Uncertainties in the Determination of Primordial D/H
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ABSTRACT

The current status of high redshift D/H measurements is discussed. I first examine whether the observations of HS1937−1009 require a low value of D/H. It is shown that the LRIS measurements of the continuum break and the high resolution Lyman series data can easily be modelled with D/H in the range $5 \times 10^{-5}$ to $10^{-4}$. I then discuss measurements on weaker Lyman limit systems. A statistical treatment of 10 partial Lyman limit systems favors $5 \times 10^{-5} \leq D/H \leq 2 \times 10^{-4}$.

1. Introduction

The advent of the 10 meter telescopes has made possible the important observational search for the value of primordial D/H from high redshift quasar absorption lines (Songaila et al. 1994) which in principle is a sensitive probe of $\Omega_{\text{baryon}}$ and is ultimately a diagnostic of the health of the standard big bang nucleosynthesis (SBBN) picture. Unfortunately, serious underestimates of the systematic difficulties in such measurements have led to overenthusiastic claims of the precision of both high (Rugers & Hogan 1996) and low (Tytler, Fan & Burles 1996) (TFB) values, with interesting repercussions for the theoretical picture, particularly as the original low value of (Tytler, Fan & Burles 1996) would have been seriously incompatible with measurements of $\Omega_{\text{baryon}}$ from the other light elements, notably $^4\text{He}$ (Olive et al. 1997). However, the prospect of an observational incompatibility with SBBN has had the stimulating effect of provoking a scrutiny of the subject, that has for instance cast serious doubt on the $D + ^3\text{He}$ argument and has even provoked the abandoning of the primary dependence of SBBN in determining $\Omega_{\text{baryon}}$ in favor of non-nucleosynthetic constraints on the cosmological parameters (Steigman et al. 1997).

In the long run, what are the prospects for obtaining a believable value for primordial D/H from quasar absorption line measurements and, perhaps more importantly, demonstrating or convincingly ruling out any variability? It is my opinion that only the accumulation of

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measurements from many systems will provide either of these answers. Considerable attention has been paid to the possibility of the chance contamination of the high values (Lytler, Burles & Kirkman 1997) by intervening Lyman forest material, a systematic problem in the use of partial Lyman limit systems, for which reason their use must always be statistical only (Songaila et al. 1994). In section 3 I will discuss my own current sample of observations of 10 PLLS quasars and argue that it favors the range $5 \times 10^{-5} \leq D/H \leq 2 \times 10^{-4}$. However, I will also attempt to show (section 2) that the alternative strategy of using higher column density systems is also ultimately susceptible to yielding (lower) limits only, this despite the best efforts to model the systematic effects (Songaila, Wampler & Cowie 1997) (SWC);Burles & Tytler 1997 (BT)).

Fortunately, some very nice measurements of other systems are beginning to appear (Webb et al. 1997;Vidal-Madjar et al. 1997) as John Webb and Alfred Vidal-Madjar discuss here. However, I would caution that the high D/H value at low redshift is also subject to the large systematic uncertainty from chance contamination by the internal hydrogen structure of the system and that it is perhaps premature to assume from this one measurement that there is variation in D/H among quasar lines of sight.

2. D/H toward HS1937–1009

There has been much controversy surrounding TFB’s low value (Tytler, Fan & Burles 1996) of $D/H = 2.3 \pm 0.3 \pm 0.3 \times 10^{-5}$ from the $z = 3.572$ Lyman limit system toward HS1937–1009, questioning the claimed small systematic errors in view of both the considerable uncertainty in the total H I column density in this system and in the lack of uniqueness of the assumed cloud distribution. Wampler (Wampler 1996) showed that simple cloud models could give D/H as high as $6.3 \times 10^{-5}$ and still be compatible with TFB’s fit. SWC measured the total H I column density from LRIS observations of the Lyman continuum break and even with their most conservative modeling of the continuum they revised the TFB H I value downward to $5.9 \times 10^{17}$ cm$^{-2}$ (Songaila, Wampler & Cowie 1997), outside the TFB published errors (Tytler, Fan & Burles 1996), and with more realistic modeling of the continuum preferred a value of about $5 \times 10^{17}$ cm$^{-2}$. BT subsequently also revised the H I column density downward based on similar low resolution spectroscopy but using a HIRES spectrum to remove the effects of the forest above the break in an LRIS spectrum; in this way they derived a higher value of $7.24 \pm 0.35 \times 10^{17}$ cm$^{-2}$ (Burles & Tytler 1997). This procedure is problematical because, while the forest can be deblended above the break from HIRES data (subject to uncertainties in continuum fitting) it can only be modeled below the break. Unless the models are a perfect representation of the forest there is a substantial
possibility of introducing matching error. The more direct process used by SWC avoids this by simply assuming continuity of the forest properties across the break.

Figure 1 shows a 3.4 hr LRIS spectrum of the quasar HS1937–1009. The spectrum has been smoothed to 50 Å resolution and the effects of the $z = 3.572$ Lyman limit system itself have been divided out for the two values of $N$(H I) = \(8.9 \times 10^{17}\) cm\(^{-2}\) given by TFB (Tytler, Fan & Burles 1996) and of $N$(H I) = \(7.24 \times 10^{17}\) cm\(^{-2}\) given by BT (Burles & Tytler 1997). The solid line shows the power law fit to the quasar spectrum, in the absence of Ly$\alpha$ forest absorption, given by (Zheng et al. 1997). The effect of the forest lines produces the deep decrement between the observed spectrum and the continuum level which is, however, quite smoothly varying at this resolution. Note that the peak at 4900 Å is the O VI emission line. The dashed line marks the continuum edge of the Lyman limit system. The TFB value is completely unphysical, in that it requires negative forest absorption. The BT value is also problematic in that it requires an abrupt drop in the forest opacity just at the position of the continuum edge, suggesting that there is indeed a mismatch between the modeling below the break and the direct deblending of the forest above it. A value of $N$(H I) \(\sim 6 \times 10^{17}\) cm\(^{-2}\) produces a smooth forest opacity above and below the break though, as argued in SWC, even this may be an overestimate of $N$(H I) because the forest opacity is expected to increase at these wavelengths (Songaila, Wampler & Cowie 1997).

However, even if one adopted the upper-bound BT value of $N$(H I) = \(7.59 \times 10^{17}\) cm\(^{-2}\) the classical problems of fitting saturated lines leave a very large uncertainty in deriving the D/H value, as was emphasized by Wampler (Wampler 1996). The original TFB cloud model gives D/H = \(3.0 \times 10^{-5}\) for $N$(H I) = \(7.24 \times 10^{17}\) cm\(^{-2}\) and D/H = \(4.0 \times 10^{-5}\) for $N$(H I) = \(6 \times 10^{17}\) cm\(^{-2}\). The latter value matches SWC’s estimate (Songaila, Wampler & Cowie 1997) of a reasonable minimum D/H ratio in this system. However, in Figure 2 we show a direct comparison of a model with $N$(H I) = \(7.5 \times 10^{17}\) cm\(^{-2}\) and D/H = \(5 \times 10^{-5}\) with the original TFB model having $N$(H I) = \(8.9 \times 10^{17}\) cm\(^{-2}\). The new model actually gives a formally better fit to a new set of HIRES observations of the quasar, but within the systematic errors both are probably adequate descriptions. With a lower, and as we have argued above, more realistic value of $N$(H I) a D/H near \(10^{-4}\) can also be accommodated, as shown in the second set of panels. The fundamental result here is simply the difficulty in fitting the saturated lines in strong Lyman limit systems and the corresponding uncertainties in determining D/H in such systems. However, it should be noted that a 2 $\sigma$ upper bound of D/H \(\leq 3 \times 10^{-5}\), required for consistency with $\eta_{10} \geq 6$ derived from non-BBN constraints (Steigman et al. 1997), would be difficult to accommodate with any proposed current value of $N$(H I).
3. Partial Lyman Limit Systems

The use of weaker Lyman limit systems avoids many of these problems because the high order Lyman series lines desaturate, which permits a direct and unambiguous measurement of the hydrogen kinematic structure. However, because of the lower $N(\text{H I})$ the D is weaker and more susceptible to chance contamination by floating H I lines. Such contamination may be either from random forest lines or from the internal kinematic structure of the Lyman limit system itself. The latter contamination is harder to deal with and persists even in low redshift objects.

In order to approach this problem in a robust way I have used my current sample of HIRES observations of ten quasars with Lyman limit systems having $5 \times 10^{16} \leq N(\text{H I}) \leq 5 \times 10^{17} \text{ cm}^{-2}$. In each case I established the kinematic structure of the H I and then determined how much D I could be present at both the true position and also at a position at $+82 \text{ km s}^{-1}$ which should, on grounds of symmetry, be on average indistinguishable from the D position if there were no significant deuterium present.

The upper limits on the D/H and false D/H ratios were calculated under both turbulent broadening and thermal broadening assumptions and are shown in Figure 3 for the more constraining thermal broadening case. Four of the ten systems have relatively weak absorption at the false red position, but in only one case is $D/H < 1.4 \times 10^{-4}$ obtained at the true position. (This rises to $2 \times 10^{-4}$ for turbulent broadening.) A rank sum test shows that the two distributions are inconsistent at the 95% confidence level, which is a rather marginal result, but does favor having $D/H > 5 \times 10^{-5}$ to bring the two sides into consistency. Together with the measured upper bounds this would give $5 \times 10^{-5} < D/H < 1.4 \times 10^{-4}$ for thermal broadening.

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Fig. 1.— The effect of different assumed values of neutral hydrogen column density on the Lyman continuum break region of the spectrum of HS1937–1009 with the effect of the Lyman limit system divided out. See text for details.
Fig. 2.— Comparison between the cloud model of TFB (dashed line) and (upper panels) one with $D/H = 5.2 \times 10^{-5}$ for the 1 $\sigma$ upper bound on the H I column density of $7.59 \times 10^{17}$ cm$^{-2}$ claimed in Burles & Tytler; and (lower panels) for a model with $N$(H I) = $5.0 \times 10^{17}$ cm$^{-2}$ (SWC’s favored value) and $D/H = 8.9 \times 10^{-5}$.
Fig. 3.— Upper bounds on D/H determined for 10 partial Lyman limit systems are shown as a function of the optical depth of the Lyman limit system (*left panel*). The same measurement carried out at the symmetrically placed redward position gives much tighter constraints (*right panel*), suggesting that there is indeed enhanced absorption caused by deuterium in the blue wing.