THE DEUTERIUM TO HYDROGEN ABUNDANCE RATIO TOWARD A FOURTH QSO: HS 0105+1619

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ABSTRACT

We report the measurement of the primordial D/H abundance ratio toward QSO HS 0105+1619. The column density of the neutral hydrogen in the z ∼ 2.536 Lyman limit system is high, log N_H = 19.422 ± 0.009 cm^-2, allowing for the deuterium to be seen in five Lyman series transitions. The measured value of the D/H ratio toward QSO HS 0105+1619 is found to be D/H = 2.54 ± 0.23 × 10^-5. The metallicity of the system showing D/H is found to be ≈ 0.01 solar, indicating that the measured D/H is the primordial D/H within the measurement errors. The gas that shows D/H is neutral, unlike previous D/H systems that were more highly ionized. Thus, the determination of the D/H ratio becomes more secure since we are measuring it in different astrophysical environments, but the error is larger because we now see more dispersion between measurements. Combined with prior measurements of D/H, the best D/H ratio is now D/H = 3.0 ± 0.4 × 10^-5, which is 10% lower than the previous value. The new values for the baryon-to-photon ratio and baryonic matter density derived from D/H are η = 5.6 ± 0.5 × 10^-10 and Ω_h^2 = 0.0205 ± 0.0018, respectively.

Subject headings: cosmology: observations — intergalactic medium — quasars: absorption lines — quasars: individual (HS 0105+1619)

1. INTRODUCTION

The standard theory of big bang nucleosynthesis (BBN) predicts the abundances of the light nuclei H, D, ^3He, ^4He, and ^7Li as a function of the cosmological baryon-to-photon ratio, η = n_B/n_e (Kolb & Turner 1990; Walker et al. 1991; Schramm & Turner 1998; Nollett & Burles 2000; Olive, Steigman, & Turner 1998; Nollett & Burles 2000; Olive, Steigman, & Walker 2000). A measurement of the ratio of any two primordial abundances gives η, and hence the baryon density, while a second ratio tests the theory. However, it is extremely difficult to measure primordial abundances because in most places gas ejected from stars has changed the abundances.

Adams (1976) suggested that it might be possible to measure the primordial D/H ratio in absorption-line systems toward QSOs. Although gas that has been inside a star will have lost all of its deuterium, in QSO absorption-line systems having typical metal abundances of 0.001–0.01 of the solar value about 0.1%–1% of the deuterium will have been lost.

The advent of the HIRES spectrograph (Vogt et al. 1994) on the W. M. Keck-I telescope gave the high signal-to-noise ratio (S/N) and spectral resolution needed to reveal deuterium (Tytler et al. 2000) in high-redshift absorption systems. We have previously measured D/H in two QSOs (Tytler, Fan, & Burles 1996; Tytler & Burles 1997; Burles & Tytler 1998a, 1998b) and placed a strong upper limit on D/H in a third (Kirkman et al. 2000).

Other QSOs give less useful constraints on D/H because their absorption systems are more complex or existing spectra are inadequate. The Lyman limit system (LLS) at z_abs = 0.701 toward QSO PG 1718+4807 might allow 10 times larger D/H, or it may give no useful constraints (Webb et al. 1997; Levshakov, Kegel, & Takahara 1998; Tytler et al. 1999). Molaro et al. (1999) claimed another QSO absorption system showed low D/H, but they and Levshakov, Agafonova, & Kegel (2000a, 2000b) note that since only the Ly_a line has been observed, the hydrogen velocity structure and the H I column density are poorly known, and the deuterium feature can be fitted using hydrogen alone.

In this paper we present a fourth QSO, HS 0105+1619, which gives strong constraints on the primordial D/H ratio.

2. OBSERVATIONS AND DATA REDUCTION

We report the detection of deuterium in the QSO HS 0105+1619 (emission-line redshift 2.64, V = 16.9, B1950 R.A. 1°50'26"97, Decl. 16°19'50"1; J2000 R.A. 1°8'6"4, Decl. 16°35'50"0), which was discovered by Hagen, Engels, & Reimers (1999), who very kindly gave us a finding chart and a low-resolution spectrum prior to publication.

We present high-quality, high-S/N spectra of HS 0105+1619 in both low and high resolution. The low-resolution spectra were obtained using the Kast double spectrograph on the Shane 3 m telescope at Lick observatory. The high-resolution spectra were obtained using the HIRES spectrograph on the Keck-I telescope. The observations are summarized in Table 1. All of the high-resolution observations were taken using the HIRES image rotator to align the direction of atmospheric dispersion along the slit and with the C5 decker, which provides an entrance aperture to the spectrograph with dimensions 1'15 × 7'5. The spectra were sampled in 2.1 km s^{-1} pixels with the Tektronix 2048 × 2048 CCD.

The HIRES spectra were flat-fielded, optimally extracted, and wavelength-calibrated using Tom Barlow's set of
TABLE 1

| Instrument | Date       | Integration Time (s) | Wavelengths Covered (Å) |
|------------|------------|----------------------|-------------------------|
| Kast       | 1998 Aug 16| 2700                 | 3200–5100               |
| HIRES      | 1999 Oct 10| 7200                 | 3200–4720               |
| HIRES      | 1999 Oct 11| 2 × 8000             | 3200–4720               |
| HIRES      | 1999 Nov 09| 1800                 | 4220–6640               |
| HIRES      | 2000 Sep 19| 2 × 7200             | 3200–4720               |
| HIRES      | 2000 Sep 20| 8600, 10800          | 3200–4720               |
| HIRES      | 2000 Sep 20| 4 × 7000             | 3200–4720               |
| Total (HIRES) | ...       | 86800               | ...                     |

* The wavelength coverage for this observation was not continuous as a result of 1–10 Å spectral order gaps.

As can be seen in Figure 1, the low-resolution Kast spectrum of HS 0105 +1619 shows a steep Lyman break at a wavelength of approximately 3230 Å, which is caused by an LLS at a redshift of $z \approx 2.54$. At this redshift we see a strong Lyα absorption line, near 4300 Å. Our analysis of the high-resolution HIRES spectrum indicates that there is an LLS at a redshift of $z \approx 2.536$, which shows deuterium and numerous metal absorption lines. We discuss the general features of the absorption below and the best fits to the data in the following section.

3.1. Hydrogen Absorption

We observe hydrogen in all Lyman series transitions through Ly17, where the spectrum abruptly ends at 3233 Å as a result of line blending near the Lyman limit. The observed Lyman transitions are shown in Figure 2.

The column density of the hydrogen is high, as Figure 2 indicates. All of the Lyman series transitions are saturated through to the Lyman limit, indicating that the column density is at least $\log N_{\text{H}_1} \geq 17.8 \, \text{cm}^{-2}$. The Lyα line has approximately 1–2 km s$^{-1}$, which is the size of the error that we have noted in our analysis of other similar spectra (Levshakov, Tytler, & Burles 2000c). The final spectrum has 2.1 km s$^{-1}$ wide pixels and an S/N of approximately 80 and 10 at the Lyα and Lyman limit of the D/H system, respectively. In Figure 1 we show the flux-calibrated Kast and HIRES spectra.

Fig. 1.—Spectrum of HS 0105 +1619. The upper panel shows the low-resolution flux-calibrated spectrum obtained with the Kast spectrograph. The lower panel shows the flux-calibrated HIRES spectrum. The flux calibration was noisy at wavelengths less than 3800 Å and was not applied to the Lyman limit, which is not shown above for the HIRES spectrum.
zero flux across about 200 km s\(^{-1}\), indicating that the column density of the system is approaching the levels found in damped Ly\(\alpha\) systems.

Inspection of Figure 2 also indicates that the absorption system is very simple. The Ly\(5\), Ly\(6\), Ly\(7\), Ly\(9\), Ly\(10\), Ly\(14\), and Ly\(15\) transitions all appear symmetric and unblended, allowing us to describe the absorber by a single component.

3.2. Deuterium Absorption

Since the column density of the hydrogen responsible for the Lyman limit appears high, we expect the associated deuterium absorption to be strong. For the first time, we observe absorption at the predicted position of deuterium, a velocity of \(v = -81.64\) km s\(^{-1}\) in the frame of the H\(\,\!\!\i\) in five
Lyman series transitions: Lyβ, Lyγ, Ly5, Ly6, and Ly7. Deuterium Lyα was not observed since it is subsumed by the absorption of the hydrogen Lyα, and deuterium Ly4 was not observed because of intervening Lyα forest absorption.

The observed absorption is narrow and appears symmetric and free of strong contamination, suggesting that, like the hydrogen, the absorption is simple and can be modeled with a single component. In all transitions where absorption is observed, the velocity of the absorption appears centered about the same value, \( v \approx -82 \text{ km s}^{-1} \), strongly indicating that the features are all Lyman transitions of the same absorber and that the absorber is consistent with being deuterium. In a later section we give a more rigorous discussion of why we believe the absorption is indeed deuterium and not hydrogen or other ions.

3.3. Metal Line Absorption

The \( z \approx 2.536 \) LLS shows a variety of metal ions, as seen in Figure 3. Unlike LLSs with column densities in the range of \( \log N_{\text{HI}} = 16.5-18 \text{ cm}^{-2} \), which show absorption predominantly in the higher ionization states, this system shows metal line absorption in neutral, low-, and high-ionization states. Since the column density of the hydrogen appears high, we expect the neutral and low-ionization metal lines to trace the H I, and with it the deuterium, in analogy with damped Lyα systems.

All of the low-ionization metal lines are extremely narrow and appear to be well described by a single component. Moreover, the low ions are all centered at \( v \approx 0 \text{ km s}^{-1} \), implying that they arise in the same gas as the H I and D I.

4. BEST PARAMETERS FOR THE \( z \approx 2.536 \) LYMAN LIMIT SYSTEM

We now give the parameters that describe the absorption in the \( z \approx 2.536 \) LLS toward HS 0105 + 1619. For all measurements, a continuum was fitted to the region under consideration to produce a unit normalized spectrum. The observed absorption features were then fitted using the VPFIT Voigt profile line-fitting routine (Webb 1987; kindly provided by R. F. Carswell) and reverified using in-house routines. For each absorber, we obtain an estimate of the column density, \( N \), the redshift, \( z \), and the velocity width, \( b \), along with their respective 1 \( \sigma \) errors. The results of this analysis are found in Table 2.

4.1. The Hydrogen

The parameters describing the hydrogen absorption responsible for the Lyman limit are obtained from various...
The Lyman limit allows for a lower limit to the column density of the hydrogen of $N_{\text{HI}} = 17.8$ cm$^{-2}$ since all observed Lyman series lines observed are saturated.

The Ly$\alpha$ line gives the most information regarding the hydrogen column density because it is insensitive to the $b$ value, even though it is sensitive to the continuum level. In Figure 5 we show the continuum used to fit the 250 Å region encompassing Ly$\alpha$ and the corresponding approximate 1 $\sigma$ levels, which amount to a $\pm 2\%$ continuum level change. To determine the effect of the continuum placement on the measured value on the column density, for all regions of the Ly$\alpha$ line we obtain a fit using the best continuum estimate and then move the continuum to the $\pm 1\sigma$ levels and refit. In all fits to the Ly$\alpha$, we choose segments of the spectra that appear to be least contaminated by other absorption.

In Figure 6 we show the fit to the core of log $N_{\text{HI}} = 19.419 \pm 0.009$ cm$^{-2}$, where the error is the quadratic sum of the error from the continuum (0.007) and the error from the fit (0.006). This fit was made for two regions on either side of the line center: 4294.5–4295.5 and 4300–4302 Å. There is additional absorption in the core between 4295.5 and 4302 Å that is readily fitted by two HI and Ly$\alpha$ lines. Their absorption is seen and fitted in Ly$\beta$, but they contribute no significant optical depth to the lower wavelength (4295–4295.5 Å) region that gives the column density of the HI that shows deuterium.

We note that contamination of the core region is possible and would lower the measured column density. However, we consider such contamination unlikely, since it would require at least two lines appearing in the right places, with
a very restricted set of parameters, to produce enough absorption to fit both sides of the core region.

The damping wings of the Ly$\alpha$ absorber also give the column density, but the exact continuum placement is now the dominant source of error because the continuum uncertainty represents a larger fraction of the total absorption in these regions. Two damping wing regions were fitted, one on either side of the line center. On the blue (lower wavelength) side, we fitted the wavelengths 4288.4–4289.3 Å, which gave $\log N_{\text{HI}} = 19.406 \pm 0.060$ cm$^{-2}$, where the errors are the range in column density allowed by the $\pm 2\%$ range in the continuum placement. For the red (higher wavelength) side, regions 4306–4307 and 4308–4309 Å were fitted, giving $\log N_{\text{HI}} = 19.475 \pm 0.040$ cm$^{-2}$.

For our best value for the H$\text{I}$ column density, we take the weighted mean of the three measurements from the core and wings: $\log N_{\text{HI}} = 19.422 \pm 0.009$ cm$^{-2}$. All three estimates of the column density are consistent with this mean.

### 4.2. The Deuterium

The determination of the parameters describing the deuterium absorption is relatively straightforward, given the presence of five unblended transitions, most of which are unsaturated. We begin by fitting the D$\text{I}$ transitions and then assess possible sources of error.
The D I transitions are well fitted by an absorber with \( \log N_{D I} = 14.810 \pm 0.029 \text{ cm}^{-2} \) and a velocity width of \( b = 9.93 \pm 0.29 \text{ km s}^{-1} \). This fit is shown in Figure 7. These values were determined by fitting the regions surrounding the deuterium in all five deuterium absorption regions simultaneously, with the redshift of the deuterium tied to the hydrogen and the parameters for the hydrogen absorption fixed at \( \log N_{HI} = 19.42 \pm 0.29 \text{ cm}^{-2} \) and \( b = 13.99 \pm 0.29 \text{ km s}^{-1} \). In all fits, the regions used to fit deuterium were constrained to be those within approximately \( \pm 150 \text{ and } 20 \text{ km s}^{-1} \) of the \( \text{H I} \) line center and are listed in Table 3. Where needed, additional \( \text{Ly}_\alpha \) forest absorption was fitted to model all absorption. The parameters for the additional lines are given in Table 4.

![Graph](image)

**Fig. 7.**—Simultaneous fit to the deuterium at \(-82 \text{ km s}^{-1}\) in five Lyman series transitions with \( \log N_{D I} = 14.81 \pm 0.03 \text{ cm}^{-2} \) and \( b = 9.93 \pm 0.29 \text{ km s}^{-1} \). Also included in the fit is the \( \text{H} \) at \( 0 \text{ km s}^{-1} \) and additional \( \text{Ly}_\alpha \) forest absorption.

**TABLE 3**

Spectral Regions Used to Measure D I

| Region | \( \lambda_{\text{min}} \) (Å) | \( \lambda_{\text{max}} \) (Å) |
|--------|-----------------|-----------------|
| \( \text{Ly}_\beta \) | 3625.1 | 3627.4 |
| \( \text{Ly}_\gamma \) | 3437.2 | 3439.2 |
| \( \text{Ly}_5 \) | 3314.2 | 3316.4 |
| \( \text{Ly}_6 \) | 3289.4 | 3291.4 |
| \( \text{Ly}_7 \) | 3273.5 | 3275.2 |

The uncertainty in the continuum level increases the error on the D I column density by one-third. Independent estimates of the continuum levels at the D I transitions had a 1 \( \sigma \) dispersion of approximately 10%, much larger than the 2\% error near \( \text{Ly}_\alpha \), where the data have been flux-calibrated and have significantly higher S/N. To gauge the effect on the error in the D I column density, we determined the parameters of the deuterium absorption independently for each line, both for the best estimate of the continuum and for a 10% higher continuum level. The difference between these two is the contribution to the error from the choice of continuum level. For each D I transition, this error was added in quadrature to the error obtained with the best continuum. The weighted mean for the five D I transitions gives \( \log N_{D I} = 14.826 \pm 0.039 \text{ cm}^{-2} \) and \( b = 9.85 \pm 0.42 \text{ km s}^{-1} \). The results of the independent fits to the different deuterium transitions with the best estimate of the continuum level can be seen in Figure 8.

![Graph](image)

**Fig. 8.**—Values of the deuterium column density, \( \log N_{D I} \), and the absorption width parameter, \( b \), for each of the five deuterium lines fitted separately. The thick cross represents the values when all lines are fitted simultaneously using the best estimate for the continuum level.
4.3. The Metals

The results of fits to the many metal lines are given in Table 2, and a subset of the fits is shown in Figure 9. In all cases, the ions were best fitted by a single component whose redshift, velocity width, and column density were all allowed to vary. Many of these ions show multiple transitions, and for any single ion, all transitions present in the spectra were fitted simultaneously.

The metals were all found to lie within 8 km s$^{-1}$ of the redshift of the hydrogen that shows deuterium. More importantly, since the column density of the hydrogen is so high, we expect the redshifts of the low and neutral ions to agree with the hydrogen since we expect the gas to be predominantly neutral. The neutral and singly ionized ions agree with the hydrogen redshift to within 2 km s$^{-1}$, while the neutral ions alone, in the first section of Table 2, agree to within approximately 1 km s$^{-1}$. The larger dispersion seen for the singly ionized ions, in the second section of the table, indicates that some of the gas making these lines is distinct from the neutral gas, but this dispersion could be insignificant because the internal wavelength errors could be 1–2 km s$^{-1}$.

The detection of O I is of particular importance in this system for two reasons. First, the ionization potential of O I is nearly identical to that of hydrogen, so it is ionized by the same photons that ionize the H I. Second, O I participates in electron transfer with H I, such that in cases in which the gas is not highly ionized, O I/O is nearly identical to H I/H, and the distribution of O I should match that of the H I and the D I. The O I absorption gives information about the temperature, bulk motion, ionization, and abundances in the neutral gas that shows the D I absorption. Since the O I is accurately modeled by a single, narrow component in four separate transitions, we gain confidence that a single-component fit to the deuterium and to the hydrogen is sufficient. The implications of the measurement of O I on the metallicity and ionization are discussed in a later section.

Since O I and H I should arise in the same gas, we use these lines to obtain the temperature of the gas that shows D I and its turbulent velocity. We model the observed $b$ as $b^2 = b_{\text{inst}}^2 + b_{\text{temp}}^2$. The instrument line broadening, $b_{\text{inst}}$, was measured from arc lamp calibration spectra to be $b_{\text{inst}} = 4.81 \pm 0.14$ km s$^{-1}$. We model the intrinsic velocity width as $b_{\text{inst}}^2 = b_{\text{temp}}^2 + b_{\text{turb}}^2$, a combination of thermal broadening and bulk motion. The thermal broadening, $b_{\text{temp}}^2 = 2kT/m = 166.41(T/10^4 \text{ K})/\text{mass (amu)}$, depends on the ion mass in atomic units, $m$, but the $b_{\text{turb}}$ is the same for all ions. All of the $b$ values quoted in this paper and listed in Table 2 refer to intrinsic line widths, but the listed errors do not include the error in $b_{\text{inst}}$ because we do not know whether this error is correlated at different wavelengths.

Fitting O I, N I, and H I alone gives $T = 1.15 \pm 0.02 \times 10^4$ K and $b_{\text{turb}} = 2.56 \pm 0.12$ km s$^{-1}$, which we show...
by the solid line in Figure 10. The errors quoted here are very much minimum values because they do not include the error in the \( b_{\text{spec}} \) or the appropriateness of the model.

Ions \( \text{C} \, \text{II} \), \( \text{Si} \, \text{II} \), and \( \text{Fe} \, \text{II} \) are all wider than predicted by this fit, presumably because a part of each line arises in gas with different velocity structure. The lines from the higher ionization ions \( \text{C} \, \text{III} \), \( \text{C} \, \text{IV} \), \( \text{N} \, \text{II} \), \( \text{Si} \, \text{III} \), and \( \text{Si} \, \text{IV} \) have velocities that differ by 0 to \(-7 \, \text{km s}^{-1}\) from the \( \text{H} \, \text{I} \) and low-ionization ions. They are not relevant to the \( \text{D} / \text{H} \) because their ionization and velocities show that they arise in different gas, a common finding for absorption systems with high \( N_{\text{H}} \) (Wolfe & Prochaska 2000), but unlike absorption systems with much lower \( N_{\text{H}} \), including PKS 1937−1009 and Q1009 + 2956.

5. IS THE OBSERVED ABSORPTION DEUTERIUM?

Now that we have determined the parameters of the absorption at the position of deuterium, we turn to the issue of confirming that the absorption is indeed deuterium and not interloping hydrogen or metal line contamination.

The primary concern with the absorption seen at the position of deuterium would be that it is caused not by deuterium but instead by interloping hydrogen. Here we argue that this scenario is unlikely for the following reasons. First, hydrogen lines in the Ly\( \alpha \) forest with the appropriate column density, \( \log N_{\text{H}} \approx 14.8 \, \text{cm}^{-2} \), have \( b > 20 \, \text{km s}^{-1} \) and not \( b \approx 10 \, \text{km s}^{-1} \) (Kim et al. 1997; Kirkman & Tytler 1997). However, such low values of \( b \) might be found in components of the LLS, which are the most likely contaminants. Second, we are able to predict the width of the deuterium using the measured widths of the other neutral ions observed that are present in the same gas. Figure 10 illustrates the concept. Since we have observed three other neutral ions (\( \text{H} \, \text{I} \), \( \text{O} \, \text{I} \), \( \text{N} \, \text{I} \)), we can use their widths to predict the width of deuterium. As Figure 10 shows, the measured value of \( b(D) \) is consistent with its predicted value. Third, hydrogen lines with \( \log N_{\text{H}} \approx 14.8 \, \text{cm}^{-2} \) often show associated metal line absorption, but as is seen in Figure 9, there is no such absorption at \(-82 \, \text{km s}^{-1}\). Finally, for the absorption to be hydrogen and not deuterium, its position would have to agree with that of deuterium to within \( 1 \, \text{km s}^{-1} \). Taken together, these arguments indicate that the observed absorption is deuterium, and not hydrogen, but we cannot quantify this because we do not know the properties of components of LLSs.

The scenario in which the absorption is metal line contamination is even less likely for a number of reasons. Any metal lines with a column density of \( \log N_{\text{metal}} \approx 14.8 \, \text{cm}^{-2} \) would show absorption in not only that ion but many others along with strong associated hydrogen absorption, some of which would be easily observed in our spectrum but were not. Also, for the observed absorption to be derived entirely from metal line contamination, such metal lines would have to appear in five different regions of the spectrum, all at positions within approximately \( 1 \, \text{km s}^{-1} \) of the predicted positions of deuterium, and with line strength scaling as the oscillator strengths expected for the deuterium Lyman series. A similar argument can be used to exclude the case in which the absorption at the position of deuterium was hydrogen, but not in the corresponding Lyman series transition (e.g., the absorption at Ly\( \alpha \) is an unrelated Ly\( \alpha \) line).

6. ELEMENTAL ABUNDANCES AND IONIZATION STATE OF THE \( z \approx 2.536 \) LYMAN LIMIT SYSTEM

Here we discuss the abundances of the elements observed in the \( z \approx 2.536 \) LLS that shows D/H. The general procedure for determining the elemental abundances is to use an ionization model to convert from the observed column densities of selected ions into elemental abundances. On the whole, the level of ionization in QSO absorption-line systems tends to decrease as the column density of the gas increases, since the gas can shield itself more from ionizing Lyman continuum radiation. Typical LLSs with \( \log N_{\text{H}} \approx 17.5 \, \text{cm}^{-2} \) are highly ionized, whereas damped Ly\( \alpha \) systems, whose column densities are greater than \( \log N_{\text{H}} = 20 \, \text{cm}^{-2} \), are typically neutral. In the case of HS 0105 + 1619, we expect the gas to be predominantly neutral (\( \text{H} / \text{H} \geq 0.5 \)), since the column density is approaching that of a damped Ly\( \alpha \) system.

6.1. Ionization and Metallicity

We modeled the ionization with the CLOUDY v90.04 package developed by Ferland (1991). As usual, we assumed a plane-parallel geometry with constant density \( n_{\text{H}} = 0.01 \, \text{cm}^{-3} \), and we approximated an isotropic background ionizing radiation by placing a point source at a very large distance. We used the Haardt-Madau ionizing spectrum (Haardt & Madau 1996). In Figure 11 we show the correc-
tion that would be added onto an observed ionic abundance to give an elemental abundance: \[ [X/H] = \log (N_X/N_{H,I}) + \log (X/H) - \log (X/H)_\odot, \]
where \( N_X \) is the column density of the ion used to infer the abundance of element \( X \). Since we hold the \( N_{H,I} \), the gas density, and the spectrum constant, these corrections are specified in terms of the intensity of the ionizing flux at 1 ryd, \( \log J_{912} \).

Because the corrections are nearly homologous with the ratio \( n_{H,I}/J_{912} \), we can account for different \( n_{H,I} \) values by simply shifting \( J_{912} \).

For the D/H absorber, we can obtain the [O/H] without ionization correction because we have four unblended O i transitions that give the most accurate \( N_O \), in any absorption system to date. The ionization correction for O i is negligible, \( \log \epsilon(O\,i/H\,i) < 0.2 \) dex, even at extreme values of \( J_{912} \), and O i/H i is equal to O/H, which gives [O/H] = −2.0.

This abundance is supported by four other elements. Figure 11 shows that the ionization corrections for Si ii, C ii, Al ii, and Fe ii are all negative. Therefore, we can place upper limits on the C, Si, Fe, and Al abundances using the observed C ii/H i, Si ii/H i, Fe ii/H i, and Al ii/H i ratios without corrections. We find [C/H] ≤ −1.9, [Al/H] ≤ −2.1, [Fe/H] ≤ −1.9, and [Si/H] ≤ −1.85, all within 0.15 dex of [O/H]. Note that these elements might have shown different abundances because they are seen in lines that have different velocities and velocity widths from the H i, D i, and O i. From N i, we find [N/H] ≈ −3.1 without ionization correction, as suggested by the other elements. This implies that N is underabundant by approximately 1.1 dex, which is not unusual for damped Ly\( \alpha \) systems with similarly low metal abundances (Centurion et al. 1998; Lu, Sargent, & Barlow 1998) but is much more N than usual in Galactic and extragalactic H ii regions (Henry, Edmunds, & Köppen 2000).

The similarity of these abundance values shows that each element is primarily in the listed ion, O i, Si ii, Fe ii, Al ii, and C ii, and that H i/H > 0.8. This low ionization requires \( J_{912}/10^{21} \) ergs \( \text{cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1} \) \(< 10^{-2} \) cm\(^{-3} \) n\(_{H,I} \) and hence a weak radiation intensity and high gas density. When we divide the \( N_{H,I} \) by the gas density, we find that the size of the cloud along the line of sight would be \( l < 1 \) kpc, assuming a homogeneous medium. If the absorbing region were spherical, its gas mass would be less than \( 1.2 \times 10^5 M_\odot \).

The observed Si iii, C iii, C iv, or Si iv absorption must come from separate, more highly ionized gas.

7. BEST-FIT VALUES FOR HS 0105 + 1619

For the gas giving D/H in HS 0105 + 1619, the best values for various parameters and the 1 \( \sigma \) errors are as follows:

1. \( \log N_{H,I} = 19.422 \pm 0.009 \) cm\(^{-2} \) (2\% error).
2. \( \log N_{D,I} = 14.826 \pm 0.039 \) cm\(^{-2} \) (9\% error).
3. \( \log (D/H) = -4.596 \pm 0.040 \) (10\% error).
4. \( D/H = 2.54 \pm 0.23 \times 10^{-5} \).
5. Temperature: \( T = 1.15 \pm 0.02 \times 10^4 K \).
6. Gaussian turbulent velocity width: \( b_{turb} = 2.56 \pm 0.12 \) km s\(^{-1} \).
7. Log oxygen abundance, on the solar scale: [O/H] = −2.0.
8. Other limits: [C/H] ≤ −1.9, [Al/H] ≤ −2.1, [Fe/H] ≤ −1.9, [Si/H] ≤ −1.85, [N/H] ≈ −3.1.
9. Neutral fraction: H i/H > 0.8.
10. Gas density: \( n > 0.01 \) cm\(^{-3} \) (for \( J_{912} \geq 10^{-21} \) ergs cm\(^{-2} \) s\(^{-1} \) Hz\(^{-1} \) sr\(^{-1} \)).
11. Extent of absorbing region along the line of sight: less than 1 kpc.
12. Mass of gas: less than \( 1.2 \times 10^5 M_\odot \).

For D/H, we added the errors on \( \log N_{H,I} \) and \( \log N_{D,I} \) in quadrature because we expect little correlation.

8. BEST VALUES FOR D/H FROM ALL QSOS

The weighted mean D/H from three QSOs, PKS 1937−1009, Q1009+2956, and HS 0105 + 1619 (the other QSO, Q0130−4021, gives a consistent upper limit), is \( \log (D/H) = -4.523 \pm 0.026 \) (6\% error). The individual parameters from our measurements of four QSOs are summarized in Table 5. The dispersion in the three measurements of D/H is larger than expected. We obtain \( \chi^2 > 7.1 \), which would be exceeded in 3\% of random samples with Gaussian errors. There are two interpretations. Either we have underestimated the errors, or there is real dispersion in D/H. We favor the former interpretation, since there are a number of systematic errors that affect each measurement and are difficult to assess. For example, we may have underestimated the effect of contamination in PKS 1937−1009 or Q1009+2956. Hydrogen absorption near the D i lines would artificially increase the D/H estimated for these objects. We now discuss another possible source of scatter in D/H, astration, the destruction of deuterium in stars.
6.7

Values for the four QSOs listed in Table 5 range from the metallicity that we have measured towards QSOs. The metal production. Systems destroy less deuterium for a given amount of destruction, there has been infall of less processed gas, and the linear in the LISM today because the destruction is saturated.

At a metallicity of 0.01 solar, we expect 0.7% to be lost at 0.01 solar. This scaling is the LISM where the metal abundance is approximately 0.7 solar, we expect 0.7% to be lost at 0.01 solar. This scaling is only approximate for many reasons: the relation is not linear in the LISM today because the destruction is saturating, there has been infall of less processed gas, and the high-mass stars that we expect polluted the absorption systems destroy less deuterium for a given amount of metal production.

We now discuss the relation between the D/H values and the metallicity that we have measured towards QSOs. The D/H values for the four QSOs listed in Table 5 range from less than $6.7 \times 10^{-5}$ to $2.54 \times 10^{-5}$, while the [Si/H] ranges from $-2.6$ to $-1.85$. Figure 12 shows that these values appear correlated, in the sense that the D/H is lower when the metallicity is higher. This is the sense expected if the deuterium has been destroyed in those absorbers with higher metallicity. The D/H for Q1009+2956, PKS 1937−1009, and HS 0105+1619 appears to decline linearly with increasing [Si/H]. The D/H declines by a factor of 0.64 between Q1009+2956 and HS 0105+1619, while the [Si/H] increases from approximately $-2.53$ to $-1.85$.

There are two arguments against the reality of the correlation. First, we do not expect such a large destruction of deuterium when the metal abundance remains this low. A decrease in the D/H by a factor of 0.64 implies that 0.64 of the atoms in the absorbing gas have not been in a star and that 0.36 have been in one or more stars, which is at least an order of magnitude more than expected. Second, the indicated rate of decrease of the D/H is much faster than expected. We expect D/H to decrease linearly with the linear, and not log, metal abundance.

Models of the evolution of the chemical abundances in our Galaxy predict that D/H will remain near the primordial value (Fig. 12, solid line) for [Si/H] < $-1$ (Prantzos 1996, Fig. 4b; Prantzos & Silk 1998, Fig. 3; Matteucci, Romano, & Molaro 1999, Fig. 7b). The D/H declines at higher abundances because a significant fraction of the atoms in the ISM have then come from within stars. The abundance at which the D/H decline becomes significant depends on the details, including the element used to gauge the metal abundance, the amount of that element ejected from stars, the fraction of the H in the ISM that has not been inside a star, the infall of gas with abundances nearer to the primordial values, and the amount of mixing.

The Galactic chemical evolution models apply on average to large volumes of gas that are well mixed. At the epoch of observation the gas may instead be isolated, and

![Figure 12](image)

**Figure 12.** Relationship between D/H measurements and metal abundances, as gauged by silicon. Standard chemical evolution models predict little change in D/H until [Si/H] $> -1$, at which time a significant fraction of the gas has come from inside stars, where the D has been destroyed. The values of [Si/H] for PKS 1937−1009 and Q1009+2956 represent the mean value, weighted by the total H column density in each component: −2.26 and −2.53, respectively. The D/H value for the LISM is from Linsky (1998), and the LISM [Si/H] is from Savage & Sembach (1990).
the elemental abundances may have been determined by relatively few stars. This will allow more stochastic variation in the D/H at a specific metal abundance, but it will not change the general expectation that D/H will remain near the primordial value as long as the metal abundances are low.

9. NEW VALUES FOR THE RELEVANT COSMOLOGICAL PARAMETERS

We take the weighted mean of the D/H values from three QSOs, PKS 1937−1009, Q1009+2956, and HS 0105+1619, as our best estimate for the primordial D/H ratio. We include all three QSOs because we believe that the dispersion in these D/H values is dominated by systematic errors. We weight by the quoted errors, which we believe indicate the relative sizes of the random errors. For the error on the best value of D/H we take the dispersion in the three values, divided by $3^{1/2}$. We do not use the error on the weighted mean, which is unrealistically small, because the dispersion on the values is larger than expected. We then estimate log $(D/H) = -4.52 \pm 0.06$ (15% error), or $D/H = 3.0 \pm 0.4 \times 10^{-5}$. This new D/H value, together with over 50 yr of theoretical work and laboratory measurements of reaction rates, leads to the following values for cosmological parameters (Esposito et al. 2000a, 2000b; Burles, Nollett, & Turner 2001b): $\eta = 5.6 \pm 0.5 \times 10^{-10}$ (from standard BBN and D/H), $\Omega_0 h^2 = 0.0205 \pm 0.0018$ (baryon density, in units of the critical density, 9% error), $Y_p = 0.2471 \pm 0.0009$ (predicted mass fraction of $^4$He, from SBBN and D/H), $^3$He/H = 1.09 $\pm 0.06 \times 10^{-5}$ (predicted from SBBN and D/H), and $^7$Li/H = $3.8^{+1.0}_{-0.8} \times 10^{-10}$ (predicted from SBBN and D/H), where the error on $Y_p$ includes the error from D/H (0.0008) and from the calculation of $Y_p$ for a given $\eta$ (0.0004) (Lopez & Turner 1999).

These values are generally consistent with most other measurements (Tytler et al. 2000; Burles, Nollett, & Turner 2001a; Olive, Steigman, & Walker 2000). For example, Pagel (2000) reviews $Y_p$ measurements and concludes that “systematic errors up to about 0.005 are still not excluded” and that “$Y_p$ is very probably between 0.24 and 0.25.” Of special note are $^7$Li and the cosmic microwave background (CMB) estimate of $\Omega_b h^2$.

The predicted value for the $^7$Li/H abundance is a factor of 2–5 times higher than measured in halo stars (Bonifacio & Molaro 1997; Ryan, Norris, & Beers 1999). Models allow at most a factor of 2 destruction of the $^7$Li in these stars (Ryan et al. 1999, 2000; Deliyannis & Ryan 2000; Tytler et al. 2000).

Recent measurements of $\Omega_b h^2$ from the CMB are in agreement with our value from D/H and SBBN. Compared to our more accurate $\Omega_b h^2$ value, the value from BOOMERANG ($\Omega_b h^2 = 0.031 \pm 0.004$; Lange et al. 2001) is approximately 3 $\sigma$ higher, that from MAXIMA-I ($\Omega_b h^2 = 0.025 \pm 0.010$; Balbi et al. 2000) is 0.5 $\sigma$ higher, and that from the Cosmic Background Imager ($\Omega_b h^2 = 0.009$; Padin et al. 2001) is just over 1 $\sigma$ lower. The agreement of these $\Omega_b h^2$ values is a dramatic validation of the physics used in SBBN and CMB.

10. SUMMARY AND DISCUSSION

We have presented the fourth quasar, HS 0105+1619, which shows an absorption system having a low deuterium to hydrogen abundance ratio: D/H = $2.54 \pm 0.23 \times 10^{-5}$ in the $z = 2.536$ Lyman limit absorption system. We first obtained low-resolution spectra in our survey for D/H QSOs with the Lick 3 m Shane telescope, and here we presented over 24 hr of spectra from the HIRES spectrograph on the Keck-I telescope.

The absorber has a high neutral hydrogen column density, log $N_{H_1} = 19.422 \pm 0.009$ cm$^{-2}$, which is 36 times larger than the next highest case studied for D/H, but 8–100 times less than standard damped Ly$\alpha$ systems. Very little is known about absorbers with log $N_{H_1} \simeq 19$ cm$^{-2}$, and this absorber may not be representative of this class because it was selected to have a very simple velocity structure and low b values.

While the absorber toward the object has by far the highest neutral H I column density of the absorbers that we have studied for D/H, it also has the lowest total hydrogen column density, by a factor of 4–7, when we correct for the ionization.

We know little about the environment around the absorber. It might be in the outer parts of a galaxy, as are LLNs at low redshift, or in a disk, as are damped Ly$\alpha$ absorbers at high redshift. Alternatively, it may be in a relatively isolated gas cloud because we see just one component, with an exceptionally small spread of velocities. In either case, numerical simulations of the growth of structure suggest that the absorbing gas has been incorporated into a galaxy by today.

For the first time, we detect deuterium absorption in five Lyman series transitions and determine log $N_{D_1} = 14.826 \pm 0.039$ cm$^{-2}$. We have strong arguments that the observed absorption is indeed deuterium and not interloping hydrogen or metal line absorption. We observe a number of associated metal line absorbers, from which we calculate that the gas is warm and neutral. The metallicity of the system is $\approx 0.01$ times solar, indicating that the measured D/H is representative of primordial D/H. We argue that HS 0105+1619 offers the most secure detection of D/H to date and that the D/H ratio determined from all QSOs has been made more secure.

10.1. HS 0105+1619 Gives the Most Secure Measurement of Primordial D/H

The measurement of primordial D/H toward HS 0105+1619 is more secure than our prior measurements toward PKS 1937−1009, Q1009+2956, and Q0130−4021 for several reasons. By “secure” we mean that we have the most information, and hence there is less chance of undetected errors that might greatly exceed those quoted. We are not explicitly referring to the size of the quoted errors, which are similar for PKS 1937−1009 and HS 0105+1619 and larger for Q1009+2956.

The absorption system in HS 0105+1619 is simple. Like Q0130−4021, the second most secure result, the absorber in HS 0105+1619 is modeled with a single component, which simplifies the measurement of the column densities. PKS 1937−1009 was modeled with two or three components, and Q1009+2956 with two to four. HS 0105+1619 is the only case to show more than one strong deuterium line, which reduces the chance of contamination and gives more reliable b values and hence $N_{b_1}$.

For HS 0105+1619 we listed above the many reasons why the absorption near the deuterium line position is deuterium. The chance of serious contamination from the Ly$\alpha$ forest will decrease with rising $N_{b_1}$. Such contamination is least likely to be significant in HS 0105+1619, followed by
PKS 1937—1009. There is some contamination in Q1009 + 2956, while for Q0130—4021 we see a lot of contamination and obtain only an upper limit on \( N_{\text{D}} \). We do not know whether the chance of contamination by components of the LLS changes with \( N_{\text{H}} \). We also expect that the chance of contamination decreases as the \( b \) value of the deuterium decreases because H lines often have larger \( b \) values. Hence, HS 0105 + 1619 is the most secure detection of deuterium.

For HS 0105 + 1619 we have the most information on the velocity field and \( b \) values because we see several D I, N I, and O I lines. For HS 0105 + 1619 the metal abundance is obtained with additional redundancy. The gas is nearly neutral, and hence we get the abundances of several elements: H, C, N, O, Al, Fe, and Si. For PKS 1937—1009 and Q1009 + 2956 we used a standard photoionization model to find the level of ionization that explained the relative abundances of ions such as C II, C III, C IV and Si II, Si III, Si IV. We obtained a solution for each element, and these agreed, which provided a check. For Q0130—4021 the ionization and metal abundances are both less well known.

10.2. The Primordial D/H Becomes More Secure

The new measurement makes the primordial D/H much more secure because in each case we are sampling gas with different physical conditions, and some systematic errors, including those associated with the measurement of column densities, may be different for each QSO. First, the new measurement is the most secure. Second, we have increased the number of QSOs in which we have measured deuterium from two to three. Third, we sample a new region of space. Each absorber is a different direction in the universe, and each samples a sight line of about 1–10 kpc, which requires about \( 10^{7–10} \ M_\odot \) of gas. Fourth, the absorbing gas covers a factor of 240 range in \( N_{\text{H}} \). Fifth, the absorption systems have differing ionization, with a range of 2000 in the H I/H II ratio. There is less variation in other parameters. The metal abundances cover a factor of 10, which is typical for QSO absorption-line systems, while the redshifts cover most of the range observable from the ground.

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