THE D/H RATIO AT \( z = 3.57 \) TOWARD Q1937−1009

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ABSTRACT

Deuterium abundance remeasurements by Burles & Tytler yielded D/H = (3.3 \pm 0.3) \times 10^{-5} and the robust upper limit D/H < 3.9 \times 10^{-5} from the \( z_a = 3.572 \) system toward Q1937−1009. In this new analysis, Burles & Tytler adopted multicomponent microturbulent models, together with the possibility of varying the local continuum level freely around each H \( \alpha \) line to improve the fit. However, the procedure failed to fit D Ly\( \beta \) adequately without recourse to an additional H Ly\( \alpha \) contamination at the position of D Ly\( \beta \). We show that this obstacle may be successfully overcome within the framework of the mesoturbulent model, which accounts (in contrast to the microturbulent approximation) for a correlated structure of the large-scale velocity field. Using the same observational data and the original continuum as determined by Tytler et al., we obtained good fits. The one-component mesoturbulent models provide D/H in the range \( \approx (3.5−5.2) \times 10^{-5} \) and \( N(H\alpha) = (5.3−7.0) \times 10^{17} \text{ cm}^{-2} \) (95% confidence). This result is consistent with that found by us from the \( z_a = 2.504 \) and \( z_a = 0.701 \) systems toward Q1009+2956 and Q1718+4807, respectively. The range for D/H common to all three analyses is D/H = \((4.1−4.6) \times 10^{-5}\). This value is consistent with standard big bang nucleosynthesis if the baryon-to-photon ratio, \( \eta \), is in the range \( 4.2 \times 10^{-10} \leq \eta \leq 4.6 \times 10^{-10} \), implying \( 0.0155 \leq \Omega\,h^2_{100} \leq 0.0167 \).

Subject headings: cosmology: observations — methods: data analysis — quasars: absorption lines — quasars: individual (1937−1009)

1. INTRODUCTION

The most distant absorption-line system with observable D \( \alpha \) Ly\( \alpha \) and Ly\( \beta \) lines is the Lyman limit system discovered by Tytler, Fan, & Burles (1996, hereafter TFB) at \( z_a = 3.572 \) toward the quasar Q1937−1009 (\( z = 3.78 \)). TFB used high-resolution (FWHM = 9 km s\(^{-1}\)) and high signal-to-noise ratio (S/N \approx 75 pixel\(^{-1}\) at the position of the Ly\( \alpha \) line) Keck spectra of Q1937−1009 to reveal hydrogen absorption throughout the entire Lyman series, as well as a few metal absorption lines with asymmetric profiles. Their first measurements of D/H based on a two-component microturbulent model (Voigt profile deconvolution analysis) gave a low value of D/H = \((2.3 \pm 0.3 \pm 0.3) \times 10^{-5} \) (1 \( \sigma \) statistical and systematic errors). This result caused a lively discussion, since the low D/H value would imply a high universal density of baryons, \( \Omega_b\,h^2 \). The lack of uniqueness in the Voigt deconvolution procedure was employed by Wampler (1996) to show that other microturbulent models could give D/H ratios that are about 3 times higher than TFB’s value and are still compatible with their fit. Wampler also suggested that the total hydrogen column density

\[ \Omega_b\,h^2 \]

may not be well determined by TFB because of either incorrect sky subtraction or improper modeling of the Ly\( \alpha \) forest structure above and below the Lyman continuum break. The latter is problematical for distant QSOs exhibiting a high-density Ly\( \alpha \) forest, and different methods of analysis have yielded by now different values for \( N(H\alpha) \): (3.8−4.9) \times 10^{17} \text{ cm}^{-2} \) by Songaila, Wampler, & Cowie (1997) and (6.9−7.6) \times 10^{17} \text{ cm}^{-2} \) by Burles & Tytler (1997). A value of \( N(H\alpha) \sim 6 \times 10^{17} \text{ cm}^{-2} \) that “produces a smooth forest opacity above and below the break” was presented recently by Songaila (1997, p. 341).

Using new constraints on \( N(H\alpha) \) from Burles & Tytler (1998, hereafter BT) reconsidered the D/H measurements from the \( z_a = 3.572 \) system. In this new approach, the metal absorption lines are not used to constrain D/H. The absorbers are separated into two groups, with low and high H \( \alpha \) column densities \( N(H\alpha) \leq 2.5 \times 10^{15} \text{ cm}^{-2} \) and \( N(H\alpha) \geq 10^{17} \text{ cm}^{-2} \), respectively. The first group does not show D \( \alpha \) and was used to fit the Ly\( \alpha \) forest features in the vicinity of the Lyman series lines from the \( z_a = 3.572 \) system. The lines of the second (main) group were described by five free physical parameters: \( N(H\alpha), N(D\alpha), z, b_{\alpha}, \) and \( T \). The best-fitting model with three main components (model 4 in BT) allows for additional free parameters characterizing the local continuum to improve the fit. BT conclude, however, that “the model fit to Ly\( \beta \) is not as good as Ly\( \alpha \), there is underabsorption in two places near D Ly\( \beta \).”

The present Letter is primarily aimed at the inverse problem in the analysis of the H + D Ly\( \alpha \) and Ly\( \beta \) absorption observed by TFB. It is shown that the mesoturbulent model based on only five physical parameters and an appropriate velocity field configuration is a sufficient description of the D Ly\( \alpha \) and Ly\( \beta \) lines with no free parameters in the continuum.

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2. MODEL ASSUMPTIONS AND RESULTS

It is generally believed that the Lyman limit systems arise in the outer regions of intervening galactic halos. We assume that the background ionizing radiation at \( z = 3.5 \) is hard enough to keep the absorbing gas photoionized with \( T_{\text{kin}} \geq 10^4 \) K. A galaxy halo is considered to be a continuous medium exhibiting a mixture of bulk motions such as infall and outflows, rotation, tidal flows, etc. The motion along the line of sight is then characterized by a fluctuating velocity field that we consider as random. For the sake of simplicity, we assume a homogeneous (H i) density and temperature \( T_{\text{kin}} \). The model closely follows the papers by Levshakov & Kegel (1997, hereafter Paper I), Levshakov, Kegel, & Mazets (1997, hereafter Paper II), and Levshakov, Kegel, & Takahara (1997, hereafter Paper III); the reader is referred to these papers for more details. Here we note only that although the distribution function for the fluctuating velocity field is assumed to be Gaussian on average, the resulting velocity distribution along a given line of sight may deviate significantly from this.

To estimate the physical parameters and an appropriate velocity field structure along the sight line, we used a reverse Monte Carlo (RMC) technique, which is described in Paper III. The algorithm requires the definition of a simulation box for the five physical parameters: \( N(\text{H} \, i) \), D/H, \( T_{\text{kin}} \), \( \sigma T_{\text{kin}} \), and \( L/L \) (here \( \sigma \) denotes the rms velocity, \( T_{\text{kin}} \) the thermal width of the hydrogen lines, \( l \) the correlation length, and \( L \) the typical thickness of the absorbing region). The continuous random function \( \nu(s) \) is represented by its sampled values at equally spaced intervals \( \Delta s \), i.e., by the vector \( \{ v_1, v_2, \ldots, v_n \} \) of the velocity components parallel to the line of sight at the spatial points \( s \) (see Paper II).

In the present study, we adopt for the physical parameters the following boundaries: \( N(\text{H} \, i) \) ranges from \( 3.8 \times 10^{17} \) to \( 7.6 \times 10^{17} \) cm\(^{-2} \); D/H, from \( 2.0 \times 10^{-5} \) to \( 3.0 \times 10^{-4} \); and \( T_{\text{kin}} \), from \( 10^{4} \) to \( 2 \times 10^{4} \) K. For \( \sigma T_{\text{kin}} \), the boundaries were set from 1.0 to 4.0 to cover the \( \sigma \) range estimated from the kinematic structure of the galactic halos observed at \( z > 2 \) (\( \sigma \) = \( 40 \pm 15 \) km s\(^{-1} \); van Ojik et al. 1997). Since for \( L/L \gg 1 \) the meso- and microturbulent profiles tend to be identical (Paper I), we consider here only moderate \( L/L \) ratios in the range 1.0–5.0. Similar to BT, we assume that the D and H lines are not required to have the identical velocities as the metal lines from the same system and that only the higher order Lyman series lines can trace the neutral hydrogen distribution. But we fix \( z_a = 3.5723145 \) (the mean \( z \) between the blue and red components of the metal lines observed by TFB) as a more or less arbitrary reference radial velocity at which \( v_j = 0 \).

Having specified the parameter space, we construct the objective function (similar to that in Paper III) to calculate \( \chi^2_{\text{min}} \). The objective function includes the following portions of the Lyman series lines that, after preliminary analysis, were chosen as most appropriate to the simultaneous RMC fitting: for H + D Lyα and Lyβ, \( \Delta v \) ranges from \( -133 \) to \( -39 \) km s\(^{-1} \) (see Figs. 1a and 1b); for Ly14, 18 km s\(^{-1} \) \( \leq \Delta v \leq 42 \) km s\(^{-1} \) (Fig. 1i); and for Ly15, \( \lambda = 4184.50 \pm 4185.00 \) Å (Fig. 1j). In the Q1937–1009 spectrum, there are many additional absorbers blending the Lyman series lines. We do not fit these additional absorptions since they do not affect significantly the D/H measurement in this system as shown by BT. The strongest absorption feature seen at \( z = 3.57295 \) (\( \Delta v = 41.7 \) km s\(^{-1} \) in Figs. 1a–1l) has, according to BT, \( N(\text{H} \, i) = 2.5 \times 10^{15} \) cm\(^{-2} \), which is less than 1% of the total \( N(\text{H} \, i) \) at \( z = 3.57 \).

The estimated parameters for a few adequate RMC profile fits are listed in Table 1. We tried to find a satisfactory result with the reduced \( \chi^2 \) per degree of freedom of \( \chi^2_{\text{min}} \leq \chi^2_{1,0.05} \) (where \( \chi^2_{1,0.05} \) is the expected \( \chi^2 \) value for \( \nu \) degrees of freedom at the credible probability of 95%). In Table 1, the \( \chi^2_{\text{min}} \) values are shown for the blue wings of the H + D Lyα and Lyβ lines (\( \nu = 40, \leq 133 \) km s\(^{-1} \) \( \leq \Delta v \leq \pm 39 \) km s\(^{-1} \), and \( \chi^4_{4,0.05} = 1.40 \), which are the only lines with observable D absorption. Moreover, these pairs are more sensitive to the fitting procedure because they had the highest S/N data. Slightly lower \( \chi^2 \) values were found in the combination with the Ly14 and Ly15 lines, which, however, have smaller weights since their data are noisy. To illustrate our results, we show in Figure 1 the best RMC solution with the lowest \( \chi^2_{\text{min}} \) value (model d).

To check the RMC solutions, we calculated hydrogen profiles up to Ly23 for each model and then superposed them on the corresponding parts of the Q1937–1009 spectrum. For all models from Table 1, the results are similar to those shown in Figure 1. We do not find any pronounced discordance of calculated and real spectra.

The derived \( \nu(s) \) configurations are not unique. Table 1 demonstrates the spread of the rms turbulent velocities from \( \approx 18 \) to \( \approx 22 \) km s\(^{-1} \). But the projected velocity distribution functions \( p(\nu) \) for models a–e are very much alike, although each of them differs considerably from a Gaussian. Figure 2 shows, as an example for such a distorted distribution (solid line histogram), the case of model d. The dotted lines show the three \( p(\nu) \) for BT’s best-fitting model with three components (model 4). Both the RMC \( p(\nu) \) and the combined BT \( p(\nu) \) distributions are asymmetric. However, the RMC solution shows a stronger blue gradient as compared with BT’s result. This is the main reason why the absorption in the blue wing of the H + D Lyβ line is enhanced without any additional H i interloper(s).

3. CONCLUSION

We have shown that the interpretation of the Q1937–1009 spectrum obtained by TFB is not unique. The data can be modeled with a higher D/H ratio if one accounts for spatial correlations in the large-scale velocity field.

The most accurate and robust RMC solution (model d) was obtained with a total hydrogen column density outside the range found by Burles & Tytler (1997) but in good agreement with the Songaila (1997) estimate. Of course, our analysis gives a certain range for \( N(\text{H} \, i) \) and D/H. This is shown in Figure 3, where different confidence regions for this pair of physical parameters are depicted for model d under the assumption that the other parameters [\( T_{\text{kin}} \), \( \sigma T_{\text{kin}} \), \( L/L \), and \( \nu(s) \)] are fixed (the computing procedure is described in Paper III). However, the confidence range for D/H narrows if we require the D/H value to be compatible with the results of our previous analyses of the D i absorption toward Q1009+2956 (\( z_a = 2.504 \); Paper III).

| Model | \( N(\text{H} \, i) \) | D/H | \( T_{\text{kin}} \) | \( \sigma \) | \( L/L \) | \( \chi(\alpha, \beta) \) |
|-------|-----------------|-----|-----------------|------|--------|--------------|
| a     | 5.60            | 4.78| 1.16            | 20.1 | 3.6    | 1.24         |
| b     | 5.94            | 4.41| 1.43            | 22.3 | 3.5    | 1.29         |
| c     | 6.04            | 4.10| 1.09            | 20.8 | 2.8    | 1.40         |
| d     | 6.15            | 4.23| 1.15            | 20.0 | 3.6    | 1.18         |
| e     | 6.85            | 3.74| 1.38            | 18.5 | 2.0    | 1.39         |

\( N(\text{H} \, i) \) is the total hydrogen column density in units of \( 10^{15} \) cm\(^{-2} \). D/H is in units of \( 10^{-4} \), \( T_{\text{kin}} \) is the kinetic temperature in units of \( 10^{4} \) K, and \( \sigma \) is the turbulent velocity in units of km s\(^{-1} \).
Fig. 1.—Observations (normalized flux) and RMC fits for Q1937−1009. (a−i) Velocity plots of the Keck High-Resolution Echelle Spectrograph echelle data obtained by TFB (dots and 1σ error bars) and the calculated RMC profiles convolved with the instrumental resolution of FWHM = 9 km s⁻¹ (solid curves), corresponding to model d in Table 1. Zero velocity corresponds to the redshift, which is the mean value between the blue and red components of the metal lines from Fig. 1 in TFB. In panel a, the error bars are too small to be distinguished. The underabsoption on the blueward side of D Lyβ is within the statistically expected scatter. (j) Lyman limit portion of the Q1937−1009 spectrum (dots and 1σ error bars), and the RMC solution (solid curve) corresponding to model d.

Fig. 2.—Probability density function p(v) of the best RMC solution shown in Fig. 1 (solid line histogram) and, for comparison, three p(v) distributions with the velocity dispersions b(H) = 16.8, 18.9, and 12.1 km s⁻¹ (dotted curves) adopted from the best-fitting microturbulent model 4 of BT. The curves are weighted by the corresponding hydrogen column densities of 4.08 × 10¹⁷, 2.15 × 10¹⁷, and 1.38 × 10¹⁷ cm⁻². The sum of all three weighted functions is shown by the solid curve.

Fig. 3.—Confidence regions in the N(H i)−D/H plane for the fitted blue wings of the H + D Lyα and Lyβ profiles from Figs. 1a and 1b when the other parameters of model d (T_eq, σv, and L/L°) and the corresponding configuration of the velocity field v(s) are fixed. The contours represent 68.3% (innermost), 95.4%, and 99.73% (outermost) confidence levels. The cross marks the point of maximum likelihood for model d (see Table 1).
and toward Q1718+4807 ($z_a = 0.701$; Levshakov, Kegel, & Takahara 1998). The range common to all three analyses is 

$$D/H = (4.1 - 4.6) \times 10^{-3}.$$ 

For Q1937−1009, this implies 

$$N(H\text{I}) \sim (5.8 - 6.5) \times 10^{17} \text{ cm}^{-2},$$

showing that model d is well within this range. From SBBN, it follows that 

$$D/H = (4.1 - 4.6) \times 10^{-3}$$

implies for the baryon-to-photon ratio, $\eta$, a value in the interval $\sim (4.2 - 4.6) \times 10^{-10}$. With the present-day photon density determined from the cosmic microwave background (e.g., Fixsen et al. 1996), one then estimates the present-day baryon density to be in the range $\Omega_B h^2 = 0.0155 - 0.0167$.

The final conclusion is that the current observations support SBBN and that there is no conflict with the D/H measurements within the generalized mesoturbulent approach.

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