The Deuterium Abundance Towards Q1937–1009

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ABSTRACT

We present a new measurement of the deuterium-to-hydrogen ratio (D/H) in the Lyman limit absorption system at $z = 3.572$ towards Q1937–1009. Tytler, Fan & Burles (1996; hereafter TFB) made the first extragalactic detection of deuterium in this absorption system, which remains the best location for a high accuracy measurement of primordial D/H. Their detailed analysis of Keck spectra gave a low value of $D/H = 2.3 \pm 0.3 \pm 0.3 \times 10^{-5}$ (1σ statistical & systematic errors). Now we present a new method to measure D/H in QSO absorption systems. We avoid many of the assumptions adopted by TFB; we allow extra parameters to treat the continuum uncertainties, include a variety of new absorption models which allow for undetected velocity structure, and use the improved measurement of the total hydrogen column density by Burles & Tytler (1997a). We find that all models, including contamination, give an upper limit $D/H < 3.9 \times 10^{-5}$ (95 % confidence). Both this and previous analyses find contamination to be unlikely in this absorption system, A $\chi^2$ analysis in models without contamination gives $D/H = 3.3 \pm 0.3 \times 10^{-5}$ (67% confidence), which is higher but consistent with the earlier results of TFB, and a second measurement of D/H towards Q1009+2956 (Tytler & Burles 1997). With calculations of standard big bang nucleosynthesis (SBBN) and the assumption that this measurement of D/H is representative of the primordial value, we find a high baryon to photon ratio, $\eta = 5.3 \pm 0.4 \times 10^{-10}$. This is consistent with primordial abundance determinations of $^4$He in H II regions (Izotov et al. 1997)

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and $^{7}\text{Li}$ in the atmospheres of warm metal-poor population II stars (Bonifacio & Molaro 1997). We find a high value for the present-day baryon density, $\Omega_b h^2 = 0.0193 \pm 0.0014$, which is consistent with other inventories of baryonic matter, from low to high redshift: clusters of galaxies, the Lyman alpha forest & the Cosmic Microwave Background.

1. INTRODUCTION

Standard Big Bang Nucleosynthesis (SBBN; Wagoner et al. 1967; Walker et al. 1991; Smith et al. 1993; Krauss & Kernan 1995; Copi et al. 1995) predicts that a measurement of the primordial ratio D/H will give the most sensitive constraint on the cosmological baryon to photon ratio, $\eta$. Using the photon density measured from the temperature of the Cosmic Microwave Background (CMB), we can then obtain the most sensitive constraint on $\Omega_b h^2$, the cosmological baryon density in units of the critical density, where $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$. Both $\eta$ and $\Omega_b$ are fundamental cosmological parameters, and measurements of D/H in QSO absorption systems can determine both to 10% accuracy. When we compare measurements of the primordial abundances of different light elements, H, D and $^{4}\text{He}$ in particular, we test the SBBN theory predictions. Measurements of D/H in different astrophysical sites also constrains the history of star formation in these sites, once the primordial value of D/H is established, because D is totally destroyed (astrated) as gas is cycled through and ejected from stars (Epstein et al. 1976).

Adams (1976) first suggested that deuterium could be measured in intergalactic gas clouds through Lyman absorption lines in the spectra of distant QSOs. Deuterium Lyman absorption lines are 82 km s$^{-1}$ on the short wavelength side of the corresponding hydrogen Lyman lines, but Adams notes that D can be detected in only very select absorption systems with simple velocity structure and high neutral hydrogen column density, $N(\text{H I}) > 10^{17}$ cm$^{-2}$ (Lyman limit systems). For high redshifts, $z > 2.5$, the Lyman series is redshifted into the optical, and the lines are accessible to large ground based telescopes. The Lyman absorption lines of D and H, and the Lyman continuum absorption of H I, constrain the column densities of D I and H I, and provide a measurement of D I/H I. The timescale for H and D ionization equilibrium is very short ($10^5$ yr) in the photoionized intergalactic medium ($n_H \approx 10^{-3}$), and we assume the ratio D I/H I is identical to D/H throughout this paper (Ikeuchi & Ostriker 1986).

The Lyman limit system at $z = 3.572$ towards Q1937–1009 is an ideal site to infer a primordial value for D/H. The system is very metal-poor, less than 1/100 solar. Deuterium is destroyed as gas is cycled through stars, but metals are produced in the cycle and the
system’s low metallicity limits the amount of deuterium which could have been destroyed. The gas in the system also has very low internal velocities, which can limit the amount of kinetic energy input through any high energy phenomena, such as supernovae or gamma ray sources.

In TFB, we presented high resolution spectra of Q1937–1009, and made the first measurement of D/H in a QSO absorption system. This system has a high total neutral hydrogen column density, Log N(H I) = 17.86 ± 0.02 cm$^{-2}$ (Burles & Tytler 1997a), and the corresponding absorption is optically thick throughout the entire Lyman series. The deuterium feature is well determined by its profile in Lyα, and the column density of D is well constrained.

In this paper, we advance the methods of TFB to place more robust constraints on D/H in this absorption systems. In section 2, we describe our new method of constraining D/H, and in section 3, we discuss the new results. In section 4, we calculate the abundances for a number of metals and discuss the ionization state of the system. In section 5, we compare our D/H value to the abundance of D in other sites, and other light elements, and we show that our D/H is probably primordial.

2. CONSTRAINTING D/H

We model the absorption spectrum along the QSO line of sight as a finite number of discrete absorbing components. Each component is modeled as a Voigt profile (Spitzer 1979), given by three parameters: column density (N), redshift (z), and velocity dispersion (b). At every wavelength, we sum the optical depth contribution of all absorption line profiles in the model. The optical depth is converted to a normalized flux, and convolved with the instrumental response. The model spectrum can then be directly compared to the observed spectrum. We use the observed spectrum described in TFB.

2.1. Previous Analysis

The TFB analysis was sophisticated since it was the first to simultaneously fit many metal and H lines, and to separate thermal and turbulent contributions to line widths. However, it also used many assumptions which we now remove.

In TFB, we modeled the absorption system with two D/H components, labeled “blue” and “red”. The strong Lyα feature also required a third H I component (which contained only 1% of the hydrogen column) to obtain an adequate fit to the spectrum of the Lyman
series. The positions of the two main components were “tied” to the velocity positions determined from the narrow metal lines which were asymmetric, and well described by these two components. We fit the model to narrow regions of the spectrum containing only the Lyman lines of interest, and did not include absorption from other Lyα lines along the line of sight. D/H was assumed to be equal in both components. The velocity dispersion of the red D line was determined from the dispersions of the corresponding H and metal lines in the red component. We found the value of D/H which gave the best fit to the data and the formal 1σ errors from the D and H column densities, log(D/H) = −4.64 ± 0.06. We investigated systematic errors due to incorrect continuum placement in the regions of Lyα and the Lyman limit, and estimated the systematic error ∆ log(D/H) = 0.06.

The TFB analysis found a consistent model and a well-defined value for the most likely value of D/H. But its limitations lay in the assumptions and the calculation of confidence levels and the total errors on D/H.

2.2. Present Analysis

In this paper, we present major improvements in our analytic techniques. We measure D/H with a variety of models and free parameters. We add new free parameters to describe the unabsorbed quasar spectrum, which we use to normalize the absorption spectrum. Previously, we treated continuum uncertainties as systematic errors. The number and velocities of the D/H components are now also free parameters. We no longer require that the D and H lines have the same velocities as the metal lines. The D and H line profiles are constrained only by the spectra covering the Lyman series lines. To include all the uncertainties from the modeling into the final uncertainty of D/H, we perform a χ² analysis as a function of D/H. Formerly, we calculated the errors from a quadrature sum of the total column density uncertainties of D and H. By calculating χ² as a function of D/H, we can include the uncertainties from all the free parameters in our models, including the velocity dispersions, velocity positions, continuum levels, and column densities. The χ² function gives the relative likelihood of all values of D/H versus the best fit value. The final confidence region can be directly calculated from the χ² function, and can be considered more “comprehensive” than the uncertainties which we reported before.
2.2.1. Total Hydrogen Column Density

The most critical addition to the present analysis is a measurement of the total hydrogen column density, \( N(\text{H I})_{\text{total}} \). From our detailed study of the Lyman continuum optical depth (Burles & Tytler 1997a), we measured \( N(\text{H I})_{\text{total}} = 17.86 \pm 0.02 \), and we use this constraint for all models. \( N(\text{H I})_{\text{total}} \) is much better constrained from the Lyman continuum absorption than from the Lyman series line profiles, which gave \( N(\text{H I})_{\text{total}} = 17.94 \pm 0.06 \pm 0.06 \) (TFB), where the first error is statistical and the second is systematic. The new \( N(\text{H I})_{\text{total}} \) provides a very strong constraint for the models, allows us to add more free parameters to the models to test a variety of models and minimize the model fit with respect to D/H.

2.2.2. New Models

Here we discuss the new models we have adopted to measure D/H. The absorbers in each model can be placed into one of two groups, depending on their association with the D/H absorption system (DHAS). The first group contains H I absorbers which will not show D I (also labeled “unassociated”), and the second group contains the high column H I absorbers which show D I and are associated with the DHAS. We refer to absorbers in the second group as the “main components”. For each unassociated absorber, we add three free parameters to the model: one each for \( N \), \( b \), and \( z \). Each main component shows two lines: one of H I and the other D I. We also add one parameter for each line to allow a separation of \( b \) into \( T \) and \( b_{\text{tur}} \), because in general \( b(\text{H I}) \) can differ from \( b(\text{D I}) \), but we tie three of the parameters in the two lines: \( z(\text{H I}) = z(\text{D I}) \), \( T(\text{H I}) = T(\text{D I}) \), and \( b_{\text{tur}}(\text{H I}) = b_{\text{tur}}(\text{D I}) \). In this paper, we do not use the metal lines to constrain D/H. The velocity dispersions of the main components are given by \( b^2 = 163.84(T/m) + b_{\text{tur}}^2 \), where \( T \) is temperature in units of \( 10^4 \) K, \( m \) is the atomic mass, and \( b \) is in units of \( \text{km s}^{-1} \). For zero turbulent velocity dispersion, we recover the thermal relation for the H I and D I lines, \( b(\text{H I}) = \sqrt{2} b(\text{D I}) \). In all models we require that \( T > 5000 \) K in the main components. Without this constraint, models which fit the data may include unobserved components with very low T. The background ionizing radiation is hard enough that the absorbing gas is unlikely to be cooler than a few \( 10^4 \) K.

The results depend on assumptions we make when constructing the models. These assumptions include the number of D/H components, the total number of free parameters, and the spectral regions which we fit. The total number of free parameters is the sum of parameters of all the absorption components and the free parameters included in the continuum. For this analysis, we have chosen 7 models, and we measure D/H for each. We
can then compare the best fit values of D/H for each model, and assess the effect of the different assumptions used in each model. All 7 models include the spectral regions listed in Table 1, the number of D/H components chosen for each model, and the 64 H I absorbers listed in Table 2.

The models are of three types. Models 1 & 2 are the simplest and include 2 and 3 D/H components, respectively, with no free parameters in the continuum. The continuum is held fixed at the initial placement of the unabsorbed continuum level, which is shown as the solid lines at unity in Figure 2. The other five models allow for free parameters in the continuum in each region. The number of allowed continuum free parameters in each region is shown in Table 2. The final two models have three D/H components, but also allow for hydrogen contamination. In Model 6, an extra hydrogen absorber is introduced at redshift \( z = 3.570958 \), which places H I Ly\( \alpha \) at the position of D-Ly\( \alpha \), and H I Ly\( \beta \) at D-Ly\( \beta \). In Model 7, the extra hydrogen absorber is introduced at \( z = 2.85670 \), which places its Ly\( \alpha \) at the position of D-Ly\( \beta \), in the blue wing of Ly\( \beta \). The model parameters are summarized in Table 3.

### 2.2.3. Fitting Procedure

We use the Levenberg-Marquardt method to minimize \( \chi^2 \) (Press et al. 1992). The details of the algorithm and computational techniques are presented in Burles (1997). The algorithm iterates until it converges on the best fit model. The \( \chi^2 \) of the final fit is assumed to be the minimum \( \chi^2, \chi^2_{\text{min}} \).

A given model will have \( M \) free parameters, and the algorithm calculates a \( M \times M \) covariance matrix for each iteration. The 1\( \sigma \) uncertainties can be directly calculated from the diagonal elements in the covariance matrix of the final iteration.

In all the models, we are interested in one parameter specifically, D/H. It is not straightforward to calculate the total uncertainty in D/H from the final covariance matrix directly, even if the errors are normally distributed. Due to the intrinsic blending of the H I and D I lines, the formal errors in column density are correlated. Instead, we choose to make D/H a free parameter in the models, and calculate \( \chi^2_{\text{min}} \) as a function of the parameter D/H.

We construct a list of D/H values, and model the spectrum for each value in the list. By designating D/H in each model, we reduce the number of free parameters, \( M \), by one for each D/H component in the model. Now each main component (components which have D absorption) has only four free parameters: \( N(\text{H I}), T, b_{\text{tur}}, \) and \( z \). \( N(\text{D I}) \) is no longer free, but is given by \( N(\text{D I}) = N(\text{H I}) \times (\text{D/H}) \). We assume that D/H is the same in all main
components.

By constructing an array of $\chi^2_{\text{min}}$ as of function of D/H, we can calculate the most likely value of D/H and the confidence levels surrounding this value. We have effectively taken a cross section of the $M$-dimensional $\chi^2$ function to calculate the uncertainties of the single parameter, D/H. The one-dimensional function, $\chi^2(D/H)$, yields both the most likely value of D/H, and confidence levels about the most likely value.

2.2.4. Continuum Level

Figure 1 shows the spectral regions stacked in velocity space. Figure 2 presents each spectral region separately on the vacuum heliocentric wavelength scale.

The unabsorbed QSO continuum is now allowed to vary to achieve the best fit. The QSO continuum is modeled by a low-order Legendre polynomial, which accounts for smooth variations in the continuum on scales of 100 km s$^{-1}$ (dashed lines in Fig. 2). In the data reduction process, we use Legendre polynomials to initially normalize the spectrum to the regions of the spectrum showing no absorption (solid line at unity in Fig. 2). In the Ly$\alpha$ forest, the continuum is not well defined due to large regions of continuous absorption. We account for this uncertainty in the continuum in the Ly$\alpha$ forest by allowing the coefficients of the Legendre polynomials to be free parameters, without bounds, in our models. Therefore, the continuum is no longer fixed to the level on which we can only speculate. In statistical language, we fit the continuum level with a set of “nuisance parameters”, which we allow to vary freely to improve the fit, because they are not of primary interest.

2.2.5. Regions of Interest

We must choose regions of the spectrum to compare to the models. If we model the entire Keck spectrum, the model would include over 1000 lines and over 40,000 pixels. For practical purposes, we cannot model the entire spectrum simultaneously, the time required to complete the fitting procedure scales as the number of lines times the number of pixels. Also, we want our model to be sensitive to D/H, and not other unrelated features in the spectrum. Therefore, we select regions of the spectrum which include at least one Lyman series line of the DHAS. In principle, we want to include all Lyman series of the DHAS, but some Lyman series lines are blended with other strong, unassociated absorption lines, and are not included in the selected regions.

In Figures 1 & 2, we show the regions of the spectrum used in the model fitting. Table
1 lists the regions used in our analysis, including the number of pixels and the order of
the Legendre polynomial used to model the unabsorbed continuum in each region. The
damping wings of the Lyα feature absorb over a large wavelength range, therefore the
span of the Lyα region is much greater than the other individual line regions. For the
higher-order Lyman lines, the regions of interest begin to overlap. The overlapping regions
are combined into a single region containing multiple Lyman lines and this region is labeled
“Ly-limit”.

2.2.6. Goodness of Fit to Different Spectral Regions

Of the 9 regions, the Lyα region (Figure 2a) has the highest SNR per pixel,
approximately 75 per 4 km s\(^{-1}\) pixel. Thus the entire fit is heavily weighted by Lyα, and
the fit is most tightly constrained by the data is in this region. Deuterium Lyα can be
seen at 5557 Å, and is composed of 3 components in the model presented here. The fitted
continuum contains 5 free parameters, and is reasonably consistent with our initial estimate
of the continuum. Only at the red edge does it begin to diverge significantly. And the
overlap between the estimated and the best fit continua lies directly at the Lyα feature.
The overlap in this region suggests that the new continuum determination will have little
effect in the Lyα region.

The Lyβ region (Figure 2b) is much smaller than Lyα. The flux returns to the
continuum much closer to the center of the Lyβ line, and there is no reason to include a
larger section around Lyβ. Again, the best fit continuum lies close to the original continuum
estimate over the entire region. The model fit to Lyβ is not as good as Lyα, there is
under-absorption in two places near D-Lyβ. The blue wing of Lyβ shows under-absorption,
but there is a significant increase in the noise over some of these pixels (4689.0 < \(\lambda\) < 4689.3
Å), which is most likely due to bad columns being rejected in the original CCD images. The
under-absorption on the blueward side of D-Lyβ is likely due to a hydrogen Lyα line (which
is fit in Model 7) that is blended with the deuterium feature. We label hydrogen lines which
overlap and blend with the deuterium features “contaminating” hydrogen. Contamination
will be discussed thoroughly in section 3.1, and introduced into our Models 6 & 7.

The models must produce a good fit to all the Lyman lines simultaneously. We
show each of the regions separately in Fig. 2 to allow a close inspection of the data and
model, and to display how well the model reproduces the observed spectrum. Notice that
there are additional absorbers overlapping the main components. These extra absorbers
add free parameters to the fit, and in general, make the model less restrictive. That is,
the parameters determining the main components cannot be as tightly constrained when
overlapping absorbers are included.

In Figure 2i, we show the spectral region with the highest order Lyman lines, Ly-12 to Ly-19. The best fit continuum shows a significant difference from the initial estimate. The unabsorbed continuum in this region was difficult to estimate due to the lack of pixels with little or no absorption. The continuum was originally estimated as a constant flux level passing near the few pixels with the highest flux. The large amount of absorption in this region did not allow for a better estimate of the unabsorbed continuum initially.

The difference between the best fit continuum (dotted line) and the initial continuum (solid line) is likely due to the simple approximation of the continuum level during the reduction. The shape of the best fit continuum is more likely and is a function of the instrumental sensitivity in this region.

There are several regions of the spectrum shown in Figure 2 of TFB which have more flux than expected by their model fit. In the models presented here, this unabsorbed flux is accounted for with the extra hydrogen components and a different continuum.

3. RESULTS

Figure 3 shows the major results of the fitting procedure with the seven models. Table 3 summarizes the D/H measurements for each model. We performed the \( \chi^2 \) minimization procedure for 100 values of D/H over the range \(-4.95 < \text{Log}(D/H) < -4.0\) for each of the seven models.

For example, Figure 3a shows the results for the 2 component model (Model 1). The solid dark gray line represents one of the components and the dashed line represents the other. These graphs show the behavior of the main component parameters as a function of D/H. The parameters sometimes display discontinuous behavior, which is due to the non-uniqueness of Voigt profile fitting. The \( \chi^2 \) minimization has found two equally likely solutions, and this exhibits itself with a discontinuous change in the parameter values. Although the fitted parameters may be non-unique, \( \chi^2_{\text{min}} \) remains a smooth function of D/H. The exact parameters which give the best fit are not well-determined, but the \( \chi^2_{\text{min}} \), and the D/H are well defined. In this analysis, we cannot attempt to model the DHAS exactly, but we can still find the relative likelihood for all values of D/H.

We cannot model the individual components exactly because of the intrinsic blending of the absorption lines. But we do find that parameters which include all the components can be measured precisely. In Figure 3, the thick solid line in the column density plot
represents the total neutral hydrogen column, $N(\text{H I})_{\text{total}}$. This is merely the sum of the column densities of all components in a given model at a specific value of D/H. We find that all seven models give a $N(\text{H I})_{\text{total}}$ which is a smooth function of D/H, even though the individual column densities in the models are not. $N(\text{H I})_{\text{total}}$ is the quantity subject to the constraint provided by Burles & Tytler (1997a), $N(\text{H I})_{\text{total}} = 17.86 \pm 0.02$. For a model which gives an arbitrarily good fit to the spectral regions, the best fit will depend only on the agreement with the $N(\text{H I})_{\text{total}}$ constraint.

We can measure D/H directly from Figure 3. With a $\chi^2$ function of one variable, the confidence levels are easily determined. The 95% confidence levels correspond to $\Delta \chi^2 = 4.0$, where $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$. For each model in Figure 3, we find the minimum of the $\chi^2$ function and list this value in Table 3. The 95% confidence levels on D/H are also listed in Table 3, and are shown as vertical dashed lines in Figure 3. The fitting procedure is not perfect, and we can see in Figure 3 that there are deviations from perfectly smooth $\chi^2$ functions.

The fitting procedure can converge before reaching the absolute minimum $\chi^2$, and we estimate that the difference between the absolute minimum and the calculated $\chi^2$ can be as large as 0.5. We take this deficiency into account by setting the 95% confidence levels at $\Delta \chi^2 = 4.5$.

All of the regions of 95% confidence in Figure 3 overlap with the central value of $N(\text{H I})_{\text{total}}$ constraint. The best fit model of D/H must not only provide the best fit to the spectral regions, but must also fit the constraint of $N(\text{H I})_{\text{total}}$. For all models, the values of $N(\text{H I})_{\text{total}}$ decrease smoothly with increasing D/H. $N(\text{D I})$ is tightly constrained by D-Ly$\alpha$ and D-Ly$\beta$, so as D/H increases, $N(\text{H I})$ must decrease, which gives smoothly varying functions of $N(\text{H I})_{\text{total}}$ for each model. In all models, the 95% confidence regions on D/H represent the model fits where the $N(\text{H I})_{\text{total}}$ constraint is well satisfied.

All seven models give consistent ranges for the 95% confidence regions, as seen in Figure 4. As expected, the models with more free parameters have larger confidence regions. Except for Model 6, which includes hydrogen contamination at Ly$\alpha$, all models are consistent with

$$\log(D/H) = -4.49 \pm 0.04,$$

or

$$(D/H) = 3.24 \pm 0.30 \times 10^{-5},$$

at 67% confidence. The shape of the $\chi^2_{\text{min}}$ functions indicate errors which are normally distributed in Log (D/H), and the 67% confidence levels should be one-half of the 95% levels.
3.1. Contamination

In Models 6 & 7, we investigate the effects of hydrogen contamination of the D-Lyman lines. Model 6 includes an additional hydrogen absorber at redshift, \( z = 3.5710 \), which places its lines near the deuterium lines. Figure 3f shows the results of the fitting procedure. For values of \( \log D/H > -4.5 \), the results are identical to Model 4, which did not include contamination. But for lower values of \( D/H \), the contaminating hydrogen absorbs a significant amount of flux at the D-Ly\( \alpha \) and D-Ly\( \beta \) lines, and gives a good fit by keeping \( N(\text{H I})_{\text{total}} \) nearly constant and lowering \( N(\text{D I}) \). Although contamination allows for lower \( D/H \) as expected, the introduction of an additional Ly\( \alpha \) absorber with three free parameters does not improve the fit significantly. This result is in sharp contrast to another \( D/H \) system, towards Q1009+2956, where contamination significantly improves \( \chi^2 \) (Burles & Tytler 1997b). We conclude that Ly\( \alpha \) contamination is not significant in this \( D/H \) system for two reasons: (1) additional parameters for contamination do not improve the \( \chi^2 \) fit, (2) the likelihood of significant contamination drawn from distributions of the Ly\( \alpha \) forest (Kirkman & Tytler 1997; Lu et al. 1997) is small (c.f. Tytler & Burles 1997, TFB, Jedamzik & Fuller 1997, Steigman 1994).

Model 7 includes contamination at the position of D-Ly\( \beta \), at \( z = 2.8565 \). This redshift is much lower than the DHAS, and the hydrogen absorber only affects D-Ly\( \beta \). The extra absorber is initially placed at the center of D-Ly\( \beta \), and is allowed to freely move to achieve the best fit to the data. The fit improves by \( \Delta \chi^2 \approx 7.0 \), as the hydrogen absorber fills in the under-absorption seen in Figure 2b. The best fit for Model 7 is shown in Figure 5, and the improvement is easily seen upon comparison with Figure 2b. The model shows under absorption in three pixels near 4689 Å (60 km/s blueward of H-Ly\( \beta \)), but these pixels fall in a region of spectra with increased noise. In conclusion, we find Model 7 is consistent with the results from the other models which did not include this contamination and the measurement of \( D/H \) is robust with any extra hydrogen absorption at Ly\( \beta \) alone.

The presence of contamination will give an overestimate of \( D/H \). Therefore, the upper limit on \( D/H \) is robust and not affected by the presence of contamination. All seven models are consistent with the upper limit, \( D/H < 3.9 \times 10^{-5} \).

4. Ionization and Metals

The metal absorption lines associated with the DHAS were analyzed by TFB. We use the two component fit \((z = 3.572201, 3.572428)\) of TFB to measure the column densities of the ions shown in Table 4. If no feature is detected at the expected positions of the ionic
transitions, then we place a 2σ upper limit on the total column density. More absorption components could be used to describe the metal lines in this DHAS, but the qualitative results will remain unchanged. We used the program CLOUDY (Ferland 1993), with an ionizing background spectrum calculated by Haardt & Madau (1996), to calculate the ionization state of the gas in each component. Table 5 shows the metallicities, temperatures, ionization parameter, and total hydrogen density in each component calculated from the CLOUDY simulations.

The equilibrium temperatures calculated from the CLOUDY simulations can be directly compared to the temperatures determined from the velocity dispersions of the H, C and Si lines. In the Blue component, we find a good agreement between the temperatures shown in Table 4. But in the Red component the CLOUDY equilibrium temperature is smaller than the temperature determined from the relative line widths, including $b_{\text{tur}}$. This may indicate another component near the velocity position of the Red component. The CLOUDY simulations did not give an acceptable fit to all ions of Si in the red component. A single phase of photoionization could not account for the three column densities observed, and the calculated $[\text{Si/H}]_{\text{red}}$ came from Si II and Si III alone. We excluded Si IV for two reasons: (1) Si IV(1393) is blended with a C IV(1550) at $z = 3.1097$, and (2) it is likely that there is another component of higher ionization that contributes to Si IV.

We have not attempted to model the metal lines with more than two components. Although the column densities of the individual components would differ, the derived metallicities of the components would not greatly differ from the results shown in Table 5. All components would have a metallicity below 1/100 solar, independent of the model used.

We can now test the TFB assumption that the H and D lines were at the velocities of the C and Si metal lines. In general, this assumption adds a systematic error to the measurement if the metal lines are not aligned with the H I and D I lines. This DHAS is rather unique, because all the metal lines, with different ionizations, show similar velocity structure. In Figure 3, the velocity positions of the Blue and Red components used by TFB lie at $\Delta v = 0, 15 \text{ km s}^{-1}$ respectively. In our models with three or four components, two of the components lie near the velocity positions of the metal lines, with considerable variation, depending on D/H. But in the two component models, the component separation for the most likely D/H is 19 km s$^{-1}$, rather than 15 km s$^{-1}$, and the Red hydrogen component is at a higher velocity position for all values of D/H. This shows that a systematic offset in the Red component was introduced in the analysis in TFB by assuming that the H and D lines fell precisely at the metal line positions in the two component model. It is difficult to translate this velocity offset into a D/H change because, as seen in Figure 3, many other coupled parameters are involved.
5. PRIMORDIAL D/H

We have measured the deuterium abundance in the DHAS at $z = 3.5722$ towards Q1937–1009. Within the statistical uncertainties, we conclude that this is the primordial value of D/H produced by Big Bang Nucleosynthesis (Reeves et al. 1973; Epstein et al. 1976). This absorption system is young ($\leq 1 \, h^{-1} \text{Gyr}$) and very metal poor ($[X/H] \leq -2.0$). These characteristics place strong constraints on stellar astration of deuterium independent of initial mass functions and star formation rates (Jedamzik & Fuller 1997; Fields 1996). To astrate significant amounts of deuterium, high mass stars would overproduce CNO and Si, and low mass stars would not have time to complete their evolution. With no post-BBN processes to create or destroy deuterium, our measured value of D/H must represent the primordial value.

5.1. Other D/H Measurements

Due to its importance in the standard cosmological model, D/H has been measured in many astrophysical sites. In the local interstellar medium, Piskunov et al. (1997) find a mean abundance ratio, $D/H_{\text{ISM}} = 1.6 \pm 0.2 \times 10^{-5}$, in the lines of sight toward nearby stars. Chengalur et al. (1997) have recently detected the D I hyperfine transition in emission toward the Galactic anticenter, and find $D/H = 3.9 \pm 1.0 \times 10^{-5}$. Abundance measurements in meteorites, the lunar soil, and the atmospheres of the Jovian planets are consistent with a pre-solar value, $D/H_{\odot} = 2.6 \pm 1.0 \times 10^{-5}$ (Gautier & Owen 1983; Geiss 1993; Encrenaz et al. 1996). In the next section, we use the local measurements of D/H with our measurement at high redshift to discuss the evolution of D/H.

Tytler & Burles (1997) have made another measurement of D/H in a high-redshift Lyman limit system towards Q1009+2956, at $z = 2.504$. Preliminary analysis of this object gives $D/H = 3.0 \pm 0.6 \times 10^{-5}$, and simulations of hydrogen contamination suggested the most likely value of $D/H = 2.5 \pm 0.5 \pm 0.4 \times 10^{-5}$ (statistical and systematic error). The measurement towards Q1009+2956 agrees very well with the result obtained in this paper towards Q1937–1009. An analysis of Q1009+2956 with the methods presented here will be presented in Burles & Tytler (1997).

There have been other reports of deuterium detections in high-redshift QSO absorption systems: towards Q0014+8118 (Songaila et al. 1994; Carswell et al. 1994; Rugers & Hogan 1996a; Rugers & Hogan 1996b), towards Q1202–0725 (Wampler et al. 1996), towards Q0420–388 (Carswell et al. 1996). These other systems do not yield measures of D/H due to either lower quality spectral data, or greater complexities in the velocity structure of the
absorption system. The next best candidate system to measure D/H, z = 3.32 towards Q0014+8118, was shown to have an interloping hydrogen cloud within 10 km s$^{-1}$ of the expected position of deuterium (Tytler et al. 1996b). Webb et al. (1997) recently deduced a D/H value at z = 0.701 towards the low redshift QSO 1718+4807 using a spectrum obtained with the Hubble Space Telescope (HST). Unlike Q1937–1009 and Q1009+2656, only one H I line was observed, so the velocity structure of the H I is not well known. Assuming a single component fit to the Ly$\alpha$, they find D/H = 20 ± 5 × 10$^{-5}$, but this value will remain suggestive unless confirmed with approved HST observations of the high-order Lyman lines.

5.2. Chemical Evolution of Deuterium

Many groups have discussed the significance of deuterium in galactic chemical evolution, and have used simple models to calculate the abundance ratio, D/H, as a function of time and metallicity (Clayton 1985; Audouze & Tinsley 1974; Steigman & Tosi 1992; Edmunds 1994; Vangioni-Flam et al. 1994; Steigman & Tosi 1995; Prantzos 1996; Fields 1996; Scully et al. 1997). In the past, deuterium evolution was required in order to extrapolate the ISM and pre-solar nebula measurements of D/H back in time, and back to zero metallicity, to constrain the primordial D/H value. But now the problem can be inverted, we can use the values of primordial D/H, pre-solar D/H, and the ISM D/H to constrain models of chemical evolution, deuterium astration as a function of time and metallicity, and the fraction of baryons which have been cycled through stars in the solar neighborhood. The ratio of the ISM and primordial values gives an astration factor in the local ISM,

$$d = \frac{(D/H)_{\text{ISM}}}{(D/H)_{p}} = 0.5 \pm 0.05. \quad (3)$$

So we can make the simple statement that one-half of the gas in the local ISM has been cycled through stars. This fraction can be used to place new limits on the stellar initial mass function and the amount of inflow and/or outflow in the local ISM. When one considers published models of chemical evolution in the ISM, the amount of deuterium astration agrees well with models incorporating standard star formation and some infall of primordial material (Edmunds 1994; Clayton 1985; Fields 1996).

5.3. The Baryon Density

Production of the light elements from Standard Big Bang Nucleosynthesis (SBBN) depends on a single parameter, $\eta$, the baryon to photon ratio during SBBN. Many groups
have calculated the abundance yields of the light elements as a function of $\eta$ (Wagoner et al. 1967; Walker et al. 1991; Smith et al. 1993; Krauss & Kernan 1995; Copi et al. 1995). The abundance yield of deuterium is a single-valued function of $\eta$, and using output from the Kawano BBN code (Kawano 1992), we find

$$\eta = 5.3 \pm 0.3 \pm 0.25 \times 10^{-10},$$

where the first error is the statistical uncertainty in the D/H measurement, and the second error represents the statistical uncertainty in the nuclear cross-sections (Smith et al. 1993). It is interesting to note that the magnitude of the measurement errors are comparable to the errors in the SBBN calculations.

If we use the present-day photon density determined from the COBE FIRAS measurements of the Cosmic Microwave Background (CMB, Fixsen et al. 1996), we can directly calculate the present-day baryon density

$$\Omega_b h^2 = 0.0193 \pm 0.0014$$

where the error includes both uncertainties in $\eta$. This value for the baryon density agrees with recent estimates of $\Omega_b h^2$ from observations of the CMB power spectrum, the intergalactic medium at $z \approx 3$, and rich galaxy clusters at $z \approx 0.3$

The power spectrum of anisotropies in the CMB determines $\Omega_b$ at the epoch of decoupling, $z \approx 1000$ (Hu & White 1996). The locations and heights of the doppler peaks in the CMB power spectrum provide constraints on $\Omega_b$. The current observational state of the CMB power spectrum does not have the precision to determine $\Omega_b$, although there are hints of the first doppler peak and statistical analyses suggest $\Omega_b < 0.28$ consistent with SBBN (Lineweaver et al. 1997). The future CMB experiments, including the satellites, MAP and Planck, promise to determine $\Omega_b$ to 2%, which will provide an independent check on our measurement and a consistency test for SBBN.

At redshifts $z < 5$, the IGM is ionized, and can be observed through absorption in high-redshift QSO spectra. Recent comparisons of high-resolution spectroscopy of the IGM and large cosmological simulations require a high baryon density to account for the observed Ly$\alpha$ forest, $\Omega_b \geq 0.017 h^{-2}$ (Rauch et al. 1997; Weinberg et al. 1997; Zhang et al. 1997). Other estimates include the baryons in protogalaxies seen in Damped Ly$\alpha$ absorption with $\Omega_{Damped} \approx 0.002 h^{-1}$ (Wolfe et al. 1995), and the baryons in the diffuse IGM which are not seen in Ly$\alpha$ absorption, $0.0001 h^{-1} < \Omega_{diff} < 0.007 h^{-3/2}$ (Reimers et al. 1997). The inventory of baryons at $z \approx 3$ demands a high cosmological baryon density consistent with our measurements of D/H.

At low redshift, only a small fraction ($\approx 10\%$) of the baryons reside in stars and visible gas, with estimates ranging from $\Omega_* \approx 0.003 - 0.007 h^{-1}$ (Persic & Salucci 1992). But a
fair sample of today’s baryons are likely to be in gas heated through supernova explosions or accretion into the large potential wells of galaxy clusters. A recent application of Oort’s method to 14 fields containing rich galaxy clusters yields a baryon density in the form of hot gas, $\Omega_{\text{gas}} \simeq 0.012 - 0.016h^{-3/2}$ (Carlberg et al. 1997), This result is valid assuming that the baryons and emitted light trace the total matter density and that clusters provide a fair sample of the baryon fraction. If most of the baryons today are in the form of hot gas, they must be collisionally ionized (Giallongo et al. 1997), and could have already been detected in a survey for O VI at $z \simeq 0.9$ (Burles & Tytler 1996).

Measurements of the total cosmological matter density $\Omega_m$ imply that baryons cannot constitute all the matter in the universe. A number of methods have been used to estimate $\Omega_m$ (c.f. Dekel et al. 1996). Peculiar velocities of galaxies can be treated as cosmic flows induced by large-scale mass distributions. In particular, cosmic flows in large-scale voids places a lower limit on the total mean matter density, $\Omega_m > 0.3$ (Dekel 1997). This limit on $\Omega_m$ places an upper limit on the baryon fraction, $f_b < 0.07$, which agrees with the fraction inferred from X-ray observations of galaxy clusters (White et al. 1993; Lowenstein et al. 1996; Myers et al. 1997) and groups (Mulchaey et al. 1996).

### 5.4. Other Light Elements

In SBBN, the determination of $\eta$ implies the primordial abundance ratios for the other light elements. We now use our D/H measurement to infer the primordial abundances of the other light elements. In the following, we use the output from the Kawano Code with $\tau = 887$ s, and $N_\nu = 3.0$. All errors are 67% confidence and include the uncertainties in the nuclear cross-sections and neutron lifetime. Our measurement infers a primordial $^4$He mass fraction $Y_p$

\[
Y_p = 0.247 \pm 0.002. \tag{6}
\]

The comparison between D and $^4$He provides a crucial test of SBBN (Cardall & Fuller 1996; Hata et al. 1997), but recent measurements of the $^4$He abundance in extragalactic metal-poor H II regions have given discrepant results. Izotov et al. (1997) compiled a homogeneous sample of 45 H II regions taken mainly from the Second Byurakan Survey (c.f. Izotov et al. 1993), and found $Y_p = 0.243 \pm 0.003$ (Izotov et al. 1997), which is consistent with the value of $Y_p$ we infer. On the other hand, Olive et al. (1997) have compiled a large sample of H II regions from studies by Olive & Steigman (1995), Izotov et al. (1994), and Izotov et al. (1997) and obtain $Y_p = 0.234 \pm 0.002$, which is not consistent with Izotov et al. (1997) nor our inferred value. The differences in the two $^4$He studies must be properly understood before a direct comparison can be made between D and $^4$He.
Olive et al. (1997) argue that the difference can be entirely accounted for in the atomic data sets and the lowest metallicity region, IZw18. Skillman & Kennicutt (1993) observed IZw18 and found $Y = 0.231 \pm 0.005$. Izotov & Thuan (1997) reobserved IZw18, and they infer $Y = 0.243 \pm 0.009$. The different results obtained for this H II region highlights the uncertainties in the current observational determinations of $Y_p$.

The primordial value of D/H infers an abundance for $^7$Li,

$$A(\text{Li}) = 2.5 \pm 0.17,$$

where $A(\text{Li}) = 12 + \log (\text{Li/H})$. The abundance of $^7$Li observed in the Spite “plateau” of warm metal-poor halo stars (Spite & Spite 1982, Spite et al. 1984, Rebolo et al. 1988, Thorburn 1994, Bonifacio & Molaro 1997) is lower but consistent with the inferred $^7$Li from D/H. Bonifacio & Molaro have recently analyzed a large sample of suitable halo stars using infrared measurements to give a better indication of effective temperatures. They find $A(\text{Li}) = 2.238 \pm 0.012 \pm 0.05$ (statistical and systematic errors, Bonifacio & Molaro 1997), and no evidence for a dispersion in the plateau abundances, nor correlations of $A(\text{Li})$ with effective temperature or metallicity. Our D/H measurements are consistent with the $^7$Li abundance found by Bonifacio & Molaro (1997), but large errors in nuclear reaction rates required in the BBN simulations also allow for non-standard depletion mechanisms in halo stars, which could have lowered the plateau by as much as 0.6 dex. (Pisoneault et al. 1992, Vauclair & Charbonnel 1995).

There do not exist any convincing measurements of a primordial $^3$He abundance, although great efforts have been made to measure $^3$He in Galactic H II regions (Balser et al. 1994) and planetary nebulae (Balser et al. 1997) using the hyperfine radio line. Stars can both produce or destroy $^3$He, so any attempts to infer the primordial abundance of $^3$He from galactic measurements are dominated by uncertainties in the chemical evolution of $^3$He. If we look at the other side of the problem, we can use our inferred primordial value

$$\frac{^3\text{He}}{\text{H}} = 1.2 \pm 0.2 \times 10^{-5}$$

(8)

to study the chemical evolution of $^3$He.

With the current state of the observations of the light elements and the associated uncertainties with inferring primordial abundances, we conclude that there is no inconsistency between deuterium and the other light elements with the predictions from SBBN. Furthermore, the determination of $\eta$ with predictions from SBBN should be heavily weighted towards measurements of D/H in QSO absorption systems (Fuller & Cardall 1996, Schramm & Turner 1997).
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6. Figure Captions

Figure 1: Velocity plots of the Keck HIRES spectrum containing Lyman series lines in the D/H absorption system towards Q1937-1009. Zero velocity corresponds to a redshift, $z = 3.572201$, which is identical to Figure 1 in TFB. The Lyman limit region shows Ly-12 through Ly-19 in separate frames to emphasize the alignment of the entire Lyman series in velocity position. The data is the solid histogram, each bin corresponds to one pixel. The gray line tracing the data is the best fit model with 3 components, Model 4. The three light tick marks represent the position of the deuterium Lyman lines, the three solid ticks near $v = 0$ mark the corresponding hydrogen Lyman lines. The fourth solid tick marks an additional hydrogen absorber, which does not show deuterium. The solid horizontal line at zero flux shows the span of the region of interest around each Lyman line. For Ly$\alpha$, the region of interest spans the entire velocity range shown in Figure 1, while the other Lyman lines have smaller regions. We use all of the spectrum covering the Lyman series from Ly-12 to the Lyman limit. Both the spectrum and model fit have been normalized to the unabsorbed quasar continuum, which was included in the fitting procedure. The $1\sigma$ error in the data values are shown by the dotted line near zero flux.

Figure 2a: Spectrum of the Ly$\alpha$ region of the DHAS. The data and model fit are displayed as in Fig. 1. represents the best fit of Model 4. The dashed line shows the is a 5th order Legendre polynomial which gave the best fit to the unabsorbed QSO continuum. The tick marks show the positions of all absorbers which lie in each region. The taller tick marks show the 3 main hydrogen absorbers. The corresponding deuterium lines are located approximately 1 Å blueward of the hydrogen lines, and are easily distinguishable with the same triple pattern. The solid line at unity represents our original estimate of the unabsorbed quasar continuum over the region.

Figure 2b: Spectrum of the Ly$\beta$ region of the DHAS. The continuum is a 3rd order Legendre polynomial. The gray line is the same model in Fig 2a.

Figure 2c: Same as Fig 2b, spectrum of the Ly$\gamma$ region of the DHAS.

Figure 2d: Same as Fig 2b, spectrum of the Ly$\delta$ region of the DHAS.

Figure 2e: Same as Fig 2b, spectrum of the Ly$\epsilon$ region of the DHAS.

Figure 2f: Same as Fig 2b, spectrum of the Ly-6 region of the DHAS.

Figure 2g: Same as Fig 2b, spectrum of the Ly-7 region of the DHAS.

Figure 2h: Same as Fig 2b, spectrum of the Ly-9 region of the DHAS.

Figure 2i: Same as Fig 2b, spectrum of the Ly-Limit region of the DHAS.
Figure 3a: Results of the fitting procedure for Model 1. The top panel shows the $\chi^2_{\text{min}}$ as a function of Log (D/H). The remaining panels show $N$, $b$, and $z$ for the main H I components which gave the best fit. The parameters are represented as thin lines with different line styles for each component. The bottom panel shows the relative velocity positions of the two components, $\Delta v = 0$ corresponds to $z = 3.572201$.

Figure 3b: Same as Fig 3a, but for Model 2 with three components.

Figure 3c: Same as Fig 3a, but for Model 3 with two components.

Figure 3d: Same as Fig 3a, but for Model 4 with three components.

Figure 3e: Same as Fig 3a, but for Model 5 with four components.

Figure 3f: Same as Fig 3a, but for Model 6 with three components and contamination at D-Ly$\alpha$.

Figure 3g: Same as Fig 3a, but for Model 7 with three components and contamination at D-Ly$\beta$.

Figure 4: 95% confidence regions of D/H for the seven models in Table 3. The central vertical tick marks show the values of D/H which gave the best fit in each model.

Figure 5: Same as Fig 2b, but with the best fit for Model 7.
Table 1. Spectral Regions used in D/H Measurement

| Region | $\lambda_{min}$ | $\lambda_{max}$ | Pixels | Order$^a$ |
|--------|-----------------|-----------------|--------|----------|
| Ly$\alpha$ | 5546.08 | 5568.57 | 301 | 5 |
| Ly$\beta$ | 4687.50 | 4692.00 | 70 | 3 |
| Ly$\gamma$ | 4445.60 | 4451.56 | 98 | 3 |
| Ly$\delta$ | 4340.40 | 4346.00 | 94 | 3 |
| Ly$\epsilon$ | 4284.70 | 4293.10 | 145 | 3 |
| Ly-6 | 4253.30 | 4257.06 | 63 | 3 |
| Ly-7 | 4232.15 | 4239.10 | 120 | 3 |
| Ly-9 | 4208.35 | 4213.10 | 82 | 3 |
| Ly-Limit | 4178.30 | 4196.56 | 325 | 3 |

$^a$Order of Legendre polynomial used for the continuum
Table 2. Group 1 Lines in D/H Models

| Log N |   b   |   z   | Log N |   b   |   z   | Log N |   b   |   z   |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 12.73 | 30.3  | 3.58001| 14.27 | 40.8  | 2.65975| 14.34 | 33.1  | 2.48516|
| 12.59 | 32.0  | 3.57881| 14.76 | 31.8  | 2.65795| 14.16 | 37.5  | 2.48387|
| 12.88 | 18.2  | 3.57864| 13.44 | 16.7  | 2.57458| 12.64 | 19.8  | 2.48218|
| 13.54 | 21.0  | 3.57846| 14.59 | 35.4  | 2.57384| 13.01 | 19.3  | 2.46537|
| 13.39 | 17.1  | 3.57781| 14.08 | 62.5  | 2.57216| 12.51 | 11.0  | 2.46489|
| 13.12 | 27.2  | 3.57749| 13.84 | 26.4  | 2.57127| 14.57 | 47.3  | 2.46359|
| 13.62 | 20.7  | 3.57673| 13.58 | 32.3  | 2.53110| 12.70 | 18.4  | 2.46265|
| 12.28 | 22.8  | 3.57584| 13.43 | 24.0  | 2.53043| 12.93 | 19.1  | 2.46216|
| 13.24 | 63.4  | 3.57503| 13.70 | 62.5  | 2.52962| 13.84 | 70.2  | 2.45247|
| 12.92 | 20.7  | 3.57381| 12.31 | 9.3   | 2.52853| 13.75 | 38.2  | 2.45109|
| 15.40 | 31.1  | 3.57295| 13.62 | 22.1  | 2.52785| 14.17 | 34.1  | 2.44969|
| 13.20 | 44.0  | 3.56964| 13.39 | 43.7  | 2.52595| 12.52 | 5.9   | 2.44885|
| 12.39 | 22.7  | 3.56837| 13.59 | 33.7  | 2.52506| 14.00 | 28.7  | 2.44785|
| 12.43 | 16.3  | 3.56760| 14.04 | 28.6  | 2.50091| 13.86 | 22.0  | 2.44761|
| 13.63 | 34.5  | 3.56699| 13.60 | 35.5  | 2.50053| 13.13 | 9.3   | 2.44647|
| 14.00 | 26.8  | 3.56640| 12.80 | 10.7  | 2.49969| 14.06 | 31.7  | 2.44450|
| 14.31 | 32.9  | 3.56495| 13.50 | 21.1  | 2.49948| 13.53 | 20.9  | 2.44366|
| 13.05 | 20.6  | 3.56427| 13.18 | 30.9  | 2.49919| 13.11 | 22.2  | 2.44332|
| 13.42 | 33.3  | 3.56333| 13.24 | 37.0  | 2.48705| 14.00 | 26.4  | 2.44115|
| 12.30 | 6.8   | 2.66147| 13.18 | 21.4  | 2.48646| 12.96 | 7.5   | 2.44042|
| 12.96 | 20.5  | 2.66101| 13.32 | 38.8  | 2.48615| 13.60 | 28.5  | 2.43971|
|       |       |       |       |       |       |       |       |       | 13.83 | 8.9   | 2.43868|
Table 3. D/H Absorption Models

| Model | Components | D/H ($-2\sigma$) | D/H ($\chi^2_{\text{min}}$) | D/H (+2$\sigma$) | $\chi^2_{\text{min}}$ | $\nu_c$ |
|-------|------------|-----------------|-----------------------------|-----------------|----------------|---------|
| 1     | 2          | −4.55           | −4.51                       | −4.46           | 424.9          | 1097    |
| 2     | 3          | −4.55           | −4.48                       | −4.41           | 420.6          | 1093    |
| 3     | 2          | −4.55           | −4.51                       | −4.47           | 394.3          | 1069    |
| 4     | 3          | −4.56           | −4.49                       | −4.44           | 387.2          | 1065    |
| 5     | 4          | −4.55           | −4.48                       | −4.42           | 383.5          | 1061    |
| 6     | 3$^d$      | −4.87           | −4.59                       | −4.43           | 382.0          | 1062    |
| 7     | 3$^e$      | −4.57           | −4.49                       | −4.42           | 379.1          | 1062    |

$^a$Number of main components in fit

$^b$95% confidence levels from $\chi^2$ test

$^c$degrees of freedom with 1298 pixels

$^d$Additional contaminating hydrogen component at Ly$\alpha$

$^e$Additional contaminating hydrogen component at Ly$\beta$
Table 4. Column Densities of Metals

|          | Blue Component | Red Component |
|----------|----------------|---------------|
| C I      | < 12.4 (2σ)    |               |
| C II     | 12.70 ± 0.08   | 13.27 ± 0.03  |
| C III    | 13.36 ± 0.09   | 13.82 ± 0.19  |
| C IV     | 12.22 ± 0.16   | 12.61 ± 0.11  |
| N I      | < 12.6 (2σ)    |               |
| N II     | < 13.9 (2σ)    |               |
| N III<sup>a</sup> | 13.15 ± 0.71   | 13.84 ± 0.39  |
| N V      | < 12.4 (2σ)    |               |
| O I      | < 12.6 (2σ)    |               |
| Si II    | 11.76 ± 0.07   | 12.41 ± 0.02  |
| Si III   | 12.73 ± 0.20   | 13.20 ± 0.05  |
| Si IV<sup>b</sup> | 12.12 ± 0.12 | 13.01 ± 0.02  |
| Fe II    | 11.58 ± 0.44   | 12.41 ± 0.10  |
| Fe III   | 12.83 ± 0.58   | 13.30 ± 0.10  |

<sup>a</sup>Absorption feature is blended in Lyα forest

<sup>b</sup>Si IV(1393) is blended with C IV(1550) at z = 3.1097
Table 5. Metallicity and Ionization State of DHAS

|                  | Blue Component | Red Component |
|------------------|----------------|---------------|
| [C/H]            | −3.0           | −2.1          |
| [N/H]            | ≤ −2.7         | ≤ −2.0        |
| [O/H]            | < −0.9         | < −0.9        |
| [Si/H]           | −2.7           | −1.9          |
| [Fe/H]           | < −1.5         | < −0.6        |
| Log U            | −2.9           | −3.0          |
| Log H I/H        | −2.35          | −2.29         |
| Log $n_H^a$(cm$^{-3}$) | −1.70           | −1.60         |
| L(kpc)           | 1.5            | 0.6           |
| $T_b^b$          | 1.62 ± 0.09    | 2.36 ± 0.09   |
| $T_e^c$          | 1.72           | 1.67          |
| $b_{tur}$        | 4.8 ± 0.8      | 8.4 ± 0.4     |

$^a$Corresponding to Log $J_0 = −21.3$

$^b$Determined from component line widths

$^c$Photoionization equilibrium temperature
