The Deuterium Abundance in the $z = 0.7$ absorber towards QSO PG1718+4807


ABSTRACT

We report a further analysis of the ratio of deuterium to hydrogen (D/H) using HST spectra of the $z = 0.701$ Lyman limit system towards the QSO PG1718+481. Initial analyses of this absorber found it gave a high D/H value, $1.8 - 3.1 \times 10^{-4}$ (??), inconsistent with several higher redshift measurements. It is thus important to critically examine this measurement. By analysing the velocity widths of the D1, H1 and metal lines present in this system, ?) report that the additional absorption in the blue wing of the Ly$\alpha$ line can not be D1, with a confidence level of 98%. Here we present a more detailed analysis, taking into account possible wavelength shifts between the three sets of HST spectra used in the analysis. We find that the constraints on this system are not as strong as those claimed by ?). The discrepancy between the parameters of the blue wing absorption and the parameters expected for D1 is marginally worse than 1$\sigma$.

?? comment on the first analysis of ??), reporting the presence of a contaminating lower redshift Lyman limit system, with log[$N$(H1)] = 16.7 at $z = 0.602$, which biases the $N$(H1) estimate for the main system. Here we show that this absorber actually has log[$N$(H1)] < 14.6 and does not impact on the estimate of $N$(H1) in the system of interest at $z = 0.701$.

The purpose of the present paper is to highlight important aspects of the analysis which were not explored in previous studies, and hence help refine the methods used in future analyses of D/H in quasar spectra.

Key words:

1 INTRODUCTION

Virtually all the deuterium (D) and the vast majority of H and $^4$He we observe today were produced during big bang nucleosynthesis (BBN). BBN also produced small amounts of $^4$He and $^7$Li. In standard BBN theory, the primordial abundances of all these light elements depend solely on the cosmological baryon density, $\Omega_b$. This allows $\Omega_b h^2$ to be measured directly by finding the primordial ratio of any two of these light elements$^1$. The ratio D/H is very sensitive to $\Omega_b h^2$, and of all the BBN light elements, D/H potentially gives the best constraints on $\Omega_b$.

QSO absorption systems provide a unique way to measure the primordial abundance of deuterium (?). Theoretically there are processes other than BBN that create D, but it has been shown (?) that the D production due to these processes is likely to be negligible compared to D production during BBN (but see also ?). Stellar nuclear reactions cause a net destruction of D, so measurements of the D abundance in sites that have undergone star formation, such as our Galaxy, provide a lower limit to the primordial D/H value. However, many QSO absorption clouds are thought to have undergone very little star formation, and we expect D/H in these clouds to be close to the primordial value. Unfortunately, very few absorption systems have the high column density ($\geq 10^{17}$ absorbers per cm$^2$), simple velocity structure and narrow linewidth that are required for the D1 line to be separated from the nearby H1 absorption (?).

Most existing D/H measurements have been made in absorption systems with a redshift large enough that the Ly$\alpha$ line falls in the visible ($z > 2.2$). For lower redshift systems the Ly$\alpha$ line falls in the UV and must be observed from space. However, it is desirable to look for low redshift absorbers as there is much larger sample of bright QSOs at lower redshifts. In addition, the number density of Ly$\alpha$ forest absorbers is much lower at low redshifts compared to high redshifts. This means it is easier to accurately measure the continuum level around the relevant absorption lines, and the chance of a randomly placed H1 line contaminating the D1 absorption is smaller.

The absorption system at $z = 0.701$ towards PG1718+4807 was first identified as an excellent candidate
for a D/H measurement from an International Ultraviolet Explorer (IUE) spectrum covering its Lyman limit (LL). Its LL is 'grey', meaning the flux does not drop to zero blue-wards of the LL. The drop in flux at the grey LL strongly constrains the column density of the absorber. The column density was high enough for the D1 Lyα line to be detected, and the sharp break at the LL suggested the velocity structure of the absorption complex was very simple. (?) published the first analysis of D/H in the z = 0.701 system, using a GHR S spectrum covering the Lyα and Si iii lines and the IUE spectrum covering the LL. (?) fitted the H1 absorption with a single cloud, assuming the redshift of the Si iii line was the same as the redshift of the H1 absorption. They found D/H of 1.8 - 3.1 × 10⁻⁴, about ten times higher than D/H measured in other, higher redshift absorption systems (~ 2 - 4 × 10⁻⁵, see ???).

?) subsequently published a further analysis of D/H in the same absorber, adding Keck/HIRES spectra of Mg ii lines associated with the z = 0.701 absorber. Using the Mg ii lines they considered several models with different constraints on the H1 component’s redshift. They found a larger range of D/H: 8 - 57 × 10⁻⁵.

?) (hereafter KTOB) published new HST STIS (Space Telescope Imaging Spectrograph) spectra covering the LL, Lyα and Si iii lines of the absorber. The spectrum of the LL has a resolution of 100 kms⁻¹, and all the Lyman series lines from Lyman-ε to Lyman-16 were resolved (see Fig. 1). This spectrum confirmed the presence of a single strong H1 component and allowed its redshift to be measured precisely. However, (?) found additional weak absorption to the red of the main H1 component. This absorption was too weak to be seen in the higher order Lyman series, but was seen in the new STIS spectrum of the Lyα line. They also claimed that the b parameter (b = √2σ, where σ is the velocity dispersion) of the putative D1 was larger than that expected for a gas with a temperature and turbulence calculated from the H1 and metal lines’ b parameters. Based on these two points they claimed that the absorption fitted as D1 in (?) and (?) is contaminated by weak H1 absorption. Due to this contamination they concluded the system does not provide evidence for a high D/H value.

We present a further analysis of D/H in the z = 0.701 absorption system, in which we look at the effect of systematic errors, not addressed in previous analyses, that affect the z = 0.701 absorption system parameters. In particular we analyse how the the putative D1 absorption’s parameters are affected by wavelength calibration errors in the HST spectra and present revised parameters for this particular absorption spectrum. These calibration effects will be important for future analyses of D/H in QSO spectra. Finally, we assess the likelihood that this absorption system shows D1 and give an estimate of D/H for this system.

2 DATA AND ANALYSIS

The QSO PG1718+4807 has been observed with the Faint Object Spectrograph (FOS), Goddard High Resolution Spectrograph (GHR S) and STIS on the HST, and the IUE

(?)². We are interested in finding the parameters of the H1 and D1 absorption. The resolutions of the FOS and IUE spectra are much lower (FWHM ~ 150 and ~ 900 kms⁻¹ respectively) than those of the GHR S and STIS spectra. The FOS and IUE spectra do not provide any useful constraints on the parameters of D1 or any H1 sub-components which may be present in the z = 0.701 absorption complex. The parameters of the main H1 component are very well determined by the STIS spectra alone (see section 2.8). Therefore we use only the GHR S and STIS spectra in our analysis.

?) detected Mg ii with Keck/HIRES. We use their best fitting parameters for Mg ii, with a modified error for the Mg ii b parameter (see section 2.8).

2.1 GHR S data

The GHR S spectra were taken using the G140M grating with a 0.2 × 0.2 aperture giving a line spread function (LSF) with a FWHM of 14 kms⁻¹. The observations consisted of 56 exposures, which were shifted and added using the IRAF routines written for this purpose by the Space Telescope Science Institute (STScI), phasesets and speccalig n. We used the pipeline reduced spectra, processed with CALHRS version 2.3.13. The wavelength range covered is 2049 – 2098 Å. The S/N per pixel near the Lyα and Si iii lines in the combined spectrum is ~10.

2.2 STIS data

The STIS observations were taken with the E230M echelle grating and the G140M longslit grating with the 0.2×0.2 aperture. The FWHM of each of the LSFs of the STIS observations are 2 pixels for the E230M echelle grating (5 kms⁻¹ per pixel) and 1.5 pixels for the G140M grating (0.06 Å or ~11 kms⁻¹ per pixel). Four exposures were taken with the G140M grating, and five with the E230M grating. In each case we used the pipeline reduced spectra (CALSTIS version 2.8). For each set of observations the exposures were rebinned to a common wavelength scale and combined using a variance weighted average. The E230M spectra cover the wavelength region 1842 – 2673 Å. The final S/N per pixel near the Lyα and Si iii lines in the averaged E230M spectrum is ~5. The G140M spectra cover the Lyman-ε transition down to the Lyman limit, a wavelength range of 1540 – 1594 Å. The S/N per pixel in the G140M averaged spectrum is ~9.

2.3 Line spread functions

The LSF of the GHR S observations can be approximated by a Gaussian, but the STIS LSFs are significantly different from a Gaussian. We used the instrumental profiles for the E230M and G140M gratings given in the STIS instrument handbook³. The actual STIS LSFs may be slightly asymmetric. The nature of this asymmetry depends on the orientation of the slit on the sky (Sahu in KTOB). We averaged the asymmetric sides of the LSF to give a symmetric

² The GHR S, STIS, FOS and IUE spectra are all available from the HST multimission data archive: http://archive.stsci.edu
The Deuterium Abundance in the $z = 0.7$ absorber towards QSO PG1718+4807

Figure 1. The STIS spectrum of the $z = 0.701$ Lyman limit, a weighted sum of four STIS exposures with the G140M grating. There appears to be Galactic C IV absorption and emission at $\sim 1548$ and $\sim 1550.5$ Å. We are unsure what is causing the absorption at $\sim 1554.5$, $1565 - 1566.5$, and $\sim 1580.5$ Å. Neither these regions, nor the regions affected by Galactic C IV absorption were included in the fit. The normalised residuals (which we define $\equiv \frac{1}{\sqrt{n}} \cdot \frac{(\text{data point} - \text{fitted value})}{\text{error}}$) and the $1\sigma$ error levels for the residuals are shown centred on $y = -0.3$. The thin curve shows the best fitting solution when the Lyα lines and the LL are fit simultaneously. This fit provides the H I parameters in Table 1.

2.4 Continuum placement

The placement of the continuum in the STIS G140M spectrum has a potentially significant effect on the fitted $b$ parameter and column density of the main H I component. To test the magnitude of this effect, we fitted the continuum of this region using several methods. Firstly we fitted a constant flux to regions apparently free of absorption. Secondly we fitted a power law $f_\lambda \propto \lambda^{-\alpha}$. Finally, the IUE spectrum covers a larger wavelength range redwards of the Lyman limit than the STIS G140M spectrum, so it may give a better estimate of the continuum than just fitting the STIS Lyman limit. We fitted the IUE Lyman limit with a 3rd order Chebyshev polynomial and scaled this continuum to the level of the STIS Lyman limit, based on regions apparently free from absorption. Each of these methods gave very similar column densities and $b$ parameters for the main H I component. The small error due to continuum fitting was added in quadrature to the statistical error. This combined error is the first error given in Table 1.

The error in continuum placement around the Lyα line, Si III line and C IV doublet (Fig. 2, 3 and 4) was determined by fitting both straight lines and 3rd order Chebyshev polynomials to regions apparently free from absorption close to each line. The differences between these two methods of continuum fitting have a negligible effect on the absorption line parameters.

2.5 Wavelength calibration and shifts between the HST spectra

Misalignment of the wavelength scale between the GHRS, STIS G140M and STIS E230M spectra can potentially affect all the fitted parameters for H I and the putative D I, and the redshift for Si III and C IV. The GHRS wavelength scale appears to be offset from the STIS wavelength scale by $\sim 0.07$ Å ($\sim 1.4$ GHRS pixels). Despite helpful discussion with Claus Leitherer from STScI we were unable to discover the reason for the discrepancy. KTOB shifted the GHRS spectrum to coincide with the STIS spectrum, finding the amount by which to shift by cross correlation over the common wavelengths covered.
Figure 2. The GHRS (above) and STIS (below) spectra covering the $z = 0.701$ Ly$\alpha$ line. The normalised residuals and their 1σ error levels are shown centred on $y = -0.4$. The thin curve shows the best fitting solution when the Ly$\alpha$ lines and the Lyman limit are fit simultaneously. This fit provides the parameters in Table 1. The contributions from the main H$\text{i}$ component, red and blue components are shown by dashed curves. Note that the ‘shape’ of the STIS E230M Ly$\alpha$ line appears to be different to that of the GHR$\text{S}$ line. In particular, the shape of the red wing and the absorption at $\sim 2067.4$ Å are different. We are not certain what causes these differences, but they may be explained by correlations in the noise.

They then checked this shift by comparing the positions of profile fits to sharp features in each spectrum. However, they do not estimate the error in their shift.

We calculate the shift by choosing the three sharpest absorption features at relatively high S/N present in each spectrum and calculating the cross correlation for each of them. The regions we used were: 2051.1 – 2053.7 Å (the Si$\text{ii}$ line), 2056.5 – 2060.4 Å (a Ly$\beta$ line at $z = 1.0065$) and 2069.6 – 2072.2 Å (a Ly$\alpha$ line at $z = 0.70326$). The three shifts for these regions were 0.070 Å, 0.072 Å and 0.058 Å respectively. The three shifts are roughly consistent, suggesting that the wavelength offset is the same across the spectrum. We take the average of these three shifts and move the GHRS spectrum by this amount to align it with the STIS spectrum, assuming that the STIS wavelength calibration is more accurate than the GHR$\text{S}$ calibration. To quantify the error in this shift, we fit the sharpest feature in each spectrum, the Si$\text{ii}$ line, with VP$\text{FIT}$. The VP$\text{FIT}$ errors in the position of each line were then added in quadrature to give an estimate of the total error in the shift. This error is $\sim 0.007$ Å, or $\sim 1$ km s$^{-1}$. This error does not have a significant effect on the parameters of the putative D$\text{t}$ or main H$\text{i}$ absorption.

For a 0.2×0.2 aperture and the MAMA detector used for the STIS observations, the absolute wavelength calibration error can be as much as 0.5 to 1.0 pixels (2σ, M$\text{A}$ in str02). In our analysis we introduce a conservative error of 0.3 pixels in the G140M and E230M wavelength calibrations. Thus we consider three different cases: (1) The wavelength calibration of both the G140M and E230M spectra are both correct, (2) the E230M spectrum wavelength scale shifted 0.3 pixels bluewards and the G140M wavelength scale 0.3 pixels redwards, and (3) the E230M wavelength scale shifted 0.3 pixels redwards and the G140M scale 0.3 pixels bluewards. Introducing even these conservative relative shifts of 0.6 pixels between the STIS E230M and G140M spectra does have a significant effect on the absorption line parameters, particularly those of the putative D$\text{t}$. This is because the redshift of the main H$\text{i}$ component is determined by the higher order Lyman series lines in the G140M spectrum. Introducing a shift between the G140M and E230M spectra means that the position of the main H$\text{i}$ absorption in the Ly$\alpha$ line changes. To compensate for this change in position, the parameters of the putative D$\text{t}$ and the red H$\text{i}$ component are also changed. We describe the effect of these shifts on the parameters of the putative D$\text{t}$ in section 2.9.

2.6 Contamination of the $z = 0.701$ system by systems at other redshifts

We attempt to identify all lines in the E230M spectrum to determine if the $z = 0.701$ absorption lines are contaminated
The Deuterium Abundance in the $z = 0.7$ absorber towards QSO PG1718+4807

Figure 3. The GHRS (above) and STIS (below) spectra covering the $z = 0.701$ Si$\text{\textsc{iii}}$ line. The normalised residuals and their 1σ error levels are shown centred on $y = 0$. The thin curve shows the best fitting solution when both lines are fit simultaneously. This fit provides the parameters in Table 1.

Figure 4. A tentative detection of the $z = 0.701$ C$\text{\textsc{iv}}$ doublet in the STIS E230M spectrum. The normalised residuals and their 1σ error levels are shown centred on $y = 0$. The thin curve shows the best fitting solution when both lines of the doublet are fit simultaneously. This fit provides the parameters in Table 1.

by H$\text{\textsc{i}}$ or metal lines from systems at different redshifts. There are six absorption systems with log[$N$(H$\text{\textsc{i}}$)] > 14.5 present in the E230M spectrum. They are at redshifts of 1.0867, 1.0674, 1.0549, 1.0318, 0.7247 and 0.5272. The Ly$\beta$ line at $z = 0.5272$ falls at $\sim 1566.5$Å, and may contribute to the absorption seen at this wavelength in the G140M spectrum (see Fig. 1). We did not include the region with this absorption when we fitted the G140M spectrum. For each log[$N$(H$\text{\textsc{i}}$)] > 14.5 system we searched the wavelength ranges covered by the G140M and E230M spectra for strong associated metal lines that may contaminate the $z = 0.701$ absorption lines, including Si$\text{\textsc{ii}}$, N$\text{\textsc{iv}}$, O$\text{\textsc{i}}$ and C$\text{\textsc{ii}}$. Only two systems show any strong metal lines: the $z = 1.0867$ system has associated Si$\text{\textsc{iii}}$ absorption, and the $z = 1.0318$ system shows N$\text{\textsc{v}}$ absorption. Galactic Fe$\text{\textsc{ii}}$ and Mn$\text{\textsc{ii}}$ absorption is also present. We found no other strong metal lines or higher order Lyman H$\text{\textsc{i}}$ transitions that may be blended with the $z = 0.701$ lines and affect our analysis.
2.8 Voigt profile fitting

Voigt profiles were fitted to the absorption lines and the best fitting parameters were determined by minimising the $\chi^2$ statistic. The program VPFIT\(^4\) was used for all line profile fitting. The absorption lines that were detected and fitted in the $z = 0.701$ system in the STIS spectra are the Ly$\alpha$ line, the Lyman series from Ly-$\alpha$ to the Lyman limit, Si$\text{iii}$ (1206.5 Å) and the C$\text{iv}$ doublet (1548.2 and 1550.8 Å). The GHRS spectrum covers the Ly$\alpha$ and Si$\text{iii}$ lines. We fitted all parameters for case (1) described in section 2.5, for no shift between the STIS spectra. The 0.3 pixel error in the uncertainty in the STIS wavelength calibrations is listed after the statistical error in Table 1 for the lines it applies to. We look at the effect of the shifts between the STIS spectra wavelength calibrations on the putative D$\text{i}$'s parameters in section 2.9.

The parameters of the main H$\text{i}$ component are tightly constrained by the unsaturated H$\text{i}$ higher order lines and the drop in flux at the grey Lyman limit. The main uncertainties in this case are the position of the continuum and the accuracy of the STIS wavelength calibration. Table 1 shows the best fitted parameters to the main H$\text{i}$ component. The error in redshift due to the error in STIS zero point wavelength calibration is given after the statistical error. The first error for each parameter given in the table is the quadrature addition of the statistical fitting error and the continuum placement error, where applicable.

The Si$\text{iii}$ line parameters were found by fitting the GHRS and STIS spectra simultaneously. Again we include separately the statistical error in redshift and the error when the wavelength calibration uncertainty of the STIS E230M spectrum is taken into account. The Si$\text{iii}$ line is offset bluewards from the main H$\text{i}$ system by 0.5 ± 1 (statistical) kms$^{-1}$. The C$\text{iv}$ line parameters were found by fitting the C$\text{iv}$ doublet in the STIS E230M spectra. The statistical error and error due to wavelength calibration are shown separately. The C$\text{iv}$ lines are offset bluewards from the main H$\text{i}$ component by 4 ± 3 (statistical) kms$^{-1}$. The best fitting $b$ parameter for C$\text{iv}$ is large compared to $b$(Mg$\text{ii}$) and $b$(Si$\text{iii}$). This difference is also seen in many damped Ly$\alpha$ absorbers (7) and is probably due to C$\text{iv}$ having a much higher ionization energy than Si$\text{iii}$ and Mg$\text{ii}$, and so being associated with a different velocity space in the absorption cloud.

We use the parameters of the Mg$\text{ii}$ lines given in KTOB to verify the errors given by KTOB, we generated a synthetic Mg$\text{ii}$ spectrum from the fitted $b$, $N$ and $z$ values they provided, at the same S/N ($\sim$70) and resolution (8 kms$^{-1}$ FWHM) as the Mg$\text{ii}$ spectrum they published. Our $\sigma(N)$ and $\sigma(z)$ were very similar to KTOB's, but our $\sigma(b)$ was larger, 1.4 kms$^{-1}$ instead of 1.1 kms$^{-1}$. We use our larger $\sigma(b)$ estimate in our analysis. The Mg$\text{ii}$ lines are offset redwards from the redshift of the main H$\text{i}$ system by 5 ± 1 (statistical) kms$^{-1}$. The systematic error for the wavelength calibration for Keck/HIRES spectra is $< 0.5$ kms$^{-1}$. This 5 kms$^{-1}$ shift may be due in part to an error in the STIS wavelength calibration (the 0.3 pixel error in wavelength calibration we consider corresponds to a velocity er-

---

\(^4\) Carswell et al., http://www.ast.cam.ac.uk/~rfc/vpfit.html
error of ~3 km s^{-1}). Even though we are not sure of the cause of this shift, it does not affect our analysis, since we use only the Mg\textsc{ii} b parameter (section 2.10).

We attempted to fit the LL and both Ly\alpha lines with a single H\textsc{i} component. The minimum reduced $\chi^2 \equiv \chi^2_{\text{min}}/(\text{no. of degrees of freedom})$ for this fit was 1.7. This fit predicted too much absorption in the higher order lines, and could not account for extra absorption in the red and blue wings of the Ly\alpha line. We needed to add two extra absorption lines, one H\textsc{i} sub-component to the red of the main component, and a putative D\textsc{i} line to the blue, to find an acceptable reduced $\chi^2$ (1.04). Table 1 gives the parameters of the red and blue H\textsc{i} components.

### 2.9 The errors on the parameters for the putative D\textsc{i}

The 1\sigma errors on the parameters in Table 1 are those calculated by VPFIT. These errors are based on the assumptions that (1): the model we have chosen (a single main H\textsc{i} component with a red and blue sub-component on either side) is correct and (2): the fitted parameters are independent and the shape of the $\chi^2$ parameter space around the minimum $\chi^2$ is parabolic. However, for the putative D\textsc{i} the column density, $b$, parameter and redshift are correlated. In addition, the $\chi^2$ parameter space is asymmetric (see Fig. 6, 7 and 8). This is due to the small number of data points that are available to constrain the parameters of the putative D\textsc{i}. It may also be due to the difference in ‘shape’ between the STIS and GHR\alpha Ly\alpha lines (see Figure 2). For these reasons, the 1\sigma errors given by VPFIT for the putative D\textsc{i} parameters may not be accurate. This is also likely to be the case for the red H\textsc{i} sub-component. For the other lines (the main H\textsc{i} component, Si\textsc{iii}, C\textsc{iv}, and Mg\textsc{ii}), the 1\sigma errors given by VPFIT will be sufficiently accurate.

We find a robust parameter error estimate for the D\textsc{i} parameters by using $\Delta \chi^2$ probability contour maps. These are generated by fixing two parameters (for instance, the $b$ parameter and redshift of the putative D\textsc{i}) and then varying the remaining parameters (the column density of the putative D\textsc{i} and all the parameters of the main H\textsc{i} component and red H\textsc{i} component) to minimise $\chi^2$. This creates a grid of $\chi^2$ values. The distribution of $\Delta \chi^2 \equiv \chi^2 - \chi^2_{\text{min}}$ is the same as that of a $\chi^2$ distribution with a number of degrees of freedom equal to the number of fixed parameters (in this case, two). Here $\chi^2_{\text{min}}$ is the smallest value of $\chi^2$ for a particular grid. Provided that errors on the data points are normally distributed, the probability contours generated in this way will be correct, irrespective of correlations between the fitted parameters (\textit{C}. We also need to consider the effect the shifts between the STIS E230M spectra have on the D\textsc{i} parameters. To do this we again consider the three shifts described in the previous section. Fig. 6, 7 and 8 show the probability contour maps for the three parameters of the putative D\textsc{i} for the three different relative shifts between the STIS Ly\alpha line and Ly\alpha spectra, representing the uncertainty in the wavelength calibration between the two spectra.

### 2.10 The putative D\textsc{i}'s $b$ parameter

We can predict what the $b$ parameter of a D\textsc{i} line associated with the main H\textsc{i} absorption from the $b$ parameters of the Si\textsc{iii}, Mg\textsc{ii} and main H\textsc{i} component. This is done by measuring the thermal line broadening, $b_{\text{therm}}$, and turbulent broadening, $b_{\text{turb}}$, by using the $b$ parameters from all available ions. If we assume the absorbing cloud has a thermal Maxwell-Boltzmann distribution and any turbulence can be described by a Gaussian velocity distribution, then the $b$ parameter for a particular ion will be given by

$$b_{\text{ion}}^2 = b_{\text{therm}}^2 + b_{\text{turb}}^2.$$ (1)

Here $b_{\text{therm}}^2 = \frac{2kT}{m}$, where $T$ is the temperature of the gas cloud, $m$ is the mass of the absorbing ion and $k$ is Boltzmann’s constant. $b_{\text{turb}}^2$ represents the Gaussian broadening due to small scale turbulence, and is the same for all ionic species. $b_{\text{therm}}^2$ is proportional to the inverse of the ion mass.

\begin{table}
\centering
\begin{tabular}{lccr}
\hline
Ion & log($N$) (cm$^{-2}$) & $z$ & $b$ (km s$^{-1}$) \\
\hline
H\textsc{i} & 17.213 \pm 0.007 & 0.701074 \pm 0.000003 \pm 0.000015 & 22.1 \pm 0.4 \\
H\textsc{i} & 13.5 & 0.70142 & 19 \\
Putative D\textsc{i} & 13.88 & 0.701108 & 22 \\
Si\textsc{iii} & 12.84 \pm 0.05 & 0.701071 \pm 0.000007 \pm 0.000009 & 14 \pm 2 \\
C\textsc{iv} & 13.18 \pm 0.08 & 0.701051 \pm 0.000019 \pm 0.000009 & 20 \pm 5 \\
Mg\textsc{ii} & 11.50 \pm 0.05 & 0.701100 \pm 0.000005 & 12.0 \pm 1.4 \\
\hline
\end{tabular}
\end{table}

\textit{a} VPFIT does not return sensible errors for this H\textsc{i} component. The reasons for this are described in section 2.9.

\textit{b} See section 2.9, Fig. 6, 7 and 8 for the putative D\textsc{i} parameter errors.
We plot $b^2$ against inverse ion mass in Fig. 9. Subject to the assumptions above, all the ions in the same cloud velocity space should lie on a straight line whose intercept gives $b_{\text{turb}}$ and slope gives the cloud temperature. Since Mg II and H I have very similar ionization potentials (IP) (13.6 eV and 15.0 eV respectively), they should trace out the same gas. The IP of Si III is somewhat higher (33.5 eV), but there is evidence that ‘intermediate’ IP ions, such as Al III, have a similar velocity structure to lower IP ions, such as Mg II (?). We assume that the Mg II and Si III lines are in the same gas as the H I and fit least squares line of best fit to these three points. This is shown as the dashed line in Fig. 9. If we use KTOB’s estimate for Mg II $\sigma(b)$, the D I point is plotted with its 1σ error bars as given by VPFT. We find a temperature of $2.05 \pm 0.12 \times 10^4$ K and a turbulent broadening of $12.1 \pm 1.3$ km s$^{-1}$. Although we use our estimate of Mg II $\sigma(b)$ rather than KTOB’s, if we do use KTOB’s Mg II $\sigma(b)$, the derived temperature and turbulent broadening do not change significantly.

### 2.11 Is the blue H I component deuterium?

If the blue component is D I, it should fall at a redshift corresponding to a velocity difference of 81.6 km s$^{-1}$ bluewards of the main H I component. In addition, it should have a $b$ parameter consistent with that predicted in the last section.

We use the contour plots described in section 2.9, combined with the $b$ parameter test in the last section, to see if the putative D I component’s parameters are consistent with those of D I. Fig. 6, 7 and 8 show how $\Delta \chi^2$ changes for a range of $b$ parameter, redshift and column density values. Note the degeneracy between the parameters, which has a
The Deuterium Abundance in the $z = 0.7$ absorber towards QSO PG1718+4807

Figure 8. $b$ parameter versus $\log_{10}(N[\text{H}])$ for the putative DI. For the left graph the Lyman limit is shifted 0.3 pixels redwards and the Ly$\alpha$ lines are shifted 0.3 pixels bluewards. For the right graph the Lyman limit is shifted 0.3 pixels bluewards and the Ly$\alpha$ lines are shifted 0.3 pixels redwards. For the centre graph the Lyman limit and Ly$\alpha$ lines are fitted with no shift. The contours represent, from innermost to outermost, the 68.4%, 95.4%, 99.73% and 99.99% confidence levels. The horizontal hashed region represents the 68.4% confidence region for the DI $b$ parameter predicted by the $b$ parameters of HI, Si III and Mg II (see Fig 9).

Figure 9. The $b$ parameter squared ($\text{km} \cdot \text{s}^{-1}$) versus the inverse ion mass ($\text{amu}^{-1}$). The dashed line is the least squares line of best fit to the Mg II, Si III, and H I points. C IV and the putative DI are shown for comparison. The error bars in each case are calculated from the 1σ errors given by VPFIT. Note that the DI error bars are not particularly meaningful (see section 2.9). The contour plots shown in Fig 6, 7 and 8 are required to determine whether $b$(DI) is consistent with $b$(H I), $b$(Mg II) and $b$(Si III).

For the left case of Fig. 7, corresponding to a fixed relative shifts between the G140M and E230M spectra, we can see that the $b$ parameter is completely consistent with that of DI, but the redshift is inconsistent. For the right case, the redshift is consistent, but the $b$ parameter is not. Where there is no relative wavelength shift between the spectra, the parameters of the blue component are inconsistent at a $\sim$ 80% confidence level. While these results do not suggest that the blue component is DI, they do not conclusively show that is is not DI.

If we take the case of no shift between the G140M and E230M spectra and assume the blue absorption is entirely due to DI, fixing the $b$ parameter and redshift at those we expect for DI, we find the ratio D/H = $(3.0 - 4.6) \times 10^{-4}$ (1σ limit).

2.12 Comparison with previous analyses of this system

We have analysed this absorption system using the same spectra presented in?, ? and KTOB, considering important systematic effects not addressed in these previous analyses.

There are several small differences in our fitted parameters for the main HI component, putative DI component and Si III line compared to KTOB’s fitted parameters. Our line spread function is slightly different from KTOB’s and we use a larger error for $b$(Mg II) (see section 2.8). We have explored the effect that relative shifts between the wavelength scales of the G140M and E230M spectra have on the parameters of the putative DI line. However, none of these effects substantially change the conclusions of KTOB.

As can be seen from Fig. 7, if a large relative shift between the G140M and E230M wavelength scales is present, the probability that the putative DI really is DI is decreased.

The most important reason for our different result from KTOB is a difference in generating our probability contours in Fig. 6, 7 and 8. When generating our $\chi^2$ contours, we varied all the parameters of all the components in the $z = 0.7$ complex. To generate the plot in KTOB’s Fig. 7, when calculating the minimum $\chi^2$ only the column density of the...
putative Dτ component was varied. The remaining putative Dτ parameters and all the parameters of the main Hτ component and the red Hτ sub-component were fixed by KTOB. This means their contours do not accurately represent the actual range of probabilities for the putative Dτ b parameter and redshift. The true confidence ranges are somewhat larger. This is the main reason we find that the putative Dτ parameters are inconsistent with those expected for Dτ and redshift. The true confidence ranges are somewhat larger than these ranges, giving Dτ(Ωb hz) ≃ 10−2 (Ωb hz) = 0.0044 ± 0.006. We can compare this range with the value of 0.0044 obtained from the CMB measurements. However, a systematic error of 0.003 is expected based on the standard BBN, no astration picture. This is due to an unaccounted for systematic error. However, it is possible that this system shows a low D/H relative to other systems with similar metallicities. At these metallicities no significant astration is thought to have occurred and the measured D/H values should be primordial. For a standard homogeneous BBN, we expect the primordial D/H to be independent of direction and redshift. Thus the inconsistency of the D/H values with lower D/H values in other QSOs and the CMB Ωb hz value supports the argument that the putative Dτ in this system is contaminated with Hτ.

3 DISCUSSION

We have analysed the z = 0.701 absorption complex towards PG 1718+4801 using HST STIS and GHRS spectra, considering systematic errors that were neglected in previous analyses. The most important of these systematic errors is the absolute wavelength calibration of the STIS G140M and E230M spectra. Introducing a relative shift, comparable to the wavelength error, between these two sets of spectra significantly alters the parameters of the putative Dτ.

We find that the parameters of the absorption line previously identified as Dτ are marginally inconsistent with those expected. In particular, the b-parameter and line position of this feature are at best consistent with the expected values at the 20% level.

We have shown that the absorption system at z = 0.602, previously claimed as having log[N(Hτ)] ≃ 16.7 in fact has log[N(Hτ)] < 14.5.

If we assume that the blue component is Dτ, we find D/H = (3.0 − 4.2) × 10−4. If significant contamination is present, then of course D/H may be significantly lower than 3.0 × 10−4.

The D/H range given here corresponds to a 1σ range for Ωb hz of 0.003 − 0.006. We can compare this range with Ωb hz estimates from other sources. Two recent estimates of the primordial Li7/H abundance are (0.91 − 1.91) × 10−10 (7) and (1.92 − 2.49) × 10−10 (7). Combining these two ranges, we find Li7(Ωb hz) = 0.0044 − 0.020. Two samples recently used to measure the He4 abundance, YP, give 0.238 ± 0.003 (The sample in *Izotov98a, using the ionization correction factor in *Gruen02a) and 0.2405 ± 0.0017 (7). Taking the highest and lowest limits of these two ranges gives He4(Ωb hz) = 0.0065 − 0.0145. Sievers et al. (2002) give CMB(Ωb hz) = 0.023 ± 0.003 based on all currently available CMB data. Taking an average of the five D/H measurements made in other QSO absorption clouds, weighted by their inverse variances, gives D(Ωb hz) = 0.021 ± 0.001.

The D/H range for the z = 0.701 QSO absorber is consistent with the Li7 range and only marginally inconsistent with the He4 range. It is significantly inconsistent with both the CMB and low QSO D/H Ωb hz ranges, however. The metallicity of this absorber is low, [Si/H] = −2.4 (7), and the QSO absorption systems used to measure D/H have similarly low metallicities. At these metallicities no significant astration is thought to have occurred and the measured D/H values should be primordial. For a standard homogeneous BBN, we expect the primordial D/H to be independent of direction and redshift. Thus the inconsistency of the