{O}} \) and \( n_{\text{H I}}/n_{\text{H}} \) 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 \([\text{O I}/\text{H I}] = -0.72 \pm 0.32, \) or \( \sim 0.19 \) Z⊙. 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 \( N_{\text{Mg II}}/N_{\text{Fe II}} \) 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 H2 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 H2 in DLAs, consistent with the main formation mechanism for H2 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 \([\text{Fe/O}] = -0.25^{+0.21}_{-0.29} \) and \([\text{Mg/O}] = -0.38 \pm 0.28 \) for the entire system, indicating mild dust depletion. If we also assume solar abundance ratios, then we...
Table 5. Column densities, $b$ values and velocity offsets for the two components showing H$_2$ based on MCMC fitting. Errors are 1σ and the $J = 5$ and 6 values are 5σ upper limits. The velocity offsets are from the redshifts of metal components 5 and 6, given in Table 3.

| $J$ | $\log_{10}N$ (cm$^{-2}$) | $b$ (km s$^{-1}$) | $\delta v$ (km s$^{-1}$) |
|-----|--------------------------|-------------------|------------------------|
| 0   | 16.17 ± 0.25             | 6.7 ± 0.6         | 3.5 ± 0.6              |
| 1   | 17.05 ± 0.28             |                   |                       |
| 2   | 16.19 ± 0.19             |                   |                       |
| 3   | 15.77 ± 0.12             |                   |                       |
| 4   | <14.5                    |                   |                       |
| 5   | <14.5                    |                   |                       |
| 0   | 15.63 ± 0.39             | 4.3 ± 0.7         | 4.3 ± 0.7              |
| 1   | 16.42 ± 0.40             |                   |                       |
| 2   | 15.65 ± 0.25             |                   |                       |
| 3   | 15.47 ± 0.18             |                   |                       |
| 4   | <14.5                    |                   |                       |
| 5   | <14.3                    |                   |                       |

can estimate the dust-to-gas ratio normalized by the value in the solar neighbourhood as

$$\kappa = 10^{2X/10}(1 - 10^{10^{Fe/X}}),$$

(2)

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 H$_2$ (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 $b = \sqrt{2kT/m}$, 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 H$_2$ 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 H$_2$ gas are probably different to those of the gas where most of the metal lines arise. It is also possible that the H$_2$ 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 H$_2$ rotational levels provide an independent measure of the temperature, discussed in the next section.

4.4 H$_2$ excitation temperature

The ratios of H$_2$ column densities in different rotational levels can be expressed as excitation temperatures, assuming a Boltzmann distribution across the levels (see Draine 2011):

$$\frac{N_I}{N_{J=0}} = \frac{g_I}{g_{J=0}} \exp\left(\frac{-B_i J(J+1)}{T_{10}}\right).$$

(3)

Figure 5. Excitation diagram for the two H$_2$ components. The error bars show the 1σ uncertainties. The slope of a line joining each pair of points is inversely proportional to the excitation temperature between those two $J$ levels. An illustrative temperature is shown for each component, but the population levels are not expected to follow a Boltzmann distribution characterized by a single temperature.

Here, $N_I$ 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 $J$. $B_i = 85.36$ K and $T_{10}$ is the excitation temperature from level $J = 0$.

Fig. 5 shows an excitation diagram for the column densities of the $J = 0$–3 transitions for the two H$_2$ 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 $\sim 100$ cm$^{-3}$ when H$_2$ 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, in 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, $J_{912, \text{IGM}} = 6.08 \times 10^{-23}$ erg cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$. The ISM-like models have a radiation field similar to the Galactic ISM ($J_{912, \text{ISM}} \simeq 400 J_{912, \text{IGM}}$), 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 on to grains. The starburst CLOUDY models assume that the absorbing cloud is 10 kpc from the galaxy and an escape velocity for UV light of 3 per cent, in addition to the IGM-like radiation field described above, without dust grains. They have $J_{912, \text{starburst}} \sim 2700 J_{912, \text{IGM}}$. 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 $J_{912, \text{AGN}} \sim 3000 J_{912, \text{IGM}}$ 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$_{\text{H I}}$. 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$_{\text{Mg I}}$/N$_{\text{Mg II}}$, N$_{\text{Si II}}$/N$_{\text{N II}}$ and N$_{\text{Si III}}$/N$_{\text{Si II}}$. 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$_{\text{H I}}$) for the grid of models based on the observed ratios, and include a Gaussian prior on the metallicity centred on the [O III/H I] 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$_{\text{H I}}$; we assume N$_{\text{H I}} = 10^{19.5}$ 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$_{\text{O VI}}$ 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$_{\text{Si III}}$/N$_{\text{Si II}}$, 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 Ni I 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$_{\text{N II}}$ is observed than is predicted. This may be due to a nitrogen underabundance, often observed in similar N$_{\text{H I}}$ 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.
the outer shell has a configuration 2Po redshift (Wolfe et al. 2003). We find an upper limit on C II the star formation rate inferred from the cooling rate in DLAs at high densities are reproduced well. As discussed in Section 5.4, the excess NC II is likely due to C I being in a self-shielded cold phase where H2 and possibly part of the Ca II reside.

However, there is still 0.5 dex too little NC II and 1 dex too little NC I predicted. In all three scenarios, we also find that the NH II 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 ~100 K gas at the core of the cloud where H2 can survive. In these models we also included contributions from cosmic rays, which can be important for cold molecular regions. Although significant amounts of H2 can co-exist with many of the metal transitions observed for these models, they still cannot correctly reproduce the Ca II or C I columns.

### 4.6 C II fine structure absorption

Singly ionized carbon (C+) has electronic structure 2s22s2p, where the outer shell has a configuration 2Pj, and thus fine structure splitting occurs between the J = 1/2 and J = 3/2 levels. Transitions from these two ground-state levels produce C II and C II+ absorption, respectively.

The ratio of C II+ to C II 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 C II+ from 10.036 of NC II+ < 1014.5 cm−2 and NC II > 1014.6 cm−2. Assuming constant n(C II+)/n(C II) over the entire complex, we find the ratio NC II+/NC II < 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 ne in cm−3 using the expression

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

We use np/ne corresponding to the ionized H fraction of 0.70 from the best-fitting CLOUDY ionization model to find ne < 10 cm−3. Using NH II we can estimate the thickness of the absorbing cloud as NH II/ne. 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 H2 gas, as we argue in the discussion that most of the C II is due to a warm ionized phase separate from H2.

#### 4.7 Molecular fraction

The molecular mass fraction is estimated by

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

assuming that most of the hydrogen associated with H2 is neutral. In this case, as for many other QSO absorption systems, it is not clear how to divide the total NH II measured from the damping wings between different absorbing components, and in principle each NH II component could have a different fH2 value. To calculate fH2, we use the total NH II from both components and conservatively assume that all NH II is associated with H2, meaning fH2 is effectively a lower limit. This gives a molecular fraction of log10 fH2 = −1.93 ± 0.36. As we discuss in the next section, given the total NH II, this is a usually high molecular fraction compared to most other higher 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 fH2. To calculate a lower limit on fH2 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, 1, 1108.5; J = 2, 1, 934.1 and J = 3, 1, 952.3) using the AOD method. This gives a lower limit of NH II = 1016.5 cm−2 or fH2 < 10−3, again assuming all of the NH II is associated with the NH II. This is still a high value relative to local H2 systems with similar NH II.

#### 5 DISCUSSION

##### 5.1 Physical conditions in the H2 cloud

To consider this system in the context of other H2 detections in absorption, we plot fH2 for local and higher redshift H2 sightlines as a function of the total hydrogen column density and NH II in Fig. 8. It is apparent that the z = 0.56 sub-DLA (the solid circle) has an unusually high fH2, given its NH II 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 fH2 distribution as a function of NH II and NH II. The left-hand panel shows a clear bimodality in the fH2−NH II distribution between high NH II, high fH2 sightlines at the top right, and lower fH2 sightlines, generally with much lower NH II. The right-hand panel shows that this is actually a bimodality between NH II values < 1016 and > 1016 cm−2. This can be understood as the onset of H2 self-shielding against UV dissociating photons.

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**Figure 7.** CLOUDY predictions (lines) and observed column densities (points) for C I, C II, C III, Si II, Si I and Ca II for the IGM-like model with Z = 0.13Z⊙. Points are plotted at the most likely U values based on constraints from the N(Hel)/N(Mg II), N(HI)/N(HII) and N(SiII)/N(Si I) ratios (Si and C III points are offset for clarity). The filled points correspond to the solid lines of the same colour, the open points to the dashed lines and the open points with dotted edges to the dotted lines. Where error bars are not shown they are smaller than the marker size. With the exception of C I and Ca II, the column densities are reproduced well. As discussed in Section 5.4, the excess NC II is likely due to C I being in a self-shielded cold phase where H2 and possibly part of the Ca II reside.
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 \( f_{\text{H}_2} \) 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 \( f_{\text{H}_2} \), \( N_{\text{HI}} \) and \( N_{\text{H}_2} \). Shading shows the regions in which H\(_2\) cannot be detected for a limit of \( N_{\text{HI}} \leq 10^{14.5} \) cm\(^{-2}\), a typical threshold for the spectra used for the different surveys. 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.

(e.g. Hirashita & Ferrara 2005; Gillmon et al. 2006). An analytic approximation from Draine & Bertoldi (1996) shows that >97 percent of H\(_2\)-dissociating photons are blocked by self-shielding once \( N_{\text{HI}} \approx 10^{16} \) 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 \( f_{\text{H}_2} \) for the MW sightlines through SMC reasonably well, although Welty et al. (2012) point out that these models overpredict the \( N_{\text{HI}} \) at which this transition occurs.

The \( N_{\text{HI}} \) at which there is sufficient shielding from the UV field to form large amounts of H\(_2\) varies depending on the dust-to-gas ratio, the strength of the UV field, and the H\(_2\) line width, so the \( N_{\text{HI}} \) at which the transition from optically thin to optically thick occurs can change from sightline to sightline. In the plane of the MW disc, the transition from low to higher \( f_{\text{H}_2} \) takes place around \( N_{\text{HI}} = 10^{20.5} - 10^{21} \) cm\(^{-2}\). It occurs at higher \( N_{\text{HI}} \) in the Large Magellanic Cloud (LMC) and SMC, both because their lower metallicities (0.5 and 0.2 \( Z_\odot \), respectively, see the appendices from Welty et al. 1997, 1999) result in a lower H\(_2\) formation rate on grains, and due to an increased UV field compared to the MW (Tumlinson et al. 2002). Gillmon et al. (2006) have also shown that the large variation in \( f_{\text{H}_2} \) along different sightlines implies that each sightline must intersect a small number of molecule-bearing clouds.

In addition to comparing to the two-phase equilibrium models of McKee & Krumholz, we can compare to simple analytic models that apply to diffuse H\(_2\) in the partially shielded regimes. Following the appendix from Jorgenson et al. (2010), the dissociation rate in \( s^{-1} \) due to photons with energies corresponding to the Lyman–Werner bands is given by

\[
R_{\text{diss}} = 1.1 \times 10^8 4\pi J_{\nu}^{\text{LW}} S_{\text{shield}},
\]

where \( J_{\nu}^{\text{LW}} \) is the strength of the incident radiation field in erg \( s^{-1} \) cm\(^{-2}\) Hz\(^{-1}\) sr\(^{-1}\) at 1000 Å, and \( 1 - S_{\text{shield}} \) is the fraction of Lyman–Werner photons processed by dust or scattered due to H\(_2\) shielding, which can be calculated using the analytic expressions from Draine & Bertoldi (1996) and Hirashita & Ferrara (2005). In formation–dissociation equilibrium, the molecular fraction can be approximated by

\[
f_{\text{H}_2} = 2 \frac{\kappa R n_{\text{HI}}}{R_{\text{diss}}},
\]

where \( R \) is the formation rate of H\(_2\) on dust grains in cm\(^3\) s\(^{-1}\), \( n_{\text{HI}} \) is the H\(_I\) particle density in cm\(^{-3}\) and \( \kappa \) is the dust-to-gas ratio relative to that in the solar neighbourhood as defined in Section 4.2. Note that the formation rate term used by Hirashita & Ferrara

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\(^5\) Dust shielding only becomes important at total H columns of \( \sim 10^{21} \) cm\(^{-2}\), assuming solar metallicity.
where $J_{SW}^{LW} = 3.2 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ and $R_{SN} = 3 \times 10^{-17} \text{ cm}^3 \text{ s}^{-1}$ are typical values measured in the solar neighborhood (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 $\kappa$ and $f_{HI}$. The upper curve and middle curves each have $n_{HI} = 10 \text{ cm}^{-3}$ with $\kappa = 0.04, 0.1 R_{SN}, 10 J_{SW}^{LW}$ and $\kappa = 1, 0.33 R_{SN}, 2 J_{SW}^{LW}$, respectively. The lower curve has $\kappa = 0.04, n_{HI} = 5 \text{ cm}^{-3}, R_{SN}$ and $0.01 J_{SW}^{LW}$. This lower curve has qualitatively different behavior from the upper two curves, because at such low molecular fractions, dust shielding from dissociating photons becomes important before $H_2$ self-shielding. Therefore, the observed variation in $f_{HI}$ 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 the $H_2$ formation–dissociation equilibrium, the combination of low $N_{HI}$ and high molecular fraction suggests that it is either in a weaker UV field, and has an increased $H_2$ formation rate, a higher $n_{HI}$ compared to the solar neighbourhood or some combination of these three. We can use limits on the column densities of the $J = 4$ and 5 levels to put upper limits on $J_{SW}^{LW}$ (Jura 1975b). These upper limits are not very stringent, however, due to weak limits on the column densities, and constrain $J_{SW}^{LW} \lesssim 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$. This is consistent with the different UV background values assumed in the CLOUDY models, which range from $\sim 10^{-12}$ for the IGM-like scenario to $\sim 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ for the ISM-like scenario.

Using $f_{HI}$ and $N_{HI}$ measured in the $z = 0.56$ sub-DLA, the measured metallicity and equation (8), we find densities of $\sim 1$–4 cm$^{-3}$ for a UV background incident radiation field, and $\sim 70$–480 cm$^{-3}$ for a MW ISM-like 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. The only direct measurement of the size of a redshifted $H_2$ absorber is by Balashev et al. (2011), through partial covering of a background QSO broad-line region. They find the region producing $H_2$ is $\sim 0.15$ pc and its surrounding neutral envelope $\sim 8$ pc, both of which are consistent with our size estimates. The upper end of our density range is consistent with values measured for higher redshift $H_2$ systems using C$\alpha$ fine structure transitions, but would result in extremely small cloud sizes.

The low total 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 $N_{HI}$ and almost as high $f_{HI}$ 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 $0.3$–$3$ 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 $f_{HI}$–$N_{HI}$ distribution for higher $z$ $H_2$ systems. This could be due to 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 $f_{HI}$ and $N_{HI}$ most similar to this system are those described by Petitjean et al. (2002) ($z = 1.973$ towards Q0013–0029 with $N_{HI} \lesssim 10^{19.4}$ cm$^{-2}$, $f_{HI} = 10^{-2.63}$), Reimers et al. (2003) ($z = 1.51$ towards HE0515–4414 with $N_{HI} = 10^{19.88}$ cm$^{-2}$, $f_{HI} = 10^{-2.64}$), and Tumlinson et al. (2010) and Milutinovic et al. (2010) ($z = 2.059$ towards Q2123–0500 with $N_{HI} = 10^{19.18}$ cm$^{-2}$, $f_{HI} = 10^{-1.54}$). The $z = 1.973$ system is a sub-DLA component that is highly depleted to the same extent as is observed for cold 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 ± 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 $f_{HI}$ and low $N_{HI}$ 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 × 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 0.7$L_\odot$ (G1) and 2$L_\odot$ (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 $10^{-2}$ cm$^{-3}$. Even assuming a factor of 10 uncertainty in the radiation field strength, this is much lower than...
the typical densities where $H_2$ is seen in both our galaxy and in other $H_2$-bearing DLAs ($n_{HI} = 10^{10} - 10^{14} \text{ cm}^{-3}$). 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 $H_2$ 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 $H_2$ resides. This is also likely the cause of the excess $N_{C I}$ over that predicted by the CLOUDY models. C I is often seen in dense components showing $H_2$ (e.g. Srianand et al. 2005) and can have extremely narrow line widths corresponding to temperatures of $\sim 100 \text{ K}$ (Jorgenson et al. 2009; Carswell et al. 2011), indicating that it occurs in the same environment as $H_2$. Thus, most of the C I and some Ca II may be from a high-density region co-spatial with $H_2$.

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 ($\sim 0.1 \text{ solar}$), significant O vi is only produced via collisional ionization for temperatures larger than $10^5 \text{ K}$, even in non-equilibrium cases (Gnat & Sternberg 2007). Thus, it is likely that a hotter medium than that producing the $H_2$ and metal lines is also present.

We conclude that the absorption is due to gas in three phases: a photoionized medium at $\sim 10^4 \text{ K}$ in which most of the metal transitions we see are produced, a cold neutral medium at $\sim 100 \text{ K}$ where the $H_2$ and C I absorption occurs and a hotter phase where O vi is produced. The $H_1$ 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 Milutinovic et al. did not report an O vi detection, but as this system was at a higher redshift, it may have been heavily blended with Ly$\alpha$ forest absorption.

The Magellanic Stream and many other HVCs comprise $10^4 \text{ K}$ ionized gas that is seen in Hz emission, $T > 10^4 \text{ K}$ hot gas producing O vi absorption and they can also contain cold neutral gas with $H_2$ (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 $L^*$ 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 $H_2$ 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 $H_2$ 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 $H_2$ 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 $H_2$ 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 $N_{H_2} \gtrsim 10^{14} \text{ cm}^{-2}$ at low redshift to be $2/9 = 22 \text{ per cent}$ (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 $N_{H_2} < 10^{20} \text{ cm}^{-2}$. This is a surprisingly large fraction given that sub-DLAs are often found to be highly ionized absorbers with $N_{HI} \lesssim 10$ per cent of their hydrogen in the form of $H_1$.

If we think that the absorption cross-section for $H_2$ 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 $30–100 \text{ per cent}$ of the observed incidence rate of systems with $N_{HI} > 10^{17.5} \text{ cm}^{-2}$ as IVCs and HVCs distributed around galaxies with $H_1$ masses between $10^{5.5}$ and $10^{10} \text{ M}_\odot$ 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 $N_{HI}$ 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 $H_2$ in further $10^{19} \text{ cm}^{-2} < N_{HI} < 10^{20.3} \text{ cm}^{-2}$ 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 $H_2$ is more likely to be found in DLAs with both these characteristics (Norterdaeme 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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6 SUMMARY

We have analysed a sub-DLA system with $N_{H_2} = 10^{19.5} \pm 0.2$ 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 $f_{H_2} > 10^{-2}$. This is higher than other sightlines with similar $N_{H_2}$, 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 $0.19^{+0.21}_{-0.12}$ 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 $10^4$ 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 $O_v$. We conclude that there are three phases in the absorber; a $T \sim 100$ K phase where the $C_1$ and $H_2$ rise, a $T \sim 10^4$ K phase where the low-ionization metal absorption occurs, and a hotter, collisionally ionized phase associated with $O_v$.

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 $N_{H_2}$, 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 $N_{H_2} \gtrsim 10^{14.5}$ cm$^{-2}$,
APPENDIX A: CORRECTING FOR WAVELENGTH SHIFTS IN THE COS EXPOSURES

When combining the COS exposures, we found there were shifts of \( \sim 20 \, \text{km s}^{-1} \) in the wavelength solution between exposures taken us-

### Table A1. Wavelength shifts required to bring COS G160M exposures with central wavelength settings 1589 and 1627 Å on to a common wavelength scale. The shift \( \lambda_0 \) that must be added to a wavelength \( \lambda \) is given by \( \Delta \lambda = \alpha \lambda + \beta \). The FUVA shift is applied to the 1627 central wavelength setting, and the FUVB shift is applied to the 1589 setting.

| Segment | Valid \( \lambda \) range (Å) | Apply to \( \lambda \) setting | \( \alpha \) | \( \beta \) |
|---------|----------------------------|-------------------------------|--------|-------|
| FUVA    | 1600–1800                  | 1627                         | \( 1.233 \times 10^{-3} \) | -2.115 |
| FUVB    | 1425–1600                  | 1589                         | \( -0.952 \times 10^{-3} \) | 1.468  |

### Table A2. Wavelength shifts inferred from the H\(_2\) absorption as function of wavelength. \( \Delta \lambda \) should be added at each wavelength \( \lambda \) to correct the wavelength scale.

| \( \lambda \) (Å) | \( \Delta \lambda \) | \( \lambda \) | \( \Delta \lambda \) |
|------------------|-------------------|-------------|-------------------|
| 1425             | -0.1009           | 1625        | -0.0062           |
| 1450             | -0.0848           | 1650        | -0.0033           |
| 1475             | -0.0679           | 1675        | -0.0011           |
| 1500             | -0.0514           | 1700        | 0.0009            |
| 1525             | -0.0365           | 1725        | 0.0029            |
| 1550             | -0.0245           | 1750        | 0.0052            |
| 1575             | -0.0160           | 1775        | 0.0080            |
| 1600             | -0.0101           | 1800        | 0.0116            |
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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