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THE DEUTERIUM-TO-HYDROGEN ABUNDANCE RATIO TOWARD THE QSO SDSS J155810.16−003120.0[1]

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ABSTRACT

We present a measurement of the D/H abundance ratio in a metal-poor damped Lyα (DLA) system along the sight line of QSO SDSS 1558−0031. The DLA system is at redshift $z = 2.70262$ and has a neutral column density of $\log N_{\rm H\,I} = 20.67 \pm 0.05$ cm^{-2} and a gas-phase metallicity [O/H] $= -1.49$, which indicates that deuterium astration is negligible. Deuterium absorption is observed in multiple Lyman series with a column density of $\log N_{\rm D\,I} = 16.19 \pm 0.04$ cm^{-2}, best constrained by the deuterium Ly11 line. We measure $\log$ D/H $= -4.48 \pm 0.06$, which when combined with previous measurements along QSO sight lines gives a best estimate of $\log$ D/H $= -4.55 \pm 0.04$, where the 1 σ error estimate comes from a jackknife analysis of the weighted means. Using the framework of standard big bang nucleosynthesis, this value of D/H translates into a baryon density of $\Omega_b h^2 = 0.0213 \pm 0.0013 \pm 0.0004$, where the error terms represent the 1 σ errors from D/H and the uncertainties in the nuclear reaction rates, respectively. Combining our new measurement with previous measurements of D/H, we no longer find compelling evidence for a trend of D/H with $N_{\rm H\,I}$.

Subject headings: cosmology: observations — quasars: absorption lines — quasars: individual (SDSS J155810.16−003120.0)

Online material: color figure, machine-readable table

1. INTRODUCTION

For the last decade, measurements of the primordial D/H ratio in QSO sight lines have provided increasingly more precise constraints on the cosmological baryon density. Although the measurement of D/H is simple in principle, compared to the other light elements produced during big bang nucleosynthesis, finding those QSO absorption lines systems which are suitable for measuring D/H has proven observationally challenging (Tytler et al. 2000).

For a QSO absorption system to show D/H, a number of criteria must be met (see Kirkman et al. 2003, hereafter K03, for a more detailed discussion). First, the hydrogen column density must be large enough (since D/H is of the order of one part in 10^5) that deuterium can be observed using modern high-resolution spectrographs. Second, the velocity structure of the hydrogen absorption must be simple enough, ideally a single component of gas, that the deuterium absorption is well resolved given the small 82 km s^{-1} offset from the hydrogen Lyman lines. Third, there can be little to no interloping Lyα forest or metal lines at the position of the deuterium absorption, since such absorption strongly complicates attempts to constrain the deuterium column density. Unfortunately, Lyα forest absorption is both ubiquitous and stochastic in high-redshift QSO spectra. Finally, the background QSO must be bright enough to obtain high signal-to-noise, high-resolution spectroscopy at $\lambda < 4000$ Å with a reasonable allotment of telescope time. Each one of these criteria act to decrease the probability that a D/H measurement can be made toward any given QSO, and since *all* the criteria must be met, the resultant probability of a QSO sight line being suitable for measuring D/H is very low, with only approximately 1% of QSOs at $z \simeq 3$ able to provide a measurement of D/H.

To date, there are few measurements of D/H in QSO spectra (Burles & Tytler 1998a, 1998b; O'Meara et al. 2001; Pettini & Bowen 2001; K03; Levshakov et al. 2002; Crighton et al. 2004). These measurements constrain the baryon density $\Omega_b h^2$ through the framework of standard big bang nucleosynthesis (SBBN), which predicts the abundances of the light elements as a function of the baryon-to-photon ratio η and the expansion rate of the universe (Kolb & Turner 1990), and through the cosmic microwave background (CMB) radiation, which provides the photon density. A measurement of the ratio of any of the light nuclei produced in SBBN gives the baryon density, and measurement of additional abundance ratios tests the theory (see Steigman [2006], Pettini [2006], and references therein for a current census of D/H and the other light-element abundances).

Recent measurements of the temperature angular power spectrum of the CMB (Spergel et al. 2006) also provide a measurement of $\Omega_b h^2$ depending on the assumptions made, with a level of accuracy roughly equal to or greater than that provided by D/H. Nevertheless, measurements of D/H are still important for a number of reasons. First, primordial D/H probes the universe at one of the earliest times accessible with current observational and theoretical techniques. Second, the light element abundances predicted from SBBN do not all agree with each other; most notably the observationally inferred abundance of ^{7}Li is significantly lower than that expected from SBBN and D/H (Fields & Sarkar 2006). Third, D/H can help constrain deviations from SBBN, such as inhomogeneous BBN (e.g., Lara et al. 2006), relic primordial particle decays (e.g., Jedamzik 2004), or nonstandard neutrino physics (e.g., Abazajian et al. 2005). Fourth, the dispersion in the measurements

[1] This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.

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of D/H is larger than would be expected from the individual measurement errors (K03); i.e., the data demand both a better understanding of the errors on the current measurements and a better understanding of the new constraints. Fifth, the value of Ω_b derived from D/H and SBBN requires many fewer priors than the CMB-derived value. Moreover, the Ω_b from D/H can be used in principle as a prior in the CMB analysis, and the ratio of the values for Ω_b from D/H and the CMB offer a precision test of the hot big bang model. Finally, the existing measurements of D/H show evidence of a trend of decreasing D/H with increasing $N_{\rm H\,I}$. K03 suggested that this trend (and the dispersion in D/H values) is due to error underestimation.

Fortunately, the Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2006), by virtue of its large sample of high-redshift QSO spectra (the Data Release 4 alone contains 5036 QSOs with $z > 2.7$) gives us a new data set to find those special sight lines that can show D/H. In this Letter, we present a new measurement of D/H in a QSO sight line from the SDSS, SDSS 1558−0031, which was chosen as part of our high-resolution survey for Lyman limit absorption (O'Meara et al. 2006).

2. OBSERVATIONS

We have obtained two high-resolution spectra of the $z = 2.83$ quasar SDSS 1558−0031 using two different spectrographs, the MIKE (Bernstein et al. 2003) echelle spectrograph on the 6.5 m Magellan Clay telescope at Las Campanas, and the upgraded HIRES (Vogt et al. 1994) spectrometer on the 10 m Keck I telescope on Mauna Kea. The MIKE spectrum was obtained as part of our ongoing high-resolution survey for Lyman limit absorption and was selected from the SDSS because of the redshift and brightness of the QSO. The MIKE spectrum was obtained on 2004 May 10 and covers the spectral range 3221–7420 Å, with an exposure time of 3600 s. The data were obtained in subarcsecond seeing with a 1″ slit, which provides resolutions of $R = 28{,}000$ and $R = 22{,}000$ on the blue and red arms of the spectrograph, respectively. The MIKE data were reduced using the MIKE reduction pipeline,[7] and have a signal-to-noise ratio of approximately 12 at $\lambda = 4000$ Å.

The HIRES spectrum was taken on 2006 April 11 and covers the spectral range 3338–6200 Å, with an exposure time of 4100 s. The data were taken in subarcsecond seeing with a 1.″148 slit, which provides a resolution of $R = 34{,}000$. The data were reduced using the HIRES reduction pipeline[8] and have a signal-to-noise ratio of approximately 20 at $\lambda = 4000$ Å. The HIRES data are the primary source for the measurement of D/H presented below owing to the higher signal-to-noise ratio and spectral resolution. With the exception of the H I Lyα line, we used the HIRES spectrum to determine all values for column densities presented in the text. Because we were more successful at fluxing data from the MIKE spectrometer, we use the flux-calibrated MIKE spectrum to constrain the $N_{\rm H\,I}$ value in the Lyα line, whose profile spans several echelle orders.

[7] See http://web.mit.edu/~burles/www/MIKE.
[8] See http://www.ucolick.org/~xavier/HIRedux/index.html.

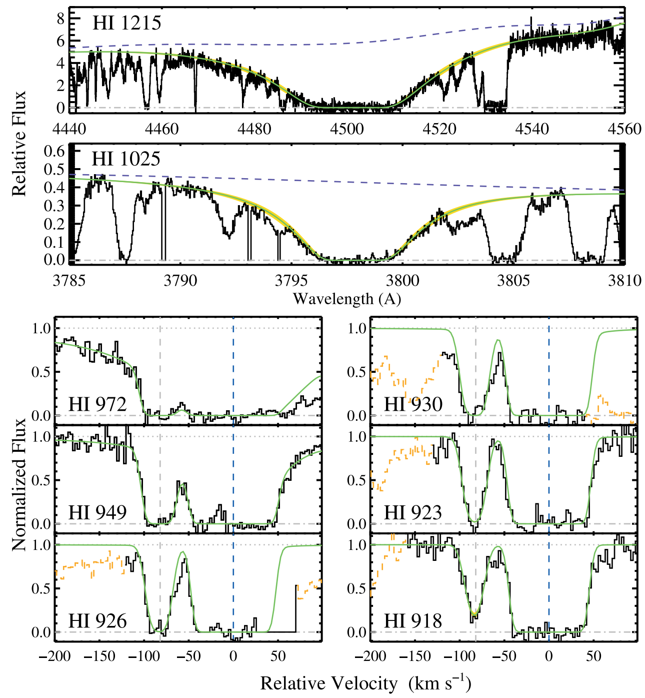

FIG. 1.—H I and D I Lyman series absorption in the $z = 2.70262$ DLA toward SDSS 1558−0031. The Lyα transition (*top panel*) comes from our MIKE spectrum of SDSS 1558−0031, and the remaining panels come from our HIRES data. For the Lyα and Lyβ transitions, we present unnormalized data, along with a dashed line that shows our estimate for the local continuum level. The remaining Lyman series transitions are shown continuum normalized. The solid green line shows the best single-component fit to the D I and H I absorption. We derive our estimates of the $N_{\rm H\,I}$ from the damping wings present in Lyα–Lyδ, and the $N_{\rm D\,I}$ from the unsaturated D I Ly11 transition (~918 Å rest wavelength).

3. ANALYSIS

Inspection of the MIKE spectrum of SDSS 1558−0031 shows that there is a DLA at $z = 2.70262$ that is also responsible for the break in flux from the Lyman limit of the absorber at $\lambda \approx 3885$ Å. The parameters that describe the observed, single component of absorption (N, b, z) for the Lyman series and metal lines in the DLA are presented in Table 1. The

TABLE 1
IONS OBSERVED IN THE $z = 2.70262$ DLA TOWARD SDSS 1558−0031

Ion	$\log N$[a] (cm^{-2})	b (km s^{-1})	z	[X/H][b]	Transition λ_r (Å)
H I	20.67[c] ± 0.05	13.56 ± 1.00	2.702646 ± 0.000010	...	1215.67, 1025.72, 972.54, 949.74
D I	16.19[c] ± 0.04	10.48 ± 0.78	2.702626 ± 0.000007	...	917.88
C II	>14.43[d]	9.69 ± 0.21	2.702611 ± 0.000003	>−2.63	1334.53, 1036.34

NOTE.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.
[a] Unless stated otherwise, the errors on the column density are from VPFIT alone.
[b] $[X/H] \equiv \log (X/H\,I) - \log (X/H)_\odot$, where we have considered only low-ion transitions and have not adopted ionization or depletion corrections, and the atmospheric solar abundances are from Grevesse et al. (2005).
[c] See text for detailed description of the values and errors for this ion.
[d] Column density measurement from the apparent optical depth method.

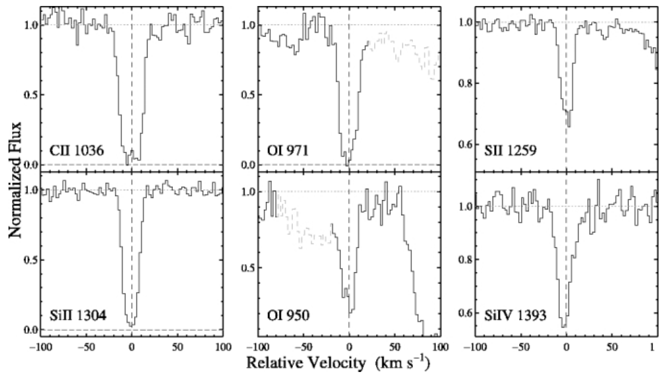

FIG. 2.—Selected metal lines in the DLA toward SDSS 1558−0031. The zero-point velocity corresponds to a redshift of $z = 2.70262$. [*See the electronic edition of the Journal for a color version of this figure.*]

parameters and their errors are derived predominately from Voigt profile fits to the data using the VPFIT routine kindly provided by R. Carswell and J. Webb. For some of the metal-line transitions, we opt instead to use the apparent optical depth technique (Savage & Sembach 1991) to measure the column densities, and then use that column density as a fixed input parameter to VPFIT to determine the z and b values for the absorption in question. The absence of metal-line absorption at the position of D argues that the observed feature in the Lyman series is not interloping H.

The hydrogen column density of the DLA is sufficiently large to show damping wings in the Lyα–Lyγ transitions (Fig. 1). These features allow for a precise measurement of the H I column density. In the case of SDSS 1558−0031 the DLA Lyα lies near the QSO emission line and the assignment of the continuum level over the full extent of the absorption feature is nontrivial. Fortunately, this issue is minimized in two ways. First, the MIKE spectrum is flux calibrated, which allows for an easier assignment of the continuum level to the Lyα line, although it is still subject to unidentified emission features inherent to the QSO. Second, the H I derived from the damping features in the higher order lines is less susceptible to large continuum shape errors, because the profile spans a significantly smaller wavelength range than the Lyα line. In particular, the Lyβ line of the DLA places an excellent constraint on the H I column density, because the line has prominent damping features, covers only ≈35 Å, and has little interloping hydrogen absorption.

To arrive at the best estimate of $N_{\rm H\,I}$ we simultaneously vary the values of $N_{\rm H\,I}$ along with the shape and amplitude of the local continuum level. This variation continues until we arrive at the value of the $N_{\rm H\,I}$ that best reproduces the data while having a reasonable continuum shape. We adopt a redshift and velocity width of the H I, $z = 2.702646 \pm 0.000010$ and $b = 13.56 \pm 1.0$, from a fit to the higher order Lyman series transitions. Of some concern is the fact that the redshift of the H I agrees only at the ≈3 km s^{-1} level with the redshift inferred from low-ion metal lines (Table 1). We note, however, that there exists some degeneracy between b the z for the Lyman series transitions we use, along with the increasing effects of poor signal-to-noise ratios for shorter wavelength data (i.e., higher up the Lyman series). Furthermore, we cannot discount the possibility that the H I gas is multicomponent; however, there is little evidence from the metal-line transitions that this is the case. Furthermore, the Lyman series lines all appear to be well fit using a single component, with a few departures due to interloping H I gas at different redshifts from the system, which shows deuterium. When we consider the Lyα–Lyγ transitions, we arrive at a best estimate of the H I of $\log N_{\rm H\,I} = 20.67 \pm 0.05$ cm^{-2}. The errors on $N_{\rm H\,I}$ are dominated by continuum uncertainties and by signal-to-noise ratios, two effects that are correlated, particularly on smaller wavelength scales.

As can be seen in Figure 1, we observe resolved absorption by deuterium in the Lyman series from Lyγ all the way through to Ly13. Because the D I column density is large, the absorption is saturated until we reach deuterium Ly11, which offers the best constraint on the $N_{\rm D\,I}$ value. For this transition, we measure $\log N_{\rm D\,I} = 16.19 \pm 0.04$ cm^{-2}, where the errors come from the error estimate of VPFIT alone (i.e., independent of continuum error). The transition suffers from mild contamination by interloping hydrogen on ≈25 km s^{-1} to the red side of the absorption profile, but this absorption has little effect on the $N_{\rm D\,I}$ value. Fits to the data including and excluding a model for the interloping hydrogen improve the χ^2 for the fit without changing the value or uncertainty in the $N_{\rm D\,I}$ value. We have also estimated $N_{\rm D\,I}$ using the AODM technique and arrived at a consistent value $\log N_{\rm D\,I} = 16.20 \pm 0.04$ cm^{-2}. The optical depth of this absorption feature is ideal for measuring a column density because it is highly insensitive to the local continuum level placement. If we vary the amplitude of the continuum level by as much as 20% about the adopted value the central value, $N_{\rm D\,I}$ changes by less than the statistical error. The $N_{\rm D\,I}$ value is further constrained by other Lyman series lines; e.g., the depth of the deuterium Ly8 transition rules out significantly larger or smaller values of $N_{\rm D\,I}$.

We obtain a value of $z = 2.702626 \pm 0.000007$ for the deuterium absorption, consistent with that of the H I and other metals. We measure a velocity width of $b = 10.48 \pm 0.78$ km s^{-1} for the deuterium absorption. Neutral hydrogen gas with $\log N_{\rm H\,I} \simeq 16.2$ cm^{-2} is not expected to have such a narrow

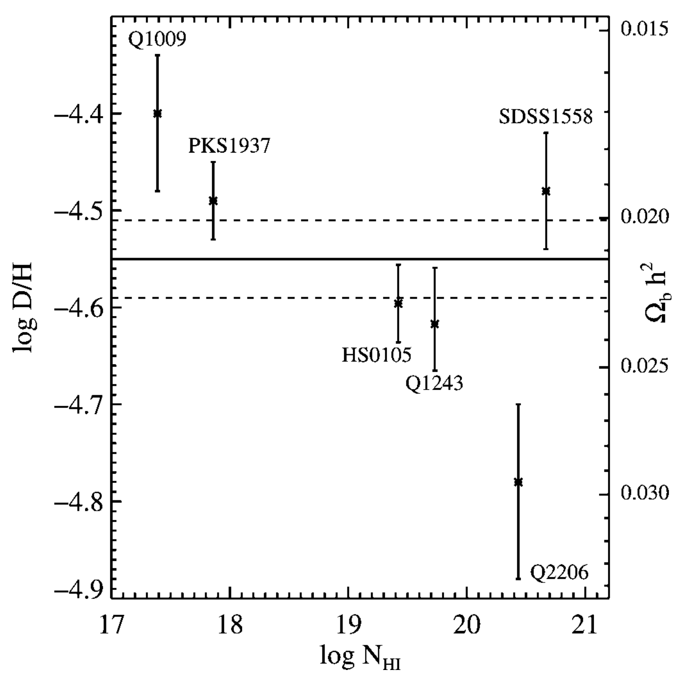

FIG. 3.—Values of the D/H ratio vs. $\log N_{\rm H\,I}$. With the new value for D/H from SDSS 1558−0031, a linear trend of D/H with $N_{\rm H\,I}$ is no longer statistically significant nor a good description of the data. The horizontal lines represent the weighted mean and jackknife errors of the six measurements, $\log {\rm D/H} = -4.55 \pm 0.04$. The right-hand axis shows how the values of D/H translate into values for $\Omega_b h^2$ using SBBN.

Doppler parameter (Kirkman & Tytler 1997), whereas the value is reasonable for D.

We detect over 30 metal-line transitions in the DLA absorber. A subset of these are summarized in Table 1 and are shown in Figure 2. In particular, we note the presence of O I absorption at $z = 2.702610 \pm 0.000005$, which is well described by a single component. O I absorption is important for measuring D/H in that O I directly traces the H I gas (see O'Meara et al. 2001), and because O I/H I ≈ O/H in most environments (especially DLA). Adopting the measured value of $\log N_{\rm O\,I} = 15.86$, we establish a metallicity of [O/H] = −1.49 for the absorber assuming the solar (atmospheric) oxygen abundance reported by Grevesse et al. (2005). This metallicity is higher than all the other extragalactic measurements of D/H. Nevertheless, a 3% solar metallicity implies minimal astration of D and we believe this system is still representative of primordial gas (see Fig. 20 of K03 and Romano et al. 2006). Finally, we note that the velocity structure of the absorber, as traced by the metal lines, is among the simplest yet observed for a DLA (Prochaska & Wolfe 2001).

4. DISCUSSION

We now discuss the value of D/H we obtain for the absorber and place it within the context of the combined D/H ratio for all QSO absorption systems. The best estimates of the H I and D I column densities in the DLA toward SDSS 1558−0031 imply a value of $\log {\rm D/H} = -4.48 \pm 0.06$. The errors on D/H stem primarily from the effect of continuum placement uncertainty on the H I column density, and the signal-to-noise ratio of the data at Ly11, where the D I column density is best constrained.

Turning now to the combined D/H value from QSO sight lines, Figure 3 shows the new value of D/H from SDSS 1558−0031 along with the previous values of D/H taken from the sample discussed in K03. We do not include the result of Crighton et al. (2004), since we feel that the errors on D/H in this system have been underestimated, particularly for the reported $N_{\rm H\,I}$ value. We do not include the results of Levshakov et al. (2002) for the reasons given in K03. The horizontal solid line shows the value for the weighted mean of the data $\log {\rm D/H} = -4.54581 \pm 0.03606$, which we round to $\log {\rm D/H} = -4.55 \pm 0.04$ to keep consistent with the literature, and the dashed lines show the $\pm 1\ \sigma$ uncertainties estimated from a jackknife analysis of the weighted means. In the case of asymmetric errors on individual D/H measurements, we have adopted the larger of the errors for the calculation of the weighting.

Prior to the addition of SDSS 1558−0031 to the sample of D/H measurements of K03, a χ^2-minimizing linear fit to the data of the form $\log {\rm D/H} = -2.914 \pm 0.467 - (0.087 \pm 0.025) \log N_{\rm H\,I}$ provided an acceptable fit to the data ($P_{(\chi^2>\chi^2_{\rm fit})} = 0.74$). With the inclusion of SDSS 1558−0031, however, we see a significant decrease in the likelihood that there is a D/H trend with $N_{\rm H\,I}$. Although the data are best fit with a nonzero slope, $\log {\rm D/H} = -3.707 \pm 0.385 - (0.044 \pm 0.021) \log N_{\rm H\,I}$, the slope differs from zero at only the 2 σ level (even before accounting for the presence of $N_{\rm H\,I}$ in both axes). Furthermore, this is not a good model of the data, with $P_{(\chi^2>\chi^2_{\rm fit})} = 0.04$. As such, the data give little confidence to the existence of a trend of D/H with $N_{\rm H\,I}$. Finally, if we were to include the Crighton et al. (2004) and Levshakov et al. (2002) results, the likelihood that D/H depends on $N_{\rm H\,I}$ is further diminished.

The presumption of a single value for D/H, however, is still not supported by the observations; the observed scatter exceeds that expected assuming the error estimates reported in the literature. Our adopted error on the best estimate for D/H from the jackknife estimation exceeds the error on the weighted mean by a factor of 2. Likewise, the χ^2 of the six measurements of D/H about the weighted mean value of $\log {\rm D/H} = -4.55 \pm 0.04$ is high, with $P_{(\chi^2>\chi^2_{\rm D/H})} = 0.01$. Although there is the possibility that the scatter in the individual D/H measurements is real, we prefer the hypothesis of K03 that the errors in some of the individual measurements, if not all of them, are underestimated. It is likely that a combination of new methods of error analysis and new QSO sight lines is required to fully address the excess scatter in the D/H measurements.

Using the framework from SBBN (Burles et al. 2001), the value for D/H of $\log {\rm D/H} = -4.55 \pm 0.04$ translates to a value for the cosmological baryon density of $\Omega_b h^2 = 0.0213 \pm 0.0013 \pm 0.0004$, where the first error term comes from the errors on D/H explained above, and the second term from the uncertainties in the nuclear reaction rates. By comparison, the *WMAP* 3 year result provides an estimate of $\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$, which lies within the 1 σ error estimate on $\Omega_b h^2$ from D/H (Spergel et al. 2006).

Finally, we note that the absorber showing D/H in the spectrum of SDSS 1558−0031 was discovered serendipitously as part of our survey for Lyman limit absorption, and is the first D/H measurement from a QSO first discovered by the SDSS. The SDSS Data Release 3 alone has 405 DLAs with redshifts optimal for D/H ($2.51 \leq z \leq 4.0$; Prochaska et al. 2005). Assuming that a small fraction of these DLAs provide measurements of D/H, the SDSS will give many tens of measurements. The situation improves further if one considers the Lyman limit systems toward the SDSS QSO sample. This contrasts with the super–Lyman limit systems (SLLSs) and DLAs that give the $N_{\rm H\,I}$ from the Lyα and Lyβ lines, and the $N_{\rm D\,I}$ from the unsaturated D I lines in the Lyman series. Because of this effect, the DLAs and SLLSs offer more path length per QSO to potentially find D/H. All of these effects combine to give a likely distribution of D/H measurements that is roughly independent of $N_{\rm H\,I}$, a hypothesis that is already being hinted at in the current sample, since two measurements come from LLSs, two from SLLSs, and two from DLAs. Altogether, the SDSS offers the best opportunity for investigating the larger than expected scatter in D/H and correlations with $N_{\rm H\,I}$, metallicity, etc.

The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. We thank M. Pettini, G. Steigman, and the referee, P. Molaro, for insightful questions and comments that improved this Letter. G. E. P. and J. X. P. are supported by NSF grant AST 03-07408. J. O. and S. B. acknowledge support from NSF grant AST 03-07705.

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