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Fundamental physics with ESPRESSO: a new determination of the D/H ratio towards PKS1937-101

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ABSTRACT

Primordial abundances of light elements are sensitive to the physics of the early Universe and can directly constrain cosmological quantities, such as the baryon-to-photon ratio η_{10} , the baryon density, and the number of neutrino families. Deuterium is especially suited for these studies: its primordial abundance is sensitive and monotonically dependent on η_{10} , allowing an independent measurement of the cosmic baryon density that can be compared, for instance, against the Planck satellite data. The primordial deuterium abundance can be measured in high H I column density absorption systems towards distant quasars. We report here a new measurement, based on high-resolution ESPRESSO data, of the primordial D I abundance of a system at redshift $z \sim 3.572$, towards PKS1937-101. Using only ESPRESSO data, we find a D/H ratio of 2.638 ± 10^{-5} , while including the available UVES data improves the precision, leading to a ratio of 2.608 ± 10^{-5} . The results of this analysis agree with those of the most precise existing measurements. We find that the relatively low column density of this system ($\log N_{\text{H I}}/\text{cm}^{-2} \sim 18$) introduces modelling uncertainties, which become the main contributor to the error budget.

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

1 INTRODUCTION

The current standard cosmological model is remarkably able to describe our Universe from a few seconds after the Big Bang to the present day. Despite this, persistent issues have yet to be solved: we do not understand the nature of Dark Energy and Dark Matter, and tensions in the determination of key cosmological parameters have emerged (see e.g. Abdalla et al. 2022).

Investigating the early Universe can offer additional clues to the puzzle. A powerful probe of the physics of the early Universe is the Big Bang Nucleosynthesis (BBN), which predicts the abundances of the first light elements (H, D, ^3He , ^4He , ^7Li). For a general review on the Big Bang Nucleosynthesis, see e.g. Cyburt et al. (2016), Mathews, Kusakabe & Kajino (2017), Fields et al. (2020), and Workman et al. (2022), chapter 24 (Fields, Molaro, Sarkar). These abundances are sensitive to the physics of the early Universe and to the cosmological model parameters: the number of neutrino families, for instance, can be constrained by measuring the He abundance (see e.g. Peimbert, Peimbert & Luridiana 2016). Another primordial

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element accessible with current facilities is D. Its abundance is of particular interest because it depends monotonically on the baryon-to-photon ratio and, as a consequence, on the baryon density. The primordial D abundance is measured in absorption systems seen in the spectrum of a background source, most commonly quasars, and computed under the assumption that the ratio of the chemical elements is equal to the ratio of the column densities of the observed neutral H and D, $D/H = N_{D_I}/N_{H_I}$, where N is the column density of the absorbing gas. As discussed in Cooke, Pettini & Steidel (2018, and references therein), processes that weaken this assumption include the astration of deuterium as gas is processed by star formation, the relative reionization states of hydrogen and deuterium, or the depletion of deuterium onto dust grains. The first two effects are expected to be one order of magnitude below the uncertainties of current measurements at low metallicities. For the third, the amount of dust is generally small for systems in which deuterium is measured (Workman et al. 2022).

As discussed in Cooke et al. (2014) and Cooke, Pettini & Steidel (2018), the best systems for measuring the primordial deuterium abundance are those with H I column density near the threshold of a Damped Lyman- α system [DLA, $\log(N_{H_I})^1 \sim 20.3$]. In this case, the Lorentzian damped wings allow a precise measurement of the total $\log N_{H_I}$, while unsaturated D I lines provide a robust measurement of $\log N_{D_I}$. Unfortunately, DLA systems showing clear D I absorption are rare: to date, only seven are known. Systems with column densities $\log N_{H_I} \sim 17.5 - 19$ are more common (Riemer-Sørensen et al. 2017, hereafter RS17), but larger uncertainties are associated with the determination of the total H I column density. A limited sample of DLAs at $z \sim 2.5 - 3.0$ have been analysed since 1996, and the Precision Sample presented by Cooke, Pettini & Steidel (2018) provides a determination of the Deuterium abundance at the 1 per cent level.

In the following, we report of a new measurement of D I/H I in the absorption system at redshift $z = 3.572$ toward PKS1937-101 (J2000 19:39:57.26 -10:02:41.5) based on new data with higher signal-to-noise ratio (S/N) and resolution compared to previous data sets. This system is peculiar due to the low metallicity ($Z/Z_{\odot} \lesssim -2$), relatively low column density, and high redshift.

Prior to the new observations presented here, PKS1937-101 was observed using HIRES (Vogt et al. 1994) and UVES (Dekker et al. 2000) spectrographs. These observations returned a value of $D I/H I = 2.62 \pm 10^{-5}$ (Riemer-Sørensen et al. 2017). However, both instruments have been shown to suffer from wavelength calibration issues (Whitmore & Murphy 2015), introducing long-range wavelength scale distortions of $\pm 200 \text{ m s}^{-1}$ into the quasar spectra, and also covered a relatively short wavelength range ($\sim 400\text{--}660 \text{ nm}$ for UVES and $\sim 380\text{--}680 \text{ nm}$ for HIRES). To overcome these shortcomings, a new spectrum of PKS 1937–101 was collected in 2019 using the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO; Pepe et al. 2021). ESPRESSO’s wavelength calibration is significantly better than those of UVES and HIRES (Schmidt et al. 2021), and its extended wavelength coverage (380–780 nm) helps identifying interlopers and systems that could contaminate the D I and H I lines not identified previously. In addition, the higher resolution of ESPRESSO allows us to better resolve the velocity structure of the system.

¹To simplify the notation, throughout the paper we use $\log(N)$ in place of $\log_{10}(N/\text{cm}^{-2})$

Table 1. The final spectrum used for the analysis consists of five combined exposures. Here, we summarize relevant information. The S/N column is the median signal-to-noise ratio along the spectrum, while the $S/N_{Ly\alpha}$ is the median S/N in the continuum just redwards of the Ly α absorption system analysed in this work, at $\lambda \sim 5562 \text{ \AA}$.

Observing time (UTC)	Exp. time (s)	S/N (pix^{-1})	$S/N_{Ly\alpha}$ (pix^{-1})
2019-08-21T23:30:03.725	3600	20	26
2019-08-22T00:41:08.617	4100	25	34
2019-08-22T01:50:11.649	4100	28	38
2019-08-22T02:59:15.783	3600	28	37
2019-08-22T04:13:54.673	2400	22	27

The paper is organized as follows: in Section 2 we describe the data collection and reduction; in Section 3 we describe the analysis of the data, the resulting D I/H I ratio, and uncertainties in the modelling of the data. In Section 4, archival data sets are included in the analyses while in Section 5 we describe a Cloudy model of the system. In Section 6, we compare our new result to other measurements, and present our conclusions in Section 7.

2 OBSERVATIONS AND DATA REDUCTION

PKS1937-101 is a bright ($V_{\text{mag}} = 16.7$) quasar at redshift $z = 3.787$. It was observed on 2019 August 22 as a part of the ESPRESSO consortium’s guaranteed time observation programme for a total of 17 800 s spread over five exposures (see Table 1). The exposures were taken using the 4-UT mode of ESPRESSO, in which all four Unit Telescopes of the VLT simultaneously observe the target and their light is combined at the ESPRESSO front end. This configuration effectively makes VLT equivalent to a 16 m telescope in area and was chosen to increase the final S/N in the data. Pixel binning along the spatial direction was 8 pixels and binning along the spectral direction was 4 pixels (the so-called ‘multi-MR84’ mode), providing a nominal spectral resolution of ~ 70000 and a wavelength coverage from 380 to 780 nm.

Data were reduced using the standard ESO ESPRESSO data reduction software (DRS) version 3.0.0. We summarize the relevant steps and refer the interested reader to Pepe et al. (2021) for more details. The main steps performed are: (i) bias, dark, and inter-order background subtraction; (ii) optimal extraction, using a modified version of the Zechmeister, Anglada-Escudé & Reiners (2014) algorithm; (iii) creation of extracted spectra, with associated error and quality maps; (iv) flat fielding and de-blazing; (v) wavelength calibration, using either Laser Frequency Comb (LFC, calibration chosen for this work) or Thorium-Argon lamps combined with Fabry-Pérot sources; (vi) extraction of the sky spectrum, and creation of a sky-subtracted 2D spectrum. The sky signal was subtracted using the smoothing recipe of the ESPRESSO DRS pipeline. This mode performs first a sliding average of the sky spectrum and then subtracts it from the science spectrum.

The five wavelength-calibrated frames were combined using the python software package ASTROCOOK (Cupani et al. 2020), resulting in a spectrum with a S/N per km s^{-1} of around 100 redwards of the Lyman- α (Ly α) emission line, and from ~ 30 to ~ 90 in the Ly α forest (Fig. 1, bottom panel). The spectrum was rebinned to a wavelength grid constant in velocity space, with pixel size corresponding to 2.0 km s^{-1} , providing a 2-pixel sampling of the full-width at half-maximum (FWHM) of the resolution element. The formal flux error vector, derived following standard propagation of the uncertainties

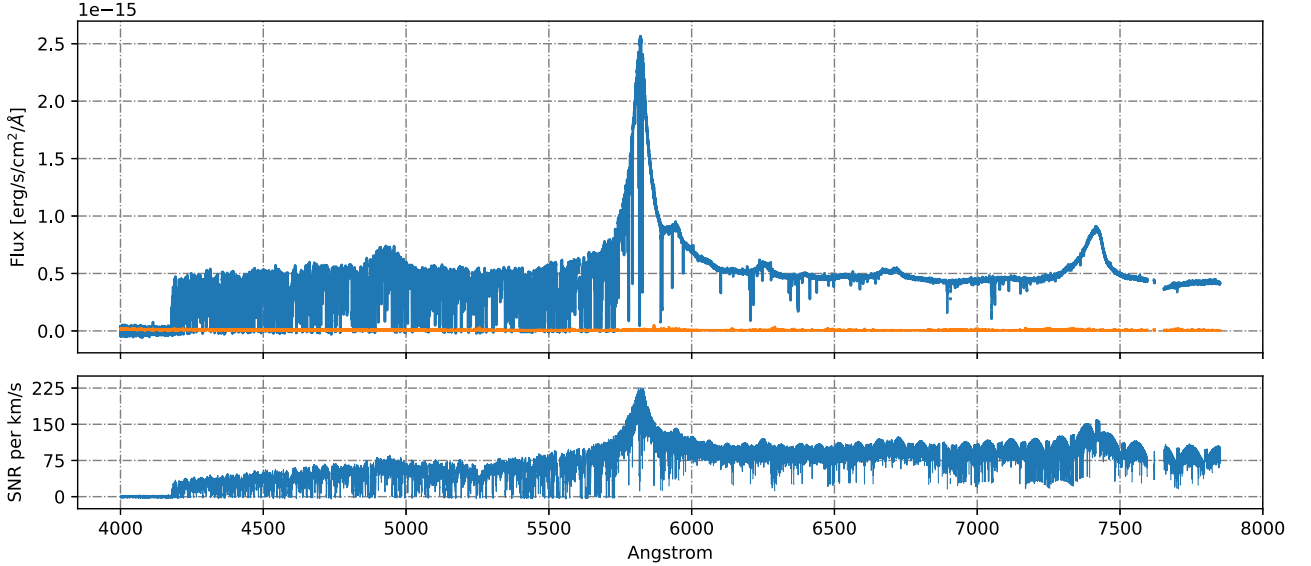


Figure 1. Top panel: wavelength calibrated ESPRESSO spectrum of PKS1937-101. The blue line represents the flux, while the orange line represents the associated error. Bottom panel: formal S/N per kms^{-1} along the spectrum.

of the five combined frames, was found to be $\sim 1.3\times$ lower than what would be expected from the observed fluctuations in flux over wavelength regions free from any features. This discrepancy does not seem related to the procedure of combination of the single spectra, but could be due to the treatment of the dark current in the reduction pipeline. A more detailed investigation of this problem goes beyond the scope of this work, as a consequence we decided to replace the error vector by the reduced root mean square error of pixel fluxes:

$$\text{RMSE}_i = \sqrt{\frac{1}{\sum_j w_j} \frac{1}{\sum_j p_j - 1} \sum_j w_j (f_j - F_i)^2}. \quad (1)$$

Above, F_i is the flux of an i -th pixel in the combined spectrum, f are the fluxes of n pixels that contribute to it, w the weights assigned to each of the n pixels, and p the fraction each of the n pixels contributing to F_i .

The quasar continuum was estimated using ASTROCOOK by applying an iterative sigma-clipping procedure to remove absorption features while masking emission lines. The continuum was then computed as the average, unclipped flux, subsequently smoothed in velocity space with a Gaussian filter ($\text{FWHM} = 200 \text{ km s}^{-1}$). This produces reliable results redwards of the $\text{Ly } \alpha$ emission, where absorption lines are generally narrow and sparse. On the other hand, on the blue side of the $\text{Ly } \alpha$ emission line, the recipe systematically underestimates the continuum. We thus manually corrected the continuum level where necessary. While this is a subjective process, it is fully repeatable owing to the capabilities of ASTROCOOK. We briefly discuss the effect of continuum placement on the line fit in Section 3.3.5.

3 DATA ANALYSIS

We fit the absorption lines of the system at $z \sim 3.572$ using VPFIT 12.4 (Carswell & Webb 2014). VPFIT is a software package used for Voigt profile fitting of absorption spectra. Each Voigt profile is parametrized by an atomic species, with corresponding atomic parameters, and up to four free parameters: the position in redshift space, the column density of the absorber, and the broadening,

or Doppler, parameter. Atomic parameters (such as the laboratory wavelength and oscillator strength) are provided within the VPFIT package and are a compilation of several sources in the literature. The free parameters are the redshift of the absorber or z , its column density or $\log(N)$, and up to two parameters describing the line broadening b . Two terms can in principle contribute to the Doppler parameter, one accounting for the turbulent (b_{turb}) and one for the thermal broadening (b_{therm}). Should the profile be broadened by fully turbulent or fully thermal broadening mechanisms, three parameters are needed to fully describe a Voigt profile. The presence of multiple species with different atomic masses in the same absorption system, however, allows for disentangling the relative contributions of the two broadening mechanisms, according to the relation:

$$b_{\text{tot}}^2 = b_{\text{turb}}^2 + b_{\text{ther}}^2 = b_{\text{turb}}^2 + \frac{2kT}{m}, \quad (2)$$

where k is the Boltzmann constant, T is the temperature of the gas, and m is the mass of the atomic species of interest.

Provided with a user-supplied model, VPFIT optimizes the free parameters using non-linear least-squares minimization. It then reports the best-fitting value for the free parameters, the corresponding errors, the χ^2 , and the reduced χ^2_{ν} (i.e. the χ^2 divided by the number of degrees of freedom, ν). χ^2_{ν} was used to guide the model building process, that is a component was added only when it was deemed necessary to reach $\chi^2_{\nu} \approx 1$.

VPFIT also requires information about the instrumental profile, which is convolved with the theoretical models before they are compared to the observed spectrum during parameter optimization. Here, the instrumental profile of ESPRESSO is assumed to be a Gaussian with a FWHM of 4.28 km s^{-1} , corresponding to the nominal resolution of the adopted ESPRESSO configuration. While the instrumental profile of ESPRESSO is known to depart from a pure Gaussian shape (Schmidt et al. 2021; Milaković et al. 2022), we retain the Gaussian form because we lack information on its exact shape, but acknowledge that this might leave certain systematic effects in our analysis. For example, if ESPRESSO's instrumental profile varies across the detector in a non-trivial way, as was recently found for a high resolution spectrograph with a similar optical design

to ESPRESSO (Milaković & Jetwha 2023), there may be intra-order and inter-order wavelength distortions that were left unaccounted for in this analysis.

Due to the large width and saturation of the H I line of the studied system, it is difficult to accurately identify its velocity structure and the number of components needed to carry out a proper fit. On the other hand, metal lines are easier to model for this system: they are unsaturated and narrower than the Ly α profiles. We derived a model for the saturated H I regions assuming that low-ionization metal species and hydrogen share the same velocity structure. In practice, we first modelled the metal lines to obtain the velocity structure of the system and the first guesses for the redshift and Doppler parameter of each H I component. Next, we fitted both metals and hydrogen transitions simultaneously, tying the redshift and Doppler parameters of metals, deuterium, and hydrogen together. The redshift parameters were required to be the same for all species, but otherwise free to vary during the fitting procedure. The same applies to the turbulent Doppler parameter and the temperature for each species.

3.1 Metal absorption lines

Starting from the metal lines detected in the studied system by RS17, we searched the ESPRESSO spectrum for all associated ionic transitions. Thanks to the extended wavelength range of the ESPRESSO spectrum, we were also able to detect the Si II 1526 Å and the C IV doublet at 1548, 1550 Å. We considered for our model six low-ionization transitions: C II 1334 Å, Si II 1193 Å, Si II 1260 Å, Si II 1304 Å, Si II 1526 Å, and Fe III 1122 Å.

Additional metal absorption lines (namely, C III 977 Å, Si III 1206 Å, C IV 1548, 1550 Å, and Si IV 1393, 1402 Å) are visible in the spectrum, but were not included in the model. C III and Si III are in the Lyman forest, where, for both lines, interlopers affect the velocity profile. High-ionization metals, such as C IV and Si IV, may not share the same velocity structure as low-ionization species. However, we checked and confirmed that the components found for the other metals were consistent with the C III, C IV, and Si III, Si IV absorption.

Finally, some commonly found metal transitions, such as O I 1302 Å, are not clearly visible in the spectrum or are heavily contaminated by telluric lines (e.g. Al II 1670 Å). Forcing the presence of O I 1302 Å, while fitting for other metal lines, returns a non-zero summed column density equal to $\log N_{\text{OI}} = 12.1 \pm 0.1$. This value is consistent with the previous determination of RS17, obtained under slightly different hypothesis, suggesting that the column density determination for O I 1302 Å is a reliable upper limit (we consider this value as an upper limit as these lines are not detected in the spectrum and are force-fitted using VPFIT based on knowledge of the position of the other metal transitions).

We initially only consider metal lines and produce a model of the six listed transitions. Three velocity components, marked 1, 2, 3 in Fig. 2, are needed.

3.2 Determination of the deuterium abundance

We applied the model derived from metal species to H I and D I. An additional line is visible bluewards of the main H I absorption in the Ly α , Ly β , and Ly γ lines (Fig. 3). There are strong indications that this line arises from D I absorption: (i) it is significantly broader than other metal lines seen in the spectrum but narrower than the associated Lyman series absorption; (ii) the shift between this line and the main H I absorption is $\sim -82 \text{ km s}^{-1}$, consistent with the expected shift between D I and H I.

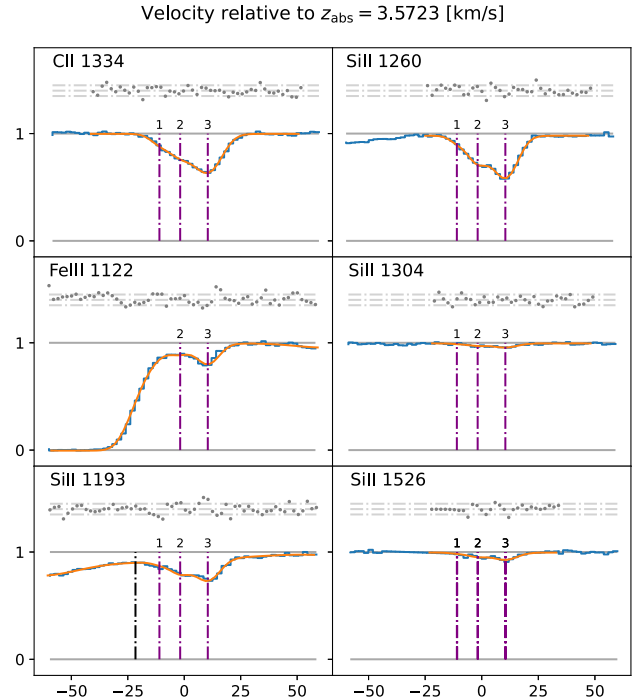


Figure 2. Low ionization metal lines used in the model to constrain the velocity structure of the hydrogen at the same redshift. Absorption components are marked with purple vertical lines, and the three components comprising the model are visible in, e.g. the C II or Si II 1260 Å lines. Black lines mark the position of unrelated H I absorption systems, while the grey line are the normalized residuals (data-model)/error, and the horizontal grey dot-dashed line are the 1- σ limits.

We assumed that low-ionization metals, hydrogen and deuterium share the same number of components, redshift and Doppler broadening. Column densities were instead free to vary independently. We fit low ionization metal lines together with the Lyman series (Ly α to Ly 9) and the corresponding deuterium series. In order to achieve a more accurate estimate of the total column density of H I and D I, we solved for their respective summed column densities across the absorption system (i.e. we directly found the summed column density for all components of the model). We forced all subcomponents to have the same D I/H I ratio (an hypothesis commonly assumed; see, e.g. Cooke, Pettini & Steidel 2018): this implicitly assumes that D I depletion, if present, affects equally all subcomponents.

Several regions require additional unrelated H I absorbers to obtain a good fit. When possible, these are modelled as Ly β or Ly γ lines with an associated Ly α transition at a longer wavelength. This provides more robust constraints on the number, column density, and position of these lines compared to the use of only Ly α .

We have not explicitly fit transitions higher than the Lyman 9, albeit visible in the spectrum, because the placement of the continuum is uncertain and several interlopers make it difficult to separate the contribution from the main system and unrelated ones. However, we checked that our model does not produce obvious defects when superimposed on those transitions. In Fig. 4, we plot the model and the ESPRESSO spectrum for the Lyman series from Lyman 10 to 20. The two are visually consistent with each other.

Finally, we fit the model to the data and determine the column densities of H I and D I finding $\log(N_{\text{HI}}) = 17.923 \pm 0.015$, $\log(N_{\text{DI}}) = 13.345 \pm 0.015$, and a D I/H I ratio of 2.638 ± 10^{-5} . The temperature of the gas, averaged across the three components,

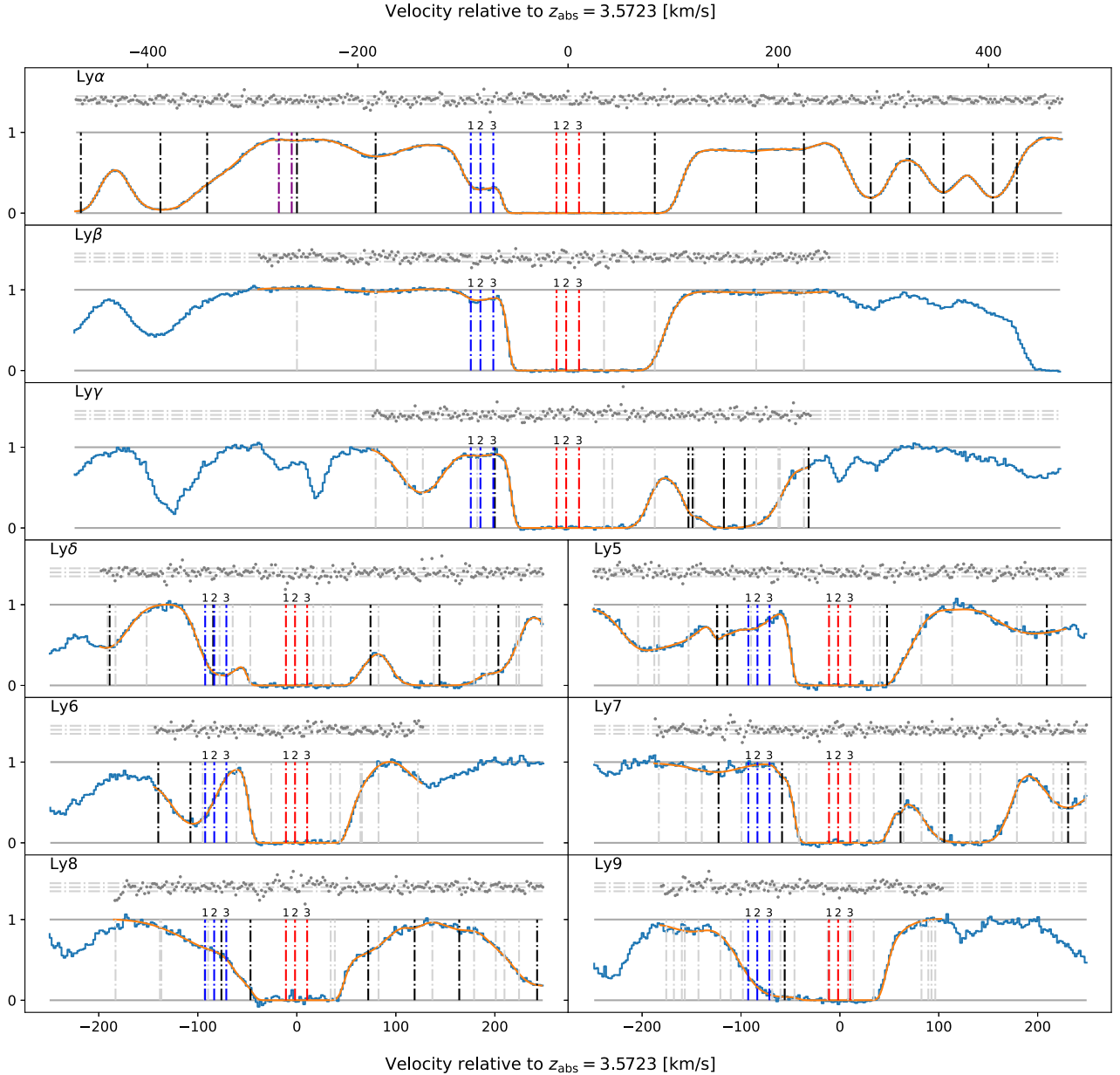


Figure 3. Model fitted to the ESPRESSO data only. The blue line shows the spectrum of PKS1937-101, while the orange line shows the model. Residuals are shown above each region, overplotting the $\pm 1\sigma$ limits. Black dash-dotted lines mark the position of interlopers (i.e. an unrelated H I system along the same line of sight). We only show interlopers added in each region: the remaining absorption is due to Lyman lines at higher redshift. Purple lines in the Ly α region mark the position of the Fe III at the same redshift of the main system. The red and blue lines mark the positions of the H I and D I components, respectively. Each component of the model is marked with a number (see the text).

is 1.68×10^4 K. The final χ^2_ν for the fit is 0.96. We report in Tables A1 and A2 all relevant parameters for all components.

3.3 Modelling uncertainty

We now explore various systematic effects that may have affected our measurements.

3.3.1 Higher excitation metal lines

Additional lines are available in the spectrum, besides those considered in the modelling: the C III 977, Si III 1206, Si IV, and C IV

doublets. We check that our model is consistent with these absorption systems, finding that extra components are needed to model these lines.

(i) Si IV, C IV: RS17 include Si IV in the fitting model for H I and D I, despite the differences in the ionization potential. Following their approach, we check if the three-component model is adequate to describe the Si IV and the C IV doublets.

We found that two and three more components were required to describe the absorption lines. One of these, marked 4 in Fig. 5, is similar to the fourth component found by RS17. The components marked as 5 and 6, on the other hand, were previously not identified

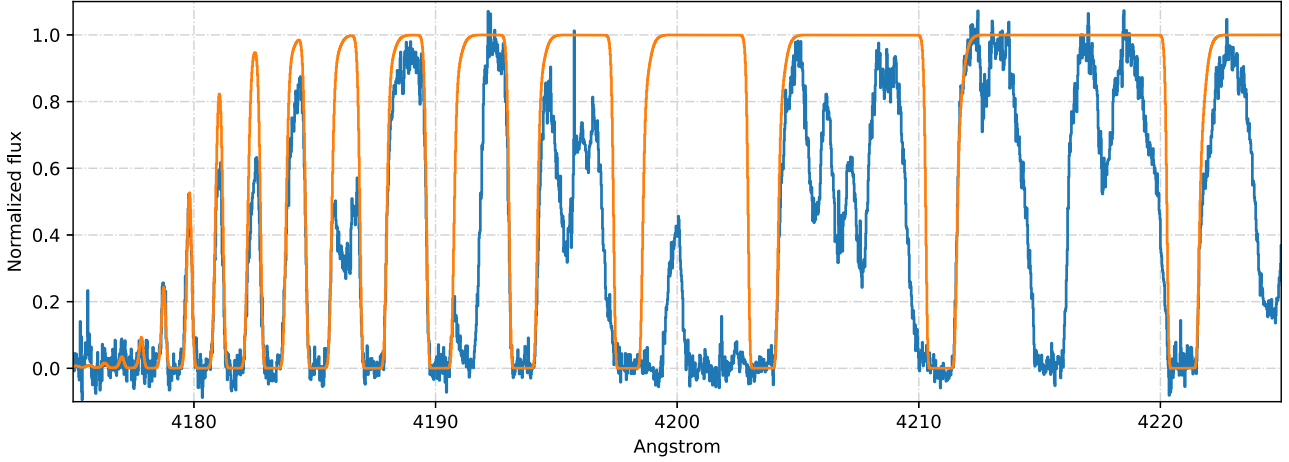


Figure 4. ESPRESSO model (orange line) overlotted onto the high order H I Lyman series lines, from Lyman 10 to Lyman 20 (blue line). The model appears to be consistent with the data.

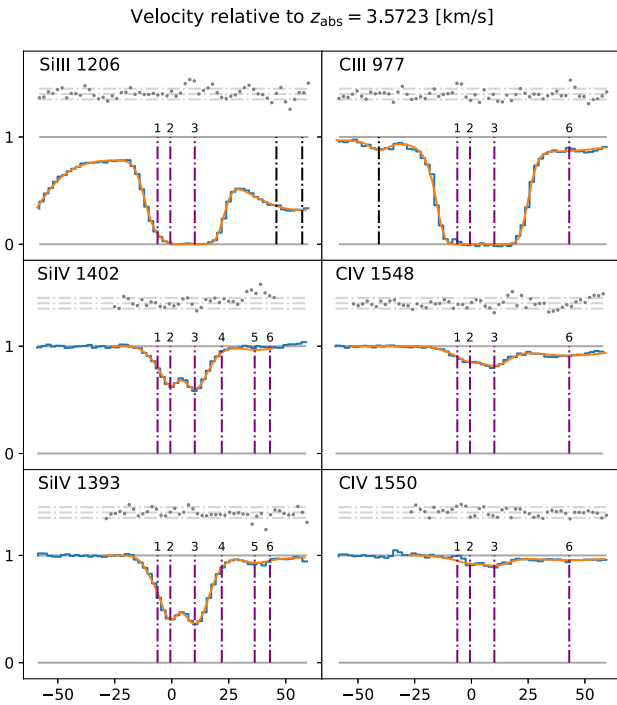


Figure 5. Additional metal lines of the system at $z = 3.5723$, not included in the model due to contamination or differences in ionization potential. As for the other figures, purple lines mark the position of metal lines, numbered on top, while black lines the position of possibly unrelated absorbers, modelled as Ly α .

as part of the absorption system due to lack of wavelength coverage in the UVES and HIRES spectra. These two components are not visible in any of the lower ionization metal lines at the same redshift, supporting the hypothesis that high-ionization lines have a different velocity structure and the choice of not including them in the fit model for hydrogen and deuterium.

(ii) C III 977, Si III 1206 Å: The three components present in all metal transitions can account for the strong absorption trough seen in Fig. 5. However, both lines are saturated and fall in the Lyman forest, and thus are likely contaminated by H I lines (black, dash-

dotted lines in Fig. 5). This is true especially for Si III, which shows a strong absorption trough that is not evident in any other metal line. Interpreting the velocity structure of C III is harder: the absorption to the left and right of the strong trough seen in Fig. 5 can either be associated to the fifth and sixth components discussed in the previous bullet point or to an additional component, marked by the number 7 in Fig. 5, to H I interlopers, or to a mix of both.

3.3.2 A model with four components

RS17 present a model comprising four components (see e.g. Fig. 1 of this reference). However, our model considers only three. We found that a fourth component is only required to adequately fit the Si IV doublet. Taking into account only low-ionization metal species, namely the Si II, C II, and Fe III transitions, VPFIT rejects the fourth component entirely. On the other hand, including the H I lines makes it so that the fourth component is kept, although with larger errors (by a factor of ~ 10) in column density, redshift, and Doppler parameters compared to the other three. In this case, the resulting D I/H I is 2.634 ± 10^{-5} , essentially unchanged with respect to the three-component model, but with significantly higher uncertainty.

If, in addition to including the fourth component, we also include all available metal species (C III 977, Si III 1206, and the C IV and Si IV doublets) and refit the model, we find a comparable hydrogen and deuterium column densities $\log(N_{\text{H I}}) = 17.925 \pm 0.015$, $\log(N_{\text{D I}}) = 13.343 \pm 0.016$ with slightly larger uncertainties and lower D I/H I ratio of 2.618 ± 10^{-5} .

3.3.3 Contamination of H I lines in the Ly α region

Contamination by hydrogen interlopers in regions with deuterium absorption is possible, although unlikely (< 3.7 per cent, as discussed in RS17). None the less, we investigate how the inclusion of an additional line in the D I region affects the results. We proceed as follows: first, we assume that no deuterium is present and model the absorption trough bluewards of the main Ly α system with a single H I component. The parameters fitted for this component are: $\log(N_{\text{H I}}) = 13.34$, $b = 18.09 \text{ km s}^{-1}$, and $z = 3.57102$. We then reintroduce the deuterium and refit the model including both the deuterium and the additional H I line. We use as starting parameters for the additional H I line the results of the aforementioned fit. Under the same assumption

used for the main model, we find $\log(N_{HI}) = 17.919 \pm 0.022$, $\log(N_{DI}) = 13.341 \pm 0.037$ and $D/H = 2.644 \pm 10^{-5}$.

3.3.4 Choice of the fitting region

An additional source of uncertainty is related to the choice of the fitting region, combined with the inclusion of continuum adjustments allowed by the VPFIT model. In particular, considering the Ly α region, we find that restricting the fitting region to ± 400 km s $^{-1}$ (Fig. 3, upper panel) leads to a lower HI column density, $\log(N_{HI}) = 17.905 \pm 0.023$ and consequently to a higher D/H ratio 2.76 ± 10^{-5} . This is caused by the exclusion of regions where the unabsorbed continuum is higher than in the ± 400 km s $^{-1}$ range: while fitting the model, VPFIT adjusts the continuum to be lower. Although this is possible, it is unlikely that this is the case, as it would require the continuum to change on small scales.

3.3.5 Continuum placement

In addition to allowing small continuum adjustments in the VPFIT model in each region, we investigate whether the position of the continuum influences the final determination and its uncertainty. To quantify this effect on the final D/H ratio, we randomly varied the placement of the continuum and re-fit the model on the newly normalized spectra. Ten different realizations were produced. To produce each realization, we multiplied the continuum of the spectrum by a slowly varying function, generated by extracting points from a Gaussian distribution centred at unity and with a standard deviation $\sigma = 0.05$. Each point was associated with a wavelength, using a range from 3000Å to 8000Å and a step of 50Å. Finally, points were interpolated with a smoothing spline and evaluated on the same wavelength scale of ESPRESSO. The model presented in the previous sections was finally fitted separately to each of the ten realizations. We computed the D/H ratio for each realization: their average is 2.639 ± 10^{-5} , where the error is taken as the standard deviation of the ten iterations. The uncertainty associated with the continuum is one order of magnitude lower than the statistical uncertainty of the fit. Summing the contributions in quadrature increases the final uncertainty on the D/H ratio by ~ 0.5 per cent. The mean error (that is, the average of the errors estimated from the ten iterations) is 0.131. Fig. 6 shows, per each iteration, the column density of deuterium and hydrogen, and the corresponding D/H ratio.

4 INCLUDING PREVIOUS DATA SETS: UVES AND HIRES

PKS1937 had also been observed with the HIRES and UVES spectrographs. We have analysed these data trying to see if they could be useful for improving the Deuterium fit.

4.1 Archival data

PKS1937 has been observed in 2006 and 2007 with UVES (Dekker et al. 2000), proposal 077.A-0166(A) (P.I. R. F. Carswell). During the execution of the programme, the object was observed with a resolution of $R = 45000$, for a total of 5.4×10^4 seconds spread among 10 individual exposures of 5.4×10^3 seconds. The spectrum used in this work was taken from the SQUAD data set (Murphy et al. 2019), a large, public collection of fully reduced, wavelength calibrated QSO spectra observed with UVES. The combined UVES spectrum has roughly half the signal-to-noise ratio per km s $^{-1}$, compared to the ESPRESSO spectrum, averaging ~ 37 in the Lyman

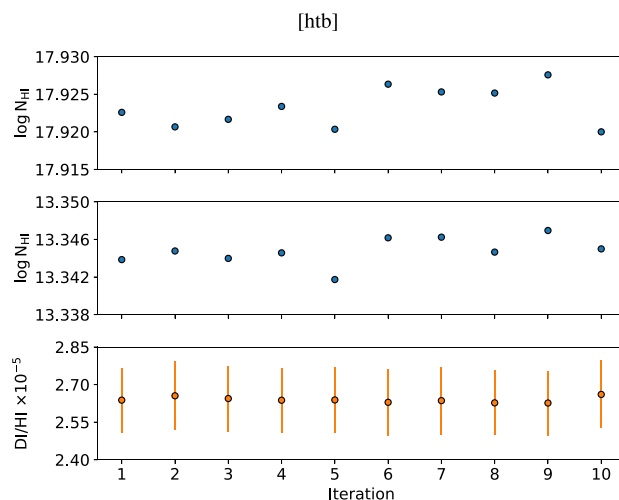


Figure 6. Top panel: H I column density for each iteration. Middle panel: same, for deuterium column density. Lower panel: same, but for the resulting D/H I.

forest and ~ 65 redward of the Ly α emission line. A detailed description of the steps taken to produce the catalogue, reduce each science frame, and produce a stacked spectrum is available in the reference paper.²

Science frames were reduced using the ESO Common Pipeline Library and combined using UVES_popler (Murphy 2018). The same tool was also used to fit a continuum on the combined spectrum. To do so, data are broken into overlapping chunks of a user-defined width, and a polynomial is fitted on each chunk. To form a smooth continuum, continua from adjacent chunks are averaged together. It should be noted that the automatic procedure does not work well in the Lyman forest, due to the small amount of un-absorbed pixels. For quasars in SQUAD, the continuum in the region of the Lyman forest was manually refitted, selecting seemingly unabsorbed peaks in the Lyman forest and interpolating between them with a low-order polynomial. As for ASTROCOOK, the procedure is subjective but fully repeatable, thanks to UVES_popler log files.

In addition to UVES, PKS1937-101 has been extensively observed using HIRES, mounted on the Keck Telescope in Hawaii. Reduced, wavelength-calibrated, and continuum normalized archival data are available as part of the KODIAQ data set (O’Meara et al. 2021), and were retrieved from SpecDB (Prochaska 2017; Prochaska et al. 2017). Three co-added spectra are available, resulting from observational programmes carried out between 1997 and 2005 (P.I. L. Cowie, N. Crighton, and D. Tytler). We refer the interested reader to the KODIAQ paper (O’Meara et al. 2021) for details about data reduction and processing.

Of the three data sets, wavelength calibration issues in one of the combined spectra were noted (P.I. D. Tytler, Fig. 7) in the form of a wavelength-dependent shift between the ESPRESSO and the HIRES data. Thus we discarded it and limited our analysis to the remaining two. The signal-to-noise ratio per km s $^{-1}$ of the two spectra combined is on average ~ 40 in the forest, 60 redward of the Ly α emission line. Finally, it should be noted that the algorithm used to estimate the continuum on HIRES data is again different from the one used for UVES or ESPRESSO spectra. In the case of

²Details of the data processing for all SQUAD QSOs are also available online at the SQUAD web page (github.com/MTMurphy77/UVES_SQUAD_DR1).

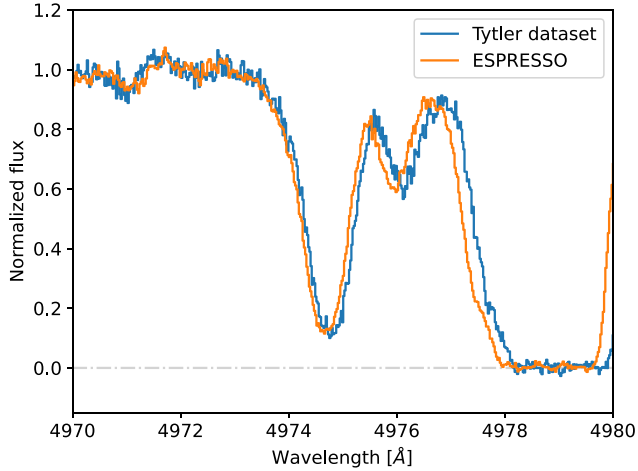


Figure 7. Example of wavelength calibration issues between the HIRES (blue) and ESPRESSO data sets (orange).

HIRES, data are continuum normalized on an order-by-order basis by fitting Legendre polynomials (with orders varying from 4th to 12th) in regions deemed free of absorption. Employing three different algorithms might produce different artefacts or systematics in the combined fit.

4.2 Fitting the ESPRESSO model on the UVES data

Before fitting the model on UVES data, we took advantage of the significantly better ESPRESSO wavelength calibration to correct the wavelength grid of the UVES data, which is known to be problematic (e.g. Rahmani et al. 2013). We did this by computing velocity shifts between UVES and ESPRESSO data, with ESPRESSO being chosen as the ‘correct’ one, and shifting the UVES wavelength scale to match that of ESPRESSO. When this is done, the UVES and ESPRESSO spectra can be fitted together without additional parameters of velocity shifts between them.

The shifts were calculated by cross-correlating the two spectra in the velocity space, which were rebinned to a common velocity grid, with a pixel size of 1.4 km s^{-1} . The choice of the pixel size did not affect the resulting shifts, as long as it is not too large ($>4.5 \text{ km s}^{-1}$). The two spectra were then subdivided into chunks, and each pair of corresponding chunks was cross-correlated with each other. We computed the cross-correlation considering relative shifts between -5 and 5 km s^{-1} , with a fixed step of $10^{-3} \text{ km s}^{-1}$. The velocity shift corresponding to the maximum of the cross-correlation function was taken as the velocity shift between two chunks.

The shifts between UVES and ESPRESSO depend weakly on the wavelength (Fig. 8). We therefore applied a single shift across the entire wavelength range compared, taken as the weighted average of the individual cross-correlation values we computed for the 10 \AA window $|v_{\text{shift}}| = 0.295 \text{ km s}^{-1}$. This shift was applied to the UVES data as a fixed parameter in the VPFIT input file.

4.3 Joint fit of UVES and ESPRESSO data

Having determined the wavelength scale corrections for the UVES spectrum, we checked whether the previously developed model to describe ESPRESSO data only also describes the UVES spectrum well. We thus obtained $\log N_{\text{H I}} = 17.922 \pm 0.026$ and $\log N_{\text{D I}} = 13.338 \pm 0.012$, well in agreement with the result based on the

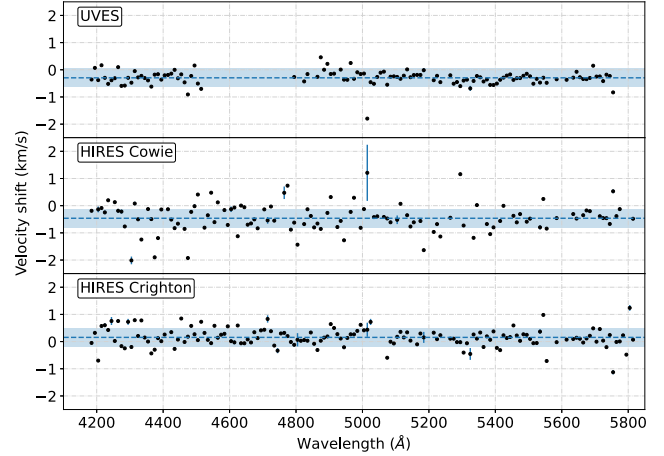


Figure 8. Velocity shift between UVES, the two HIRES, and ESPRESSO spectra as a function of wavelength. The error-bars on the y-axis represent the scatter in the determination of the velocity shift when computing the cross-correlation from 10 slightly different starting velocity values, equally spaced within a pixel. The adopted shifts, assumed to be constant, are $|v_{\text{shift}}| = 0.295$, 0.463 , and 0.154 km s^{-1} , respectively.

ESPRESSO spectrum alone, although with a slightly lower hydrogen column density. The corresponding D I/H I is 2.606 ± 10^{-5} .

We also performed a joint fit of the ESPRESSO and the corrected UVES data as VPFIT allows different data sets to be fit at the same time, using the same model, without having to resort to stacking or data manipulation techniques. The column densities derived from the joint fit are $\log N_{\text{H I}} = 17.922 \pm 0.012$ and $\log N_{\text{D I}} = 13.338 \pm 0.012$, leading to D I/H I of 2.608 ± 10^{-5} .

Fixing the velocity shift makes it so that the uncertainty in the determination of the shift itself is not propagated to the D I/H I ratio. To estimate the uncertainty associated with this decision, we rerun the joint fit, but now fixing the shift to -0.295 ± 0.334 , that is to 0.039 and $-0.6290 \text{ km s}^{-1}$ (the central value $\pm 1\sigma$). The resulting D I/H I associated with these shifts between UVES and ESPRESSO are, respectively, 2.612 ± 10^{-5} and 2.599 ± 10^{-5} . The statistical uncertainty dominates, and including the systematic uncertainty from the velocity shift increases the error on the final determination by about 1 per cent.

4.4 Joint fit of ESPRESSO, UVES, and HIRES data

The HIRES data were corrected in an analogous way as the UVES data, after which we performed a joint fit of the ESPRESSO, UVES, and HIRES data. Interestingly, despite the increase in S/N achieved by including additional data (~ 10 per cent compared to the combination of ESPRESSO and UVES data), we find slightly larger errors in the $\log N_{\text{H I}}$ and $\log N_{\text{D I}}$ compared to the joint fit in ESPRESSO and UVES: $\log N_{\text{H I}} = 17.928 \pm 0.019$, $\log N_{\text{D I}} = 13.343 \pm 0.017$, D I/H I = 2.595 ± 10^{-5} . The higher uncertainty can be attributed to several factors, including different normalizations for each spectra or region-dependent wavelength shifts (see Section 6.2). Because of this, we consider only the combined ESPRESSO + UVES data henceforth.

5 CLOUDY MODEL OF THE SYSTEM

We use Cloudy (Ferland et al. 2017) to estimate the metallicity of the system, the temperature of the absorber, and the hydrogen density.

Table 2. Results of the optimization process from Cloudy, and inferred column densities from the modelling. Metal species marked with * are formally upper limits, either because column densities were determined by force-fitting absorption lines at the position of the absorber (in the case of O I), or the lines are in the Lyman forest, and as such a part of the absorption can be attributed to Ly α interlopers (everything else).

Metal species	Cloudy (cm ⁻²)	Fit (cm ⁻²)
C II	13.38	13.35 ± 0.06
C III*	14.44	<14.25
C IV	12.88	13.01 ± 0.14
Si II	12.45	12.42 ± 0.07
Si III*	13.53	<13.90
Si IV	12.79	13.10 ± 0.10
Fe III*	12.80	<13.33
O I*	11.23	<12.10
n_H (cm ⁻³)	-2.49	-
Z/Z_\odot	-2.45	-

Cloudy is a spectral synthesis code designed to simulate astrophysical environments and predict their spectra. Given the presence of several transitions with different ionization stages in the spectrum, we use the `optimize` function to estimate the quantities mentioned above.

We assume the gas to be in photoionization equilibrium with the ultraviolet ionizing background. We chose the HM12 option, i.e. an isotropic ionizing background with the contribution of both quasars and galaxies, with a variable escape fraction (f_{esc}) depending on the redshift of interest (Haardt & Madau 2012). The contribution of the CMB, although negligible, is also taken into account. We approximate the absorption systems as a plane parallel slab with hydrogen density n_H and metallicity Z/Z_\odot : these two quantities are free parameters, and the best-fitting value was estimated by Cloudy during the optimization process. We allowed the optimizer to explore a reasonably large range for both quantities: the allowed interval for the hydrogen density is $-5 < \log(n_H) < 2$ cm⁻³, for metallicity $-3 < \log(Z/Z_\odot) < 0$. We used the median point as initial guesses for each interval. Both initial guesses and the allowed ranges are consistent with values found in the literature.

Table 2 reports the Cloudy output. The simulated column densities are generally consistent with those estimated by the fit. The most obvious exception to this is Fe III, which appears to have significantly higher column density in our VPFIT model. This can be explained by the fact that the Fe III lines lie in the Lyman forest and, as such, might be affected by Ly α interlopers or imperfect continuum placement.

The estimated hydrogen density for the cloud, n_H , is lower (by a factor of 3) than the minimum value determined by RS17, who compared the column density ratios observed with a grid of Cloudy models and estimated it to be $-2.11 < n_H < -1.72$ cm⁻³. The best estimate of metallicity is consistent with previous determinations ($-2.5 < Z/Z_\odot < -1.99$, RS17) and recent analysis of low-metallicity systems (Lofthouse et al. 2023). We note that our simulation uses an updated UV background with respect to RS17: re-running the model using the HM05 UV background, same as RS17, yields $n_H = -2.27$ cm⁻³, closer to the lower limit found by RS17. Finally, we obtain an average temperature for the system of 1.76×10^4 K, in good agreement with the temperature estimated by VPFIT.

6 DISCUSSION

Inferring the H I column density is an inherently difficult task and various authors have reported different values for this absorption

system, with inconsistent conclusions. Tytler, Fan & Burles (1996) found a value of $\log N_{\text{H I}} = 17.94 \pm 0.3 \pm 0.3$, where the first error is statistical and the second is systematic. The estimate was subsequently revised to $\log N_{\text{H I}} = 17.86 \pm 0.02$ cm⁻² based on the LRIS, HIRES, and Kast data (Burles & Tytler 1997). Improvement in the determination was achieved by developing a new method to estimate the H I column density from the Lyman continuum optical depth. This result was however inconsistent with results from Songaila, Wampler & Cowie (1997, $\log N_{\text{H I}} < 17.7$ cm⁻²) or Wampler (1996), who again estimated a lower $\log N_{\text{H I}}$ column density.

In addition to measurements of the H I column density, PKS1937-101 has three previous determinations of the D/H ratio (Tytler, Fan & Burles 1996; Burles & Tytler 1998; Riemer-Sørensen et al. 2017). Tytler, Fan & Burles (1996) estimated a D/H ratio of 2.3 ± 10^{-5} , while improvements in the determination of H I from Burles & Tytler (1998) lead to an updated value of 3.3 ± 10^{-5} . However, in their analysis, metal components were not used to better constrain the velocity structure of the system. Instead, the position and the number of components for D I and H I are only constrained using Lyman lines. The discrepancy between their final determination and the value presented in this paper is due to the different H I column density, lower in Burles & Tytler (1998) than the present measurement (Table 3).

More recently, the system has been revisited by RS17, who used data from Keck/LRIS, Keck/HIRES, and VLT/UVES. They report a value of the primordial D/H I of 2.62 ± 10^{-5} . Their determination of D/H is consistent and within 1σ of the one presented in this paper, albeit with smaller uncertainties. There are, however, some differences: our model does not include high-ionization metal species, which might not faithfully trace the H I velocity structure, leading to a three-component model (Section 3.3.2 shows how including a fourth component is only required to adequately fit the Si IV doublet). In addition to this, in this work interlopers are modelled, when possible, as Ly β or Ly γ lines with an associated Ly α line at a longer wavelength, instead of simple Ly α ; this should make the model more robust, as interlopers are constrained more precisely. We also note that the determination from the ESPRESSO data, even when combined with UVES, leads to a slightly larger uncertainty than RS17. We show that systematic uncertainties are significant (Section 3.3), and as such that the errors in previous analyses might be underestimated.

6.1 Determinations of D/H from other systems in the literature

We compare the determination presented in this work against the determinations from other systems, including the Precision Sample defined by Cooke, Pettini & Steidel (2018). In Table 4, we report the ‘robust’ D/H measurements initially selected by Pettini et al. (2008) and updated in subsequent articles (RS15, RS17; Zavarygin et al. 2018) with the new determination derived in this paper for the system at $z = 3.572$ in PKS1937-101. Values from the same table are plotted in Fig. 9.

Qualitatively, there is no apparent correlation between redshift, metallicity, column density of the absorber and the D/H ratio. In particular, the absence of correlation with redshift strengthens the result by Cooke, Pettini & Steidel (2018) since the updated sample spans a wider redshift range.

The collection presented in this section is inhomogeneous and includes results obtained with different hypotheses [for example, Noterdaeme et al. (2012); Balashev et al. (2016) assume a constant ratio of O I/H I across all components of the system, Cooke, Pettini & Steidel (2018) allow the temperature of hydrogen and deuterium to vary independently]. Averaging all the measurements reported

Table 3. Summary of the D I/H I measurements for the system at $z = 3.572$ in PKS 1937–101 quoted in the text.

Publication	$\log N_{D_I}$	$\log N_{H_I}$	D I/H I ($\times 10^{-5}$)	# of components	Res. power
Tytler, Fan & Burles (1996)	13.30 ± 0.04	17.94 ± 0.05	2.3 ± 0.6	2	37 000
Burles & Tytler (1998)	///	17.86 ± 0.02	3.24 ± 0.30	2	37 000
RS17 (UVES)	13.332 ± 0.0287	17.925 ± 0.0063	2.58 ± 0.175	4	45 000
RS17 (HIRES)	13.357 ± 0.0244	17.925 ± 0.0066	2.70 ± 0.157	4	37 000–49 000
RS17 (Combined)	13.344 ± 0.0056	17.921 ± 0.0068	2.62 ± 0.051	4	37 000–49 000
This work (ESPRESSO)	13.345 ± 0.015	17.923 ± 0.015	2.638 ± 0.128	3	70 000
This work (UVES)	13.338 ± 0.012	17.923 ± 0.026	2.60 ± 0.17	3	45 000
This work (HIRES)	13.357 ± 0.029	17.895 ± 0.019	2.89 ± 0.23	3	37 000–49 000
This work (ESPRESSO + UVES)	13.338 ± 0.012	17.922 ± 0.012	2.608 ± 0.102	3	–
This work (ESPRESSO + HIRES)	13.353 ± 0.0079	17.910 ± 0.013	2.770 ± 0.094	3	–
This work (ESPRESSO + UVES + HIRES)	13.343 ± 0.017	17.928 ± 0.019	2.595 ± 0.152	3	–

Table 4. Collection of measurements of the primordial deuterium abundance from the literature. Starred QSOs are part of the Precision Sample presented in Cooke, Pettini & Steidel (2018).

Reference	Quasar	Redshift of the system	$\log N_{H_I}$	[X/H]	D/H ($\times 10^5$)
Pettini & Bowen (2001)	Q2206-199	2.076	20.436 ± 0.008	–2.04 [Si/H]	1.65 ± 0.35
Balashev et al. (2016)	J1444+2919	2.437	19.983 ± 0.010	–2.04 [O/H]	1.97 ± 0.33
Zavarygin et al. (2018)	Q1009+2956	2.504	17.362 ± 0.005	–2.50 [Si/H]	2.48 ± 0.41
Cooke, Pettini & Steidel (2018)*	Q1243+3047	2.525	19.761 ± 0.026	–2.77 [O/H]	2.39 ± 0.10
O’Meara et al. (2001)*	HS 0105+1619	2.536	19.40 ± 0.01	–1.77 [O/H]	2.58 ± 0.15
Pettini et al. (2008)*	Q0913+072	2.618	20.312 ± 0.008	–2.40 [O/H]	2.53 ± 0.10
Noterdaeme et al. (2012)	J0407-4410	2.621	20.45 ± 0.10	–1.99 [O/H]	2.80 ± 0.8
O’Meara et al. (2006)*	J1558-0031	2.702	20.75 ± 0.03	–1.55 [O/H]	2.40 ± 0.14
Cooke et al. (2016)*	SDSS J1358+0349	2.853	20.524 ± 0.006	–2.804 [O/H]	2.62 ± 0.07
D’Odorico, Dessauges-Zavadsky & Molaro (2001)	QSO 0347–3819	3.025	20.63 ± 0.09	–1.25 [Zn/H]	2.24 ± 0.67
Pettini & Cooke (2012)*	J1419+0829	3.049	20.392 ± 0.003	–1.92 [O/H]	2.51 ± 0.05
Cooke et al. (2014)*	J1358+6522	3.067	20.50 ± 0.01	–2.33 [O/H]	2.58 ± 0.10
Srianand et al. (2010)	J1337+3152	3.168	20.41 ± 0.15	–2.68 [Si/H]	1.2 ± 0.5
Riemer-Sørensen et al. (2015)	Q1937-101	3.256	18.09 ± 0.03	–1.87 [O/H]	2.45 ± 0.28
Fumagalli, O’Meara & Prochaska (2011)	J1134+5742	3.411	17.95 ± 0.05	< –4.20 [Si/H]	2.04 ± 0.61
This work	PKS1937-101	3.572	17.922 ± 0.023	–2.52 [O/H]	2.608 ± 0.102

in Table 4, we find simple and weighted averages of 2.32 ± 10^{-5} and 2.512 ± 10^{-5} , respectively. As expected, the weighted average is consistent with the results of Cooke, Pettini & Steidel (2018), as 7 out of 16 measurements in Table 4 are also in the Precision Sample. These also have the smallest formal errors, so it is expected that the weighted average of all 16 measurements in Table 4 is close to the Precision Sample average. The simple average, on the other hand, is lower and inconsistent with the value provided by the Precision Sample at the level of $\sim 2\sigma$. This is due to the measurements with very discrepant lower values, which, however, also have larger error bars, and in general to the fact that the sample has not been analysed homogeneously. Taking into account only measurements with an error estimate lower than 10 per cent the simple mean results in 2.53 ± 10^{-5} , while the weighted average is almost unchanged 2.531 ± 10^{-5} . On the other hand, comparing against the Precision Sample, for which Cooke, Pettini & Steidel (2018) report a determination of the primordial deuterium abundance of 2.527 ± 10^{-5} , we find that the result from ESPRESSO data alone is in agreement as is the one obtained with the combination of ESPRESSO and UVES data, at the $\sim 0.8\sigma$ level.

Finally, we compare the new determination with the most recent results from the Planck Collaboration (Planck Collaboration VII 2020). Converting CMB data to deuterium abundance requires prior knowledge of nuclear reaction rates, and the Planck Collaboration presents three possibilities ($D/H = 2.587 \pm 0.13, 2.455 \pm 0.081,$

2.439 ± 0.082), depending on the nuclear reaction rates considered. The combined ESPRESSO and UVES measurement agrees with these results at $0.2\sigma, 1.2\sigma$ and 1.3σ , respectively (Fig. 9). More recently, the LUNA experiment updated the cross-section of the deuterium burning $D(p, \gamma)^3\text{He}$ reaction (Mossa et al. 2020) and provided a new determination of D I/H I of $2.52 \pm 0.03 \pm 0.06 \times 10^{-5}$, in agreement with the determination of this work at the 0.7σ level (Fig. 10). Thus, no significant tension is found, even if the offset in the central value suggests that systematic uncertainties for this system might be underestimated.

6.2 About the uncertainty

The results obtained in this analysis have a higher uncertainty than RS17. This is somewhat unexpected, given the higher resolution, S/N, and significantly better wavelength calibration of ESPRESSO. We attribute this to two aspects: on the one hand, we attempt to fit together spectra from three different instruments. On the other hand, comparing the joint UVES and HIRES results with those obtained on single spectra, we recognize an unusual scaling in the final uncertainty reported by RS17.

With respect to the first point, UVES and HIRES have been shown in the past to be affected by systematics in the wavelength calibration. To account for this, we pre-compute the velocity shift of each fitting region and use the average value as a fixed parameter during the

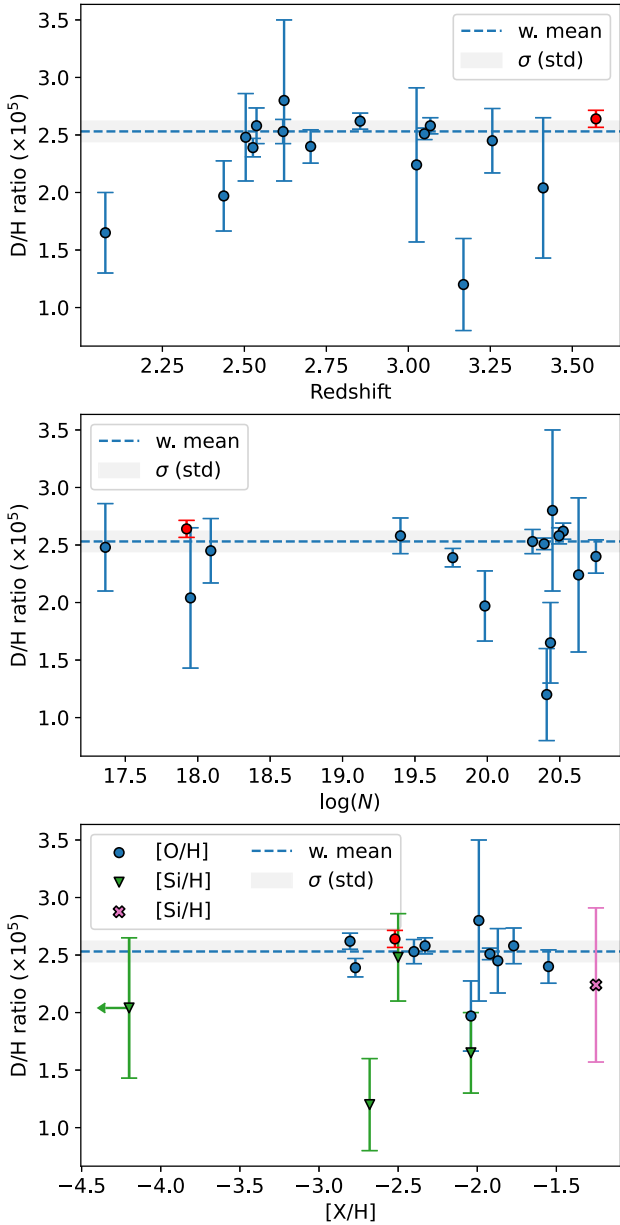


Figure 9. Data from Table 4, plotted from top to bottom against redshift, H I column density and metallicity of the absorber. The red point is the new measurement reported in this work, the grey, dashed line the weighted mean of measurements in Table 4, while the grey shaded regions represent the 1σ standard deviation. In the bottom panel, metallicity is estimated through different metal ratios, colour coded according to the legend on the top left. No clear correlations are evident.

optimization procedure. This is somewhat unique to this work: in RS17, for instance, a velocity shift between regions is allowed as a free parameter. In addition to this, each spectrum is reduced following slightly different prescriptions, and the continuum is determined with different algorithms. Systematic effects are thus expected and are hard to control. We argue that the increase in the uncertainty in the final measurement simply reflects the increased incompatibility of the input spectra. In support of this, fitting the model on HIRES data alone yields higher (albeit still consistent) D I/H I than ESPRESSO, UVES, or the combination of the two ($D I/H I_{\text{HIRES}} = 2.89 \pm 10^{-5}$).

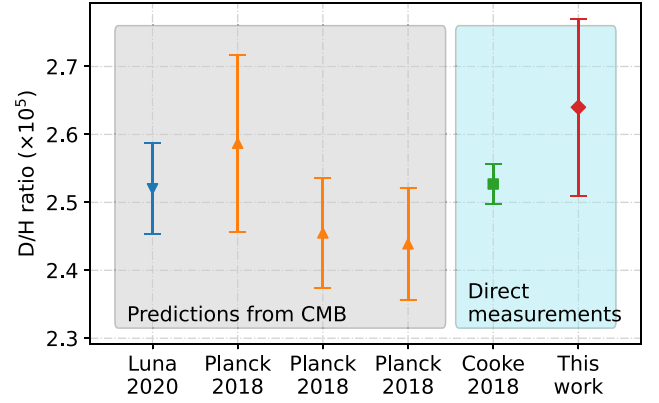


Figure 10. Primordial deuterium abundance from the LUNA experiment (Mossa et al. 2020), Planck data and the Precision Sample presented in Cooke, Pettini & Steidel (2018), compared to the results of this work. Planck provides three different measurements, depending on the assumed nuclear rates (Planck Collaboration VII 2020).

In addition to this, we also note an atypical trend in the scaling of the final uncertainties reported by RS17: the uncertainty when fitting the model on single spectra (either UVES or HIRES) is a factor of three larger than the corresponding value found on the combined fit. Instead, we would expect the error to scale with the square root of S/N. This would lead to an uncertainty on the final determination of ~ 0.11 : systematics would further increase this number. This is quantified in Sections 3.3.5 and 3.3.4. We find that, for example, the choice of a narrower fitting region combined with continuum adjustments shifts the central value of the D I/H I by nearly one σ . Based on these arguments, we show that the uncertainty of the determination is higher than previously reported and is likely dominated by systematics rather than statistical uncertainty.

7 SUMMARY AND CONCLUSIONS

We have presented a new determination of the abundance of primordial deuterium in an absorption system at redshift $z = 3.572$ seen towards the quasar PKS1937-101. The system was already studied in the past with different instruments (Tytler, Fan & Burles 1996; Burles & Tytler 1998; Riemer-Sørensen et al. 2017). It is a Lyman limit system ($\log N_{\text{H I}} \sim 17.9$) showing a clear absorption due to D I at the redshift of the H I Ly α and Lyman β lines. The analysis was carried out using new ESPRESSO data, of higher quality compared to previous measurements based on UVES and HIRES data alone. The new ESPRESSO data have 50 per cent higher S/N per kms^{-1} at almost double spectral resolution and significantly better wavelength calibration. In addition to the analysis of the ESPRESSO data alone, archival data have been included to further reduce the final measurement uncertainties.

Based on ESPRESSO data alone, we found a D I/H I of 2.638 ± 10^{-5} (Section 3.2). This is slightly higher than the most recent measurement by RS17, although consistent within the respective error bars. Including archival UVES data, we found $D/H = 2.608 \pm 10^{-5}$ (Section 4.2), while the inclusion of HIRES data did not decrease the uncertainty, possibly indicating that we have reached the limit of statistical errors (Section 4.4 and Section 6.2). The systematic effects that may explain this are difficult to model. The determination of the joint ESPRESSO+UVES fit is consistent with the weighted mean presented by Cooke, Pettini & Steidel (2018) based on the Precision Sample ($\sim 0.8\sigma$ level), Planck data (0.2, 1.2, 1.3 σ level;

Planck Collaboration VII 2020), and recent results from the LUNA experiment ($\sim 0.7\sigma$ level; Mossa et al. 2020).

Using ESPRESSO data, we discussed uncertainties in the modelling. We quantified the impact of continuum estimation uncertainties on the final measurement and investigated whether a fourth component is needed, finding that it is only required to adequately fit higher ionization lines, but it is removed when considering low-ionization metals, D1 and H1. Furthermore, we found that choosing a smaller fitting region for the Ly α region leads to a higher determination of D/H of 2.76 ± 10^{-5} : this is due to VPFIT adjusting the continuum to be lower, reducing the H1 column density. Our model also fits well the higher order Lyman series lines.

Surprisingly, the final determination from the ESPRESSO+UVES data carries higher uncertainties than those reported by RS17. Column densities of H1 lines in the Lyman limit range ($17.3 \leq \log N_{\text{H I}} \leq 19$), as the one analysed here, are hard to constrain precisely because the line is saturated but it is not yet showing the Damped wings of the Lorentzian profile. This is evidenced by the disagreement among independent determinations. Moreover, systematic errors from the continuum placement or the choice of the fitting region are significant.

Finally, we combine the results of this work with a collection of results from the literature. A weighted average of the sample leads to $D/H = 2.512 \pm 10^{-5}$. This changes to $D/H = 2.531 \pm 10^{-5}$ if we exclude measurements with uncertainties greater than 10 per cent. Considering the whole sample, we do not find any correlation between the D/H ratio and the redshift, metallicity or the H1 column density, confirming the findings of Cooke, Pettini & Steidel (2018). The results of the combined sample are also consistent with both Planck (Planck Collaboration VII 2020) and LUNA (Mossa et al. 2020) experiments: no significant tension is evident.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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APPENDIX A: VPFIT MODEL

Table A1. We report for each transition included in the model the corresponding column density, redshift, and total b parameter. For the transitions where we fit for both b_{turb} and T we report the error separately for both quantities, and not on the b_{tot} . For transitions marked with *, the reported column density is the sum of the column densities across the three components, and only report the error on the sum.

Transition	$\log(N)$	$\Delta \log(N)$	z	Δz	b_{tot} (kms^{-1})	Δb_{tot} (kms^{-1})	b_{turb} (kms^{-1})	Δb_{turb} (kms^{-1})	T (K)	ΔT (K)
C II	12.27719	0.09592	3.5721324	0.0000112	5.10710	////	2.01	2.15	1590	459
C II	12.80011	0.05103	3.5722725	0.0000050	6.72580	////	4.76	0.87	1630	5190
C II	13.14995	0.01827	3.5724591	0.0000036	7.63190	////	5.72	0.32	1840	1110
Si II	11.07122	0.16452	3.5721324	0.0000000	3.67030	////	2.01	2.15	1590	459
Si II	11.92929	0.04499	3.5722725	0.0000000	5.68360	////	4.76	0.87	1630	5190
Si II	12.22167	0.01869	3.5724591	0.0000000	6.60520	////	5.72	0.32	1840	1110
Fe III	12.68527	0.08734	3.5722725	0.0000000	5.22720	////	////	////	////	////
Fe III	13.20000	0.02378	3.5724591	0.0000000	6.16460	////	////	////	////	////
H I	13.49750	0.01004	3.2179784	0.0000096	45.4376	0.9483	////	////	////	////
H I	13.17590	0.31649	3.2192094	0.0002257	33.3361	8.9871	////	////	////	////
H I	13.75953	0.07837	3.2195409	0.0000044	20.8896	1.0158	////	////	////	////
H I	14.66222	0.08622	3.2209637	0.0000079	28.3678	0.7715	////	////	////	////
H I	14.92678	0.05668	3.2210411	0.0000097	19.5230	1.0635	////	////	////	////
H I	14.37814	0.01210	3.2238886	0.0000066	25.1154	0.3731	////	////	////	////
H I	13.51177	0.00527	3.2256770	0.0000037	26.5957	0.3201	////	////	////	////
H I	14.13789	0.01365	3.2246176	0.0000099	27.8596	0.5640	////	////	////	////
H I	11.90997	0.09105	3.2228270	0.0000323	16.4572	3.6905	////	////	////	////
H I	12.75313	0.12461	3.4818366	0.0000234	17.9989	2.0488	////	////	////	////
H I	13.55302	0.11481	3.4826829	0.0000083	24.7134	2.0620	////	////	////	////
H I	13.75280	0.19026	3.4833953	0.0000726	55.8278	6.6979	////	////	////	////
H I	12.55664	0.08984	3.4836069	0.0000130	13.1128	1.5776	////	////	////	////
H I	13.22525	0.40686	3.4847351	0.0004795	59.1222	9.0805	////	////	////	////
H I	14.46741	0.00494	3.4860559	0.0000021	27.4336	0.1766	////	////	////	////
H I	12.77936	0.13431	3.4871438	0.0000120	23.9338	2.9068	////	////	////	////
H I	12.86475	0.15360	3.4878010	0.0002088	56.8514	3.9931	////	////	////	////
H I	12.14067	0.09033	3.4893585	0.0000291	20.4586	3.2330	////	////	////	////
H I	12.32798	0.08783	3.4903180	0.0000230	26.0675	3.4951	////	////	////	////
H I	17.92361	0.01547	3.5721324	0.0000000	16.3286	0.0000	////	////	////	////
H I	17.38427	0.11517	3.5722725	0.0000000	17.0856	0.0000	////	////	////	////
H I	17.46396	0.05434	3.5724591	0.0000000	18.3583	0.0000	////	////	////	////
D I	13.34481	0.01514	3.5721324	0.0000000	11.6781	0.0000	////	////	////	////
D I	12.80547	0.00000	3.5722725	0.0000000	12.5836	0.0000	////	////	////	////
D I	12.88516	0.00000	3.5724591	0.0000000	13.6409	0.0000	////	////	////	////
H I	13.42287	0.00717	3.5632977	0.0000053	32.3439	0.4975	////	////	////	////
H I	13.23902	2.29951	3.5643157	0.0005578	22.4179	9.8904	////	////	////	////
H I	13.56131	0.90470	3.5647841	0.0000404	14.5604	8.3881	////	////	////	////
H I	14.20576	0.48146	3.5649199	0.0003255	34.5775	7.9958	////	////	////	////
H I	13.16800	0.38599	3.5652351	0.0000398	11.3401	2.7810	////	////	////	////
H I	14.03812	0.01663	3.5663878	0.0000076	27.5262	0.5996	////	////	////	////
H I	13.55277	0.04721	3.5670652	0.0000420	35.2826	1.8478	////	////	////	////
H I	12.14010	0.06582	3.5683673	0.0000328	21.5655	3.4345	////	////	////	////
H I	13.04629	0.01142	3.5695084	0.0000068	31.4880	0.7736	////	////	////	////
H I	15.76831	0.70475	3.5728219	0.0004595	29.0785	6.4334	////	////	////	////
H I	13.72076	1.87345	3.5735586	0.0004771	21.5114	9.2989	////	////	////	////
H I	13.10764	0.04477	3.5750312	0.0000521	57.6792	5.5815	////	////	////	////
H I	12.23112	0.18153	3.5757240	0.0000160	17.2274	3.4219	////	////	////	////
H I	13.64665	0.00514	3.5766944	0.0000023	20.5472	0.2636	////	////	////	////
H I	12.57496	0.08553	3.5772601	0.0000156	12.8801	1.5762	////	////	////	////
H I	13.54550	0.01491	3.5777517	0.0000049	20.1200	0.7205	////	////	////	////
H I	13.60914	0.14873	3.5784697	0.0000411	19.7491	1.6802	////	////	////	////
H I	12.55723	1.63382	3.5788174	0.0007554	22.3322	3.6585	////	////	////	////
H I	12.23596	0.10544	3.5796144	0.0000286	16.4360	3.4158	////	////	////	////
H I	12.59238	0.03925	3.5801276	0.0000178	18.7243	1.4348	////	////	////	////
H I	13.22402	0.01686	3.5817311	0.0000062	29.2061	0.9144	////	////	////	////
H I	12.28541	0.16346	3.5817898	0.0000163	12.4031	2.2539	////	////	////	////
H I	12.61916	0.13766	2.6569922	0.0000857	36.5521	9.7131	////	////	////	////
H I	12.63054	0.17887	2.6606367	0.0000191	13.5772	4.1641	////	////	////	////
H I	13.33306	0.50016	2.6592406	0.0001951	21.1861	8.3306	////	////	////	////
H I	13.96424	0.43684	2.6596522	0.0000395	16.7285	5.9622	////	////	////	////
H I	14.12626	0.32432	2.6598944	0.0001896	30.2413	8.3448	////	////	////	////

Table A1 – continued

Transition	log(N)	$\Delta \log(N)$	z	Δz	b_{tot} (kms ⁻¹)	Δb_{tot} (kms ⁻¹)	b_{turb} (kms ⁻¹)	Δb_{turb} (kms ⁻¹)	T (K)	ΔT (K)
??	12.92620	0.43025	2.6592894	0.0000184	7.8699	2.7932	////	////	////	////
H I	12.97916	0.03992	2.5698604	0.0000192	23.3382	1.9266	////	////	////	////
H I	12.80392	0.11076	2.5711063	0.0000337	14.6142	2.4086	////	////	////	////
H I	14.31257	0.07072	2.5738291	0.0000231	33.6546	4.5900	////	////	////	////
H I	13.57488	0.07094	2.5745386	0.0000196	19.3668	1.0655	////	////	////	////
H I	12.76783	0.20193	2.5729993	0.0000419	16.8660	6.2359	////	////	////	////
H I	13.03850	0.05278	2.5754521	0.0000227	25.1392	2.0029	////	////	////	////
H I	12.32696	0.42836	2.5257436	0.0000211	6.0693	2.0157	////	////	////	////
H I	12.39755	0.38378	2.5258665	0.0000804	10.0218	5.6534	////	////	////	////
H I	13.38328	0.08656	2.5257474	0.0000346	80.1206	1.0527	////	////	////	////
H I	13.33289	0.23233	2.5277668	0.0001658	36.8602	9.1620	////	////	////	////
H I	13.56498	0.04497	2.5296692	0.0000249	64.0627	4.3216	////	////	////	////
H I	13.57421	0.20761	2.4990371	0.0005172	73.5544	4.3406	////	////	////	////
H I	13.44619	0.09070	2.4994164	0.0000068	21.1994	1.8436	////	////	////	////
??	11.95068	0.12458	2.4829808	0.0000142	5.9523	2.3065	////	////	////	////
H I	12.62854	0.07857	2.4822349	0.0000206	27.8076	3.8507	////	////	////	////
??	11.98511	0.17310	2.4843733	0.0000110	2.3946	2.2016	////	////	////	////
H I	12.90598	0.22810	2.4868100	0.0000597	22.4348	8.4080	////	////	////	////
H I	13.41392	0.06346	2.4863433	0.0000332	26.4205	2.3093	////	////	////	////
H I	13.64106	0.14584	2.4848864	0.0000729	24.8313	4.3022	////	////	////	////
H I	13.48436	0.10874	2.4712119	0.0001014	47.0441	6.4405	////	////	////	////
H I	13.45318	0.15149	2.4715520	0.0000375	18.1789	3.3932	////	////	////	////
H I	13.61457	0.05130	2.4753132	0.0000179	21.8047	1.0605	////	////	////	////
H I	12.07801	0.13165	2.4734717	0.0000226	11.2243	3.6924	////	////	////	////
H I	13.16757	0.02739	2.4729291	0.0000122	26.8911	1.9385	////	////	////	////
H I	13.70755	0.04148	2.4749054	0.0000225	25.7499	1.3743	////	////	////	////
H I	12.41494	0.08154	2.4739942	0.0000204	19.0407	3.2312	////	////	////	////
H I	14.18948	0.03554	2.4632222	0.0000269	36.8891	1.4545	////	////	////	////

Table A2. Interlopers that contribute as Lyman β or Lyman γ to the fitting regions. A limited number of transitions, marked as ‘Unknown’ in the table, did not show a corresponding Lyman β or γ in the fitting regions but were required for convergence of the fit, and are thus listed here. The column densities and b_{tot} parameters listed in the table are obtained under the assumption that these transitions are caused by H I, according to the VPFIT default.

Transition	log(N)	z	b_{tot} (kms $^{-1}$)	Transition	log(N)	z	b_{tot} (kms $^{-1}$)
H I	13.725	3.33306	43.49	H I	11.916	3.18239	10.58
H I	14.148	3.33321	23.28	H I	13.646	3.14762	17.90
H I	12.940	3.33406	30.18	H I	13.024	3.14857	29.28
Unknown	12.598	3.33535	5.34	H I	12.610	3.14954	21.36
Unknown	12.597	3.33563	8.12	H I	13.833	3.15078	23.66
Unknown	11.553	3.33589	1.76	H I	13.421	3.15125	19.34
H I	13.411	3.33581	54.25	H I	13.606	3.37168	37.19
Unknown	12.272	3.33618	4.39	H I	13.817	3.37277	23.06
Unknown	11.898	3.33648	4.61	H I	13.606	3.37168	37.19
H I	12.929	3.33695	21.45	H I	13.817	3.37277	23.06
H I	13.057	3.33811	36.28	H I	13.079	3.37140	15.26
H I	13.096	3.33814	40.18	H I	12.646	3.37320	19.72
H I	14.352	3.23251	21.80	H I	12.692	3.37492	55.41
H I	13.885	3.23384	41.77	H I	12.299	3.37440	3.11
H I	15.119	3.23556	32.92	H I	12.732	3.37683	55.39
H I	13.058	3.23673	18.99	H I	11.766	3.37499	10.55
H I	14.528	3.23770	29.51	H I	11.977	3.37175	5.62
H I	13.482	3.23923	33.15	H I	11.729	3.37223	6.19
H I	14.000	3.23067	37.35	H I	12.366	3.12955	14.57
H I	14.305	3.45857	24.65	H I	15.049	3.13059	28.17
H I	13.724	3.44979	20.32	H I	13.106	3.13223	78.61
H I	14.512	3.45031	43.96	H I	13.229	3.35231	27.12
H I	14.421	3.45322	88.19	H I	12.866	3.35478	55.59
H I	12.919	3.45699	43.84	H I	12.777	3.35603	26.98
H I	14.519	3.45987	30.85	H I	12.410	3.35395	19.71
H I	15.161	3.46056	28.97	H I	12.602	3.35308	27.77
H I	14.495	3.46143	17.85	H I	11.914	3.35965	12.44
H I	14.067	3.46228	23.03	H I	11.645	3.35704	12.59
H I	14.682	3.46417	20.98	H I	13.759	3.11792	26.21
H I	13.028	3.46802	31.45	H I	13.026	3.11775	56.69
H I	12.746	3.46878	23.68	H I	12.681	3.12132	27.41
H I	13.187	3.46941	6.16	H I	12.512	3.11782	11.40
H I	13.391	3.46942	25.08	H I	12.566	3.11951	20.98
H I	13.907	3.46440	41.01	H I	12.133	3.12037	15.36
H I	12.853	3.45565	29.48	H I	12.933	3.11858	32.72
H I	14.793	3.45332	36.89	H I	12.711	3.11682	36.77
H I	13.088	3.46294	37.56	H I	12.087	3.11560	21.49
H I	12.318	3.46555	20.00	H I	12.919	3.09982	90.19
H I	11.745	3.45483	8.14	H I	13.998	3.10029	23.13
H I	13.224	3.45219	19.20	H I	12.387	3.10095	14.14
H I	13.684	3.17379	28.70	H I	12.624	3.10114	16.75
H I	13.983	3.17480	22.47	H I	13.323	3.10202	37.07
H I	14.200	3.17562	25.02	H I	13.491	3.10322	24.13
H I	13.688	3.17643	28.67	H I	12.267	3.10436	19.62
H I	13.295	3.17753	15.13	H I	12.370	3.10340	11.60
H I	14.373	3.17777	40.62	H I	11.603	3.10194	4.46
H I	13.669	3.17913	23.71	H I	12.971	3.10031	10.64
H I	13.726	3.18095	33.59	H I	12.213	3.10056	4.62
H I	13.075	3.18197	19.54	H I	12.981	3.32722	26.49
H I	13.458	3.18294	28.16	H I	13.716	3.32823	24.11
H I	12.910	3.18366	32.69	H I	13.051	3.33003	31.69
H I	13.479	3.18502	22.77	H I	13.107	3.33111	35.49
H I	12.429	3.17366	10.30	H I	13.143	3.32896	29.62
H I	12.178	3.18309	8.68	H I	13.082	3.32730	24.75
H I	12.991	3.17826	14.57	–	–	–	–

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