A UNIFORM PRIMORDIAL DEUTERIUM ABUNDANCE STEMMED FROM QSO OBSERVATIONS

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Abstract

The discordance between ‘low’ and ‘high’ primordial D/H measurements can be considerably reduced if the analysis of the H+D profiles accounts for the correlated velocity field of bulk motion. We have re-estimated the value of D/H at $z = 3.572$ towards Q1937–1009 (‘low’ D/H = $(3.3 \pm 0.3) \times 10^{-5}$) and at $z = 0.701$ towards Q1718+4807 (‘high’ D/H = $(2.0 \pm 0.5) \times 10^{-4}$) and found that a single D/H value from the range $(3.5-5.2) \times 10^{-5}$ (2σ C.L.) is sufficient to describe both spectra. This result supports homogeneous models of BBN. The obtained D/H ratio and the measurements of high $^4$He abundance in extra-galactic H II regions [3] and $^7$Li abundance in metal-poor halo stars [2] are consistent, within the errors, with the predictions of standard BBN for $3.6 \leq \eta_{10} \leq 5.4$, which corresponds to $0.013 \leq \Omega_b h^2_{100} \leq 0.020$.

1 Introduction

The light elements D, $^3$He, $^4$He and $^7$Li are produced in big bang nucleosynthesis (BBN). In the standard hot homogeneous BBN model their relative abundances depend on a single parameter $\eta$ – the ratio between the number of baryons and photons at the epoch of nucleosynthesis (see e.g. [4]). The value of $\eta$ is not, however, predicted by the big bang theory. It can only be estimated from observations. To fix $\eta$, the measurements of the $(D/H)_p$ ratio (the subscript $p$ throughout denotes primordial abundance) can be carried out from spectra of distant quasars [1]. Such measurements, together with other three light element abundances, provide the complete test of the standard BBN model.

Recent high-redshift D abundances are, however, very discrepant (cf. [3] and [15]). It was suggested that there may be inhomogeneity in $(D/H)_p$ of at least a factor of ten. This implies that big bang nucleosynthesis may have occurred inhomogeneously [3] and there may not be a unique primordial deuterium abundance as first pointed out in [3].

In these proceedings, we show one possibility how to reconcile the observed $(D/H)_p$ values. We demonstrate that the discrepancy between ‘high’ and ‘low’ D/H measurements may be overcome in the framework of the line broadening process which accounts for the spatial correlations in the intervening velocity field.
2 The D/H measurements

We consider two examples of real data which yielded two limiting D/H values in the previous studies. The first one is the absorbing region with observable hydrogen and deuterium Lyα and Lyβ lines at \( z = 3.572 \) towards Q1937–1009 where a ‘low’ D/H ratio of \( (3.3 \pm 0.3) \times 10^{-5} \) was measured in [3]. The second one is the H+D Lyα blend with D/H = \( (2.0 \pm 0.5) \times 10^{-4} \) seen at \( z = 0.701 \) towards Q1718+4807 [14]. The latter D/H value is at the upper end of the D/H range measured from QSO spectra.

The foregoing estimations were obtained through the Voigt profile fitting analysis. This analysis ignores the large-scale correlations in the velocity field and thus may produce very misleading results when applied to the case where the spatial correlations in bulk motion are significant (see [7], [8], and [9]).

Our method takes into account the correlated structure of the radial velocity field. The model supposes a continuous absorbing region of a thickness \( L \) exhibiting a mixture of bulk motions of different types. The gas motion along a given line of sight is described by a fluctuating (random) velocity field. For the sake of simplicity, we assume a homogeneous (H I) density and kinetic temperature \( T_{\text{kin}} \). The velocity field is characterized by its rms amplitude \( \sigma_t \) and a correlation length \( l > 0 \) (the reader is referred to [10] for more details).

To estimate physical parameters and an appropriate velocity field structure along the sightline, \( v(s) \), we used a reverse Monte Carlo (RMC) technique. Our algorithm requires the definition of a simulation box for the five physical parameters: \( N(\text{H I}), D/\text{H}, T_{\text{kin}}, \sigma_t/v_{\text{th}}, \) and \( L/l \) (here \( v_{\text{th}} \) denotes the thermal width of the hydrogen lines). The velocity, which is the continuous random function of the coordinate \( s \), is represented by its sampled values at equally spaced intervals \( \Delta s \), i.e. by the vector \( \{v_1, v_2, \ldots, v_k\} \) of the components parallel to the line of sight at the spatial points \( s_j \) (see [10]).

The obtained results for the \( z = 3.572 \) and \( z = 0.701 \) systems are summarized in Figure 1. Upper left panel in this figure shows confidence regions in the ‘N(H I)–D/H’ plane for the simultaneously fitted blue wings of the H+D Lyα and Lyβ profiles (Q1937–1009) when the other parameters \( (T_{\text{kin}} = 1.15 \times 10^4 \text{ K}, \sigma_t/v_{\text{th}} = 1.46, \) and \( L/l = 3.6) \) and the corresponding configuration of the velocity field \( v(s) \) are fixed. The contours represent 68.3% (innermost), 95.4%, and 99.7% (outermost) confidence levels. The filled circle marks the point of maximum likelihood for model (d) from [11] where \( \chi^2_{\text{min}} \) per degree of freedom is 1.18. Lower left panel demonstrates the confidence range for D/H from the second system (Q1718+4807). The vertical dashed lines restrict the N(H I)$_{\text{total}}$ value in accord with [15]. The maximum likelihood point (filled circle) corresponds to D/H = \( 5.4 \times 10^{-5}, N(\text{H I}) = 1.71 \times 10^{17} \text{ cm}^{-2}, T_{\text{kin}} = 1.5 \times 10^4 \text{ K}, \) \( \sigma_t = 26 \text{ km s}^{-1}, \) and \( L/l = 3.5 \) with \( \chi^2_{\text{min}} = 0.804 \). This point is slightly shifted with respect to the best model (e) from [12] with \( \chi^2_{\text{min}} = 0.897 \) (open circle) because in the present study a wider simulation box for the physical parameters was adopted. The contours in this panel represent 68.3% (inner) and 95.4% confidence levels.

These two measurements of D/H in the high-redshift systems reveal no variations of the deuterium abundance within the quality of the data sets. We can, therefore, compare SBBN predictions with observational abundances which are shown in Figure 1 as well. The theoretical SBBN relative abundances of D, \(^4\text{He}, \) and \(^7\text{Li} \) (solid curves in the right panels) and their uncertainties (dashed curves) as function of \( \eta \) are taken from [14]. The abundances of D and \(^7\text{Li} \) are number ratios, whereas \( Y_p \) is the mass fraction of \(^4\text{He} \). In the upper right panel, the rectangle height corresponds to the \( 2\sigma \) uncertainty region for D/H from the \( z = 3.572 \) system (which provides the highest quality data to date). We do not show here the corresponding bounds from the \( z = 0.701 \) system since its H+D profile was obtained with seven times lower signal-to-noise ratio resulting in a wider D/H uncertainty range which entirely overlaps the \( z = 3.572 \)
confidence interval for D/H. The rectangle heights in two lower panels give the bounds from recent measurements of extra-galactic \( Y_p \) in metal-poor H II regions \[5\] and \(^7\)Li in warm metal-poor population II (halo) stars \[2\]. We do not depict an error box representing another \(^4\)He abundance measurement \[13\], since (i) our D/H value is not consistent with \( Y_p = 0.234 \pm 0.002 \) found in \[5\] and (ii) the estimations of \( Y_p \) in \[5\] and \[13\] are not in agreement. The rectangle widths give the 2\(\sigma\) uncertainty regions for \( \eta \) in the SBBN calculations. The shaded region is the window for \( \eta \) common to all results. It specifies 2\(\sigma\) confidence levels in \( \eta \).

Taken at face values, the shaded \( \eta \)-region \( 3.6 \leq \eta_{10} \leq 5.4 \) leads directly to the estimation of the present-day baryonic density. Using the present-day number density of photons of the cosmic background radiation (\( T = 2.73 \) K), we can obtain \( 0.013 \leq \Omega_b h^2 \leq 0.020 \), where \( H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1} \).

Now we can conclude that in the framework of our model we do not detect any variations of the D/H ratio. This result supports SBBN. However, more information on the H+D absorption-line systems is needed to verify this statement unambiguously.

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Figure 1: *Upper left* – Confidence regions for the simultaneously fitted H+D Lyα and Lyβ profiles from the $z = 3.572$ system towards Q1937–1009. *Lower left* – Confidence regions for the fitted H+D Lyα profile observed at $z = 0.701$ towards Q1718+4807. *Right* – Comparison of predicted by SBBN primordial abundances with observational bounds. See text for more details.