A High Deuterium Abundance at z=0.7; Evidence for Cosmic Inhomogeneity?

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Abstract. Recent HST/GHRS observations of the $z = 0.7010$ absorber toward the QSO 1718+4807 (selected because of apparently ideal characteristics for measuring D/H) yield a D/H significantly higher D/H than some recent high-redshift measurements. Our analysis indicates $D/H = 1.8 - 2.5 \times 10^{-4}$. This may indicate a cosmological inhomogeneity in the deuterium abundance of at least a factor of ten.

1 Introduction, target selection and observations

Measuring D/H in QSO absorbers is observationally difficult for a number of reasons: (1) ill-placed H I Ly$\alpha$-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. Here we report results from one object which appears to have the ideal characteristics 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 (by KML) 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. HST observations were obtained in Cycle 4 using the Goddard High Resolution Spectrograph (HRS) and the G270M grating of the spectral region covering the Ly$\alpha$ and Si III absorption lines. The spectra were extracted, binned to linear wavelength scales and corrected to vacuum, heliocentric wavelengths using standard procedures.
2 Parameter estimation

Parameter estimates were derived using VPFIT \cite{12}, an unconstrained optimisation $\chi^2$ minimisation (Gauss-Newton) algorithm. Descent to the minimum in $\chi^2$-parameter space is obtained using first and second derivatives of $\chi^2$ with respect to the free parameters. Reliable parameter error estimates are obtained from the parameter covariance matrix.

When simultaneously fitting several lines in the same QSO absorption system, we are able to ‘tie’ physically related parameters, resulting in a more stringent test of the model being fitted, and tighter constraints on the remaining free parameters. The simplest example is simultaneously fitting a single cloud with D and H. 6 parameters are required to fit as two individual features, but only 4 ($z$, $N$(HI), $N$(DI), $b$(HI)) if physically related parameters are tied; we can constrain the Doppler parameter for deuterium $b$(DI) to lie between $b$(HI) and $b$(HI)/$\sqrt{2}$.

Combining several different datasets of very different spectral resolution and signal-to-noise (as is the case here where IUE and HST data are analysed simultaneously) is straightforward, minimising a single $\chi^2$, where contributions to the overall $\chi^2$ from individual datasets are appropriately weighted.

3 D/H for single cloud model

3.1 Fits to Ly$\alpha$, SiIII, Lyman limit

Although the cloud parameters are determined in the manner above, i.e. by simultaneously fitting all parameters to both data sets, the parameter constraints arise essentially as follows. The IUE spectrum of the partial Lyman limit provides an extremely accurate determination of the H I column density ($\log N$(HI) = 17.24 $\pm$ 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 with respect to the Si III redshift, showing additional absorption in the blue wing at the position corresponding to D I (Figure 1). Since Si III accurately constrains the position of the D I feature and because the Doppler parameter $b$(D I) is constrained by the overall system fit, only one free parameter, $N$(D I), is required to fit the excess absorption seen at the position corresponding to D. The D I column density is thus accurately determined and is $\log N$(D I) = 13.57 $\pm$ 0.06 cm$^{-2}$. The Doppler parameters are dominated by non-thermal broadening with an inferred cloud temperature of $1.9 \times 10^4$ K and Doppler parameters of $b$(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, the measured deuterium abundance lies in the range D/H = $1.8 - 2.5 \times 10^{-4}$. 
3.2 Fits to Lyα and Lyman limit only, excluding Si III

The strongest Si III component in an absorption complex need not align with the strongest H I component. We thus investigate whether the results above are sensitive to the assumption that \( z(\text{Si III}) = z(\text{Ly} \alpha) \) by fitting Lyα and the Lyman limit only. The H I redshift is no longer constrained by that of Si III. A priori one expects a larger error on the remaining column density estimates, plus the D I column density could change if Si III is shifted with respect to H I. The result of doing this is that \( \log N(\text{D I}) = 13.62 \pm 0.06 \text{ cm}^{-2} \), so the measured deuterium abundance lies in the range \( \text{D/H} = 1.8 - 3.1 \times 10^{-4} \).

3.3 Why D/H is unlikely to be low

We can fix \( \text{D/H} = 2.5 \times 10^{-5} \), re-fit allowing all other parameters to vary, and compare the resulting \( \chi^2_{\text{min}} \) with the best fit \( \chi^2_{\text{best}} \) derived with both H I and D I column densities free to vary. The result is a substantially worse fit, with \( \chi^2_{\text{min}} = \chi^2_{\text{best}} + 57 \). The best fit with D/H constrained to be low is illustrated in Figure 2. Note the poor fit to the blue wing of the Lyα feature and how the system redshift has been pushed slightly lower in order to partially compensate for the additional absorption at the D I position (especially noticeable in Si III). In the next section we discuss why D/H is unlikely to be low, even in the presence of a second badly blended absorbing component.
Figure 2: Best fit to GHRS Lyα Si III, and IUE Lyman limit, with D/H constrained to be $2.5 \times 10^{-5}$.

3.4 Why a single cloud model is most appropriate

The simple velocity structure here contrasts with the more complex nature of the higher redshift systems reported so far, both those which give low D/H measurements \[1, 9, 10\] and those which give high values \[3, 6, 7, 8\]. To examine the possibility that a weak H I cloud is present somewhere near the expected position of D I, we re-fitted the data replacing D I with H I. The best fit resulted in the new H I line falling at $-86 \pm 5$ km s$^{-1}$ from the strong component, which agrees with the expectation for D I in both direction and magnitude. 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. Finally, if we assume a random distribution of clouds, the observed line number density suggests a probability of an interloper falling within $\pm 4\sigma$ of the actual position of D I of $\sim 1\%$. Whilst a random distribution will not generally represent the underlying cloud distribution in any complex, we note that this particular absorber was selected specifically on the basis of a sharp Lyman limit. It would therefore be incorrect to estimate the interloper probability on the basis of a cloud-cloud correlation function derived from a larger sample of absorbers, where no such selection had taken place.

We can explore the possibility of multiple structure further, by artificially
inserting additional components and re-fitting. We have done this in two independent ways. First, we pursue the possibility above, i.e. a potentially low D/H, but this time assuming velocity structure is present in the cloud. To do this we model the spectrum with a double cloud where D/H is forced to be the same in each, and re-fit for a range in velocity separation from 5 to 81 km s$^{-1}$. The upper value corresponds to the splitting between D I and H I. For no value of the double cloud separation do we find a value of $\chi^2$ below that for the single cloud. Furthermore, for a separation of less than 30 km s$^{-1}$, the $\chi^2$ lies at over 3$\sigma$ above the single cloud value. Thus a double cloud model appears unable to mimic a high D/H.

To see what the inferred D/H is in the presence of a second cloud, we take an illustrative double cloud separation of 10 km s$^{-1}$, and re-fit allowing all other parameter to vary. In this case, a careful choice of free parameters is essential; the Lyman limit constrains the total N(H I) extremely well, although the two individual N(H I) are very poorly determined. For this reason, the H I column density parameters are the total N(H I) and N(H I) for one of the clouds. Although we maintain the same number of free parameters, this choice results in well determined N(H I) for each cloud. We can also choose whether to force D/H to be the same in each cloud, or allow it to vary. The range of results deduced from both options is D/H = 1.3$ - 3.7 \times 10^{-4}$, so the earlier general conclusion remain unaltered.

Taken together, these points indicate that the most reasonable and likely interpretation of the data is that we have detected D I.

4 Discussion

4.1 A Comment on the reliability of low D/H values

A hotly debated issue during this session concerns the reliability of the low D/H measured towards 1937-1009 [9, 10, 11], the main points being that the inferred D/H could be somewhat larger if N(H I) has been underestimated, either due to errors in establishing the continuum level below the Lyman limit, or if undetected velocity structure is present. Two methods have been discussed addressing the former point: (a) a statistical approach (modeling the statistical Ly$\alpha$ distribution) and (b) a ‘spectrum-specific’ approach (estimating N(H I)’s for each and every cloud in the spectrum which is able to contribute opacity to the relevant regions of the Lyman limit). We merely comment here that although method (a) can in principle estimate the average opacity to arbitrarily high accuracy, fluctuations from one sightline to the next are likely to be large. Method (b) will also be error-prone because for any given ensemble of absorption lines, some clouds will have indeterminable parameters. The most believable approach is to treat the continuum level below the Lyman limit as an additional free parameter.

However, we comment finally that whilst there may be some uncertainty
in the value of D/H estimated towards 1937-1009, it is unlikely to be great enough to change D/H to be as high as the value we derive for 1718+4807.

4.2 Cosmic D/H inhomogeneity?

A ratio $D/H = 2.0 \times 10^{-4}$, as obtained here toward 1718+4807, corresponds to a mass fraction of $^4\text{He} \ Y \approx 0.233 \pm 0.002$, $^7\text{Li}/H \approx 1.8^{+0.7}_{-0.6} \times 10^{-10}$ and $\Omega_B \approx 0.006 \pm 0.003 \ h^{-2}$, where $h$ denotes the value of the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$ and the errors only include 1σ errors on the nuclear cross-sections of BBN. Remarkably, these figures agree precisely with the measured abundances, $Y \approx 0.233 \pm 0.005$ and $^7\text{Li}/H \approx 1.8^{+0.5}_{-0.3} \times 10^{-10}$. The above baryonic mass density parameter may be compared with the measured amount of visible matter in galaxies, $\Omega_{\text{vis}} \sim 0.002-0.005 \ h^{-1}$. This shows that a high primordial deuterium abundance leaves little room for baryonic dark matter and supports the view that the missing mass inferred from dynamical studies must be non-baryonic. On the other hand, a low $(D/H)_p$ implies BBN values of $^4\text{He}$ and $^7\text{Li}/H$ which differ from the measured values by amounts corresponding to 2σ observational limits (although it removes any difficulty in explaining rapid deuterium destruction).

The interpretation above sidesteps the apparently significant difference between our measurement and the low value claimed in reference [9], where $D/H = 2.3 \pm 0.6 \times 10^{-5}$, compared to ours of $D/H = 1.8 - 2.5 \times 10^{-4}$ (1σ) or $D/H = 1.5 - 3.0 \times 10^{-4}$ (2σ). Whilst further observations might correct one or both of these measurements, the most reasonable interpretation of the data at the moment is that the difference is real. We speculate that these observations may be the first to reveal the presence of fluctuations in the baryon-to-photon number at the epoch of big bang nucleosynthesis [2, 4].

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