A precise deuterium abundance: remeasurement of the $z = 3.572$ absorption system towards the quasar PKS1937–101

S. Riemer-Sørensen,1,2⋆ S. Kotuš,3⋆ J. K. Webb,4 K. Ali,5 V. Dumont,4,6 M. T. Murphy3 and R. F. Carswell7

1Institute of Theoretical Astrophysics, The University of Oslo, Boks 1072 Blindern, NO-0316 Oslo, Norway
2ARC Centre of Excellence for All-sky Astrophysics (CAASTRO), Institute of Theoretical Astrophysics, The University of Oslo, Boks 1072 Blindern, NO-0316 Oslo, Norway
3Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn VIC 3122, Australia
4School of Physics, University of New South Wales, Sydney NSW 2052, Australia
5International Centre for Radio Astronomy Research (ICRAR), University of Western Australia, 35 Stirling Hwy, Crawley WA 6009, Australia
6Department of Physics, University of California, Berkeley, CA 94720-7300, USA
7Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

Accepted 2017 March 16. Received 2017 March 14; in original form 2016 May 23

ABSTRACT

The primordial deuterium abundance probes fundamental physics during the big bang nucleosynthesis and can be used to infer cosmological parameters. Observationally, the abundance can be measured using absorbing clouds along the lines of sight to distant quasars. Observations of the quasar PKS1937–101 contain two absorbers for which the deuterium abundance has previously been determined. Here, we focus on the higher redshift one at $z_{\text{abs}} = 3.572$. We present new observations with significantly increased signal-to-noise ratio that enable a far more precise and robust measurement of the deuterium to hydrogen column density ratio, resulting in $D/\text{H} = 2.62 \pm 0.05 \times 10^{-5}$. This particular measurement is of interest because it is amongst the most precise assessments to date and it has been derived from the second lowest column-density absorber [$N(\text{H} I) = 17.9 \text{ cm}^{-2}$] that has so far been utilized for deuterium abundance measurements. The majority of existing high-precision measurements were obtained from considerably higher column density systems [i.e. $N(\text{H} I) > 19.4 \text{ cm}^{-2}$]. This bodes well for future observations as low column density systems are more common.

Key words: nuclear reactions, nucleosynthesis, abundances – quasars: absorption lines – cosmological parameters – primordial nucleosynthesis.

1 INTRODUCTION

Any presence of non-standard physics, e.g. from dark matter or additional neutrinos, during the epoch of big bang nucleosynthesis (BBN) may change the conditions under which the light elements such as deuterium, helium and lithium formed and their resulting abundances (e.g. Steigman 2012; Bœhm, Dolan & McCabe 2013; Nollett & Steigman 2014; Archidiacono et al. 2015). While the abundances (e.g. Steigman 2012; Bœhm, Dolan & McCabe 2013; Archidiacono et al. 2015) to distinguish between more detailed scenarios (e.g. Di Valentino, Melchiorri & Mena 2013; Steigman 2013).

The abundance of deuterium traces the number density of baryons at early times, which can also be determined from the cosmic microwave background (CMB; Fixsen 2009). Planck provides the highly precise measurement of $\Omega_b h^2 = 0.0225 \pm 0.00016$ (where $h$ is the dimensionless Hubble parameter $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$) at the time of recombination (Planck Collaboration III 2016), which can be compared to the value obtained from BBN to infer any time evolution.

In this paper, we present a new and precise measurement of the deuterium abundance in the absorption system at $z_{\text{abs}} = 3.572$ towards the quasar PKS1937–101 (B1950, emission redshift $z_{\text{em}} = 3.787$; Lanzetta et al. 1991). The deuterium abundance has previously been determined in two well-separated absorption systems in the sight-line to PKS1937–101 at $z_{\text{abs}} = 3.256$ (Crighton et al. 2004) and $z_{\text{abs}} = 3.572$ (Tytler, Fan & Burles 1996; Burles & Tytler 1998). Here, we focus on the $z_{\text{abs}} = 3.572$ absorber, previously suggested as an ideal absorber for a $D/\text{H} I$ measurement, due to its low metallicity, high column density and simple velocity structure (Tytler et al. 1996). The low-redshift system was re-analysed in a companion paper (Riemer-Sørensen et al. 2015). Since the first measurements were published, PKS1937–101 has been the target of extensive observations with both the Ultraviolet and Visual Echelle Spectrograph (UVES) at the Very Large Telescope (VLT) and the High Resolution Echelle Spectrometer (HIRES) at the Keck
The observational data used in this paper are listed in Table 1. In Section 2, we present the observational data, and the analysis details in Section 3. The results are presented in Section 3.6 with the conclusions in Section 5.

3 OBSERVATIONS

The observational data used in this paper are listed in Table 1. It includes all the observations listed in table 1 of Riemer-Sørensen et al. (2015) plus an additional publicly available Keck observation.1

The observations are reduced and continuum-fitted using standard procedures as described in Riemer-Sørensen et al. (2015). In Section 3.2, we discuss possible continuum-level uncertainties and how we account for them.

The individual quasar exposures taken with similar grating settings and slit-widths (i.e. resolving powers) were combined with inverse-variance weighting. This provided a total of five final spectra that, if combined, would completely cover the wavelength range of 4100–6400 Å. The average signal-to-noise ratio of the fitted Lyman regions varies from 14 to 65 for pixel sizes of 2.5–4.3 km s\(^{-1}\) (the individual values are given in Table 2).

| Date             | Primary investigator | Instrument | Settings\(^a\) | Resolving power | Resolution\(^b\) \(\sigma_v (\text{km s}^{-1})\) | Observation time (ks) |
|------------------|---------------------|------------|----------------|----------------|---------------------------------|----------------------|
| 1996-08-09       | Songaila            | Keck LRIS  | \(w = 0.7 \text{ arcsec} \text{ and } 1.5 \text{ arcsec}\) | 1500, 300       | 400                             | 2.4, 2.7             |
| 1997-10-02       | Cowie               | Keck HIRES | C5 (1.148 arcsec, 4000/6480 Å) | 37 000          | 3.5                             | 4 × 2.4              |
| 1997-10-03       | Cowie               | Keck HIRES | C5 (1.148 arcsec, 3910/6360 Å) | 37 000          | 3.5                             | 4 × 2.4              |
| 1997-10-04       | Cowie               | Keck HIRES | C5 (1.148 arcsec, 3910/6360 Å) | 37 000          | 3.5                             | 2 × 2.4 + 1 × 1.4    |
| 2005-07-01       | Crighton            | Keck HIRES | B5 (0.861 arcsec, 3630/8090 Å) | 49 000          | 2.8                             | 6 × 3.6              |
| 2005-08-12       | Tyler               | Keck HIRES | C5 (1.148 arcsec, 3790/6730 Å) | 37 000          | 3.5                             | 2 × 6.4 + 1 × 6.0    |
| 2006-04-10       | Carswell\(^c\)      | VLT UVES   | DICHR\#1 (1.0 arcsec, 3900/5800 Å) | 45 000          | 2.8                             | 1 × 5.4              |
| 2006-06-01       | Carswell\(^c\)      | VLT UVES   | DICHR\#1 (1.0 arcsec, 3900/5800 Å) | 45 000          | 2.8                             | 2 × 5.4              |
| 2006-06-25       | Carswell\(^c\)      | VLT UVES   | DICHR\#1 (1.0 arcsec, 3900/5800 Å) | 45 000          | 2.8                             | 1 × 5.4              |
| 2006-07-21       | Carswell\(^c\)      | VLT UVES   | DICHR\#1 (1.0 arcsec, 3900/5800 Å) | 45 000          | 2.8                             | 1 × 5.4              |

\(^a\) Slit width for LRIS, slit width, cross-disperser angle and central wavelength for HIRES, and slit width and central wavelength of the blue/red arms for UVES.

\(^b\) Velocity width of the resolution element, \(\sigma_v\), as determined by illuminating the instrument with a Thorium–Argon lamp. The individual \(\sigma_v\) have been \(\chi^2\) optimized as described in Section 3.3.

\(^c\) All VLT UVES observations belong to the ESO programme with ID 077.A-0166(A).

Notes. a) Specific to the analysis described in this paper.

Table 1. Observations included in the analysis (including those of table 1 in Riemer-Sørensen et al. 2015).

2 ANALYSIS AND RESULTS

A more complete description of the analysis methods is given in Riemer-Sørensen et al. (2015). Here, we provide additional details specific to the analysis described in this paper.

1 Keck Observatory Archive; http://www2.keck.hawaii.edu/koa/public/koa.php.

3.1 Spectral fitting

The five individual spectra (Section 2) are fitted simultaneously but separately, rather than being combined into a single, composite spectrum as is more commonly the approach. For visualization we use a variance-weighted stacked spectrum of the HIRES and UVES spectra as shown in Fig. 1. We fit six heavy element transitions: \(\text{Fe}\) \(\text{II} 1122, \text{Si}\) \(\text{II} 1193, \text{Si}\) \(\text{II} 1304, \text{Si}\) \(\text{IV} 1393, \text{Si}\) \(\text{IV} 1402\) and \(\text{C}\) \(\text{II} 1334\), and nine Lyman transitions (from Lyman \(\alpha\) to Lyman 9) together with the saturated Lyman limit in the lower resolution spectrum from the Low Resolution Imaging Spectrometer (LRIS) at the Keck Telescope. We include the LRIS Lyman limit data to better constrain the hydrogen column density.

To optimize the accuracy of our measurement, we solve for the total column density in the absorption complex rather than the column densities of the individual subcomponents. We force the column density ratio of \(\text{D}\)/\(\text{H}\) to be identical across all subcomponents, which corresponds to assuming that any deuterium depletion mechanisms act uniformly on all components. This is a reasonable assumption as the total metallicity of the absorber is less than 1/100th of the solar value (Section 3.7). The column densities of the other species are allowed to vary between components.

To assess whether the scatter in current deuterium measurements (see Table 4 and Fig. 4) might be correlated with the observing telescopes, we also fitted the model to the spectra from Keck alone and from VLT alone, in addition to the entire data set.
Precise deuterium measurement at \( z = 3.572 \)

Figure 1. The composite spectrum, created by combining the four different exposure stacks used in the analysis with variance weighting (thick black), the final model fit (thick green/light grey) and the residuals between the two (grey, above the spectrum in each panel) normalized by the 1\( \sigma \) error array (indicated by light blue horizontal lines). This composite spectrum is not used in the analysis; it is for visualization purposes only and the analysis uses the four exposure stacks simultaneously to constrain the model fit parameters. The vertical dot-dashed lines mark the velocity components A–D: red/light grey for H I, blue/dark grey for D I, light blue/light grey for heavy elements. Interloping H I absorption is marked by light grey vertical dotted lines. The model from Tytler et al. (1996) (without blends) is overplotted (thin orange/grey). It is clear that we find a different structure particularly for the metals.

3.2 Velocity shifts and continuum

As in Riemer-Sørensen et al. (2015), we explicitly allow for small velocity shifts between individual exposures that are expected to arise from slit-centring and wavelength calibration differences. We effectively force all regions from a given spectrum to have identical shifts. The only exception is the VLT spectrum of the Lyman 5 region where the preferred velocity shift (\( \approx 1.1 \) km s\(^{-1}\)) differs to the other regions in the same spectrum (\( \approx 0.5 \) km s\(^{-1}\)) and we have introduced that shift as an extra free parameter during the \( \chi^2 \) minimization process. Allowing independent shifts in any of the other regions did not improve the \( \chi^2 \) per degree of freedom (\( \chi^2/\text{dof} \)).

To account for possible uncertainties in the continuum level determination, we fit a local continuum in each region. Where a reasonable amount of unabsorbed continuum is available on both sides of the line, we allow for a local slope on the continuum (Cu 1334 and Lyman \( \beta \), 5, 7, 8), but otherwise we keep the slope fixed at zero (Fe \( \pi \), Si \( ii \), Si \( iv \) and Lyman \( \alpha \), \( \gamma \), 4, 6, 9).

Both the continua and the best-fitting velocity shifts are given in Table A1, and we apply them before combining the spectra for visualization as shown in Fig. 1.

3.3 Spectral resolution

The spectral resolution in velocity units, \( \sigma_v \), is given in the telescope manuals\(^2\) based on exposures with a Thorium–Argon lamp. For science exposures of the quasar, the slit may not be uniformly filled, unlike for the Thorium–Argon exposures. This may lead to a difference between the Thorium–Argon line width and the actual spectral resolution. We explored this possibility by varying the spectral resolution of each individual fitting region so as to minimize the overall \( \chi^2 \) for the fit while keeping all other parameter

---

\(^2\) http://www2.keck.hawaii.edu/inst/hires/slitres.html, http://www.eso.org/sci/facilities/paranal/instruments/uves/inst.html for the individual settings based on
values fixed. Of the 72 individually fitted regions, the resolution was changed from the Thorium–Argon estimate for 14, of which only three required more than a 20 per cent adjustment. After this optimization, the resolutions were kept fixed during the fit. Re-running the fit after the adjustments of the resolution improved the total $\chi^2$/dof by $\sim$0.15.

### 3.4 Models

The absorption signature just bluewards of the strongest hydrogen lines (Lyman $\alpha$, $\beta$ and $\gamma$) is visible in the composite spectrum in Fig. 1. Its velocity is offset by $-88 \pm 13$ km s$^{-1}$ from the main absorption, consistent with the expected deuterium–hydrogen separation of 82 km s$^{-1}$. Further, this absorption line is significantly narrower than other nearby Lyman lines, but significantly broader than is typical for heavy element absorption lines. We thus interpret this line as being due to D I (see also Section 4.1).

The composite spectrum in Fig. 1 shows that the Si IV absorption comprises at least two velocity components, which are both slightly asymmetric. We model this with four Voigt profiles (velocity components A, B, C, D) that we require to have identical redshifts, temperatures and turbulent $b$-parameters across all species, but individual summed column densities. Only the column density ratio of O I to H I is assumed to be the same for components A–D, the remaining relative abundances are free to vary. The B and C components are clearly visible in all heavy elements, while A and D have lower column densities and D is not required to adequately fit the weaker metal transitions of C II and Fe III for which the column densities drop below the threshold value of log ($N$/H) $< 8$ and are removed from the fit.

Adding additional components to the system did not improve the $\chi^2$/dof significantly. To avoid biasing, the final model for the absorption system was selected based on $\chi^2$/dof without checking the impact on the D/H ratio.

The presence of multiple heavy element species makes it possible to simultaneously fit for both temperature and $b$-parameters for the main components (A–D).

The best-fitting $\chi^2$/dof is 1.04 with the resulting parameters given in Table A1 and the H I and D I column densities given in Table 3.

The species of C II, Si II, Fe III and H I have significantly lower ionization potentials than Si IV, which therefore may not always trace the full velocity structure of the lower ionization species (Wolfe & Prochaska 2000; Fox et al. 2007). In locations where we find Si IV there is also bound to be hydrogen, but it may not be in the form of H I. In the model fitting, this is taken into account by keeping the column densities of the individual species unrelated. If the fit is good (based on $\chi^2$/dof) without H I for a given component in Si IV VPFIT will automatically remove the component. Consequently, the probability of finding the correct velocity structure is higher when we use the entire range of metals available, and including the higher ionization species should not bias D I/H I. We note that all components present in Si IV are also present in Si II, but with the velocity structure much better resolved in Si IV. Refitting without Si IV leads to a simpler velocity structure with only two components, but also a significant increase in $\chi^2$/dof, e.g. 1.19–1.59, for the C II regions. We conclude from this that Si IV helps significantly in determining the velocity structure.

O I is not clearly present in the individual spectra, but when fitting all spectra simultaneously, we obtain a non-zero summed column density based on O I 1302 under the assumption of constant O/H across all components (see Table A1). The O I column density is used as input for CLOUDY simulations in Section 3.7 to determine the metallicity of the absorber.

### 3.5 Fitting the Lyman limit

The high-resolution spectra of the Lyman limit contain many blended Lyman series lines that makes it harder to establish a reliable continuum level and complicates the modelling. Instead, we
verify that the model derived using the first nine lines in the Lyman series is consistent with the observed Lyman limit data as shown in Fig. 2.

### 3.6 Resulting deuterium and hydrogen column densities

Table 3 gives the resulting column densities of D I and H I and the ratios derived using the different data subsets. The main result from combining these measurements is a D I/H I column density ratio of $2.62 \pm 0.05 \times 10^{-5}$.

The spectra from the two different telescopes separately provide consistent results within the 1σ uncertainties, with the Keck spectrum leading to a slightly higher estimate of the D I/H I ratio: $(D/H)_{\text{Keck}} = 2.70 \pm 0.16 \times 10^{-5}$ compared to $(D/H)_{\text{VLT}} = 2.58 \pm 0.18 \times 10^{-5}$. This difference is much less than the combined uncertainties involved and there is no evidence to suspect any systematic deviation between the two telescopes.

The uncertainties quoted above and in Table 3 are only statistical; they derive from the signal-to-noise ratio of the spectra and do not include any systematic error estimates. However, the larger values of the uncertainties are mostly dominated by the limitations of the CLOUDY simulations, we used a plane parallel geometry and a Haardt–Madau HM05 model as the ultraviolet background source. We generate a grid of models with the hydrogen number density bounded by $5 < n(H)_{\text{cm}^{-3}} < 204$, where the high-density limit comes from the upper limit to C II*/C II ratio determined as in Riemer-Sørensen et al. (2015).

The O I/H I and Si II/H I ratios are fairly insensitive to $n(H)$ and provide an allowable range of metallicity of $-3 \lesssim \log(Z/Z_\odot) < -1$ given the observational data. The left-hand panel of Fig. 3 shows the $n(H)$ range obtained by comparing CLOUDY models with the observed abundances. The lower ionization species agree with one another, leading to a conservative number density constraint $-2.11 < \log(n(H)) < -1.72$.

From the Voigt profile fit, we obtain a marginal detection of O I with a summed column density of log $N(O I) = 12.060 \pm 0.127$. The O I/H I ratio is sensitive to the metallicity $Z$ within the given $n(H)$ range as shown in the right part of Fig. 3 (arrows) and provides a constraint of $-2.50 < \log(Z/Z_\odot) < -1.99$. The simplest of chemical evolution models, as investigated by Fields et al. (2001), indicates little to no depletion of primordial deuterium for $log(Z/Z_\odot) < -1$; hence, this system appears to be a good estimator of initial D/H, given the allowable metallicity range.

We check the consistency of the CLOUDY models by comparing the output gas temperature with that estimated by VPFIT. The CLOUDY models take into account the average properties of all four components and provide a temperature range of $T_{\text{cloud}} = 14500 - 16300$ K. From VPFIT, the temperature is best determined for the dominating individual components A and C. The resulting temperatures of $T_{\text{VPFIT}} = 16410 \pm 370$ K and $T_{\text{VPFIT}} = 18650 \pm 658$ K, respectively, are based on absorption in all considered species. As can be seen, the temperature of models generated by CLOUDY is in reasonable agreement with that estimated by VPFIT.

Integrating through the absorbing cloud, i.e. allowing for varying particle density through the absorbing cloud, and taking into account the metallicity uncertainty, the cloud size is estimated as 2.7 ± 1.7 kpc.

### 4 DISCUSSION

#### 4.1 Hydrogen contamination of deuterium lines

It is possible that the line identified as deuterium may be contaminated by a weak hydrogen line. Assuming the hydrogen column density distribution to be a power law with index $\beta = 1.7$
The discrepancies between our new measurement and that of Burles & Tytler (1998b) may be due to several factors such as continuum placement, number of components and assumptions about physical properties of the absorber.

The continuum placement has been discussed in the literature. Wampler (1996) suggested models with three to six times larger H\(\text{i}\) column densities, while Songaila, Wampler & Cowie (1997) obtained log (N(H\(\text{i}\)) < 17.7 from the LRIS spectrum used in this analysis. Without supplementary high-resolution spectra, their continuum may have been poorly estimated. According to Burles & Tytler (1997), the unabsorbed continuum was underestimated in Songaila et al. (1997), but comparing with the high-resolution spectra, we find that it is more likely to be overestimated. However, as we treat the local continua as free parameters, the discrepancy with Burles & Tytler (1998b) more likely origins in the different numbers of fitted components. We have overlapped the initial model from Tytler et al. (1996) on the stacked spectrum in Fig. 1 (without additional hydrogen blends). Burles & Tytler (1998b) did not use any of the heavy element lines to derive D/H\(\text{i}\), and consequently their (\(\chi^2\)-based) choice of two components relies purely on the Lyman \(\alpha\) blending feature. The assumption is based on visual similarities in the spectrum combined with a significant increase in the Lyman \(\alpha\) blending feature. This leads to a conservative estimate of the blending probability of 3.7 per cent. If we consider only the dominant component (A), the probability reduces to 0.25 per cent supporting the claim that the observed feature is likely to be deuterium.

We also checked whether any heavy element lines from other absorbers along the line of sight fall in the regions fitted to obtain D/H\(\text{i}\). We identified tentative systems with lines from commonly found heavy elements (Al, C, Fe, Mg, Si) at \(z = [0.560, 0.567, 0.603, 0.896, 3.008, 3.095, 3.256, 3.291, 3.45, 3.553, 3.572, 30]\). The only potentially problematic candidate is from Fe\(\text{II}\) 1144 at \(z = 3.095\) that falls very close to D1 in Lyman \(\beta\). However, no other Fe\(\text{II}\) lines are present anywhere in the spectrum at this redshift, some of which have larger oscillator strengths than Fe\(\text{II}\) 1144. We therefore assume the Fe\(\text{II}\) 1144 at \(z = 3.095\) is too weak to significantly bias the deuterium column density.

### 4.2 Comparison with previous measurements

Using an independent sample of Keck HIRES exposures, and only two velocity components to model the hydrogen absorption, Burles & Tytler (1998b) estimated the D/H\(\text{i}\) ratio in the same absorber to be D/H\(\text{i}\) = 3.3 ± 0.3 \(\times\) 10\(^{-5}\) without using the heavy element lines. The initial measurement presented in Tytler et al. (1996) was improved with an H\(\text{i}\) column density measurement of log (N(H\(\text{i}\))) = 17.86 ± 0.02 based on the HIRES spectra with additional low-resolution spectra from LRIS and the Kast spectrograph on the Shane 3 metre Telescope at the Lick Observatory (Burles & Tytler 1997, 1998b).

### 4.3 The deuterium sample

Table 4 provides an updated version of the deuterium sample given in table 4 of Riemer-Sorensen et al. (2015), comparing the new D/H\(\text{i}\) measurement presented in this paper to the sample from Pettini et al. (2008) combined with recent measurements with similar precisions from Fumagalli, O’Meara & Prochaska (2011), Noterdaeme et al. (2012), Cooke et al. (2014), Riemer-Sorensen et al. (2015) and Balashev et al. (2016).

| Reference                         | Absorption redshift | log (N(H\(\text{i}\))) | [X/H] | D/H\(\text{i}\) \((\times\) 10\(^{-5}\)) | 100\(\Omega_{\text{b}}\) \(\chi^2\) |
|-----------------------------------|---------------------|-----------------------|-------|-----------------------------------|------------------|
| Burles & Tytler (1998a)           | 2.504               | 17.4 ± 0.07           | −2.55 Si | 4.00 ± 0.70                      | 1.66 ± 0.18      |
| Pettini & Bowen (2001)            | 2.076               | 20.4 ± 0.15           | −2.23 Si | 1.65 ± 0.35                      | 2.82 ± 0.36      |
| Kirkman et al. (2003)             | 2.426               | 19.7 ± 0.04           | −2.79 O | 2.43 ± 0.35                      | 2.24 ± 0.20      |
| Fumagalli et al. (2011)           | 3.411               | 18.0 ± 0.05           | −4.20 Si | 2.04 ± 0.61                      | 2.49 ± 0.05      |
| Noterdaeme et al. (2012)          | 3.621               | 20.5 ± 0.10           | −1.99 O | 2.80 ± 0.80                      | 2.05 ± 0.35      |
| Cooke et al. (2014), Pettini & Cooke (2012) | 3.050               | 20.392 ± 0.003       | −1.92 O | 2.51 ± 0.05                      | 2.19 ± 0.02      |
| Cooke et al. (2014), O’Meara et al. (2001) | 2.537               | 19.4 ± 0.01           | −1.77 O | 2.58 ± 0.15                      | 2.16 ± 0.04      |
| Cooke et al. (2014), Pettini et al. (2008) | 2.618               | 20.3 ± 0.01           | −2.40 O | 2.53 ± 0.10                      | 2.18 ± 0.03      |
| Cooke et al. (2014)               | 3.067               | 20.5 ± 0.01           | −2.33 O | 2.58 ± 0.07                      | 2.16 ± 0.03      |
| Cooke et al. (2014), O’Meara et al. (2006) | 2.702               | 20.7 ± 0.05           | −1.55 O | 2.40 ± 0.14                      | 2.25 ± 0.03      |
| Riemer-Sorensen et al. (2015)     | 3.255               | 18.1 ± 0.03           | −1.87 O | 2.45 ± 0.28                      | 2.23 ± 0.16      |
| Balashev et al. (2016)            | 2.437               | 19.98 ± 0.01          | −2.04 O | 1.97 ± 0.33                      | 2.54 ± 0.26      |
| This work                        | 3.572               | 17.925 ± 0.006        | −2.26 O | 2.62 ± 0.05                      | 2.14 ± 0.03      |
| Weighted average\(^d\)           | –                   | –                     | –     | 2.55 ± 0.03                      | 2.17 ± 0.03      |
| Unweighted average\(^d\)         | –                   | –                     | –     | 2.53 ± 0.17                      | 2.18 ± 0.08      |
| Planck Collaboration III (2016)   | –                   | –                     | –     | 2.45 ± 0.05                      | 2.225 ± 0.016    |

Notes. The conversion between D/H\(\text{i}\) and \(\Omega_{\text{b}}\)\(\chi^2\) is based on nuclear rates from Coc et al. (2015) for standard BBNs.

\(^d\)Without the Balashev et al. (2016) and Noterdaeme et al. (2012) measurements.
Precise deuterium measurement at \( z = 3.572 \)

**Figure 4.** The D/H ratios and metallicities from the literature sample defined in Table 4 plotted as a function of redshift (\( z \)), \( \text{H}_1 \) column density \((\log (N_{\text{H}_1}/\text{cm}^{-2}))\) and metallicity ([X/H]). The 1\( \sigma \) uncertainty in the weighted mean, \( \text{D}/\text{H}_1 = 2.55 \pm 0.03 \times 10^{-5} \), is shaded orange while the outer cyan shading indicates the root-mean-square deviation amongst the measurements. The inner dark shading indicates the constraint on D/H1 derived from the Planck measurements assuming standard BBN.

Fig. 4 supersedes fig. 4 from Riemer-Sørensen et al. (2015), illustrating the properties of the absorption systems for the results given in Table 4. As in Riemer-Sørensen et al. (2015), we again find no apparent correlation between any of the parameters, including deuterium and hydrogen column density versus redshift or metallicity.

The measurement from Balashev et al. (2016) is derived from a fairly complicated absorption system under the assumption that the O/H1 ratio is identical for all components. The same assumption is applied in Noterdaeme et al. (2012). It is unclear whether this assumption is appropriate for a high-precision measurement and we leave out these two measurements from further comparisons.

A new sample of very precise deuterium abundance measurements (\( \approx 4 \) per cent uncertainties) was presented by Cooke et al. (2014). They selected absorbers using narrow selection criteria to allow both precise and robust measurements; for example, they restricted the column density range to damped and sub-damped Lyman \( \alpha \) systems, i.e. \( \log (N_{\text{H}_1}/\text{cm}^{-2}) \geq 19 \). The obtained precision demonstrated the future prospects for deuterium as a cosmological probe. However, several important potential systematic errors remain, including the difficulties of modelling the uncertain velocity structure of individual absorbers, and estimating the uncertainties relating to continuum placement.

It is therefore necessary to obtain a significant sample of deuterium measurements so that it becomes possible to detect any plateau in D/H versus redshift or metallicity in order to obtain the primordial value, rather than relying on a small number of measurements where any intrinsic scatter cannot be reliably detected.

At \( z = 3.572 \), our new measurement has the highest redshift in the sample and one of the lowest column densities. The precision we obtain is comparable to those of Cooke et al. (2014) despite the new system being more complicated and lower column density. This demonstrates the future possibilities for a sample of high-resolution measurements as low column density absorbers are a lot more common than high column density absorbers. The last decade has seen a massive increase in the number and quality of high-resolution quasar spectra that have not yet been systematically searched for suitable low column density absorbers with visible deuterium lines.

The weighted and unweighted averages centre on very nearby values of \( (\text{D}/\text{H}_1) = 2.53 \pm 0.17 \) and \( (\text{D}/\text{H}_1) = 2.55 \pm 0.03 \), respectively, which can be compared with the recent prediction from standard BBN of \( (\text{D}/\text{H}_1) = 2.45 \pm 0.05 \) (Coc et al. 2015; Planck Collaboration III 2016). The deviation between the weighted average and Planck value is \((2.55 - 2.45)/\sqrt{0.03^2 + 0.05^2} = 1.7\sigma \); that is, there is no significant difference. However, the offset in the central values may indicate that some systematic error still remains despite the increasing data quality.

Fig. 4 does not reveal any strong correlations between D/H and redshift, metallicity or column density, but some scatter remains. According to recent chemical evolution modelling, we should expect some internal scatter in D/H measurements arising purely from the difference in the merger and star formation history of individual haloes (Dvorkin et al. 2016). Further high-precision measurements are...
needed to establish whether the different halo histories can explain the remaining scatter.

The most outlying D/H values in the sample are also the measurements with the highest uncertainties. If we define a high-precision sample by requiring \( \delta(D/H)/(D/H) < 0.15 \), we automatically exclude the four most outlying points in Fig. 4 and the weighted average become \( (D/H)_w = 2.56 \pm 0.03 \) consistent with the full sample value of \( 2.55 \pm 0.03 \).

### 4.4 The baryon fraction

Assuming that the total deuterium-to-hydrogen ratio is reflected by \( D/H \), we can derive the primordial value \( (D/H)_p \), because there are no sources of astrophysical production (Epstein, Lattimer & Schramm 1976; Prodanović & Fields 2003) and the destruction rate in stars is low at the relevant redshifts and metallicities (Romano et al. 2006; Dvorkin et al. 2016).

\( \Omega_b h^2 \) can be obtained using fitting relations for standard BBN calculations (e.g. Simha & Steigman 2008; Steigman 2007, 2012; Coc et al. 2015). The most recent update with particular focus on the nuclear reactions gives (Coc et al. 2015)

\[
10^3(D/H) = (2.45 \pm 0.04) \left( \frac{\Omega_b h^2}{0.022^{+25}_{-22}} \right)^{-1.657},
\]

where the uncertainty of 0.04 reflects the measured uncertainties in the nuclear reaction rates. The results from the existing D/H measurements and the averaged values are listed in Table 4. Several of the measurements in the table have percentage level statistical uncertainty, which is comparable to the uncertainty on the nuclear reaction rates. However, most of the quoted uncertainties do not take systematic uncertainties into account. In particular, the uncertainties related to the number of modelled components and the risk of hydrogen blends at the position of deuterium requires high-resolution, high-quality spectra and are best controlled by having a large sample of high-precision measurements.

### 4.5 Dipole fit

Variations in fundamental constants such as the fine structure constant, the hadronic masses or binding energies would lead to variations in the light element abundances (Dmitriev, Flambaum & Webb 2004; Dent, Stern & Wetterich 2007; Flambaum & Wiringa 2007; Berengut, Flambaum & Dmitriev 2010). Berengut et al. (2011) investigated whether the observed scatter in the D/H measurements could be due to a dipole similar to the one observed for the fine structure constant (Webb et al. 2011; King et al. 2012). Although the significance of the fine structure constant dipole may be somewhat reduced by instrumental effects (Whitmore & Murphy 2015), here we investigate whether a dipole in the same direction is preferred by the deuterium measurements and we also consider the dipole direction as a free parameter. The dipole is described by

\[
\log(N(D)/N(H)) = m_D + d_D r \cos(\psi(\phi_d, \theta_d)),
\]

where \( m_D \) is the average observed deuterium abundance (the monopole), \( d_D \) is the magnitude of the dipole, \( r = ct \) is the look-back distance and \( \psi(\phi_d, \theta_d) \) is the angle between a given observation with (RA, Dec.) = (\( \phi \), \( \theta \)) and the dipole direction (\( \phi_d \), \( \theta_d \)) given by

\[
\cos \psi = \cos(\phi - \phi_d) \cos(\theta - \theta_d) + \sin(\theta) \sin(\theta_d).
\]

The best fits with and without fixing the direction of the dipole are shown in Fig. 5 and the parameters given in Table 5. The preferred slopes are close to zero with uncertainties larger than the preferred value and consequently consistent both with a small dipole and with no dipole. Despite the increase in sample size and precision, the scatter does not allow us to draw any firm conclusions about anisotropy.

We also fit to the high-precision sample defined by less than 15 per cent uncertainty on D/H (Section 4.4). For fixed position, this is consistent with no dipole. When fitting the high-precision sample for the position, a dipole is preferred with around 2\( \sigma \) significance, but with a very large uncertainty on the direction and a \( \chi^2 \ll 1 \) indicating too many free parameters in the fit.

---

**Figure 5.** The best fit to the dipole model of Berengut et al. (2011) for fixed position (thick green line) and varying position (dashed blue line) as well as the observed abundances relative to the dipole directions (green and blue data points) and the average of the deuterium measurements (the monopole, thin grey line). The lower panel is a zoom of the y-axis. The crosses mark the high precision sample defined by less than 15 per cent uncertainty on D/H. The fits to the high-precision sample (not shown) lies very close to the full sample fits. The parameters are given in Table 5.

**Table 5.** Best-fitting parameters for fitting the variation in the deuterium measurements with the dipole model in equation (2).

|          | Full sample Fixed position | Fit position | High precision sample Fixed position | Fit position |
|----------|---------------------------|--------------|---------------------------------------|--------------|
| \( m_D \) | 4.592(6)                  | 4.59(1)       | 4.592(4)                              | 4.590(6)     |
| \( d_D \) | 0.00002(114)              | 0.0012(14)    | 0.0025(75)                            | 0.0014(6)    |
| RA (\( h \)) | 17.4 \pm 1.0             | 24.0 \pm 5.3  | 17.4 \pm 1.0                          | 0 \pm 2      |
| Dec. (\( ^\circ \)) | 61 \pm 10         | 29.5 \pm 70.7 | 61 \pm 10                             | 21.5 \pm 32  |
| \( \chi^2/dof \) | 15.55                   | 13.80         | 4.01                                  | 1.50         |
| \( \Delta BIC \) | 1.56                     | 1.72          | 0.67                                  | 0.38         |

**Notes.**

- Difference in Bayesian Information Criterion \( \Delta BIC = BIC_{slope} - BIC_{no\ slope} \).
- Evidence for preference of a zero slope model (no dipole) relative to a model with dipole based on the Bayesian Information Criterion.
4.6 Inhomogeneities

An interesting aspect of D/\HI is that deuterium was produced when the universe was 100 sec old and the temperature around 10^9 K. At that time the horizon size was 2ct = 6 × 10^23 cm. By today, this causally connected region has expanded by a factor of about 10^9/3 and so spans 2 × 10^23 cm or ~1 kpc. Regions larger than this (or collapsing down from regions larger than this) will have been causally disjoint at the time of deuterium synthesis. This implies that a sufficiently large sample of deuterium measurements will allow us to measure the homogeneity of the universe.

4.7 Dark matter constraints

Primordial element abundances may be very sensitive to the presence of the low-mass dark matter (Steigman 2012; Behm et al. 2013; Nollett & Steigman 2014; Archidiacono et al. 2015; Stadnik & Flambaum 2015). For example, in scenarios where a scalar dark matter field interacts with the standard model fields during nucleosynthesis spatial variation in the D/\HI ratio may arise (Stadnik & Flambaum 2015). Using the dipole constraints from Section 4.5, we can improve the constraint on the product of the fractional energy density’s spatial gradient with the interaction strength by a factor of roughly 40 relative to Stadnik & Flambaum (2015) as a consequence of the improved dipole constraint. The comparison of the calculated and measured deuterium abundances should lead to another breakthrough in the precision (Berengut, Stadnik & Flambaum, private communication).

5 CONCLUSIONS

From the analysis of the zabs = 3.572 absorption system in high-quality Keck and VLT spectra of quasar PKS1937–101, we make the following conclusions:

(i) We find the D/\HI ratio in this absorber to be 2.62 ± 0.05 × 10^{-3} that corresponds to 100\Omega_b\h^2 = 2.14 ± 0.03 for standard BBN. This value deviates by 1.7\sigma from the Planck measurement of 100\Omega_b\h^2 = 2.225 ± 0.016 and is considered consistent.

(ii) Independent fits to this absorption system using Keck and VLT spectra give consistent results.

(iii) The analysis presented here shows that lower column density systems can provide a precision on D/\HI comparable to higher column density DLAs (Cooke et al. 2014). This is important because the neutral hydrogen column density distribution in quasar absorption systems is a steep power law, with lower column density systems being more common. A statistically large sample of measurements is therefore feasible and necessary to reveal a plateau of primordial values as a function of, e.g. metallicity.

(iv) The spatial variation of the observed high-precision deuterium abundances is consistent with no dipole.

Deuterium abundance measurements using quasar absorption systems offer rare tests of the standard model of BBN and models with non-standard physics. While CMB measurements do offer high-precision measurements of the baryon density, a model of BBN must be assumed. However, beyond-standard models involving, for example, additional relativistic particle species or dark matter particles, often imply different conditions in the two epochs that can lead to different D/\HI expectation values (Steigman 2013). Therefore, studying both epochs observationally and comparing the independent constraints on the baryon density is an important opportunity to discover or rule out physics beyond the standard model.

ACKNOWLEDGEMENTS

We would like to thank N. Crighton for useful discussions and comments, and an anonymous referee for constructive comments. This research is based on observations collected at the European Organization for Astronomical Research in the Southern hemisphere, Chile, proposal ID 077-A-0166 obtained by PIs Carswell, Kim, Haehnelt and Zaroubi. It is also based on observations collected with the Keck Observatory Archive (KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExScI), under contract with the National Aeronautics and Space Administration. The Keck data were obtained by PIs Songaila, Cowie, Crighton and Tyler. MTM thanks the Australian Research Council for Discovery Project grant DP130100568 that supported this work. Parts of this research were conducted by the Australian Research Council Centre of Excellence for All-sky Astrophysics (CAASTRO), through project number CE110001020.

REFERENCES

Archidiacono M., Hannestad S., Hansen R. S., Tram T., 2015, Phys. Rev. D, 91, 065021
Aver E., Olive K. A., Skillman E. D., 2015, J. Cosmol. Astropart. Phys., 7, 011
Bahcall J., Wolfe R., 1968, ApJ, 152
Balashev S. A., Zavarygin E. O., Ivanvich A. V., Telikova K. N., Varshalovich D. A., 2016, MNRAS, 458, 2188
Berengut J., Flambaum V., Dmitriev V., 2010, Phys. Lett. B, 683, 114
Berengut J. C., Flambaum V. K., King J. A., Curran S. J., Webb J. K., 2011, Phys. Rev. D, 83, 123506
Burles S., Tytler D., 1997, AJ, 114, 1330
Burles S., Tytler D., 1998a, ApJ, 499, 699
Burles S., Tytler D., 1998b, ApJ, 507, 732
Behm C., Dolan M. J., McCabe C., 2013, J. Cosmol. Astropart. Phys., 8, 41
Coc A., Pettjejan P., Uzan J.-P., Vangioni E., Descouvemont P., Iliadis C., Longland R., 2015, Phys. Rev. D, 92, 123526
Cooke R. J., Pettini M., Jorgenson R. A., Murphy M. T., Steidel C. C., 2014, ApJ, 781, 31
Crighton N. H. M., Webb J. K., Ortiz-Gil A., Fernández-Soto A., 2004, MNRAS, 355, 1042
Dent T., Stern S., Wetterich C., 2007, Phys. Rev. D, 76, 063513
Di Valentino E., Melchiorri A., Mena O., 2013, J. Cosmol. Astropart. Phys., 11, 18
Dmitriev V. F., Flambaum V. V., Webb J. K., 2004, Phys. Rev. D, 69, 063506
Dvorkin I., Vangioni E., Silk J., Petitjean P., Olive K. A., 2016, MNRAS, 458, L104
Epstein R. I., Lattimer J. M., Schramm D. N., 1976, Nature, 263, 198
Ferland G. J. et al., 2013, Rev. Mex. Astron. Astrofis., 49, 137
Fields B. D., Olive K. A., Silk J., Cassé M., Vangioni-Flam E., 2001, ApJ, 563, 653
Fixsen D. J., 2009, ApJ, 707, 916
Flambaum V. V., Wiringa R. B., 2007, Phys. Rev. C, 76, 054002
Fox A. J., Ledoux C., Petitjean P., Srianand R., 2007, A&A, 473, 791
Fumagalli M., O’Meara J. M., Prochaska J. X., 2011, Science, 334, 1245
Izotov Y. I., Thuan T. X., Guseva N. G., 2014, MNRAS, 445, 778
Kim T.-S., Partl A. M., Carswell R. F., Müller V., 2013, A&A, 552, A77
King J. A., Webb J. K., Murphy M. T., Flambaum V. V., Carswell R. F., Bainbridge M. B., Wilczynska M. R., Koch E. F., 2012, MNRAS, 422, 3370
Kirkman D., Tytler D., Suzuki N., O’Meara J. M., Lubin D., 2003, ApJS, 149, 1
Lanzetta K. M., Wolfe A. M., Turnshek D. A., Lu L., McMahon R. G., Hazard C., 1991, ApJ, 77, 1
Nollett K. M., Steigman G., 2014, Phys. Rev. D, 89, 083508

MNRAS 468, 3239–3250 (2017)
Table A1. The best-fitting parameter values for the four component model.

| Component | Redshift | Species | log ($N/\text{cm}^{-2}$) | $b_{\text{h,obs}}$ or $b_{\text{h,der}}$ (km s$^{-1}$) | $T$ (10$^4\text{K}$) |
|-----------|----------|---------|--------------------------|---------------------------------|-------------------|
| A         | 3.572 135 ± 0.000 007 | H I  | 17.575 | 2.36 ± 1.43 | 1.64 ± 0.03 |
|           |          | D I  | 12.994 | 2.36 ± 1.43 | 1.64 ± 0.03 |
|           |          | C II | 12.360 | 2.36 ± 1.43 | 1.64 ± 0.03 |
|           |          | Si II | 11.197 | 2.36 ± 1.43 | 1.64 ± 0.03 |
|           |          | Fe III | 12.502 | 2.36 ± 1.43 | 1.64 ± 0.03 |
|           |          | Si IV | 12.031 | 2.36 ± 1.43 | 1.64 ± 0.03 |
| B         | 3.572 268 ± 0.000 002 | H I  | 17.311 | 2.15 ± 0.76 | 1.81 ± 0.42 |
|           |          | D I  | 12.730 | 2.15 ± 0.76 | 1.81 ± 0.42 |
|           |          | C II | 12.777 | 2.15 ± 0.76 | 1.81 ± 0.42 |
|           |          | Si II | 12.031 | 2.15 ± 0.76 | 1.81 ± 0.42 |
|           |          | Fe III | 12.810 | 2.15 ± 0.76 | 1.81 ± 0.42 |
|           |          | Si IV | 12.678 | 2.15 ± 0.76 | 1.81 ± 0.42 |
| C         | 3.572 451 ± 0.000 002 | H I  | 17.402 | 4.51 ± 0.23 | 1.87 ± 0.07 |
|           |          | D I  | 12.821 | 4.51 ± 0.23 | 1.87 ± 0.07 |
|           |          | C II | 13.160 | 4.51 ± 0.23 | 1.87 ± 0.07 |
|           |          | Si II | 12.311 | 4.51 ± 0.23 | 1.87 ± 0.07 |
|           |          | Fe III | 13.220 | 4.51 ± 0.23 | 1.87 ± 0.07 |
|           |          | Si IV | 12.822 | 4.51 ± 0.23 | 1.87 ± 0.07 |
| D         | 3.572 682 ± 0.000 020 | H I  | 15.943 | 1.58 ± 0.86 | 4.35 ± 0.94 |
|           |          | D I  | 11.362 | 1.58 ± 0.86 | 4.35 ± 0.94 |
|           |          | Si II | 11.242 | 1.58 ± 0.86 | 4.35 ± 0.94 |
|           |          | Si IV | 11.082 | 1.58 ± 0.86 | 4.35 ± 0.94 |

Summed

| Species | $\sum \log (N)$ |
|---------|----------------|
| H I     | 17.925 ± 0.006 |
| D I     | 13.345 ± 0.006 |
| C II    | 13.357 ± 0.029 |
| Si II   | 13.345 ± 0.006 |
| Fe III  | 13.419 ± 0.029 |
| Si IV   | 13.080 ± 0.005 |
| O I     | 12.060 ± 0.127$^b$ |

Velocity shift

| Data | Shift (km s$^{-1}$) |
|------|---------------------|
| setup 2 | Setup 3  |
| setup 5 | Setup 10  |
| VLT Lyman 5 |          |

$^a$Values measured from the UV absorption on the redshifted system.

$^b$The systematic uncertainty in the velocity shift.

SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

APPENDIX A: MODEL
Table A1 – continued.

| Blends                     | Redshift | Species | log (N) | $b$ (km s$^{-1}$) |
|----------------------------|----------|---------|---------|-------------------|
| Si IV 1193 Å               | 3.487 11 | H$_1$   | 13.048  | 36.93             |
|                            | 3.487 89 | H$_1$   | 12.073  | 9.77              |
| Si IV 1304 Å               | 3.411 50 | H$_1$   | 13.062  | 21.61             |
| Fe II 1122 Å               | 3.221 10 | H$_1$   | 14.952  | 21.04             |
|                            | 3.222 83 | H$_1$   | 12.096  | 22.28             |
|                            | 3.223 76 | H$_1$   | 14.191  | 20.91             |
| Si IV 1393 Å               | 4.242 75 | unknown | 12.214  | 17.29             |
| H I 1216 Å (Lyman $\alpha$)| 3.580 17 | H$_1$   | 12.372  | 13.77             |
|                            | 3.579 73 | H$_1$   | 12.571  | 30.64             |
|                            | 3.578 47 | H$_1$   | 13.661  | 21.94             |
|                            | 3.577 75 | H$_1$   | 13.476  | 17.68             |
|                            | 3.577 33 | H$_1$   | 12.935  | $^{d}21.91$       |
|                            | 3.576 68 | H$_1$   | 13.644  | 20.45             |
|                            | 3.575 60 | H$_1$   | 12.827  | 29.26             |
|                            | 3.575 03 | H$_1$   | 12.270  | 15.70             |
|                            | 3.574 62 | H$_1$   | 12.372  | $^{d}29.61$       |
|                            | 3.573 36 | H$_1$   | 13.465  | 6.89              |
|                            | 3.573 08 | H$_1$   | 14.999  | $^{d}29.58$       |
|                            | 3.569 51 | H$_1$   | 13.085  | 34.30             |
|                            | 3.569 35 | H$_1$   | 11.473  | 8.32              |
|                            | 3.568 25 | H$_1$   | 12.331  | 27.72             |
|                            | 3.567 15 | H$_1$   | 13.450  | 31.23             |
|                            | 3.566 39 | H$_1$   | 14.084  | 29.03             |
|                            | 3.564 97 | H$_1$   | 14.131  | 27.00             |
|                            | 3.564 71 | H$_1$   | 14.029  | 40.28             |
| H I Å (Lyman $\gamma$)     | 2.656 62 | H$_1$   | 11.920  | 8.50              |
|                            | 2.656 13 | H$_1$   | 13.487  | 26.67             |
|                            | 2.656 93 | H$_1$   | 12.459  | 14.64             |
|                            | 2.659 21 | H$_1$   | 12.526  | 8.41              |
|                            | 2.659 74 | H$_1$   | 14.345  | 37.06             |
|                            | 2.660 65 | H$_1$   | 12.686  | $^{d}20.00$       |
|                            | 2.661 01 | H$_1$   | 12.841  | 9.13              |
|                            | 2.661 39 | H$_1$   | 12.579  | 12.88             |
| H I Å (Lyman 4)            | 2.569 77 | H$_1$   | 13.442  | 27.41             |
|                            | 2.571 24 | H$_1$   | 13.847  | 23.74             |
|                            | 2.573 07 | H$_1$   | 13.026  | $^{d}20.00$       |
|                            | 2.573 78 | H$_1$   | 14.632  | 30.51             |
|                            | 2.574 49 | H$_1$   | 13.727  | 23.11             |
| H I Å (Lyman 5)            | 2.524 87 | H$_1$   | 13.374  | 26.72             |
|                            | 2.525 28 | H$_1$   | 13.154  | 22.48             |
|                            | 2.525 77 | H$_1$   | 12.834  | 12.51             |
|                            | 2.526 09 | H$_1$   | 12.916  | 20.95             |
|                            | 2.527 94 | H$_1$   | 12.845  | $^{d}20.21$       |
| H I Å (Lyman 6)            | 2.499 14 | H$_1$   | 13.443  | 58.82             |
|                            | 2.499 45 | H$_1$   | 13.548  | 23.38             |
|                            | 2.500 11 | H$_1$   | 11.793  | 1.31              |
|                            | 2.502 24 | H$_1$   | 13.156  | 26.30             |
|                            | 2.502 69 | H$_1$   | 12.542  | 17.98             |
| H I Å (Lyman 7)            | 2.481 72 | H$_1$   | 11.550  | 1.00              |
|                            | 2.482 19 | H$_1$   | 12.755  | 27.04             |
|                            | 2.483 05 | H$_1$   | 12.312  | 12.89             |
|                            | 2.484 32 | H$_1$   | 13.050  | $^{d}20.00$       |
|                            | 2.485 12 | H$_1$   | 14.446  | 31.57             |
| H I Å (Lyman 8)            | 2.469 46 | H$_1$   | 13.255  | 26.35             |
|                            | 2.471 50 | H$_1$   | 13.541  | 20.62             |
|                            | 2.471 01 | H$_1$   | 13.213  | 31.34             |
|                            | 2.472 92 | H$_1$   | 13.177  | 31.21             |
|                            | 2.474 37 | H$_1$   | 13.019  | $^{d}40.65$       |
|                            | 2.474 92 | H$_1$   | 13.812  | 30.13             |
|                            | 2.475 34 | H$_1$   | 13.489  | 19.67             |
| Blends         | Redshift | Species | log (N) | b (km s\(^{-1}\)) |
|---------------|----------|---------|---------|-------------------|
| H\(\lambda\) Å (Lyman 9) | 2.462 14 | H\(_{1}\) | 12.992  | 39.16             |
| 2.462 65      | H\(_{1}\) | 12.744  | 16.01   |                   |
| 2.463 17      | H\(_{1}\) | 14.130  | 29.01   |                   |

Notes. \(^{a}\)For the summed column densities, the individual uncertainties are not determined. \(^{b}\)Based on a constant ratio of O\(_{1}\)/H\(_{1}\) across all components. \(^{c}\)setup 2, setup 3, setup 5 and setup 10 corresponds to the four different stacks of the Keck observations in Table 1, while all the VLT exposures are combined into one spectrum. \(^{d}\)A few of the b-parameters were fixed to prevent them from getting unphysically large.