Measurements of the deuterium abundance in quasar absorption systems

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Abstract. Observational constraints on the primordial deuterium-to-hydrogen ratio (D/H) can test theories of the early universe and provide constraints on models of big bang nucleosynthesis (BBN). We measure deuterium absorption in high-redshift, metal-poor QSO absorption systems and directly infer the value of primordial D/H. We present two measurements of D/H, and find D/H = 3.3 ± 0.3 × 10^{-5} at z = 3.572 towards QSO 1937-1009 and D/H = 4.0 ± 0.7 × 10^{-5} at z = 2.504 towards QSO 1009+2956. Both measurements use multiple-component Voigt profile analysis of high resolution, high signal-to-noise spectra and determinations of the Lyman continuum optical depth in low resolution spectra to constrain the column densities of deuterium and hydrogen. The measurements are consistent with a single primordial value of D/H = 3.4 ± 0.3 × 10^{-5}. This is a relatively low value, which supports homogeneous models of BBN and standard models of galactic chemical evolution. With standard BBN, we find a cosmological baryon-to-photon ratio, η = 5.1 ± 0.3 × 10^{-10}, and a present-day baryon density in units of the critical density, Ω_b h^2 = 0.019 ± 0.001. These values are consistent with high abundance measurements of ^4He in extragalactic H II regions[^1], and estimates of ^7Li in warm, metal-poor halo stars[^2].

1. The Significance of Deuterium

In the first one thousand seconds of the universe, light nuclei (D, ^3He, ^4He, and ^7Li) are created during the epoch of BBN[^3].[^4]. In the standard model[^5] the nuclear yields

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[^3]: with three light neutrino species
of the light elements depend on a single parameter, $\eta$, the baryon-to-photon ratio. The density of photons in the universe is accurately known from the temperature of the cosmic microwave background\cite{5}. Therefore, a determination of a single primordial light element abundance gives a measure of $\eta$ and the present-day density of baryons, $\Omega_b$. The abundance ratio of deuterium to hydrogen (D/H) is a sensitive function of $\eta$, and a measurement of primordial D/H places the strong constraints on $\eta$ and $\Omega_b$. For example, a measurement of D/H with an uncertainty of 20% corresponds to 12% uncertainty in both $\eta$ and $\Omega_b$.

The determination of the primordial abundance ratio of D/H is a difficult task. For the last 25 years, BBN has stood as the only known cosmological source for deuterium nuclei\cite{6}. The deuteron is a fragile nucleus, and is easily and totally destroyed through stellar processing\cite{7}. With no other source of D besides BBN, any observational measurement of D/H will always give a lower limit to the primordial ratio. Local observations, in either the solar system or interstellar medium, provide a strong lower bound to the primordial abundance, $D/H > 1.6 \times 10^{-5}$\cite{8}. Inferring an upper limit from local measurements of D/H requires a problematic extrapolation with models of chemical evolution over the last 10 billion years of stellar processing in the galaxy\cite{9}.

In these proceedings, we will describe new measurements of D/H at high redshift in intergalactic absorption systems detected along the line of sight to distant quasars (QSOs). In 1976, Adams\cite{10} realized that high redshift systems showing strong Ly$\alpha$ absorption would provide an ideal site to determine the primordial ratio of D/H. Some of the more compelling reasons include (1) the high redshift allows much less time for D/H to be significantly altered from the primordial value, (2) the absorption systems are very metal poor (less than 1/100 solar metallicity in most cases), which limits the amount of destruction of D due to stellar processing, (3) most high redshift absorbers are not likely to be associated with galaxies, (4) the systems which are useful in a measurement of D/H must have low temperatures ($T < 20000$ K) and very small turbulent motions, which limits the amount of energy which could be introduced into the system.

2. The QSO Absorption Systems

Modern spectroscopy of high redshift QSOs reveal hundreds of discrete absorption features which correspond to intervening clouds of gas which lie along the line of sight. A small subset of these absorbers can yield a measurement of D/H, the set defined by the following criteria:

The neutral hydrogen column density (number of atoms per square cm) must exceed $10^{17}$ cm$^2$.

The velocity structure along the line of sight must be both simple and narrow. Simple, in that only a few components with small velocity separations are detected in absorption.

The redshift of the absorber must be high, $z_{\text{abs}} > 2.5$, to shift all of the desired absorption features into optical wavelengths which can be observed by large ground based telescopes.
In addition, we prefer systems which show weak or undetectable metal absorption lines, and lie along the line of sight to the brightest QSOs (which makes high-resolution spectroscopic observations practical).

The criteria listed above places severe limits on the sample of absorption systems. Out of the hundreds of absorbers along the line of sight to each QSO, we find systems to measure D/H in less than 3% of the lines of sight. That is, less than 0.01% of the absorbers in the entire observable sample are suitable systems. Needless to say, QSO absorption systems which show deuterium are rare.

The recent success of the high redshift D/H measurements rely on a method to increase the likelihood of finding these rare systems. Systems with the required high HI column densities are optically thick to photons with energies above one Rydberg, and exhibit very prominent continuous absorption in QSO spectra. These systems are known as Lyman limit systems. Lyman limit systems are easy to detect in low resolution spectra, which gives a much faster means to find likely systems, compared to obtaining high resolution data of random lines of sight to look for deuterium absorption. The top panel of Figure 1 shows a low resolution spectrum of QSO 1937–1009. The Lyman limit system at \( z = 3.572 \) is responsible for the continuous absorption of flux below 4200 Å.

The Lyman limit serves not only to identify the systems, but the optical depth of the absorption is directly proportional to the HI column density in the system. The role of the Lyman limit measurements will be discussed in detail in the next section.

Figure 1 shows a schematic view of two absorption features in the deuterium system towards QSO 1937–1009. The low resolution spectrum in the top panel covers a large spectral range and is plotted in units of flux per Å. The spectrum shows the intrinsic shape of the QSO continuum, including emission features, but also depicts the sharp increase in absorption at wavelengths shorter than Lyα emission at 5850 Å, due to the intervening Lyα absorption systems (the “Lyα forest”). The next set of panels zooms in on two specific regions in the spectrum, corresponding to the wavelengths of Lyα and singly ionized carbon (C II) redshifted to \( z = 3.572 \) (\( \lambda = \lambda_0(1 + z) \)). The two regions are noticeably different. The left hand panel shows the high density of lines in the Lyα forest at high redshift surrounding the strong Lyα line of the deuterium system. The right hand panel shows only the weak optically thin absorption from C II, and shows the absence of any other features nearby, so there is no confusion. The bottom panels show the profiles of the Lyα and C II. Deuterium absorption can be see on the left wing of the H I Lyα feature. The isotopic separation of D and H lines is -82 km s\(^{-1}\); the D I energy levels are shifted up in energy by a factor of 1.000272 compared to hydrogen, due to the small change in the reduced mass from the additional neutron. The middle and bottom panels show spectra obtained with the high resolution echelle spectrograph (HIRES)\(^{[1]}\). The spectra have a resolution of 8 km s\(^{-1}\) FWHM, which is sufficient to resolve the deuterium lines. The spectra have been normalized to allow a direct analysis of the absorption features. The intrinsic QSO continuum was modeled with a low order polynomial in each region. The next section will describe the method to measure D/H from the Lyman series absorption profiles of D I and H I.

3. The Deuterium Measurements

Here we present the spectra and analysis of the two absorption systems which yield the best measurements of D/H at high redshift. For a more detailed description of the
Figure 1. QSO 1937-1009: See text for more details

Top: Lick spectrum (FWHM = 4 Å)

Middle and Bottom: Keck+HIRES spectrum of the Lyα region (left) and C II region (right) at $z = 3.5722$
method and analysis, the reader is referred to larger papers[^12]–[^15]. A brief description is given here.

### 3.1. The Method to Measure D/H

We construct a model fit with discrete absorption lines, given by Voigt profiles, convolved with the instrumental resolution. Each Voigt profile is given by three parameters, the column density (N), the redshift (z), and the intrinsic velocity dispersion along the line of sight (b). Each hydrogen line profile with a large hydrogen column, \( N(\text{H I}) > 10^{16} \text{ cm}^{-2} \) has a corresponding deuterium profile at the same redshift. The velocity dispersion of both the H I and D I profile are given by two parameters, the temperature and turbulent velocity dispersion. In short, we substitute the free parameters of \( b(\text{H I}) \) and \( b(\text{D I}) \) with two parameters, T and \( b_{\text{tur}} \), which are identical in both H I and D I absorption lines. We also assume that D/H is global, that is, all components have the same ratio of \( N(\text{D I})/N(\text{H I}) \).

We select regions of the HIRES spectrum which contain the absorption features of the Lyman series and are not severely blended by unrelated lines in the Ly \( \alpha \) forest. The continuum is modeled as a low order polynomial in each region, and the coefficients of the polynomial are treated as free parameters in the fitting process to statistically allow for continuum uncertainties.

In this analysis, a measure of D/H is the goal, so we study the goodness of fit \( \chi^2 \) as a function of D/H. To directly study the effect of D/H on the model fit, we model the spectra with hundreds of iterations. In each iteration, we specify D/H, let all other parameters go free, and find the best \( \chi^2 \) associated with the specified value of D/H. We iterate over a large range in D/H, and measure the most likely value of D/H by locating the minimum of \( \chi^2 \) as a function of D/H. This method has much to offer. The parameters describing the profiles and continuum are sometimes highly correlated. The true uncertainty in D/H can not be determined by calculating the individual parameter uncertainties near the minimum of the \( \chi^2 \) function. We must explicitly map the \( \chi^2 \) dependence on D/H to include the correlations which are present in the model.

### 3.2. QSO 1937-1009

Tytler et al (1996)[^15] made the first measurement of low D/H in the absorption system at \( z = 3.572 \) towards Q1937–1009. We analyzed the high-resolution spectrum (8 hrs of exposure), which resolved the entire Lyman series up to Ly-19, as well as associated metal lines. By profile fitting the Lyman lines, with the position of the velocity components given by the metal lines, we find D/H = \( 2.3 \pm 0.3 \pm 0.3 \times 10^{-5} \) (statistical and systematic errors). The largest uncertainty in the measurement is the neutral hydrogen column density, \( \log N(\text{H I}) = 17.94 \pm 0.06 \pm 0.05 \), and the uncertainty stems from the saturated Lyman profiles (discussed in detail below). We then obtained a high quality low-resolution spectra from Keck with LRIS[^17], which gave better sensitivity short-ward of the Lyman limit, to directly measure the total \( N(\text{H I}) \) in the system and therefore place better constraints on D/H. Utilizing both the high and low-resolution spectra, we find \( \log N(\text{H I}) = 17.86 \pm 0.02 \) by a direct measurement of the optical depth short-ward of the Lyman limit at 4200 Å (Burles & Tytler 1997a). With this constraint and the more sophisticated method described above, we measure D/H = \( 3.3 \pm 0.3 \times 10^{-5} \) (Burles & Tytler 1997b).
Figure 2. Lyman series of Q1937-1009 at $z = 3.5722$. 
Figure 3. Lyman limit region of Q1009+2956 at $z = 2.504$.
*Top:* HIRES spectrum (FWHM = 8 km/s) showing lines Ly-11 to Ly-24. *Bottom:* Lick spectrum (FWHM = 4 Å) and model fit short-ward of Lyman limit. The solid line shows the best fit and dotted lines show $1\sigma$ errors.
The Lyman lines used in the fitting procedure are shown in Figure 2. The spectra have been shifted to a velocity scale by the simple transformation, 

\[ \frac{v}{c} = \frac{\lambda}{\lambda_0(1+z)} - 1.0, \]

where \( \lambda_0 \) is the rest wavelength of the Lyman line, and \( z \) is the redshift corresponding to zero velocity, in this case \( z = 3.57221 \).

Although the positions of the metal line components were previously used to constrain the fit \[15\], the present analysis does not require any information from the metal lines in the fitting procedure. The use of the metal lines can be justified for this system, but in general, one is likely to introduce systematics by including the metal lines, and it remains a good policy to leave all other lines except H and D out of the fitting procedure.

4. QSO 1009+2946

We discovered an absorption system at \( z = 2.504 \) towards Q1009+2956 ideal for a measurement of \( \text{D/H} \) \[16\]. This system has a lower hydrogen column density, \( \log N(\text{H I}) = 17.39 \pm 0.06 \). The highest order Lyman lines become unsaturated, which yields a precise measurement of \( N(\text{H I}) \) in both low and high resolution spectra (Fig. 3). Over twelve hours of Keck+HIRES produced a very high quality spectrum of the entire Lyman series, resolving the entire series up to Ly-22. We find strong evidence for contamination of the deuterium Ly\( \alpha \) absorption feature, which introduces the largest uncertainty in the measurement. Figure 4 shows the Ly\( \alpha \) line responsible for the contamination. The profiles of D I (dashed lines) and H I (dash-dotted lines) are shown explicitly, with the weak contaminating hydrogen line (dotted) falling just blueward (to the left) of D I. We include this contamination as a free parameter and find \( \text{D/H} = 4.0 \pm 0.7 \times 10^{-5} \) \[13\].
5. Conclusions

These two measurements of D/H in QSO absorption systems are the best and most robust measures to date. Deuterium has been identified and analyzed in a number of other QSO absorption systems[8]. We have found another two systems which place a strong upper limit on D/H at $D/H < 10^{-4}$. Combined with the two measurements described above, the four independent systems support a low primordial abundance of deuterium, and together give $D/H = 3.4 \pm 0.3 \times 10^{-5}$. If this represents the primordial value, nucleosynthesis calculations from standard BBN models with three light neutrinos give $\eta = 5.1 \pm 0.3 \times 10^{-10}$ and $\Omega_B h^2_{100} = 0.019 \pm 0.001$.

The constraints from D/H can be utilized to constrain cosmological models, quantify dark matter both in unobserved baryons and non-baryons, specify the zero point for models of deuterium evolution[9], test directly the predictions of standard BBN by comparing with other light element abundances[19], and limit the amount of small scale entropy fluctuations in the early universe[20].

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