Review of Big Bang Nucleosynthesis and Primordial Abundances

David Tytler*, John M. O’Meara, Nao Suzuki and Dan Lubin

Center for Astrophysics and Space Sciences; University of California, San Diego; MS 0424; La Jolla; CA 92093-0424, USA

Received September 10, 1999; revised version received January 11, 2000; accepted January 13, 2000

Abstract

Big Bang Nucleosynthesis (BBN) is the synthesis of the light nuclei, Deuterium (D or $^2$H), $^4$He, $^6$Li and $^7$Li during the first few minutes of the universe. This review concentrates on recent improvements in the measurement of the primordial (after BBN, and prior to modification) abundances of these nuclei. We mention improvement in the standard theory, and the non-standard extensions which are limited by the data.

We have achieved an order of magnitude improvement in the precision of the measurement of primordial D/H, using the HIRES spectrograph on the W. M. Keck telescope to measure D in gas with very nearly primordial abundances towards quasars. From 1994 – 1996, it appeared that there could be a factor of ten range in primordial D/H, but today four examples of low D are secure. High D/H should be much easier to detect, and since there are no convincing examples, it must be extremely rare or non-existent. All data are consistent with a single low value for D/H, and the examples which are consistent with high D/H are readily interpreted as H contamination near the position of D.

The new D/H measurements give the most accurate value for the baryon to photon ratio, $\eta$, and hence the cosmological baryon density. A similar density is required to explain the amount of Ly$\alpha$ absorption from neutral Hydrogen in the intergalactic medium (IGM) at redshift $z \approx 3$, and to explain the fraction of baryons in local clusters of galaxies.

The D/H measurements lead to predictions for the abundances of the other light nuclei, which generally agree with measurements.

The remaining differences with some measurements can be explained by a combination of measurement and analysis errors or changes in the abundances after BBN. The measurements do not require physics beyond the standard BBN model. Instead, the agreement between the abundances is used to limit the non-standard physics.

New measurements are giving improved understanding of the difficulties in estimating the abundances of all the light nuclei, but unfortunately in most cases we are not yet seeing much improvement in the accuracy of the primordial abundances. Since we are now interested in the highest accuracy and reliability for all nuclei, the few objects with the most extensive observations give by far the most convincing results.

Earlier measurements of $^4$He may have obtained too low a value because the He emission line strengths were reduced by undetected stellar absorption lines. The systematic errors associated with the $^4$He abundance have frequently been underestimated in the past, and this problem persists. When two groups use the same data and different ways to estimate the electron density and $^4$He abundance, the results differ by more than the quoted systematic errors. While the methods used by Izotov and Thuan [1] seem to be an advance on those used before, the other method is reasonable, and hence the systematic error should encompass the range in results.

The abundance of $^7$Li is measured to high accuracy, but we do not know how much was produced prior to the formation of the stars, and how much was destroyed (depleted) in the stars. $^4$Li helps limit the amount of depletion of $^7$Li, but by an uncertain amount since it too has been depleted.

BBN is successful because it uses known physics and measured cross-sections for the nuclear reactions. It gives accurate predictions for the abundances of five light nuclei as a function of the one free parameter $\eta$. The other initial conditions seem natural: the universe began homogeneous and hotter than $T > 10^4$ K (30 Mev). The predicted abundances agree with most observations, and the required $\eta$ is consistent with other, less accurate, measurements of the baryon density.

Abundance measurements of the baryon density, from the CMB, clusters of galaxies and the Ly$\alpha$ forest, will give $\eta$. Although the accuracy might not exceed that obtained from D/H, this is an important advance because BBN then gives abundance predictions with no adjustable parameters.

New measurement in the coming years will give improved accuracy. Measurement of D/H in many more quasar spectra would improve the accuracy of D/H by a factor of a few, to a few percent, but even with improved methods of selecting the target quasars, this would need much more time on the largest telescopes. More reliable $^4$He abundances might be obtained from spectra which have higher spectral and spatial resolution, to help correct for stellar absorption, higher signal to noise to show weaker emission lines, and more galaxies with low metal abundances, to minimize the extrapolation to primordial abundances. Measurements of $^7$Li, Be and Boron in the same stars and observations of a variety of stars should give improved models for the depletion of $^7$Li in halo stars, and hence tighter constraints on the primordial abundance. However, in general, it is hard to think of any new methods which could give any primordial abundances with an order of magnitude higher accuracy than those used today. This is a major unexploited opportunity, because it means that we can not yet test BBN to the accuracy of the predictions.

1. Introduction

There are now four main observations which validate the Big Bang theory: the expansion of the universe, the Planck spectrum of the Cosmic Microwave Background (CMB), the density fluctuations seen in the slight CMB anisotropy and in the local galaxy distribution, and BBN. Together, they show that the universe began hot and dense [2].

BBN occurs at the earliest times at which we have a detailed understanding of physical processes. It makes predictions which are relatively precise (10% – 0.1%), and which have been verified with a variety of data. It is critically important that the standard theory (SBBN) predicts the abundances of several light nuclei (H, D, $^3$He $^4$He and $^7$Li) as a function of a single cosmological parameter, the baryon to photon ratio, $\eta \equiv n_b/n_\gamma$ [3]. The ratio of any two primordial abundances should give $\eta$, and the measurement of the other three tests the theory.

The abundances of all the light elements have been measured in a number of terrestrial and astrophysical environments. Although it has often been hard to decide when these abundances are close to primordial, it has been clear for decades (e.g. [4,5]) that there is general agreement with the BBN predictions for all the light nuclei. The main development in recent years has been the increased accuracy of measurement. In 1995 a factor of three range in the baryon density was considered $\Omega_b = 0.007 \pm 0.024$. The low end of this range allowed no significant dark baryonic matter. Now the new D/H measurements towards quasars give $\Omega_b = 0.019 \pm 0.002 (95\%)$ – a 13% error, and there have been improved measurements of the other nuclei.

1.1. Other reviews

Many reviews of BBN have been published recently: e.g. [6–12,13], some of which are lengthy: e.g. [14–16]. All modern cosmology texts contain a summary. Several recent books contain the proceedings of meetings on this topic:
[17–19,20]. The 1999 meeting of the International Astronomical Union (Symposium 198 in Natal, Brazil) was on this topic, as are many reviews in upcoming special volumes of Physics Reports and New Astronomy, both in honor of the major contributions by David N. Schramm.

2. Physics of BBN

Excellent summaries are given in most books on cosmology e.g.: [3,21–24], and most of the reviews listed above, including [25], and [11].

2.1. Historical development

The historical development of BBN is reviewed by [6,10,13,26,27]. Here we mention a few of the main events.

The search for the origin of the elements lead to the modern Big Bang theory in the early 1950s. The starting point that the universe had an explosion of a dense unstable “primeval atom”. By 1938 it was well established that the abundances of the elements were similar in different astronomical locations, and hence potentially of cosmological significance. Gamow [29,30] asked whether nuclear reactions in the early universe might explain the abundances of the elements. This was the first examination of the physics of a dense expanding early universe, beyond the mathematical description of general relativity, and over the next few years this work developed into the modern big bang theory. Early models started with pure neutrons, and gave final abundances which depended on the unknown density during BBN. Fermi and Turkevich showed that the lack of stable nuclei with mass 5 and 8 prevents significant production of nuclei more massive than 7Li, leaving 4He as the most abundant nucleus after H. Starting instead with all possible species, Hayashi [31] first calculated the neutron to proton (n/p) ratio during BBN, and Alpher [32] realized that radiation would dominate the expansion. By 1953 [33] the basic physics of BBN was in place. This work lead directly to the prediction of the CMB (e.g. Olive 1999b [7]), it explained the origin of D, and gave abundance predictions for 4He similar to those obtained today with more accurate cross-sections.

The predicted abundances have changed little in recent years, following earlier work by Peebles (1964) [39], Hoyle and Tayler (1964) [40], and Wagoner, Fowler and Hoyle (1967) [34]. The accuracy of the theory calculations have been improving, and they remain more accurate than the measurements. For example, the fraction of the mass of all baryons which is 4He, \( Y_p \), is predicted to within \( \delta Y_p < \pm 0.0002 \) [35]. In a recent update, Burles et al. [6] uses Monte-Carlo realizations of reaction rates to find that the previous estimates of the uncertainties in the abundances for a given \( \eta \) were a factor of two too large.

2.2. Key physical processes

2.2.1. Baryogenesis

The baryon to photon ratio \( \eta \) is probably determined during baryogenesis [3,36,37]. It is not known when baryogenesis occurred. Sakharov [38] noted that three conditions are required: different interactions for matter and anti-matter (CP violation), interactions which change the baryon number, and departure from thermodynamic equilibrium. This last condition may be satisfied in a first order phase transition, the GUT transition at \( 10^{-35} \) s, or perhaps the electroweak transition at \( 10^{-11} \) s. If baryogenesis occurred at the electroweak scale, then future measurements may lead to predictions for \( \eta \), but if, alternatively, baryogenesis is at the GUT or inflation scale, it will be very hard to predict \( \eta \) (J. Ellis personal communication).

The matter/anti-matter asymmetry of the universe (the \( \eta \) value) is attracting discussion in the popular science press because of the inauguration of major experiments to study CP violation in B mesons ([41,42]; Economist, May 8 1999, 85-87).

2.2.2. The main physical processes in BBN

At early times, weak reactions keep the n/p ratio close to the equilibrium Boltzmann ratio. As the temperature, \( T \), drops, n/p decreases. The n/p ratio is fixed (“frozen in”) at a value of about 1/6 after the weak reaction rate is slower than the expansion rate. This is at about 1 s, when \( T \approx 1 \text{MeV} \). The starting reaction \( n+p \rightarrow D + \gamma \) makes D. At that time photodissociation of D is rapid because of the high entropy (low \( \eta \)) and this prevents significant abundances of nuclei until, at 100 s, the temperature has dropped to 0.1 MeV, well below the binding energies of the light nuclei. About 20% of free neutrons decay prior to being incorporated into nuclei. The \(^4\text{He}\) abundance is then given approximately by assuming that all remaining neutrons are incorporated into \(^4\text{He}\).

The change in the abundances over time for one \( \eta \) value is shown in Fig. 1, while the dependence of the final abundances on \( \eta \) is shown in Fig. 2, together with some recent measurements.

In general, abundances are given by two cosmological parameters: the expansion rate and \( \eta \). Comparison with the strength of the weak reactions gives the n/p ratio, which determines \( Y_p \). \( Y_p \) is relatively independent of \( \eta \) because
n/p depends on weak reactions between nucleons and leptons (not pairs of nucleons), and temperature. If \( \eta \) is larger, nucleosynthesis starts earlier, more nucleons end up in \( ^4\text{He} \), and \( Y_p \) increases slightly. \( \text{D} \) and \( ^3\text{He} \) decrease simultaneously in compensation. Two channels contribute to the abundance of \( ^7\text{Li} \) in the \( \eta \) range of interest, giving the same \( ^7\text{Li} \) for two values of \( \eta \).

3. Measurement of primordial abundances

The goal is to measure the primordial abundance ratios of the light nuclei made in BBN. We normally measure the ratios of the abundances of two nuclei in the same gas, one of which is typically \( \text{H} \), because it is the easiest to measure.

The two main difficulties are the accuracy of the measurement and departures from primordial abundances. The state of the art today (1σ) is about 3% for \( Y_p \), 10% for \( \text{D}/\text{H} \) and 8% for \( ^7\text{Li} \), for each object observed. These are random errors. The systematic errors are hard to estimate, usually unreliable, and potentially much larger.

By the earliest time at which we can observe objects, redshifts \( z \approx 6 \), we find heavy elements from stars in most gas. Although we expect that large volumes of the intergalactic medium (IGM) remain primordial today [43], we do not know how to obtain accurate abundances in this gas. Hence we must consider possible modifications of abundances. This is best done in gas with the lowest abundances of heavy elements, since this gas should have the least deviations caused by stars.

The nuclei \( \text{D}, ^3\text{He}, ^6\text{Li} \) and \( ^7\text{Li} \) are all fragile and readily burned inside stars at relatively low temperatures of a few 10⁶ K. They may appear depleted in the atmosphere of a star because the gas in the star has been above the critical temperature, and they will then also be depleted in the gas returned to the interstellar medium (ISM). Nuclei \( ^3\text{He}, ^7\text{Li} \) and especially \( ^4\text{He} \) are also made in stars.

3.1. From observed to primordial abundances

Even when heavy element abundances are low, it is difficult to prove that the light nuclei abundances are primordial. Arguments include the following.

Helium is observed in the ionized gas surrounding luminous young stars (H II regions), where O abundances are 0.02 to 0.2 times those in the sun. The \( ^4\text{He} \) mass fraction \( Y \) in different galaxies is plotted as a function of the abundance of O or N. The small change in \( Y \) with O or N is the clearest evidence that the \( Y \) is almost entirely primordial (e.g. [7] Fig. 2). Regression gives the predicted \( Y_p \) for zero O or N [44]. The extrapolation is a small extension beyond the observed range, and the deduced primordial \( Y_p \) is within the range of \( Y \) values for individual H II regions. The extrapolation should be robust [45], but some algorithms are sensitive to the few galaxies with the lowest metal abundances, which is dangerous because at least one of these values was underestimated by Olive, Skillman and Steigman [46].

For deuterium we use a similar argument. The observations are made in gas with two distinct metal abundances. The quasar absorbers have from 0.01 to 0.001 of the solar C/H, while the ISM and pre-solar observations are near solar. Since \( \text{D}/\text{H} \) towards quasars is twice that in the ISM, 50% of the \( \text{D} \) is destroyed when abundances rise to near the solar level, and less than 1% of \( \text{D} \) is expected to be destroyed in the quasar absorbers, much less than the random errors in individual measurements of \( \text{D}/\text{H} \). Since there are no other known processes which destroy or make significant \( \text{D} \) (e.g. [4,47]), we should be observing primordial \( \text{D}/\text{H} \) in the quasar absorbers.

Lithium is more problematic. Stars with a variety of low heavy element abundances (0.03 – 0.0003 of solar) show very similar abundances of \( ^7\text{Li} \) ([48] Fig. 3), which should be close to the primordial value. Some use the observed values in these “Spite plateau” stars as the BBN abundance, because of the small scatter and lack of variation with the abundances of other elements, but three factors should be considered. First, the detection of \( ^7\text{Li} \) in two of these stars suggests that both \( ^7\text{Li} \) and some \( ^7\text{Li} \) was created prior to the formation of these stars. Second, the possible increase in the abundance of \( ^7\text{Li} \) with the iron abundance also indicates that the \( ^7\text{Li} \) of the plateau stars is not primordial. If both the iron and the enhancement in the \( ^7\text{Li} \) have the same origin we could extrapolate back to zero metals [49].
The primordial abundance of $^3$He is the hardest to estimate, because stars are expected to both make and destroy this isotope, and there are no measurements in gas with abundances well below the solar value.

3.2. Key observational requirements

By way of introduction to the data, we list some of the key goals of ongoing measurements of the primordial abundances.

- $^4$He: High accuracy, robust measurement in a few places with the lowest metal abundances.
- $^3$He: Measurement in gas with much lower metal abundances, or an understanding of stellar production and destruction and the results for all stars integrated over the history of the Galaxy (Galactic chemical evolution).
- D: The discovery of more quasar absorption systems with minimal H contamination.
- $^7$Li: Observations which determine the amount of depletion in halo stars, or which avoid this problem. Measurement of $^6$Li, Be and B to help estimate production prior to halo star formation, and subsequent depletion.

Since we are now obtaining “precision” measurements, it seems best to make a few measurements with the highest possible accuracy and controls, in places with the least stellar processing, rather than multiple measurements of lower accuracy. We will now discuss observations of each of the nuclei, and especially D, in more detail.

4. Deuterium in quasar spectra

The D/H abundance ratio is both the most sensitive measure of the baryon density [5] and has the simplest evolution. No known processes make significant D, because it is so fragile ([4.50–52.86]). Gas ejected by stars should contain zero D, but substantial H, thus D/H decreases over time as more stars evolve and die.

We can measure the primordial abundance in quasar spectra. The measurement is direct and accurate, and with one exception, simple. The exception is that the absorption by D is often contaminated or completely obscured by absorption from H, and even in the rare cases when contamination is small, superb spectra are required to distinguish D from H.

Prior to the first detection of D in quasar spectra [53], D/H was measured in the ISM and the solar system. The primordial abundance is larger, because D has been destroyed in stars. Though generally considered a factor of a few, some papers considered a factor of ten destruction [54]. At that time, most measurements of $^4$He gave low abundances, which predict a high primordial D/H, which would need to be depleted by a large factor to reach ISM values [55].

Reeves et al. [4] noted that the measurement of primordial D/H could provide an excellent estimate of the cosmological baryon density, and they used the ISM $^3$He +D to conclude, with great caution, that primordial D/H was plausibly $7 \pm 3 \times 10^{-5}$.

Adams [56] suggested that it might be possible to measure primordial D/H towards low metallicity absorption line systems in the spectra of high redshift quasars. This gas is in the outer regions of galaxies or in the IGM, and it is not con-

---

Fig. 3. Optical spectrum of quasar 1937–1009, which shows the best example of primordial D/H. The top spectrum, from the Kast spectrograph on the 3-m telescope at Lick observatory, is of low spectral resolution, and high signal to noise. The continuum emission, from the accretion disk surrounding the black spot at the center of the quasar, is at about 6 flux units. The emission lines showing more flux (near 4950, 5820, 5940, 6230, 6700 and 7420 Å) arise in gas near the quasar. The absorption lines, showing less flux, nearly all arise in gas which is well separated from, and unrelated to the quasar. The numerous absorption lines at 4200 – 5800 Å are H I Lyα from the gas in the intergalactic medium. This region of the spectrum is called the Lyα forest. This gas fills the volume of the intergalactic medium, and the absorption lines arise from small, factor of a few, fluctuations in the density of the gas on scales of a few hundred kpc. The Lyα lines were all created by absorption of photons with wavelengths of 1216 Å. They appear at a range of observed wavelengths because they have different redshifts. Hence Lyα absorption at 5800 Å is near the QSO, while that at 5000 Å is nearer to the absorber. The abrupt drop in flux at 4180 Å is caused by H I Lyman continuum absorption in the absorber at z = 3.572. Photons now at < 4180 Å had more than 13.6 eV when they passed through the absorber, and they ionized its H I. The 1% residual flux in this Lyman continuum region has been measured in spectra of high signal to noise (Burles and Tytler 1998a [62]) and gives the H I column density, expressed as H I atoms per cm$^2$ through the absorbing gas. The lower plot shows a portion of a spectrum with much higher resolution taken with the HIRES spectrograph on the Keck-I telescope. We mark the Lyα absorption lines of H I and D from the same gas. The column density of D is measured from this spectrum. Dividing these two column densities we find D/H = $3.3 \pm 0.3 \times 10^{-5}$ (95% confidence), which is believed to be the primordial value, and using SBBN predictions, this gives the most accurate measurements of η and Ωh.
nected to the quasars. The importance of such measurements was well known in the field since late 1970s [57], but the task proved too difficult for 4-m class telescopes ([58–60]). The high SNR QSO spectra obtained with the HIRES echelle spectrograph [61] on the W.M. Keck 10-m telescope provided the breakthrough.

There are now three known absorption systems in which D/H is low: first, D/H = 3.24 ± 0.3 × 10⁻⁵ in the zₐₜₛ = 3.572 Lyman limit absorption system (LLS) towards quasar 1937–1009 [53,62] (shown in Fig. 3); second, D/H = 4.0 ± 0.3 × 10⁻⁵ in the zₐₜₛ = 2.504 LLS towards quasar 1009+2956 [63], and third, D/H < 6.7 × 10⁻⁵ towards quasar 0130–4021 [64]. This last case is the simplest found yet, and seems especially secure because the entire Lyman series is well fit by a single velocity component. The velocity of this component and its column density are well determined because many of its Lyman lines are unsaturated. Its Lyα line is simple and symmetric, and can be fit using the H parameters determined by the other Lyman series lines, with no additional adjustments for the Lyα absorption line itself. There is barely enough absorption at the expected position of D to allow low values of D/H, and there appears to be no possibility of high D/H. Indeed, the spectra of all three QSOs are inconsistent with high D/H.

There remains uncertainty over a case at zₐₜₛ = 0.701 towards quasar 1718+4807, because we lack spectra of the Lyman series lines which are needed to determine the velocity distribution of the Hydrogen, and the published spectra are of unusually low signal to noise, with about 200 times fewer photons per km⁻¹s⁻¹ than those from Keck. Webb et al. [65,66] assumed a single hydrogen component and found D/H = 25 ± 5 × 10⁻⁵, the best case for “high D/H”. Levshakov et al. [67] allow for non-Gaussian velocities and find D/H ∼ 4.4 × 10⁻⁵, while Tytler et al. [68] find 8 × 10⁻⁵ < D/H < 57 × 10⁻⁵ (95%) for a single Gaussian component, or D/H as low as zero if there are two hydrogen components, which is not unlikely. This quasar is then also consistent with low D/H.

Recently Molaro et al. [69] claimed that D/H might be low in an absorber at z = 3.514 towards quasar APM 08279+5255, though they noted that higher D/H was also possible. Only one H I line, Lyα, was used to estimate the hydrogen column density N_HI (measured in H I atoms per cm⁻² along the line of sight) and we know that in such cases the column density can be highly uncertain. Their Fig. 1 (panels (a) and (b)) shows that there is a tiny difference between D/H = 1.5 × 10⁻⁵ and 21 × 10⁻⁵, and it is clear that much lower D is also acceptable because there can be additional H contamination in the D region of the spectrum. Levshakov et al. [70] show that log N_HI = 15.7 (too low to show D) gives an excellent fit to these spectra, and they argue that this is a more realistic result because the metal abundances and temperatures are then normal, rather than being anomalously low with the high N_HI preferred by Molaro et al.

The first to publish a D/H estimate using high signal to noise spectra from the Keck telescope with the HIRES spectrograph were Songaila et al. [71], who reported an upper limit of D/H < 25 × 10⁻⁵ in the zₐₜₛ = 3.32 Lyman limit system (LLS) towards quasar 0014+813. Using different spectra, Carswell et al. [60] reported < 60 × 10⁻⁵ in the same object, and they found no reason to think that the deuterium abundance might be as high as their limit. Improved spectra [72] support the early conclusions: D/H < 3.5 × 10⁻⁵ for this quasar. High D/H is allowed, but is highly unlikely because the absorption near D is at the wrong velocity, by 17 ± 2 km s⁻¹, it is too wide, and it does not have the expected distribution of absorption with velocity, which is given by the H absorption. Instead this absorption is readily explained entirely by H at a different redshift and D/H ∼ 0.

Very few LLS have a velocity structure simple enough to show deuterium. Absorption by H usually absorbs most of the quasar flux near where the D line is expected, and hence we obtain no information of the column density of D. In these extremely common cases, very high D/H is allowed, but only because we have essentially no information.

All quasar spectra are consistent with low primordial D/H ratio, D/H ∼ 3.4 × 10⁻⁵. Two quasars (1937–1009 and 1009+2956) are inconsistent with D/H ≥ 5 × 10⁻⁵, and the third (0130–4021) is inconsistent with D/H ≥ 6.7 × 10⁻⁵. Hence D/H is low in these three places. Several quasars allow high D/H, but in all cases this can be explained by contamination by H, which we discuss more below, because it is controversial.

4.1. ISM D/H

Observations of D in the ISM are reviewed by Lemoine et al. [73]. The first measurement in the ISM, D/H = 1.4 ± 0.2 × 10⁻⁵, using Lyman absorption lines observed with the Copernicus satellite [74], have been confirmed with superior HST spectra. A major program by Linsky et al. [75,76] has given a secure value of D/H = 1.6 ± 0.1 × 10⁻⁵ for local ISM (< 20 pc).

Some measurements have indicated variation, and especially low D/H, in the local and more distant ISM towards a few stars [55,73]. Vidal-Madjar and Gry [55] concluded that the different lines of sight gave different D/H, but those early data may have been inadequate to quantize complex velocity structure [77]. Variation is expected, but at a low level, from different amounts of stellar processing and infall of IGM gas, which leaves differing D/H if the gas is not mixed in a large volume.

Lemoine et al. [78] suggested variation of D/H towards G191-B2B, while Vidal-Madjar et al. [79] described the variation as real, however new STIS spectra do not confirm this, and give the usual D/H value. The STIS spectra [80] show a simpler velocity structure, and a lower flux at the D velocity, perhaps because of difficulties with the background subtraction in the GHRS spectra.

Hébrand et al. [81] report the possibility of low D/H < 1.6 × 10⁻⁵ towards Sirius A, B.

The only other instance of unusually low D/H from recent data is D/H = 0.74_{-0.13}^{+0.19} × 10⁻⁵ (90%) towards the star δ Ori [82]. We would much like to see improved data on this star, because a new instrument was used, the signal to noise is very low, and the velocity distribution of the D had to be taken from the N I line, rather than from the H I.

Possible variations in D/H in the local ISM have no obvious connections to the D/H towards quasars, where the absorbing clouds are 100 times larger, in the outer halos young of galaxies rather than in the dense disk today,
and the influence of stars should be slight because heavy element abundances are 100 to 1000 times smaller.

Chengalur, Braun and Burton [83] report $D/H = 3.9 \pm 1.0 \times 10^{-5}$ from the marginal detection of radio emission from the hyper-fine transition of $D$ at 327 MHz (92 cm). This observation was of the ISM in the direction of the Galactic anti-center, where the molecular column density is low, so that most D should be atomic. The $D/H$ is higher than in the local ISM, and similar to the primordial value, as expected, because there has been little stellar processing in this direction.

Deuterium has been detected in molecules in the ISM. Some of these results are considered less secure because of fractionation and in low density regions, HD is more readily destroyed by ultraviolet radiation, because its abundance is too low to provide self shielding, making HD/H$_2$ smaller than $D/H$.

However, Wright et al. [84] deduce $D/H = 1.0 \pm 0.3 \times 10^{-5}$ from the first detection of the 112 $\mu$m pure rotation line of HD outside the solar system, towards the dense warm molecular clouds in the Orion bar, where most D is expected to be in HD, so that $D/H \approx$ HD/H$_2$. This $D/H$ is low, but not significantly lower than in the local ISM, especially because the H$_2$ column density was hard to measure.

Lubowich et al. [85,86] report $D/H = 0.2 \pm 1 \times 10^{-5}$ from DCN in the Sgr A molecular cloud near the Galactic center, later revised to $0.3 \times 10^{-5}$ (private communication 1999). This detection has two important implications. First, there must be a source of D, because all of the gas here should have been inside at least one star, leaving no detectable D. Nucleosynthesis is ruled out because this would enhance the Li and B abundances by orders of magnitude, contrary to observations. Infall of less processed gas seems likely. Second, the low $D/H$ in the Galactic center implies that there is no major source of D, otherwise $D/H$ could be very high. However, this is not completely secure, since we could imagine a fortuitous cancellation between creation and destruction of D.

We eagerly anticipate a dramatic improvement in the data on the ISM in the coming years. The FUSE satellite, launched in 1999, will measure the D and H Lyman lines towards thousands of stars and a few quasars, while SOFIA (2002) and FIRST (2007) will measure HD in dense molecular clouds. The new GMAT radio telescope should allow secure detection of D 92 cm emission from the outer Galaxy, while the Square Kilometer Array Interferometer would be able to image this D emission in the outer regions of nearby galaxies; regions with low metal abundances. These data should give the relationship between metal abundance and D/H, and especially determine the fluctuations of D/H at a given metal abundance which will better determine Galactic chemical evolution, and, we hope, allow an accurate prediction of primordial D/H independent of the QSO observations.

### 4.2. Solar system D/H

The D/H in the ISM from which the solar system formed 4.6 Gyr ago can be deduced from the D in the solar system today, since there should be no change in D/H, except in the sun. Measurement in the atmosphere of Jupiter will give the pre-solar D/H provided (1) most of Jupiter's mass was accreted directly from the gas phase, and not from icy planetesimals, which, like comets today, have excess D/H by fractionation, and (2) the unknown mechanisms which deplete He in Jupiter's atmosphere do not depend on mass. Mahaffy et al. [87] find $D/H = 2.6 \pm 0.7 \times 10^{-5}$ from the Galileo probe mass spectrometer. Feuchtgruber et al. [88] used infrared spectra of the pure rotational lines of HD at 37.7 $\mu$m to measure $D/H = 5.5^{+2.2}_{-1.1} \times 10^{-5}$ in Uranus and $6.5^{+2.4}_{-1.4} \times 10^{-5}$ in Neptune, which are both sensibly higher because these planets are known to be primarily composed of ices which have excess D/H.

The pre-solar D/H can also be deduced indirectly from the present solar wind, assuming that the pre-solar D was converted into $^3$He. The present $^3$He/$^4$He ratio is measured and corrected for (1) changes in $^3$He/H and $^4$He/H because of burning in the sun, (2) the changes in isotope ratios in the chromosphere and corona, and (3) the $^3$He present in the pre-solar gas. Geiss and Gloeckler [89] reported $D/H = 2.1 \pm 0.5 \times 10^{-5}$, later revised to 1.94$ \pm 0.36 \times 10^{-5}$ [90]. The present ISM $D/H = 1.6 \pm 0.1 \times 10^{-5}$ is lower, as expected, and consistent with Galactic chemical evolution models, which we now mention.

### 4.3. Galactic chemical evolution of D

Numerical models are constructed to follow the evolution of the abundances of the elements in the ISM of our Galaxy.

The main parameters of the model include the yields of different stars, the distribution of stellar masses, the star formation rate, and the infall and outflow of gas. These parameters are adjusted to fit many different data. Such Galactic chemical evolution models are especially useful to compare abundances at different epochs, for example, D/H today, in the ISM when the solar system formed, and primordially.

In an analysis of a variety of different models, Tosi et al. [91] concluded that the destruction of D in our Galaxy was at most a factor of a few, consistent with low but not high primordial D. They find that all models, which are consistent with all Galactic data, destroy D in the ISM today by less than a factor of three. Such chemical evolution will destroy an insignificant amount of D when metal abundances are as low as seen in the quasar absorbers.

Others have designed models which do destroy more D [7,92–94], for example, by cycling most gas through low mass stars and removing the metals made by the accompanying high mass stars from the Galaxy. These models were designed to reduce high primordial D/H, expected from the low $Y_p$ values prevalent at that time, to the low ISM values. Tosi et al. [91] describe the generic difficulties with these models. To destroy 90% of the D, 90% of the gas must have been processed in and ejected from stars. These stars would then release more metals than are seen. If the gas is removed (e.g. expelled from the galaxy) to hide the metals, then the ratio of the mass in gas to that in remnants is would be lower than observed. Infall of primordial gas does not help, because this brings in excess D. These models also fail to deplete the D in quasar absorbers, because the stars which deplete the D, by ejecting gas without D, also eject carbon. The low abundance of
carbon in the absorbers limits the destruction of D to <1% [52].

4.4. Questions about D/H

Here we review some common questions about D/H in quasar spectra.

4.4.1. Why is saturation of absorption lines important?

Wampler [95] suggested that the low D/H value towards Q1937–1009 might be inaccurate because in some cases the H absorption lines have zero flux in their cores; they are saturated. Songaila, Wampler and Cowie [96] suggested that this well known problem might lead to errors in the H column density, but later work, using better data and more detailed analyses [97] has shown that these concerns were not significant, and that the initial result [98] was reliable.

Neutral deuterium (D1) is detected in Lyman series absorption lines, which are adjacent to the H I lines. The isotopic shift of 82 km s\(^{-1}\) is easily resolved in high resolution spectra, but it is not enough to move D out of the absorption by the H. The Lyman series lines lie between 1216Å and 912Å, and can be observed from the ground at redshifts > 2.5.

Ideally, many (in the best cases > 20) Lyman lines are observed, to help determine the column density and velocity width (b values, \(b = \sqrt{2} \alpha\), measured in km s\(^{-1}\)) of the H. But in some cases only Ly\(_\alpha\) has been observed so far (Q1718+4807, APM 08279+5255), and these give highly uncertain D/H, or no useful information.

The column densities of H and D are estimated from the precise shapes of their absorption lines in the spectra. For H, the main difficulties are the accuracy of the column density and the measurement of the distribution in velocity of this H. For D the main problem is contamination by H, which we discuss below.

It is well known that column densities are harder to measure when absorption lines become saturated. The amount of absorption increases linearly with the column density as long as only a small fraction of the photons at the line central wavelength are absorbed. Lines saturate when most photons are absorbed. The amount of absorption then increases with the log of the column density.

Wampler [95] suggested that D/H values could be 3 – 4 times higher in Q1937–1009 than measured by Tytler, Fan and Burles [53]. He argued that saturation of the H Lyman series lines could allow lower \(N_{\text{HI}}\). This would lead to residual flux in the Lyman continuum, which would contradict the data, but Wampler suggested that the background subtraction might have been faulty, which was not a known problem with H I RES.

Tytler and Burles [98] explained why Wampler’s general concerns were not applicable to the existing data on Q1937–1009. Thirteen Lyman series lines were observed and used to obtain the \(N_{\text{HI}}\). The cross section for absorption (oscillator strength) decreases by 2000 from the Ly\(_\alpha\) to the Ly-19 line. This means that the lines vary significantly in shape, and this is readily seen in spectra with high resolution and high signal to noise. The background subtraction looked excellent because the line cores were near zero flux, as expected.

Songaila, Wampler and Cowie [96] measured the residual flux in the Lyman continuum of the D/H absorber in Q1937–1009. They found a lower \(N_{\text{HI}}\) and hence a higher D/H. Burles and Tytler [97] presented a more detailed analysis of better data, and found a lower \(N_{\text{HI}}\), consistent with that obtained from the fitting of Lyman series lines. They explained that Songaila, Wampler and Cowie [96] had underestimated \(N_{\text{HI}}\) because they used poor estimates of the continuum level and the flux in the Lyman continuum.

In summary, saturation does make the estimation of \(N_{\text{HI}}\) harder. Column densities of H might be unreliable in data with low spectral resolution, or low signal to noise, and when only a few Lyman lines are observed. The above studies show that it is not a problem with the data available on Q1937–1009, Q1009 + 2956, Q0014 + 8118 and Q0130–4021. For the first two quasars, we obtain the same answer by two independent methods, and for the last three the higher order Lyman lines are not saturated.

Saturation is avoided in absorbers with lower \(N_{\text{HI}}\), but then the D lines are weaker, and contamination by H lines becomes the dominant problem.

4.4.2. Hidden velocity structure

To obtain D/H we need to estimate the column densities of D and H. Column densities depend on velocity distributions, and when lines are saturated, it is hard to deduce these velocity distributions. Similar line profiles are made when the velocity dispersion is increased to compensate for a decrease in the column density. We mentioned above that this degeneracy is broken when we observe lines along the Lyman series.

For Q1937–1009, which has the most saturated H lines of the quasars under discussion, Burles and Tytler [62] showed that the D/H did not change for arbitrary velocity structures, constrained only by the spectra. The same conclusion was obtained for Q1009 + 2956 [63]. The favorable results for these two quasars do not mean that we will always be able to break the degeneracy. That must be determined for each absorption system.

There are two reasons why hidden velocity structure is not expected to be a major problem. First, we are concerned about hidden components which have high columns and low enough velocity dispersions that they hide inside the wider lines from lower column gas. Such gas would be seen in other lines which are not saturated: the D lines and the metal lines from ions with similar (low) ionization. Second, we search for D in absorbers with the simplest velocity distributions. They tend to have both narrow overall velocity widths and low temperatures, which makes it much harder to hide unseen components. Typically, the main component accounts for all of the absorption in the higher order Lyman lines, and these lines are too narrow for significant hidden absorption.

4.4.3. Correlated velocity structure: mesoturbulence

In a series of papers, Levshakov et al. [99–101] have developed and demonstrated a viable alternative model for the velocity distribution.

In most papers, absorption lines are modelled by Voigt profiles. The line width is the sum of the thermal broadening, turbulent broadening, and the instrumental resolution, each of which is assumed to be Gaussian. When an absorption line is more complex than a single Voigt, gas centered at other velocities is added to the model. As the signal to noise
increases, we typically see that more velocity components are required to fit the absorption. Each component has its own physical parameters: central velocity, velocity dispersion (rms of thermal and turbulent broadening), ionization, column densities and elemental abundances. Prior to its use with quasars, this fitting method was developed for the ISM, where it represents gas in spatially separate clouds.

Levshakov and co-workers have proposed a different type of model, the mesoturbulent model, in which the gas velocities are correlated, and the column density per unit velocity is varied to fit the absorption line profiles. They assume that the absorption comes from a single region in space, and they calculate the distribution of the gas density down the line of sight. To simplify the calculations, in early Reverse Monte-Carlo models, they assumed that the gas temperature and density were constant along the line of sight, which is not appropriate if there are separate discrete clouds of gas with differing physical conditions.

The effects of mesoturbulence on the D/H absorbers towards Q1937−1009 [99], Q1009 + 2956 [67] and Q1718 + 4807 [100] were examined in detail using this early model. In the first paper they allowed the \( N_{\text{HI}} \) to vary far from the observed value (\( N_{\text{HI}} = 7.27 \times 10^{17} \)) and consequently they found a variety of \( N_{\text{HI}} \), but when the \( N_{\text{HI}} \) is held within range, the D/H is \( 3.3 \times 10^{-5} \), exactly the same as with the usual model [62]. For the second quasar, the D/H obtained is again similar to that obtained in the usual way. The results are the same as with the usual model in part because the H and D line widths are dominated by thermal and not turbulent motions, and for these two quasars the total \( N_{\text{HI}} \) is not affected, because it is measured from the Lyman continuum absorption, which does not depend on velocity.

Recently they have developed a new model called MCI [70,101] appropriate for absorption systems which sample different densities. They now use H I and metal ions to solve for two random fields which vary independently along the line of sight: the gas density and the peculiar velocities. This model allows the temperature, ionization and density to all vary along the line of sight.

The mesoturbulent model of Levshakov et al. [67] and the microturbulent Voigt model give the same column densities and other parameters when one of the following conditions apply:

1. The line of sight through the absorbing gas traverses many correlation lengths.
2. Each velocity in a spectrum corresponds to gas at a unique spatial coordinate.
3. The absorbing regions are nearly homogeneous, with at most small fluctuations in density or peculiar velocities, or equivalently, thermal broadening larger than the turbulent broadening.

The Voigt model could give the wrong result when two or more regions along the line of sight, with differing physical conditions, give absorption at the same velocity. A remarkable and unexpected example of this was reported by Kirkman and Tytler [102] who found a Lyman limit system which comprised five main velocity components. Each component showed both C IV and O VI absorption at about the same velocity, but in each of the five components, the O VI had a larger velocity dispersion, and hence came from different gas than the C IV. While this LLS is much more complex than those in which we can see D, this type of velocity structure could be common.

All authors other than Levshakov and collaborators use standard Voigt fitting methods to determine column densities, for several reasons. The Voigt method was used, with no well known problems, for many decades to analyze absorption in the ISM, and the ISM is well modeled by discrete clouds separated in space. The Levshakov et al. [67] methods are more complex. In early implementations, Levshakov et al. [67] made assumptions which are not suitable for all absorbers. The current methods require weeks of computer time, and in many cases the two methods have given the same results.

We conclude that, when we have sufficient data, velocity structure is not a problem for the absorbers like those now used for D/H.

4.4.4. Was the primordial D high but depleted in the absorbers? The idea here is that the average BBN D/H was high, and it has been depleted in the three absorbers which show low D. There are two options: local depletion in some regions of the universe, and uniformly global depletion. We conclude that there is no known way to deplete D locally, and global depletion seems unlikely.

First we list seven observations which together rule out local depletion, including that suggested by Rugers and Hogan [103].

1. We note that D/H is also low in our Galaxy, and that Galactic chemical evolution accounts for the difference from the low primordial D. Hence we know of four places where D is low and consistent with a single initial value.
2. If the BBN D/H was high, let us say ten times larger at \( 3 \times 10^{-5} \), then the depletion in all four places, widely separated in space, must be by a similar factor: Q1937−1009: 0.90 ± 0.02; Q1009 + 2956: 0.88 ± 0.02; Q0130−4021: > 0.80; local ISM in our Galaxy: 0.86 – 0.93, where for the Galaxy alone we assume that Galactic chemical evolution reduced the initial D/H by a factor of 1.5–3 [91].
3. The quasar absorption systems are large – a few kpc along the line of sight [98], far larger than can be influenced by a single star or supernovae. The gas today in the local ISM is a mixture of gas which was also distributed over a similar large volume prior to Galaxy formation.
4. The abundance of the metals in the quasar cases are very low; too low for significant (> 1%) destruction of D in stars [52].
5. The quasar absorbers are observed at high redshifts, when the universe is too young for low mass stars (< 2 solar masses) to have evolved to a stage where they eject copious amounts of gas.
6. The quasar absorbers are observed at about the time when old stars in the halo of our Galaxy were forming. These stars may have formed out of gas like that seen in the quasar spectra, but with high density. We expect that much of the gas seen in absorption is in the outer halo regions of young galaxies, and that
some of it was later incorporated into galaxies and halo stars.

7. The ratio of the abundances of Si/C in the quasar absorbers is similar to that in old stars in the halo of our Galaxy. This abundance ratio is understood as the result of normal chemical evolution.

Global destruction of D prior to $z = 3$, or in the early universe, remains a possibility, but it seems contrived.

Gnedin and Ostriker [104] discuss photons from early black holes. Sigl et al. [105] show that this mechanism creates 10 times more $^4\text{He}$ than observed, and Jedamzik and Fuller [52] find the density of gamma ray sources is improbably high.

Holtmann et al. [106,107], showed that particles which decay just after BBN might create photons which could photodissociate D. With very particular parameters, the other nuclei are not changed, and it is possible to get a D/H which is lower than from SBBN with the same $\Omega_b$. Hence low D and low $Y_p$ can be concordant. An exception is $^4\text{Li}$ which is produced with $^4\text{Li}/^7\text{Li} \simeq 10^{-12}$, which is about the level observed in two halo stars. There is no conflict with the usual conclusion that most $^4\text{Li}$ is made by Galactic cosmic rays prior to star formation, because the observed $^6\text{Li}$ has been depleted by an uncertain amount. This scenario has two difficulties: Burles (private communication) notes that there might be a conflict with the $\Omega_b$ measured in other ways, and it seems unlikely that the hypothetical particle has exactly the required parameters to change some abundances slightly, within the range of measurement uncertainty, but not catastrophically.

Most conclude that there are no likely ways to destroy or make significant D.

4.4.5. Could the D/H which we observe be too high? The answer to this question from Kirshner is, that the D/H could be slightly lower than we measure, but not by a large amount. We discuss two possibilities: measurement problems and biased sampling of the universe.

First we consider whether the D/H in the quasar absorbers could be less than observed. This can readily happen if the D is contaminated by H, but a large reduction in D/H is unlikely because the D line widths match those expected in $Q_{1937-1009}$ and $Q_{1009 + 2956}$. We do not know how the ISM D/H values could be too high, and Galactic chemical evolution requires primordial D/H to be larger than that in the ISM, and similar to the low value from quasars. Hence it is unlikely that the D/H is much below the observed value.

Second, we consider whether the absorbers seen in the quasar spectra are representative. The absorbers are biased in three ways: they represent regions of the universe with well above (100–1000 times) the average gas density at $z = 3$, and amongst such high density regions, which are observed as Lyman Limit absorption systems, they have relatively low temperatures ($2 \times 10^4$ K), and simple quiescent velocity structures. The last two factors are necessary to prevent the H absorption from covering up that from D, while the high density follows from the high density of neutral H which is needed to give detectable neutral D. It is likely that the gas in the absorbers at $z = 3$ has by today fallen into a Galaxy, though this is not required because some gas will be heated as galaxies form, preventing infall. The low temperatures and quiescent velocities argue against violent astrophysical events, and there are no reasons to think that the absorbers are any less representative than, say, the gas which made up our Galaxy.

We should also consider whether the quasar absorbers might be unrepresentative because of inhomogeneous BBN. In this scenario regions with above average density will have below average D/H, but the evolution of density fluctuations could be such that the low density regions fill more volume [47,108], so that they are more likely to dominate the observed universe today. In that scenario the $\Omega_b$ derived from the D/H would be below the universal average, and the observed (low) value of D/H would be “high” compared to expectation for SBBN with the same $\Omega_b$. This scenario will be tested when we have observations of many more quasars.

4.4.6. Is there spatial variation in D/H towards quasars? It seems highly likely that the D is low in the three quasars which show low D, and we discussed above why it is hard to imagine how this D could have been depleted or created since BBN. Hence we conclude that the low D/H is primordial.

Are there other places where D is high? All quasar spectra are consistent with a single low D/H value. The cases which are also consistent with high D are readily explained by the expected H contamination. We now explain why we have enough data to show that high D must be rare, if it occurs at all.

High D should be much easier to find than low D. Since we have not found any examples which are as convincing as those of low D, high D must be very rare. If D were ten times the low value, the D line would be ten times stronger for a given $N_{\text{H}}$, and could be seen in spectra with ten times lower signal to noise, or 100 times fewer photons recorded per Å. If such high D/H were common, it would have been seen many times in the high resolution, but low signal to noise, spectra taken in the 1980’s, when the community was well aware of the importance of D/H. High D would also have been seen frequently in the spectra of about 100 quasars taken with the HIRES spectrograph on the Keck telescope. In these spectra, which have relatively high signal to noise, high D could be detected in absorption systems which have 0.1 of the $N_{\text{H}}$ needed to detect low D. Such absorbers are about 40–60 times more common than those needed to show low D/H, and hence we should have found tens of excellent examples.

4.4.7. Why is there lingering uncertainty over D? Today it is widely agreed that D is low towards a few quasars. There remains uncertainty over whether there are also cases of high D, for the following reasons:

- measurements have been made in few places;
- contamination of D by H looks very similar to D, and resembles high D;
- both the low $Y_p$ values reported during the last 25 years, and the $^7\text{Li}$ abundance in Spite plateau halo stars, with no correction for depletion, imply low $\Omega_b$, low $\eta$, and high D/H for SBBN; and
- the first claims were for high D.
In most cases, the apparent conflicts over D/H values concern whether the absorption near the expected position of D is mostly D or mostly H. Steigman [109] and all observational papers discussed this contamination of D by H. Carswell et al. [60] noted that contamination was likely in Q0014+813 and hence the D/H could be well below the upper limit. Songalia et al. [71] stated: “because in any single instance we can not rule out the possibility of a chance H contamination at exactly the D offset, this result [the high D/H] should be considered as an upper limit until further observations of other systems are made.” Burles et al. [72] showed that Q0014+813 is strongly contaminated, does not give a useful D/H limit. For Q1718+4807 we [68] and Levshakov, Kegel and Takahara [100] have argued that contamination is again likely.

There are many reasons why contamination is extremely common:

- H absorption looks just like that from D,
- H is 30,000 times more common,
- spectra of about 50 quasars are needed to find one example of relatively uncontaminated D,
- high signal to noise spectra are needed to determine if we are seeing H or D, and
- these spectra should cover all of the Lyman series and metal lines, because we need all possible information.

When H contaminates D, the resulting D/H will be too high. It is essential to distinguish between upper limits and measurements. There are only two measurements (Q1937–1009 and Q1009 + 2956). They are measurements because we were able to show that the D absorption line has the expected width for D. All other cases are upper limits, and there is no observational reason why the D/H should be at the value of the limit. In many cases, all of the D can be H, and hence and D/H = 0 is an equally good conclusion from the data.

Only about 2% of QSOs at z ≃ 3 have one absorption system simple enough to show D. All the rest give no useful information on D/H. Typically, they do not have enough H to show D, or there is no flux left at the position of D. In such cases the spectra are consistent with high, or very high, D/H, but it is incorrect to conclude that D/H could be high in ≃ 98% of absorption systems because these systems are not suitable to rule out high D/H. Rather, we should concentrate on the few systems which could rule out both high and low D/H.

We will continue to find cases like Q1718+4807 which are consistent with both low and high D/H. As we examine more QSOs we will find cases of contamination which look exactly like D, even in the best spectra, by chance. But by that time we will have enough data to understand the statistics of contamination. We will know the distribution function of the contaminating columns and velocities, which we do not know today because the D/H absorbers are a rare and special subset of all Lyman limit absorbers. When absorbers are contaminated we will find a different D/H in each case, because the N_{HI}, velocity and width of the contaminating H are random variables. But we will be able to predict the frequency of seeing each type of contamination. If there is a single primordial D/H then we should find many quasars which all show this value, with a tail of others showing apparently more D/H, because of contamination. We will be able to predict this tail, or correct individual D/H for the likely level of contamination. When we attempted to correct for contamination in the past [53,68,110], we used the statistics of H I in the Lyz forest because we do not have equivalent data about the H I near to the special LLS which are simple enough to show D/H. Such data will accumulate at about the same rate as do measurements of D/H, since we can look for fake D which is shifted to the red (not blue) side of the H I.

There are large differences in the reliability and credibility of different claimed measurements of D/H in quasar spectra, and hence much is missed if all measurements are treated equally. It also takes time for the community to criticize and absorb the new results. Early claims of high D/H [103,111] in Q0014+8118 are still cited in a few recent papers, after later measurements [72] with better data, have shown that this quasar gives no useful information, and that the high D/H came from a “spike” in the data which was unfortunately an artifact of the data reduction.

In summary, the lack of high quality spectra, which complicates assessment of contamination by H, is the main reasons why there remains uncertainty over whether some absorbers contain high D.

4.5. Why we believe that the D/H is Primordial

Here we review why we believe that the low D/H is primordial. These arguments are best made without reference to the other nuclei made in BBN, because we wish to use the abundances of these nuclei to test SBBN theory.

- D/H is known to be low in four widely separated locations: towards three quasars, and in the ISM of our Galaxy.
- The extraction of D/H from quasar spectra is extremely direct, except for corrections for contamination by H, which make D/H look too large.
- Since contamination is common, all data are consistent with low D/H, and no data require high D/H.
- High D/H is rare, or non-existent, because it should be easy to see in many existing spectra, but we have no secure examples.
- The low D/H in the quasars, pre-solar system and in the ISM today are all consistent with Galactic chemical evolution.
- The quasar absorption systems are large – many kpc across, as was the initial volume of gas which collapsed to make our Galaxy.
- The abundance of the metals in the quasar cases are very low, and much too low for significant (>1%) destruction of D in stars.
- The quasar absorbers are observed at high redshifts, when the universe is too young for low mass stars to have evolved to a stage where they eject copious amounts of gas.
- The ratio of the abundances of Si/C in the absorbers is normal for old stars in the halo of our galaxy, indicating that these elements were made in normal stars.
- In the quasar absorbers, the temperatures and velocities are low, which argues against violent events immediately prior to the absorption.

© Physica Scripta 2000
• If BBN D/H were high, the hypothetical destruction of D would have to reduce D/H by similar large amounts in all four places.
• The above observations make local destruction of D unlikely.
• There are no known processes which can make or destroy significant D.
• Global destruction of D by photodissociation in the early universe requires very specific properties for a hypothetical particle, and is limited by other measures of \( \Omega_b \).

4.6. Conclusions from D/H from quasars
Most agree that D is providing the most accurate \( \eta \) value [11], although some have one remaining objection, that there might also be quasar absorbers which show high values of D/H [7,112].

The D/H from our group (Burles, Kirkman, Fan [62–64,97]), together with over 50 years of theoretical work and laboratory measurements of reaction rates, leads to the following values for cosmological parameters (unlike most errors quoted in this review, which are the usual \( 1 \sigma \) values, the following are quoted with 95% confidence intervals):

- \( D/H = 3.4 \pm 0.5 \times 10^{-5} \) (measured in quasar spectra),
- \( \eta = 5.1 \pm 0.5 \times 10^{-10} \) (from BBN and D/H),
- \( Y_p = 0.246 \pm 0.0014 \) (from BBN and D/H),
- \( \bar{\Omega}_{b} = 3.5^{+1.4}_{-0.9} \times 10^{-10} \) (from BBN and D/H),
- 411 photons cm\(^{-3}\) (from the CMB temperature),
- \( \rho_b = 3.6 \pm 0.4 \times 10^{-31} \) g cm\(^{-3}\) (from CMB and \( \eta \)),
- \( \Omega_{b}h^2 = 0.019 \pm 0.002 \) (from the critical density \( \rho_c \)),
- \( N_{c} < 3.29 \) (from BBN, D/H and \( Y_p \) data).

If we accept that D/H is the most accurate measure of \( \eta \), then observations of the other elements have two main roles. First, they show that the BBN framework is approximately correct. Second, the differences between the observed and predicted primordial abundances teach us about subsequent astrophysical processes. Recent measurements of \(^4\)He [1] agree with the predictions. It appears that some \(^3\)Li has been destroyed in halo stars [113], and \(^3\)He is both created and destroyed in stars [134].

5. Helium
The high abundance of \(^4\)He allows accurate measurements in many locations. However, \(^4\)He is also produced by stars, and since such high accuracy is required, the primordial abundance is best measured in locations with the least amounts of stellar production. High accuracy is desired, since D/H predicts \( Y_p \) to within 0.0014 (\( \delta Y_p / Y_p = 0.006 \), 95% confidence), which is well beyond the typical accuracy of astronomical abundance determinations. In the local ISM, the amount of \(^4\)He from stars is about \( Y = 0.01 – 0.04; \) much less than \( Y_p \), but ten times the desired accuracy for \( Y_p \).

Helium has been seen in the intergalactic medium, where Carbon abundances are < 0.01 solar, and possibly zero in much of the volume. Strong absorption is seen from the He II Lyz line at 304Å in the redshifted spectra of quasars [114], however it is difficult to obtain an abundance from these measurements, because nearly all He is He III which is unobservable, and we do not know the ratio He II/He to within an order of magnitude. The strength of the He II absorption does mean that there is abundant He in the intergalactic gas [115], which has low metal abundances, which is consistent with BBN, and probably not with a stellar origin for the \(^4\)He.

The best estimates of the primordial abundance of He are from ionized gas surrounding hot young stars (H II regions) in small galaxies. The two galaxies with the lowest abundances have 1/55 and 1/43 of the solar abundance. The \(^4\)He and H abundances come from the strengths of the emission lines which are excited by photons from near by hot stars.

Values for \( Y_p \) from these extragalactic H II regions have been reported with small errors for more than 25 years, e.g.:

- \( Y_p = 0.216 \pm 0.02 \) [44],
- \( Y_p = 0.230 \pm 0.004 \) [116],
- \( Y_p = 0.234 \pm 0.008 \) [117],
- \( Y_p = 0.236 \pm 0.005 \) [118],
- \( Y_p = 0.228 \pm 0.005 \) [119],
- \( Y_p = 0.234 \pm 0.002 \pm 0.005 \) [46] (random, and systematic errors).
- \( Y_p = 0.246 \pm 0.0014 \) (95% prediction from low D/H and SBBN).

These values are lower than the value now predicted by low quasar D/H and they appear incompatible, because of the small errors. However Skillman et al. [120] argued that errors could be much larger than quoted, allowing \( Y_p < 0.252 \), and Pagel [121] (and private communication 1994) agreed this was possible.

The measurement of \( Y_p \) involves three steps. Emission line flux ratios must be measured to high accuracy, which requires good detector linearity and flux calibration, and corrections for reddening and stellar He I absorption. These fluxes must be converted to an abundance, which requires correction for collisional ionization and neutral He. Correction for unseen neutral He depends on the spectral energy distribution adopted for the ionizing radiation and might change \( Y_p \) by 1 – 2 percent. Then the primordial abundance must be deduced from the \( Y \) values in different galaxies.

Izotov, Thuan and Lipovetsky [122,123] have been pursuing a major observational program to improve the determination of \( Y_p \). They have found many more low metallicity galaxies and have been reporting consistently higher \( Y_p \) values, most recently in their clear and persuasive paper [1]:

- \( Y_p = 0.244 \pm 0.002 \) from regression with O/H and
- \( Y_p = 0.245 \pm 0.001 \) from regression with N/H.

The four main reasons why these values are higher are as follows, in order of importance [1,124,125]. (Skillman, and Thuan personal communications 1998).

1. When stellar He I absorption lines underlying He emission lines are not recognized, the derived \( Y_p \) is too low. This is a important for IZw18 [124] which has the lowest metallicity and hence great weight in the derivation of \( Y_p \), and perhaps for many other galaxies.
2. The emission line fluxes must be corrected for collisional excitation from the metastable level. At low abundances, which correlate with high temperatures, these corrections can be several percent. The amount of correction depends on the density. There
are no robust ways to measure these densities, and differing methods, used by different groups, give systematically different results. Izotov and Thuan [124] solve for the He II density, while Olive, Skillman and Steigman [46] use an electron density from the S II lines.

3. Izotov and Thuan [124] have spectra which show weaker lines, and they use the five brightest He lines, while Olive et al. [46] usually use only Heli 6678.

4. Izotov and Thuan [1,124] correct for fluorescent enhancement, which increases the Y values from a few galaxies.

For these reasons Izotov and Thuan [124] obtain higher Y values for individual galaxies which have also been observed by Olive, Skillman and Steigman [46]. Izotov and Thuan [124] find a shallower slope for the regression to zero metal abundance (see [11] Fig. 6), and most importantly, using higher quality Keck telescope spectra, they obtain high \( Y_p = 0.2452 \pm 0.0015 \) (random errors), from the two galaxies with the lowest metal abundances [126].

These measurement difficulties, combined with the recent improvements, lead most to conclude that the \( Y_p \) is in accord with the SBBN. The Izotov and Thuan [1] values are very close to the low D/H predictions, while the lower \( Y_p \) quoted by Olive [7], 0.238 \( \pm 0.002 \pm 0.005 \), is also consistent when the systematic error is used.

It is clear that the systematic errors associated with the \( Y_p \) estimates have often been underestimated in the past, and we propose that this is still the case, since two methods of analyzing the same Helium line fluxes give results which differ by more than the quoted systematic errors. While the Izotov and Thuan [124] method has advantages, we do not know why the method used by Olive, Skillman and Steigman [46] should give incorrect answers. Hence the systematic error should be larger than the differences in the results: 0.007 using the most recent values, or 0.011 using earlier results.

6. \(^3\)He

The primordial abundance of \(^3\)He has not been measured. This is most unfortunate, since it is nearly as sensitive as D to the baryon density during BBN. \(^3\)He is harder to measure than D because the difference in wavelength of \(^3\)He and \(^4\)He lines is smaller than for D, and the Lyman series lines of He II, main absorption lines of He in the IGM, are in the far ultraviolet at 228–304 Å which is hard to observe because of absorption in the Lyman continuum of H I at 8812 Å.

Rood, Steigman and Tinsley [127] argued that it was unlikely that \(^3\)He could be used to complement cosmological information from D because low mass stars should make a lot of \(^3\)He, increasing the current ISM value to well above that in the pre-solar system ISM, and in potential conflict with observations at that time. This conflict has been confirmed. The pre-solar and current \(^3\)He abundances are similar [128], in contradiction with expectation [129,130], for unknown reasons. Measurements do show enhanced \(^3\)He in Planetary nebulae, as expected from the production in the associated low mass stars, but this is not reflected in the ISM as a whole.

It was suggested ([131], see review by Hata et al. [132]) that the uncertainty over the amount of destruction of D could be circumvented using the sum of the abundances of D + \(^3\)He, since the destroyed D should become \(^3\)He, and \(^3\)He is relatively hard to destroy. The primordial D + \(^3\)He should then be \( \leq \) the same sum observed today, as more \(^3\)He is made in stars over time. However, there are two problems with this scenario. First, the \(^3\)He should increase over time, which it does not, implying that some stars destroy \(^3\)He, and second, the \(^3\)He abundance should be about constant in the ISM today, which it appeared not to be in early data [133]. Hence, just prior to the measurement of D in quasars, most concluded that D + \(^3\)He in the Galaxy does not provide secure cosmological information [10,45,132].

Balser et al. [134] report on a 14 year program to measure \(^3\)He in the Galactic H II regions. Using models for the gas density structure, they find an average \(^3\)He/H = 1.6 \( \pm 0.5 \times 10^{-5} \) for a sub-sample of seven simple nebulae. No variation is seen with Oxygen abundance over a factor of ten, and there is little scatter [135]. This value may represent the average in the ISM today, but it is not known how to use this to obtain primordial abundances.

These measurements are relevant to stellar nucleosynthesis and Galactic chemical evolution, and are consistent with a cosmological origin for the \(^3\)He, but we suggest that gas with much lower metal abundances will need to be observed to derive a secure primordial abundance for \(^3\)He.

7. Lithium

Lithium is observed in the solar system, the atmospheres of a wide variety of stars and in the ISM. Arnould and Forestini [136] review light nuclei abundances in a variety of stars and related stellar and interstellar processes, while halo stars are reviewed by [48,49,113,137].

Old halo stars which formed from gas which had low iron abundances show approximately constant \(^7\)Li/H \( \approx 1.6 \times 10^{-10} \) and little variation with iron abundance or surface temperature from 5600 – 6300 K. The lack of variation amongst these “Spite plateau” stars [138] (references in [7]) shows that their \(^7\)Li is close to primordial.

Since the halo stars formed about ten times more \(^7\)Li has been produced in the inner Galaxy. Abundances of \(^7\)Li/H \( \approx 10^{-9} \) are common, and some stars show more, presumably because they make \(^7\)Li. Stars typically destroy \(^7\)Li when they evolve, accounting for the low abundances, \( < 10^{-11} \), in evolved stars. Stars with deeper convection zones, such as halo stars with lower surface temperatures, show less \(^7\)Li, because they have burnt it in their interiors.

Here, and in the next section on \(^6\)Li, we will mention the following topics:

- measurement of current surface abundances on the Spite plateau,
- change in \(^7\)Li with iron abundance,
- creation of \(^7\)Li and \(^6\)Li after BBN and prior to halo star formation,
- depletion of these nuclei in the atmospheres of the halo stars,
- stars with differing \(^7\)Li, and
- gravitational settling.
The recent homogeneous data on 22 halo stars, with a narrow range of temperature on the “Spite plateau”, have very small random errors and show that most (not all) stars with similar surface properties have the same $^7\text{Li}/H$ [113]. Earlier data showed more scatter, which some considered real (references in [139]), and hence evidence of depletion. The Ryan, Norris, and Beers [113] sample shows a clear increase of $^7\text{Li}$ with iron abundance, as had been found earlier. This trend appears to be real, because the data and stellar atmosphere models used to derive the $^7\text{Li}$ abundance do not depend on metallicity. But it was not found by Bonifacio and Molaro [140], perhaps because of larger scatter in temperatures and iron abundance. This trend is not understood, and there are several possible explanations. It may have been established in the gas from which the stars formed, perhaps from cosmic rays in the ISM, or from AGB stars. Alternatively, we speculate that it might instead relate to depletion of the $^7\text{Li}$ in the stars. In either case, the BBN $^7\text{Li}$ will be different from that observed: smaller if the $^7\text{Li}$ was created prior to the star formation, and higher if the trend is connected to destruction in the stars. More on this below.

Creation of $^7\text{Li}$ in the ISM by cosmic ray spallation prior to the formation of the halo stars is limited to 10–20% because Be would also be enhanced by this process [7,113].

A clear summary of arguments for and against significant depletion is given by Cayrel [48]. There are two main reasons why depletion is believed to be small: the negligible dispersion in $^7\text{Li}$ for most halo stars on the plateau, and the presence of $^6\text{Li}$. The main arguments for depletion are that it is expected, it clearly occurs in some stars, some halo stars on the plateau show differing abundances, and stars in the globular cluster M92 which have similar ages, composition and structure, show a factor of two range in $^7\text{Li}$.

Different depletion mechanisms include mixing induced by rotation or gravity waves, mass loss in stellar winds and gravitational settling. Some models predict either variation from star to star, or trends with temperature, which are not seen for the stars on the plateau. For example, the rotationally induced mixing model implies that stars with different angular momentum histories will today show different $^7\text{Li}$. Ryan, Norris and Beers [113] find that the small scatter in their data, especially after the removal of the correlation with the iron abundance, limits the mean depletion in these models to < 30%, much less than the factor of two needed to make $^7\text{Li}$ agree exactly with the predicted abundance from low D/H.

Some stars which should lie on the plateau have very low $^7\text{Li}$, while others show a range of abundances (see ref. in [113]). Differences are also seen between halo field stars [113] and stars in the globular cluster M92 [141,143], which show a factor of two spread in $^7\text{Li}$. These observations are not understood.

Gravitational settling (diffusion) of heavier elements reduces the $^7\text{Li}$ in the atmospheres of stars. However, the depletion should be most in the hottest (highest mass) stars, which is not seen, and not understood. Vauclair and Charbonnel [144] proposed that small stellar winds might be balancing the settling. Vauclair and Charbonnel [145] noted that the peak abundances inside the stars are independent of both mass and iron abundance. Normal stellar models predict that these peak abundances will not be seen in the stellar atmospheres, because convection does not reach this far down into the stars. However they point out that if some mechanism does mix gas from the $^7\text{Li}$ peak zone into the bottom of the convection zone then the stars on the plateau would have similar abundances as observed. Assuming that the observed abundances are those from the peaks inside the stars, they find that the initial abundance in the stars was $^7\text{Li}/H = 2.2 \pm 0.6 \times 10^{-10}$, without free parameters, which is still below but statistically consistent with the prediction from low D of $3.5_{-0.9}^{+1.1} \times 10^{-10}$.

7.1. Primordial $^7\text{Li}$

Ryan, Norris and Beers [113] conclude $^7\text{Li}/H \simeq 10^{-10}$, with small random errors and three sources of systematic error, each up to a factor of 1.3, from the effective temperatures, stellar atmospheres and enhancement prior to star formation. Bonifacio and Molaro [140] found $^7\text{Li}/H = 1.73 \pm 0.05 \pm 0.2 \times 10^{-10}$. These abundances are both below the value of $3.5_{-0.9}^{+1.1} \times 10^{-10}$ (95%) from BBN and our D/H, but unlike [113], we feel they are not inconsistent given the quoted systematic errors, the lack of understanding of depletion, and the variation amongst similar stars. We do not know how to estimate the systematic errors connected with these issues. Given the comparative simplicity of D/H, we prefer to use it and SBBN, and we stick with our earlier suggestion [53] that $^7\text{Li}$ in the Spite plateau halo stars is depleted by about a factor of two. Most, but not all agree that this is reasonable. Depletion by much larger factors, which was discussed a few years back, is now our of favor because of improved models. Improved modelling of rotational mixing, has lead to better fits to high metal abundance (population I) stars, which can be applied to halo (population II) stars, while the initial rotation rates of the halo stars may be lower than was assumed (Deliyannis private communication).

In summary, both the data and theory tells us that the $^7\text{Li}$ on the Spite plateau is not exactly the primordial value. The correction is probably small, less than a factor of two, but we do not yet know its value.

If we are to attain a primordial $^7\text{Li}$ abundance we must either (1) understand why its abundance varies from star to star, and learn to make quantitative predictions of the level of depletion, or (2) make measurements in relatively unprocessed gas.

We are optimistic that primordial $^7\text{Li}$ will be measured to high precision. Compared to D and He, the observations are simple: 15 – 20 mÅ absorption lines in relatively empty spectra of often bright stars ($V = 11$). The best data have small errors. We anticipate that further studies will determine the amount of $^7\text{Li}$ produced prior to the formation of the stars, and the subsequent depletion in these stars. The possible increase in $^7\text{Li}$ with iron abundance is a clue, as are the $^6\text{Li}$, Be and B abundances in the same stars.

7.2. $^6\text{Li}$

The primordial $^6\text{Li}$ abundance has not been observed, but $^6\text{Li}/H$ has been measured in two stars on the Spite plateau. The abundance is well below that expected from SBBN, but $^6\text{Li}$ is used to help determine the primordial BBN $^7\text{Li}$ abundance in two ways. First, the presence of $^6\text{Li}$ limits the amount of destruction of $^7\text{Li}$, because $^6\text{Li}$ is more fragile
than $^7$Li. Second, if the observed $^6$Li was made prior to the formation of the stars, then some, perhaps much $^7$Li [139], may have been made by similar processes. The first point is often presented as evidence that the $^7$Li on the Spite plateau is close to primordial (e.g. less that a factor of two depletion, according to [78]), but the second point is cause for caution.

$^6$Li has been detected in only two stars on the Spite plateau, because the absorption line at 6707.97Å is weak and fully blended with $^7$Li at 6707.81Å. This is a difficult observation. The $^6$Li makes the absorption line slightly asymmetric, and this is detected using models of the line broadening, which are tested on other absorption lines which are expected to have similar profiles because they arise in the same layers of the stellar atmosphere. Following the impressive first detection by [146] and [147], and Cayrel et al. [148] report $^6$Li/$^7$Li = 0.052 ± 0.019 in HD84937, while Smith, Lambert and Nissen [139] report $^6$Li/$^7$Li = 0.06 ± 0.03 in BD + 26 3578. It is not known whether these detections are representative of halo stars on the Spite plateau. Most assume that they are, but they could be above normal, perhaps by a lot; Smith et al. report $^6$Li/$^7$Li = 0.00 ± 0.03 for six other stars.

The SBBN makes $^6$Li/H ≈ 10$^{-13.9}$ [149,150], using the $\eta$ from D/H, which is 500 times less than the measured abundance of 7 $\times$ 10$^{-12}$ in the two halo stars. The SBBN isotope ratio is $^6$Li/$^7$Li = 3 $\times$ 10$^{-3}$, a factor of 2000 less than observed in these two stars. This is not considered a contradiction with SBBN, because $^6$Li, and some $^7$Li at the same time, can be made elsewhere.

The $^6$Li is usually assumed to have been present in the gas when the stars formed, but it could be made later, e.g. when cosmic rays strike the star or in stellar flares [141]. Production by cosmic rays in the ISM prior to the star formation is most favored [142]. With this assumption, the effects on $^7$Li can be calculated in two steps. First, determine the ratio of $^6$Li/ $^7$Li in the production process (the production ratio). Second, correct for the depletion of $^6$Li in the stars to determine the initial abundance of $^6$Li. The amount of $^7$Li produced along with the initial $^6$Li is then specified.

Cosmic rays in the early ISM could have made $^6$Li and some $^7$Li prior to the formation of the Spite plateau halo stars. The production ratio depends on the reaction and energies (e.g. [139]). Two reactions of cosmic rays in the ISM are considered to produce $^6$Li. Smith, Lambert and Nissen [139] find that $^6$Li/Be ratios imply that most $^6$Li was made in $\alpha$ + $\alpha$ fusion reactions, rather than in spallation (e.g. O + p $\rightarrow$ $^6$Li) which is favored by [142] and [150]. The production ratio is $^6$Li/$^7$Li $\approx$ 2 for the $\alpha$ + $\alpha$ reaction.

Standard stellar models [141] predict that much of the initial $^6$Li will have been destroyed in the stars. The more that was destroyed, the more $^6$Li and non-BBN $^7$Li should have been in the initial gas to give the observed abundances. Depending on the destruction mechanism, the destruction of $^6$Li may also destroy $^7$Li, but this is usually ignored.

When we choose the amount of depletion of $^6$Li, we fix the amount present when the stars formed. If the $^6$Li has been depleted by a large factor, $\approx$ 100, then the stars would have begun with $^6$Li/$^7$Li similar to the production ratio, and essentially all of the $^7$Li would be non-primordial [139], which is an unusual conclusion [196].

Ryan, Norris and Beers [113] assume that 50% of the $^6$Li and none of the $^7$Li was destroyed, and use a production ratio of 1.5 to conclude that the BBN $^7$Li was 0.84 of that now in the stars. Since nearly all observations of Li are made at low resolution, the $^6$Li and $^7$Li lines are not resolved, they correct for the $^6$Li. If the two stars with observed $^6$Li are normal, then the BBN $^7$Li is about 79% of the observed Li absorption.

Many other papers discuss this topic. Olive and Fields [14] give a summary. Cayrel et al. [148] use models for the formation of Li, Be and B and calculate the expected abundance of $^6$Li when the stars formed, and find that the observed abundance implies little depletion of $^6$Li, and a $^7$Li depletion of less than 25%. Vangioni-Flam et al. [150] also argue that $^6$Li is not much depleted, and find that its BBN abundance, extrapolated back to before the production by spallation, is compatible with a BBN abundance of $3 \times 10^{-13} – 5.6 \times 10^{-14}$.

All eagerly await the measurement of $^6$Li, together with Beryllium, in more stars.

8. Beryllium

The primordial abundance of Beryllium has not been observed. The production in SBBN is $^{9}$Be/H $< 10^{-17}$ [149,150], orders of magnitude below the observed level. Inhomogeneous BBN allows much higher abundances, possibly approaching detection [149].

Be is observed. It is created in the ISM when cosmic rays strike C, N and O nuclei, and it is destroyed in stars. It is difficult to use Be to constrain the cosmic ray production of Li because the production ratio is highly model dependent [151]. Beryllium is observed in the atmospheres of halo stars, including those on the Spite plateau. Boesgaard et al. [152] have found that Be increases with Iron, and that Be increases 8 times faster than Oxygen, a rate consistent with cosmic ray creation. There is some evidence for a spread in Be as a given Fe/H, but no sign of a primordial plateau, down to Be/H $= 10^{-13.5}$.

9. Are the different nuclei concordant or is there a crisis?

Nearly everyone believes that the primordial abundances are consistent with BBN (e.g. [1,7,11,72,153,154]), but there are many lingering questions about the measurements. The reader will readily detect the two attitudes described by Audouze [54]: “optimistic”, and “agnostic and perhaps heretical” in many papers. Each of us tends to adopt differing attitudes for each nucleus and astrophysical processes. This review favors D/H because it is simple and familiar.

Steigman [109] noted that there was “a hint of an emerging crisis” because the “He abundances appeared to be lower than expected using the $\eta$ from the other nuclei, but he recommended much more careful study of the uncertainty in BBN predictions, chemical evolution, and observational uncertainties including systematic effects. Hata et al. [155] and Steigman [156] stated that “there is a conflict”, referring to the differences in $\eta$ implied by low D and low $Y_p$ values.

Whether or not there is a crisis depends on the confidence assigned to the answers to three questions:
• Is primordial D/H low everywhere, or are there also some places with high values?
• Is Y_\beta low, high, or uncertain?
• Has ^7Li in halo stars been depleted by a factor of two?

Some combinations of answers are not consistent with SBBN. Recent data make low D/H seem secure in three quasars plus the ISM, hence the issue is whether there are also other places with high primordial D. Low D/H is compatible with high Y_\beta and depleted ^7Li, but not with low Y_\beta or undepleted ^7Li. High D is compatible with low Y_\beta and undepleted ^7Li, but it is incompatible with the three sites which show low D/H and with Galactic chemical evolution. A factor of ten D depletion would be required in all four places. Low Y_\beta is compatible with undepleted ^7Li and high D, but is incompatible with the low D.

A good case has been made for high Y_\beta, explanations have been given why earlier results gave lower values, and the uncertainty appears to be larger than quoted. Hence D and Y_\beta are in agreement.

The ^7Li observed in stars on the Spite plateau is lower than values consistent with low D. Depletion might provide an explanation, but the amount of depletion and the dominant mechanism are not known. The lack of scatter implies little depletion, less than expected, which some, [49,113], conclude is not sufficient to match low D. Bonifacio and Molaro [140] find a higher ^7Li, but still below the level required to match low D without depletion.

10. Non-standard BBN

The many different forms of non-standard BBN have been reviewed by Coles and Lucchin [22] and Jedamzik [157]. Much work has been devoted to inhomogeneous baryon distributions during BBN, additional relativistic particles, decaying particles, large neutrino chemical potentials (e.g. [158]), sterile neutrinos (e.g. [159]), magnetic fields (e.g. [160]), anti-matter domains (e.g. [161]), and alternative theories of gravity (e.g. [162]).

10.1. Inhomogeneous BBN

Following early discussion of inhomogeneous BBN (IBBN) by Epstein and Lattimer [163] and Hogan [164], many detailed studies of different types of inhomogeneity have been published. Malaney and Mathews [165] and Kainulainen, Kurki-Suonio, and Sihvola [154] give reviews. IBBN has been discussed to allow larger Omega_b than standard BBN, to allow differing values of D/H in the universe, and to reconcile low Y_\beta with low D/H values.

One exciting goal of this work was to determine whether inhomogeneity could give the observed abundances with Omega_b much larger than the usual value, and perhaps large enough to account for all gravitating matter, without the need for non-baryonic dark matter (e.g. [104,108,164]). The best upper limit on Omega_b comes from the lowest observed D/H, which until recently was in the ISM. In standard BBN, a higher Omega_b is ruled out because BBN would make less than the observed ISM D/H, and no other way to make D is known. In IBBN the D/H in the ISM comes from low density regions, allowing a higher average density. The current observations, with some exceptions, fit SBBN well, and hence IBBN allows only a slight increase in Omega_b.

Inhomogeneities can be imagined over a wide range of distance scales. The smallest scales, < 10^{-5} pc, mix prior to BBN, leaving homogeneous SBBN. Small scales mix during BBN. Intermediate scales which mix after BBN give abundances which are constant in space today, but the abundances are different from SBBN with the same Omega_b. Extra D would be made in regions with low density during BBN, giving enhanced D/H everywhere today. Large scales (> 1 kpc) may have avoided mixing, and could give different D/H in different locations today. The near isotropy of the CMB limits inhomogeneities to < 1 Mpc.

Jedamzik and Fuller [47] found it difficult to match observed abundances of ^7Li with large scale primordial isocurvature baryon number fluctuations. Most overly dense regions of the universe with masses greater than the local baryon Jeans mass would have to collapse (to prevent observation of the ^7Li which is overproduced) and smaller scale fluctuations would have to be absent or suppressed. Gnedin, Ostriker and Rees [166] and Copi, Olive and Schramm [167] reached similar conclusions. Copi, Olive and Schramm [168] also showed that large scale (> 1 Mpc) isocurvature perturbations conflict with the smoothness of the CMB, but do not rule out inhomogeneity [52].

Kainulainen, Kurki-Suonio, and Sihvola [154] review IBBN. The Omega_b can be higher than in SBBN provided the distance scale of the baryon inhomogeneity is near to optimal to maximize neutron diffusion effects. The distance scale expected for inhomogeneities arising in the electroweak transition are too small (10^{-6} to 10^{-5} pc today) to have major effects, although not below the accuracy of BBN abundance calculations. QCD inhomogeneities are not so limited. However, a low D/H < 5 x 10^{-5} still requires Y_\beta > 0.240 even in IBBN, which helps reconcile low D/H and low Y_\beta measurements, especially when we accept that the errors on Y_\beta are larger than quoted.

Rehm and Jedamzik [161] studied BBN in the presence of anti-matter domains. Annihilation is preferentially on neutrons, and in a limiting case the resulting universe is without light nuclei, in violation of the measured abundances. With small amount of anti-matter, both the low Y_\beta and low D/H measurements are matched.

Early results for IBBN looked promising. Today it appears that the scales are too small to have major effects, and measurements of primordial abundances, especially upper limits on ^7Li, with modest depletion (< factor of two), are usually used to give limits on the inhomogeneity, rather than to argue that inhomogeneity helps explain discordant data or allows different conclusions about Omega_b.

10.2. The number of relativistic particles and their decays

The main idea here is that the ^4He abundance depends on the number of relativistic particles during BBN. Extra particles, such as neutrinos or supersymmetric particles, which are relativistic during BBN, lead to faster expansion, larger n/p and a larger Y_\beta.

Steigman, Schramm and Gunn [169] calculated that BBN limited the number of families to N_e < 5 to match the ^4He abundance. The range allowed by SBBN and laboratory measurements have both narrowed over the years and agree well today [11,170]. A recent update [6] gives N_e < 3.20 (95%) from SBBN, although a larger range is obtained if a wider variety of measured abundances are
11. Cosmological baryon density

The measurement of the baryon density is now a highly active area of research. In the coming years, we anticipate that higher accuracy measurements of the baryon density, from the CMB, clusters of galaxies, and the Ly$\alpha$ forest, will give a new rigorous test of BBN [11]. This test can be viewed from two directions. First, we can use the baryon density to fix the last free parameter in SBBN, and second, we can compare the different baryon density measurements, which should be identical if SBBN is correct, and all baryons are counted in the measurements made at later times.

In addition to BBN, the baryon density is measured in four ways: in the IGM, in clusters of galaxies, using simulations of galaxy formation, and directly from the CMB. All agree with the value from SBBN using low D/H, but today they are each about an order of magnitude less accurate.

11.1. $\Omega_b$ from the IGM Lyman-$\alpha$ forest absorption

The gas in the IGM is observed through H I Ly$\alpha$ absorption in the spectra of all QSOs. Gunn and Peterson [176] discussed how redshift produces continuous absorption in the ultraviolet spectra of QSOs. Density fluctuations in the IGM trun this continuous absorption into the Ly$\alpha$ forest absorption lines. The IGM fills the volume of space, and at redshifts $z > 1$ [177] it contains most of the baryons.

The baryon density is estimated from the total amount of H I absorption, correcting for density fluctuations which change the ionization. The gas is photoionized, recombin- ation times are faster in the denser gas, and hence this gas shows more H I absorption per unit gas. Using the observed ionizing radiation from QSOs, we have a lower limit on the ionizing flux, and hence a lower limit on the ionization of the gas. If the gas is more ionized than this, then we have underestimated the baryon density in the IGM.

Three different groups obtained similar results [178–180]: $\Omega_b > 0.035 h_{100}^{-2}$. This seems to be a secure lower limit, but not if the IGM is less ionized than assumed, because there is more neutral gas in high density regions, and these were missing from simulations which lack resolution.

We do not have similar measurements at lower redshifts, because the space based data are not yet good enough, and the universe has expanded sufficiently that simulations are either too small in volume or lack resolution. Cen and Ostriker [177] have shown that by today, structure formation may have heated most local baryons to temperatures of $10^5$–$10^7$ K, which are extremely hard to detect [177,181].

11.2. Clusters of galaxies

Clusters of galaxies provide an estimate of the baryon density because most of the gas which they contain is hot and hence visible. The baryons in gas were heated up to 8 keV through fast collisions as the clusters assembled. The mass of gas in a cluster can be estimated from the observed X-ray emission, or from the scattering of CMB photons in the Sunyaev-Zel'dovich (SZ) effect. Other baryons in stars, stellar remnants and cool gas contribute about 6% to the total baryon mass.

The cosmological baryon density is obtained from the ratio of the baryonic mass to the total gravitating mass [182]. Numerical simulations show that the value of this ratio in the clusters will be similar to the cosmological average, because the clusters are so large and massive, but slightly smaller, because shock heating makes baryons more extended than dark matter [183,184]. The total mass of a cluster, $M_t$, can be estimated from the velocity dispersion of the galaxies, from the X-ray emission, or from the weak lensing of background galaxies. We then use $\Omega_b/\Omega_m \approx M_b/M_t$. The baryon fraction in clusters in the last factor is about 0.10$ h_{100}^{-2}$ (SZ effect: [185]), or 0.05–0.13$ h_{100}^{-3/2}$ (X-ray: [186]), or 0.11$ h_{100}^{-3/2}$ (X-ray: [187,188]). Using $\Omega_m = 0.3 \pm 0.2$ from a variety of methods [189], we get $\Omega_b \approx 0.03$, with factor of two errors. These $\Omega_b$ estimates count only observed baryons.

11.3. Local dark baryonic matter

The baryon density estimated in the Ly$\alpha$ forest at $z \approx 3$ and in local clusters of galaxies are both similar to the that from
SBBN using low D/H. This implies that there is little dark baryonic matter in the universe [190]. This result seems conceptually secure, since there is little opportunity to remove baryons from the IGM at $z < 3$ or to hide them in dense objects without making stars which we would see [191], and the clusters are believed to be representative of the contents of the universe as a whole today. However, the numerical estimates involved are not yet accurate enough to rule out a significant density (e.g. 0.5 $\Omega_b$) of baryonic MACHOS.

11.4. Simulations of the formation of Galaxies
Ostriker (private communication) notes that the $\Omega_b$ can be constrained to a factor of two of that derived from SBBN using low D/H by the requirement that these baryons make galaxies. Semi-analytic models can also address the distribution of baryons in temperature and the total required to make observed structures (Frenk and Baugh, personal communication).

11.5. CMB
The baryon density can be obtained from the amplitude of the fluctuations on the sky of the temperature of the CMB. The baryons in the IGM at $z \simeq 1300$ scattered the CMB photons. The amplitude of the fluctuations is a measure of $\Omega_b h^2$, and other parameters. Published data favor large $\Omega_b$, with large errors, however dramatic improvements are imminent, and future constraints may approach or exceed the accuracy of $\Omega_b$ from SBBN [192,193].

12. The achievements of BBN
Standard Big Bang Nucleosynthesis (SBBN) is a major success because the theory is well understood, close connections have developed between theory and observation, and observations are becoming more reliable.

The early attempts to include physics in the mathematical model of the expanding universe lead to an understanding of the creation of the elements and the development of standard big bang theory, including the predictions of the CMB.

The general success of SBBN is based on the robustness of the theory, and the resulting predictions of the abundances of the light nuclei. The abundances of $^4$He, $^7$Li and D can be explained with a single value for the free parameter $\eta$, and the implied $\Omega_b$ agrees with other estimates.

This agreement is used to limit physics beyond that in SBBN, including alternative theories of gravity, inhomogeneous baryon density, extra particles which were relativistic during BBN, and decays of particles after BBN. After decades of detailed study, no compelling major departures from SBBN have been found, and few departures are allowed.

Using SBBN predictions and measured abundances, we obtain the best estimates for the cosmological parameters $\eta$ and $\Omega_b$.

The abundances of D, $^4$He and $^7$Li have all been measured in gas where there has been little stellar processing. In all three cases, the observed abundance are near to the primordial value remaining after SBBN. The D/H measured toward QSOs has the advantage of simplicity: D is not made after BBN, there are no known ways to destroy D in the QSO absorbers, and D/H can be extracted directly from the ultraviolet spectra, without corrections. There are now three cases of low D/H which seem secure. There remains the possibility that D/H is high in other absorbers seen towards other QSOs, but such high D must be very rare because no secure cases have been found, yet they should be an order of magnitude easier to find than the examples which show low D.

We use low D/H as the best estimator of $\eta$ and the baryon density. SBBN then gives predictions of the abundance of the other light nuclei. These predictions suggest that $Y_P$ is high, as suggested by Izotov, Thuan and collaborators. Low D also implies that $^7$Li has been depleted by about a factor of two in the halo stars on the Spite plateau, which is more than some expect.

The high $\Omega_b$ from SBBN plus low D/H is enough to account for about 1/8th of the gravitating matter. Hence the remaining dark matter is not baryonic, a result which was established decades ago using SBBN and D/H in the ISM.

The near coincidence in the mass densities of baryons and non-baryonic dark matter is perhaps explained if the dark matter is a supersymmetric neutralino [194].

At redshifts $z \simeq 3$ the baryons are present and observed in IGM with an abundance similar to $\Omega_b$. Hence there was little dark, or missing baryonic matter at that time. Today the same is true in clusters of galaxies. Outside clusters the baryons are mostly unseen, and they may be hard to observe if they have been heated to $10^5 - 10^7$K by structure formation.

The number of free parameters in BBN has been decreasing over the years: Fermi and Terkovich gave nuclear reaction rates, the half-life of the neutron was measured, and then the number of families of neutrinos was measured. In standard BBN we are now left with one parameter, the baryon density, which is today measured with D/H using SBBN. When, in the next few years, this parameter is also measured, SBBN will have no free parameters. When free parameters can be adjusted to obtain consistency with the data, it is hard to tell if a hypothesis is correct. The agreement between SBBN theory and measurement has grown stronger over the decades, as more parameters were constrained by independent measurements, and abundance measurements improved. This is the most convincing evidence that BBN happened and has been understood.

Acknowledgements
This work was funded in part by grant G-NASA/NAG5-3237 and by NSF grants AST-9420443 and AST-9900842. We are grateful to Steve Vogt, the PI for the Keck HIRES instrument which enabled our work on D/H. Scott Burles and Kim Nollett kindly provided the figures for this paper. It is a pleasure to thank Scott Burles, Constantine Deliyannis, Carlos Frenk, George Fuller, Yuri Izotov, David Kirkman, Hannu Karki-Suonio, Sergei Lesshakov, Keith Olive, Jerry Ostriker, Evan Skillman, Gary Steigman and Trinh-Nuan Thuan for suggestions and many helpful and enjoyable discussions. We thank the organizers of this meeting, Lars Bergstrom, Per Carlson and Claes Fransson for their gracious hospitality.

References
1. Izotov, Y.I. and Thuan, T.X., Astrophys. J. 500, 188 (1998a).
2. Turner, M. S., in “The Proc. of Particle Phys. and the Universe” (ed. D. O. Caldwell) (AIP, Woodbury, NY, 1999) astro-ph/9904359.
3. Kolb, E. W. and Turner, M. S., “The Early Universe,” (Addison Wesley 1990).
176. Gunn, J. E. and Peterson, B. A., Astrophys. J. 142, 1633 (1965).
177. Cen, R. and Ostriker, J. P. 1999, Astrophys. J. 514, 1 (1999).
178. Rauch, M. et al., Astrophys. J. 489, 7 (1997).
179. Weinberg, D. H., Miralda-Escude, J., Hernquist, L. and Katz, N.,
    Astrophys. J. 490, 564 (1997).
180. Zhang, Y., Meiksin, A., Anninos, P. and Norman, M. L.,
    Astrophys. J. 496, 63 (1998).
181. Maloney, P. R. and Bland-Hawthorn, Astrophys. J. Lett. astro-
    ph/9907197.
182. White, S. D. M., Navarro, J. F., Evrard, A. and Frenk, C.,
    Nature 366, 429 (1993).
183. Cen, R. and Ostriker, J. P., Astrophys. J. 429, 4 (1994).
184. Pen, U., Astrophys. J. Suppl. 115, 19 (1998).
185. Grego, L. et al., Bull. Am. Astron. Soc. 192, 1707, 194, 5807, and
    in preparation (1998).
186. Boute, D. A. and Canizares, C. R., Astrophys. J. 457, 565
    (1996).
187. Rines, K., Forman, W., Pen, U. and Jones, C., Astrophys. J. 517, 70
    (1999).
188. Arnaud, M. and Evrard, A. E., Mon. Not. R. Astron. Soc.
    astro-ph/9806353 (1999).
189. Bahcall, N. A., Ostriker, J. P., Perlmutter, S. and Steinhardt, P. J.,
    Science 284, 1481 (1999).
190. Freese, K., Fields, B. and Graff, D., in Proceedings of the 19th Texas
    Symposium on Relativistic Astrophysics and Cosmology astro-
    ph/9904401 (1999).
191. Madau, P. and Pozzetti, L., Mon. Not. R. Astron. Soc., astro-
    ph/9907315 (1999).
192. Kamionkowski, M., Jungman, G., Kosowsky, A. and Spergel, D. N.,
    in AAS Pacific Conf. Ser. 99 (eds. S. S. Holt and G. Sonneborn),
    p. 74 (1996).
193. Lineweaver, C. H., Barbosa, D., Blanchard, A. and Bartlett, J. G.,
    Astron. Astrophys. 322, 365 (1997).
194. Ellis, J. R. astro-ph/9903003.
195. Nollett, K. M. and Burles, S., Phys. Rev. D., in press,
    astro-ph/0003440 (2000).
196. Nollett, K. M., Lemoine, M. and Schramm, D. N., Phys. Rev. C56
    1144 astro-ph/9612197 (1997).