A High Deuterium Abundance at z=0.7

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Of the light elements, the primordial abundance of deuterium, (D/H)p, provides the most sensitive diagnostic1 for the cosmological mass density parameter ΩB. Recent high redshift D/H measurements are highly discrepant2,3,4,5,6, although this may reflect observational uncertainties7,8. The larger D/H values, which imply a low ΩB and require the Universe to be dominated by non-baryonic matter (dynamical studies indicate a higher total density parameter), cause problems for galactic chemical evolution models since they have difficulty in reproducing the large decline down to the lower present-day D/H. Conversely, low D/H values imply an ΩB greater than derived from 7Li and 4He abundance measurements, and may require a deuterium abundance evolution that is too low to easily explain. Here we report the first measurement at intermediate redshift, where the observational difficulties are smaller, of a gas cloud with ideal characteristics for this experiment. Our analysis of the z = 0.7010 absorber toward 1718+4807 indicates D/H = 2.0 ± 0.5 × 10−4 which is in the high range. This and other independent observations suggests there may be a cosmological inhomogeneity in (D/H)p of at least a factor of ten.

Measurements can be achieved using absorption line spectroscopy of gas clouds intersecting the sight-lines to distant, background quasars by measuring the strengths of the absorption lines of the H I and D I Lyman series. The D I transitions occur at an isotopic shift of −81 km s−1 with respect to the H I series. Such a measurement is observationally difficult for a number of reasons9,10: (1) ill-placed H I Lyα-forest absorption lines can masquerade as deuterium and (2) most QSO absorption
systems exhibit complex internal velocity structure, which may render parameter estimation for individual components of interest unreliable or impossible. To overcome the first difficulty, we searched for suitable absorbers at intermediate redshifts (i.e. at $z < 1$), where the number density of Lyα-forest systems is far lower than at high redshifts. To overcome the second difficulty, we searched for suitable absorbers with apparently simple velocity structure. We found one object which appears optimal for a D/H analysis; only one absorbing component is revealed by the data and the velocity dispersion in that component is small enough to easily detect and accurately measure the deuterium abundance.

The absorber at redshift $z = 0.7010$ toward the QSO 1718+4807 ($z_{\text{em}} = 1.084$, $m_V = 15.3$) was selected on the basis of a remarkably abrupt partial Lyman-limit discontinuity in the International Ultraviolet Explorer (IUE) spectrum. The extreme sharpness of the Lyman break clearly indicates simple velocity structure and low velocity dispersion parameter. This simple velocity structure contrasts with the complex nature of the higher redshift systems reported so far, both those which give low D/H measurements and those which give high values so the measured column densities (based on Lyα and the Lyman limit alone) are likely to be more reliable than in those cases. Hubble Space Telescope (HST) spectra were obtained of the spectral region covering the Lyman-α and Si III transitions using the Goddard High Resolution Spectrograph and the G270M grating. All spectra were extracted, binned to linear wavelength scales and corrected to vacuum, heliocentric wavelengths using standard procedures. Absorption-line parameter estimates were derived using VPFIT, a computer program based on Gauss-Newton unconstrained optimisation. Parameter errors were derived from the diagonal terms of the parameter covariance matrix computed at the best fit.

The D/H we derive from the combined data is $D/H = 2.0 \pm 0.5 \times 10^{-4}$ which is approximately an order of magnitude larger than recent ground–based measurements of high-redshift absorbers (although the reliability of these measurements is presently a matter of debate) and an order of magnitude larger than a recent intermediate redshift measurement at $z=0.5$. It is of course possible that our high value is caused by a weak H I line which just happens to fall very close to the D I wavelength. Unfortunately, a posteriori statistics do not provide a reliable means of assessing the probability of this because the absorption cloud we have studied was specifically selected as having uniquely simple velocity structure, a property which itself implies a low probability of an H I interloper successfully mimicking D I. We note however that the probability of a randomly placed interloper mimicking deuterium is extremely small; using the observed number density of absorbers in the spectrum and adopting a generous 4-sigma tolerance on the line position, it is less than 1 percent.

To examine this possibility further, we re-fitted the data replacing D I with H I (so that the redshift of the putative interloper was a free parameter). The best fit resulted in the new H I line falling at $-86 \pm 5$ km s$^{-1}$ from the strong component, implying that the detected absorption feature is deuterium and not an interloper. Furthermore, the Doppler parameter of this putative H I interloper ($b = 21 \pm 4$ km s$^{-1}$) lies between that of the strong H I component but greater than
the Si III value, which is again consistent with the expectation for D I. Taken together, these points indicate that the most reasonable and likely interpretation of the data is that we have detected D I.

A further possibility is that some other transition from an absorbing cloud at some other redshift just happens to coincide with the D I wavelength at z_{abs} = 0.701024. The closest candidate is ISM Cr II λ2066.16. The D I feature falls at 2067.31 Å. This corresponds to a shift of \sim 170 \text{ km s}^{-1}, thus so Cr II λ2066.16 is not a serious contender for D I contamination. Furthermore, Cr II λ2056 is not observed and yet has an oscillator strength 2 times higher than Cr II λ2066.16. We conclude that no Cr II contamination occurs.

We cannot reliably estimate the heavy element abundances of the z_{abs} = 0.701024 system, since the only species in the observed range is Si III (log N(Si III) = 12.81 \pm 0.04 \text{ cm}^{-2}). An upper limit can be derived, but this only constrains the abundances to be less than solar; they could easily be very much lower. We note that it would be astonishing if the z_{abs} = 0.701024 system turned out to have already undergone substantial chemical evolution and yet exhibit such a high D/H. Future observations of any unsaturated absorption lines in this system (potentially Mg II or Fe II, for example) should yield reliable heavy element abundance constraints. Astration (deuterium destruction in stars) means that any particular D/H detection provides a lower limit to the primordial value. Therefore, because our measured D/H is high, the lack of information about the heavy element abundances does not alter the interpretation of the data described below.

In standard models of galactic chemical evolution, the mass fraction of deuterium decreases steadily with time, by a factor \sim 2 – 3 over 10 Gyr, so that when plotted versus metallicity, it appears constant until a metallicity 1/10 solar and drops abruptly thereafter. The two extremes of the recent high redshift D/H observations imply radically different consequences for the baryonic density parameter, \Omega_B, and its cosmological significance. A high (D/H)_p would be in excellent agreement with standard homogeneous BBN and the observed “primordial” abundances of \text{^{4}He} and \text{^{7}Li}, but observations of D/H in the interstellar medium then require destruction of deuterium by a factor \sim 10 up to the present epoch. Whether this much astration can be easily explained by chemical evolution models is unclear, although some recent models may succeed.
such rapid deuterium destruction, but if too low, may still be problematic if the implied astration is too small compared to predictions).

Several explanations have been put forward which could explain discrepant values of the D/H ratio. Post-BBN chemical evolution processes might result in strong deuterium depletion in some gas clouds, giving rise to low observed abundances. By redshifts $z \approx 3 - 4$, stars down to $\sim 2M_\odot$ have had time to eject deuterium-poor gas. However, the observational upper limits on C/H and Si/H in clouds at high redshift where $D/H \sim 2.5 \times 10^{-5}$ imply metal abundances less than $\sim 10^{-2}$ solar, constraining the fraction of gas which has been cycled through stars to be less than about 5%. Such models appear to offer reasonable compatibility with light element abundance observations only by admitting unreasonable stellar populations, such as a primordial population of supermassive stars of mass $M \gtrsim 1000M_\odot$, or an initial mass function strongly peaked around $M \approx 6M_\odot$.

Alternatively, primordial isocurvature baryon fluctuations could account for a variation of the $(D/H)_p$ ratio by a factor $\sim 10$ but only on scales corresponding to a Jeans mass of $M_J \sim 10^5 - 10^6M_\odot$. For a specific class of these models, there are opposing views as to whether or not the observed isotropy of the cosmic microwave background rules out substantial intrinsic D/H fluctuations. We note, however, that homogeneous, critical-density models with a low baryonic component, $\Omega_B < 0.01 h^{-2}$, appear to predict degree–scale microwave background fluctuations which are significantly below those actually observed. Also, assuming no segregation between baryons and dark matter, X-ray observations of galaxy clusters support this point since for critical-density models they independently suggest baryonic density parameters of $\Omega_B > 0.02 h^{-3/2}$. Both of these types of observation therefore appear to be in conflict with a baryonic density parameter for a homogeneous universe as low as that derived from our results for $D/H$ in the $z_{\text{abs}} = 0.701024$ gas cloud reported here. Therefore our results indicate that either the universe does not have a critical total density, or, if it does, Big-Bang nucleosynthesis must have occurred inhomogeneously.

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Fig. 1.— Data and fits for 1718+4807. The top panel illustrates the HST H I and D I profile, showing the model profiles for H I (dotted line), D I (dashed line) and H I+D I (solid line). The middle panel illustrates the HST Si III $\lambda$1206.51 profile and fit. The HST spectrum was observed on 3/3/1995 (total integration time 282 minutes). The spectral resolution is 20,000. The bottom panel illustrates the IUE spectrum and fit. The pixel size is 1.18 Å and the adopted spectral resolution is 2.5 pixels. To minimise the number of free parameters, we adopted a single redshift for H I, D I and Si III lines and the Lyman limit. The parameter constraints arise as follows. The IUE spectrum provides an accurate determination of the H I column density ($\log N$(H I) = 17.24 ± 0.01 cm$^{-2}$). The Si III $\lambda$1206 absorption line supports the single component velocity structure implied by the IUE Lyman limit and determines the cloud redshift precisely ($z_{abs} = 0.701024 \pm 0.000007$). The Ly$\alpha$ absorption is clearly asymmetric, showing additional absorption in the blue wing at the position corresponding to D I. Since Si III accurately constrains the D I position and because the Doppler parameter (which is equal to $\sqrt{2}$ times the RMS velocity dispersion) $b$(D I) is constrained by the overall fit, only one free parameter, $N$(D I), is required to fit the excess absorption seen at the D position. The D I column density is thus accurately determined and is $\log N$(D I) = 13.57 ± 0.06 cm$^{-2}$. The Doppler parameters are dominated by non-thermal broadening with an inferred temperature of $1.9 \times 10^4$ K and $b$(H I) = 25.5 km s$^{-1}$ and $b$(D I) = 22.2 km s$^{-1}$ and $b$(Si III) = 18.7 km s$^{-1}$, with the same error on each of $\sigma = 0.5$ km s$^{-1}$. From the above, we derive D/H = 2.0 ± 0.5 x 10$^{-4}$. 
