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Deuterium and the baryonic density of the universe

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Abstract

Big bang nucleosynthesis (BBN) is the creation of the light nuclei, deuterium, ^{3}He, ^{4}He and ^{7}Li during the first few minutes of the universe. Here we discuss recent measurements of the D to H abundance ratio, D/H, in our galaxy and towards quasars. 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 to 1996, it appeared that there could be a factor of 10 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, η, and hence the cosmological baryon density. A similar density is required to explain the amount of Lyα absorption from neutral hydrogen in the intergalactic medium (IGM) at redshift $z \simeq 3$, 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. © 2000 Elsevier Science B.V. All rights reserved.

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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 [1].

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, $\eta \equiv n_b/n_\gamma$ [2]. The ratio of any two primordial abundances should give η, 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. [3,4]) 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 $\Omega_b = 0.007 - 0.024$. The low end of this range allowed no significant dark baryonic matter. Now the new D/H measurements towards quasars give $\Omega_b = 0.019 \pm 0.0024$ (95%) – a 13% error, and there have been improved measurements of the other nuclei.

Many reviews of BBN have been published recently, e.g. [5–12] some of which are lengthy, e.g. [13–15]. Several recent books contain the proceedings of meetings on this topic: [16–19]. The 1999 meeting of the International Astronomical Union (Symposium 198 in Natal, Brazil) was on light elements, as were many reviews in a special volume of New Astronomy, 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. [20–23], and most of the reviews listed above, including [24,10]. The historical development of BBN is reviewed by [25,12,26,9,5].

2.1. Baryogenesis

The baryon-to-photon ratio η is probably determined during baryogenesis [2,27,28], but we do not know when baryogenesis occurred. Sakharov [29] 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 η, but if, alternatively, baryogenesis is at the GUT or inflation scale, it will be very hard to predict η (J. Ellis, personal communication).

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 $\frac{1}{6}$ after the weak reaction rate is slower than the expansion rate. This is at about 1 s, when $T \simeq 1$ MeV. The starting reaction $\mathrm{n} + \mathrm{p} \rightleftarrows \mathrm{D} + \gamma$ makes D. At that time photo-dissociation of D is rapid because of the high entropy (low η) 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}He abundance is then given approximately by assuming that all remaining neutrons are incorporated into ^{4}He.

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

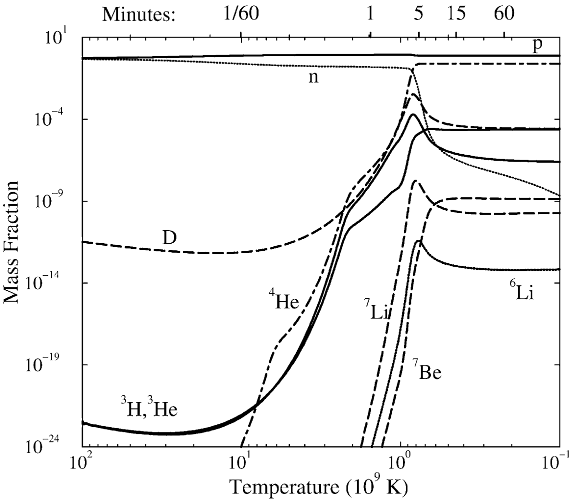

Fig. 1. Mass fraction of nuclei as a function of temperature for $\eta = 5.1 \times 10^{-10}$, from Nollet and Burles (1999) and Burles et al. [5].

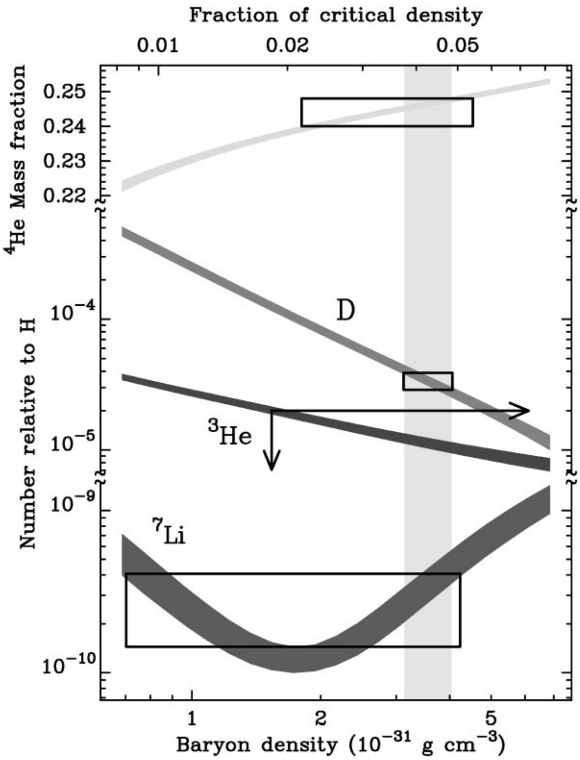

Fig. 2. Abundances expected for the light nuclei ^{4}He, D, ^{3}He and ^{7}Li (top to bottom) calculated in standard BBN. New estimates of the nuclear cross-section errors from Burles et al. [13] and Nollet and Burles (1999) were used to estimate the 95% confidence intervals which are shown by the vertical widths of the abundance predictions. The horizontal scale, η, is the one free parameter in the calculations. It is expressed in units of the baryon density or critical density for a Hubble constant of 65 km s^{-1} Mpc^{-1}. The 95% confidence intervals for data, shown by the rectangles, are from Izotov and Thuan [104] (^{4}He); Burles and Tytler [54] (D); Gloeckler and Geiss 1996 (^{3}He); Bonifacio and Molaro 1997 (^{7}Li extended upwards by a factor of two to allow for possible depletion).

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

The predictions of the abundances have changed little in recent years, following earlier work by Peebles [30], Hoyle and Tayler [31], and Wagoner et al. [32]. The accuracy of the theory calculations have been improving, and they remain much more accurate than the measurements. For example, the fraction of the mass of all baryons which is ^{4}He, Y_p, is predicted to within $\delta Y_p < \pm 0.0002$ [33]. In a recent update, Burles et al. [5] uses Monte-Carlo realizations of reaction rates to find that the previous estimates of the uncertainties in the abundances for a given η were a factor of two too large.

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 H, because it is the easiest to measure.

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

By the earliest time at which we can observe objects, redshifts $z \simeq 6$, we find heavy elements from stars in most gas. Although we expect that large volumes of the intergalactic medium (IGM) were primordial then [34], we do not know how to obtain accurate abundances in this gas, because it is of very low density. Hence we must consider possible modifications of abundances. This is best done in gas with the lowest abundances of heavy elements, because most stars which change abundances, also produce and distribute heavy elements.

The nuclei D, ^{3}He, ^{6}Li and ^{7}Li are all fragile and readily burned inside stars at relatively low temperatures of a few 10^6 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 be depleted in the gas returned to the interstellar medium (ISM). Nuclei ^{3}He, ^{7}Li and especially ^{4}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 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 0.02–0.2 times those in the sun. The ^{4}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. [6], Fig. 2). Regression gives the predicted

Y_p for zero O or N [35]. 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 [36], 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 et al. [37].

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 D/H towards quasars is twice that in the ISM, 50% of the D is destroyed when abundances rise to near the solar level, and less than 1% of D is expected to be destroyed in the quasar absorbers, much less than the random errors in individual measurements of D/H. Since there are no other known processes which destroy or make significant D (e.g. [3,38]), we should be observing primordial D/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}Li ([39], 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 ^{6}Li in two of these stars suggests that both ^{6}Li and some ^{7}Li was created prior to the formation of these stars. Second, the possible increase in the abundance of ^{7}Li with the iron abundance also indicates that the ^{7}Li of the plateau stars is not primordial. If both the iron and the enhancement in the ^{7}Li have the same origin we could extrapolate back to zero metals [40], as for ^{4}He, but the enhanced ^{7}Li may come from cosmic-ray interactions in the ISM, which makes extrapolation less reliable. Third, the amount of depletion is hard to estimate. Rotationally induced mixing has a small effect because there is little scatter on the Spite plateau, but other mechanisms may have depleted ^{7}Li. In particular, gravitational settling should have occurred, and left less ^{7}Li in the hotter plateau stars, but this is not seen, and we do not know why. More on this later.

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.

Deuterium gives the most accurate measurement of η for several reasons: first, D has been measured in gas with very low abundances (like Li, but unlike ^{3}He); second, its astrophysical evolution is simple (like ^{4}He but unlike ^{3}He and ^{7}Li); third, abundances can be obtained directly from spectra, with few corrections, (unlike ^{4}He, ^{3}He and ^{7}Li); and fourth, D/H is highly sensitive to η (like ^{3}He, but unlike ^{4}He and ^{7}Li).

Since we are now obtaining "precision" measurements, it now 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. For D the main observational goal remains the discovery and measurement of more quasar absorption systems which have, by chance, minimal H contamination.

4. Deuterium in quasar spectra

The abundance of deuterium (D or ^{2}H) is the most sensitive measure of the baryon density [4]. No known processes make significant D, because it is so fragile ([3,41–43]). Gas ejected by stars

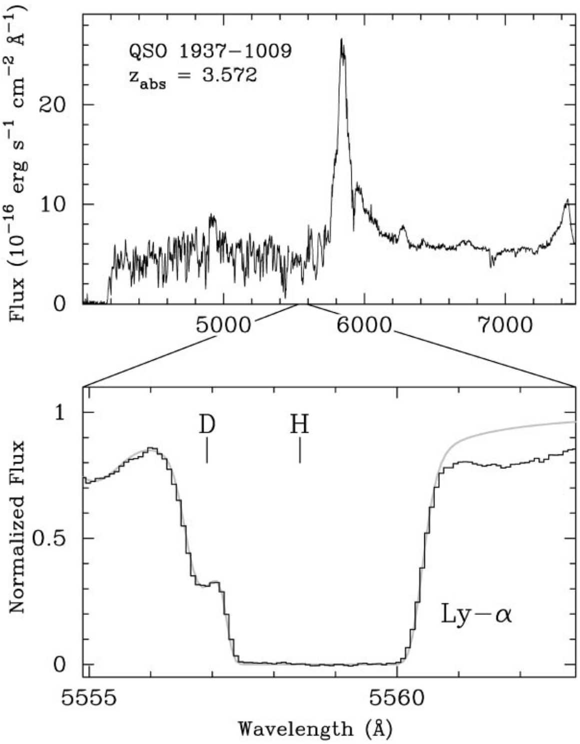

Fig. 3. Optical spectrum of quasar 1937 − 1009, which shows the best example of primordial D/H. The top spectrum, from the Kast spectrograph on the 3-m telescope at Lick observatory, is of low spectral resolution, and high signal to noise. The continuum emission, from the accretion disk surrounding the black hole 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 absorptoin 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 spectrun 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 us. 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 though the absorber, and they ionized its H I. The 1% residual flux in this Lyman continuum region has been measured in spectra of higher signal to noise [88] 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-1 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 primoridal value, and using SBBN predictions, this gives the most accurate measurements of η and Ω_b.

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 the absorption from H, and even in the rare cases when contamination is small, superb spectra are required to distinguish D from H.

Contamination by H is about 1000 times more important than the destruction of D in stars. If stellar processing were the main uncertainty, then we would use the highest measured D/H as the best indication of the primordial value. However, contamination by H is extremely common, and has a much larger effect. We expect that stellar processing has reduced D/H by $< 1\%$ in the quasar absorbers with abundances below 0.01 solar, while contamination of the D lines by H can make D/H appear > 10 times too large.

Prior to the first detection of D in quasar spectra [44], 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 10 destruction [45]. At that time, most measurements gave low abundances for ^{4}He, which predict a high primordial D/H in SBBN. A large amount of depletion was then needed to bring the primordial D/H down to ISM values [46].

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

Adams [47] 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 connected to the quasars. The importance of such measurements was well known in the field in the late 1970s [48], but the task proved too difficult for 4-m class telescopes [49–51]. The high SNR QSO spectra obtained with the HIRES echelle spectrograph [52] 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, $\mathrm{D/H} = 3.24 \pm 0.3 \times 10^{-5}$ in the $z_{\mathrm{abs}} = 3.572$ Lyman limit absorption system (LLS) towards quasar $1937 - 1009$ [44,53]; second, $\mathrm{D/H} = 4.0^{+0.8}_{-0.6} \times 10^{-5}$ in the $z_{\mathrm{abs}} = 2.504$ LLS towards quasar $1009 + 2956$ [54], and third, $\mathrm{D/H} < 6.7 \times 10^{-5}$ towards quasar $0130 - 4021$ [55]. 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. 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 values of $\mathrm{D/H} \simeq 20 \times 10^{-5}$. Indeed, the spectra of all three QSOs are inconsistent with high D/H.

There remains uncertainty over a case at $z_{\mathrm{abs}} = 0.701$ 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 these spectra are of unusually low signal to noise, with about 200 times fewer photons per $\mathrm{km\,s^{-1}}$ than those from Keck. Webb et al. [56,57] assumed a single hydrogen component and found $\mathrm{D/H} = 25 \pm 5 \times 10^{-5}$, the best case for high D/H. Levshakov et al. [58] allow for non-Gaussian velocities and find $\mathrm{D/H} \sim 4.4 \times 10^{-5}$, while Tytler et al. [59] find $8 \times 10^{-5} < \mathrm{D/H} < 57 \times 10^{-5}$ (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. [60] 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 $N_{\rm HI}$ 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 $D/H = 1.5 \times 10^{-5}$ and 21×10^{-5}, and it is clear that much lower D is also acceptable because there can be H additional contamination in the D region of the spectrum. Levshakov et al. [61] show that $\log N_{\rm HI} = 15.7$ (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 $N_{\rm HI}$ 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. [62], who reported an upper limit of $D/H < 25 \times 10^{-5}$ in the $z_{\rm abs} = 3.32$ Lyman limit system (LLS) towards quasar 0014 + 813. Using different spectra, Carswell et al. [51] reported $< 60 \times 10^{-5}$ in the same object, and they found no reason to think that the deuterium abundance might be as high as their limit. Improved spectra [63] support the early conclusions: $D/H < 35 \times 10^{-5}$ for this quasar. High D/H is allowed, but is highly unlikely because the absorption near D is at the wrong velocity, by $17 \pm 2\,{\rm km\,s^{-1}}$, it is too wide, and it does not have the expected distribution of absorption in velocity, which is given by the H absorption. Instead this absorption is readily explained entirely by H ($D/H \simeq 0$) at a different redshift.

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, $D/H \sim 3.4 \times 10^{-5}$. Two quasars (1937 − 1009 and 1009 + 2956) are inconsistent with $D/H \geq 5 \times 10^{-5}$, and the third (0130 − 4021) is inconsistent with $D/H \geq 6.7 \times 10^{-5}$. 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 this is the key topic of controversy.

4.1. ISM D/H

Observations of D in the ISM are reviewed by Lemoine et al. [64]. The first measurement in the ISM, $D/H = 1.4 \pm 0.2 \times 10^{-5}$, using Lyman absorption lines observed with the Copernicus satellite [65], have been confirmed with superior HST spectra. A major program by Linsky et al. [66,67] has given a secure value for local ISM ($< 20\,{\rm pc}$) $D/H = 1.6 \pm 0.1 \times 10^{-5}$.

Some measurements have indicated variation, and especially low D/H, in the local and more distant ISM towards a few stars [46,64]). Vidal-Madjar and Gry [46] concluded that the different lines of sight gave different D/H, but those early data may have been inadequate to quantify complex velocity structure [68]. 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. [69] suggested variation of D/H towards G191-B2B, while Vidal-Madjar et al. [70] described the variation as real, however new STIS spectra do not confirm this, and give the usual D/H value. The STIS spectra [71] 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. [72] report the possibility of low $D/H < 1.6 \times 10^{-5}$ towards Sirius A, B.

The only other instance of low D/H from recent data is $D/H = 0.74^{+0.19}_{-0.13} \times 10^{-5}$ (90%) towards the star δ Ori [73]. 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 in the dense disk, and the influence of stars should be slight because heavy element abundances are 100–1000 times smaller.

Chengalur et al. [74] 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. [75] deduce $D/H = 1.0 \pm 0.3 \times 10^{-5}$ from the first detection of the 112 μm 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 $D/H \simeq HD/H_2$. 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. [76,77] report $D/H = 0.2 \pm 0.1 \times 10^{-5}$ (later revised to 0.3×10^{-5}, private communication 1999) from DCN in the Sgr A molecular cloud near the Galactic center. 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 82 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 expect, 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 planetessimals, 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. [78] find $\mathrm{D/H} = 2.6 \pm 0.7 \times 10^{-5}$ from the Galileo probe mass spectrometer. Feuchtgruber et al. [79] used infrared spectra of the pure rotational lines of HD at 37.7 μm to measure $\mathrm{D/H} = 5.5^{+3.5}_{-1.5} \times 10^{-5}$ in Uranus and $6.5^{+2.5}_{-1.5} \times 10^{-5}$ 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 $^3\mathrm{He}/^4\mathrm{He}$ ratio is measured and corrected for (1) changes in $^3\mathrm{He/H}$ and $^4\mathrm{He/H}$ 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 [80] reported $\mathrm{D/H} = 2.1 \pm 0.5 \times 10^{-5}$, later revised to $1.94 \pm 0.36 \times 10^{-5}$ [81].

The present ISM $\mathrm{D/H} = 1.6 \pm 0.1 \times 10^{-5}$ 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. These 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. [82] 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 [6,83–85], 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. [82] 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 $< 1\%$ [43].

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 [86] suggested that the low D/H values might be inaccurate because in some cases the H absorption lines have zero flux in their cores; they are saturated. Songaila et al. [87] suggested that this well-known problem might lead to errors in the H column density, but additional work, using better data and more detailed analyses [88] has shown that these concerns were not significant, and that the initial result [89] was reliable.

Neutral deuterium (D I) is detected in Lyman series absorption lines, which are adjacent to the H I lines. The separation of $82\,\mathrm{km\,s^{-1}}$ 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 1216 and 912 Å, 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 (N_{HI}, measured in H I atoms per $\mathrm{cm^{-2}}$ along the line of sight) and velocity width (b values, $b = \sqrt{2}\sigma$, measured in $\mathrm{km\,s^{-1}}$) of the H. But in some cases only Lyα has been observed (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 [86] has suggested that D/H values could be 3–4 times higher in Q1937 − 1009 than measured by Tytler et al. [44]. He argued that saturation of the H Lyman series lines could allow lower N_{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 HIRES.

Tytler and Burles [89] 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_{HI}. The cross section for absorption (oscillator strength) decreases by 2000 from the Lyα 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 et al. [87] measured the residual flux in the Lyman continuum of the D/H absorber in Q1937 − 1009. They found a lower N_{HI} and hence a higher D/H. Burles and Tytler [88] presented a more detailed analysis of better data, and found a lower N_{HI}, consistent with that obtained from the fitting of Lyman series lines. They explained that Songaila et al. [87] had underestimated N_{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_{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_{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 [53] 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 [54]. 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.

4.5. *Correlated velocity structure*: *mesoturbulence*

In a series of papers, Levshakov et al. [90–92] have 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 [90], Q1009 + 2956 [58] and Q1718 + 4807 [91] were examined in detail using this early model. In the first paper they allowed the N_{HI} to vary far from the observed value ($N_{\mathrm{HI}} = 7.27 \times 10^{17}$ [88]), and consequently they found a variety of N_{HI}, but when the N_{HI} is held within range, the D/H is 3.3×10^{-5}, exactly the same as with the usual model [53]. 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_{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 [61,92] 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. [58] 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) If 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 et al. [55] 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. [58] methods are more complex. In early implementations, Levshokov et al. [58] 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.

4.5.1. *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 [94].

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 34×10^{-5}, then the depletion in all four, 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 [82].
3. The quasar absorption systems are large – a few kpc along the line of sight [89], 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 [43].
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 [95] discuss photons from early black holes. Sigl et al. [96] show that this mechanism creates 10 times more ^{3}He than observed, and Jedamzik and Fuller [43] find the density of gamma-ray sources is improbably high.

Holtmann et al. [97,98] 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 Ω_b. Hence low D and low Y_p can be concordant. An exception is ^{6}Li which is produced with $^6\mathrm{Li/H} \simeq 10^{-12}$, which is about the level observed in two halo stars. There is no conflict with the usual conclusion that most ^{6}Li is made by Galactic cosmic-rays prior to star formation, because the observed ^{6}Li has been depleted by an uncertain amount. This scenario has two difficulties: Burles (private communication) notes that there would be a conflict with the Ω_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.

4.5.2. 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 Q1937 − 1009 and Q1009 + 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 (2×10^4 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 [99], [38], so that they are more likely to dominate the observed universe today. In that scenario the Ω_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 Ω_b. This scenario will be tested when we have observations of many more quasars.

4.5.3. 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 10 times the low value, the D line would be 10 times stronger for a given N_{HI}, 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 1980s, 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_{HI} 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.

4.5.4. 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}Li abundance in Spite plateau halo stars, with no correction for depletion, imply low Ω_b, low η, 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 [100] and all observational papers discussed this contamination of D by H.

Carswell et al. [51] noted that contamination was likely in Q0014 + 813 and hence the D/H could be well below the upper limit. Songalia et al. [62] stated: “because in any single instance we cannot 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. [63] showed that Q0014 + 813 is strongly contaminated, does not give a useful D/H limit. For Q1718 + 4807 we [59] and Levshokov et al. [91] 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 $z \simeq 3$ have one absorption systems 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 $\simeq 98\%$ 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 some 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 $N_{\rm HI}$, 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 alternatively, to correct individual D/H for the likely level of contamination. When we attempted to correct for contamination in the past [44,101,59], we used the statistics of H I in the Lyα 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 [94,102] in Q0014 + 8118 are still cited in a few recent papers, after later measurements [63] 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.

4.5.5. *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.
- 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 Ω_b.

4.5.6. *Conclusions from D/H from quasars*

Most agree that D is providing the most accurate η value [10], although some have one remaining objection, that there might also be quasar absorbers which show high values of D/H [103,6].

The D/H from our group [88,54,53], 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 1σ values, the following are quoted with 95% confidence intervals):

- $\mathrm{D/H} = 3.4 \pm 0.5 \times 10^{-5}$ (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)
- $^7\mathrm{Li/H} = 3.5^{+1.1}_{-0.9} \times 10^{-10}$ (from BBN and D/H)
- 411 photons cm^{-3} (from the CMB temperature)
- $\rho_b = 3.6 \pm 0.4 \times 10^{-31}\,\mathrm{g\,cm}^{-3}$ (from CMB and η)
- $\Omega_b h^2 = 0.019 \pm 0.0024$ (from the critical density ρ_c)
- $N_\nu < 3.20$ (from BBN, D/H and Y_p data).

If we accept that D/H is the most accurate measure of η, 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 [104] agree with the predictions:

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

It appears that some ^{7}Li has been destroyed in halo stars [105], and ^{3}He is both created and destroyed in stars.

5. 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 Lyα forest, will give a new rigorous test of BBN [10]. This test can be viewed from two directions. First, we can use the baryon density to fix the last free parameter in BBN, 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.

5.1. Ω_b from the IGM Lyman-α forest absorption

The gas in the IGM is observed through H I Lyα absorption in the spectra of all QSOs. Gunn and Peterson [106] discussed how redshift produces continuous absorption in the ultraviolet spectra of QSOs. Density fluctuations in the IGM turn this continuous absorption into the Lyα forest absorption lines. The IGM fills the volume of space, and at redshifts $z > 1$ [107] 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, recombination 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 [108–110]: $\Omega_b > 0.035h_{70}^{-2}$. 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 [107] 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 [107,111].

5.2. 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 [112]. 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 [113,114]. 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 $\Omega_b/\Omega_m \simeq M_b/M_t$. The baryon fraction in clusters in the last factor is about $0.10h_{70}^{-1}$ (SZ effect: [115]), or $0.05 - 0.13h_{70}^{-3/2}$ (X-ray: [116]), or $0.11h_{70}^{-3/2}$ (X-ray: [117,118]). Using $\Omega_m = 0.3 \pm 0.2$ from a variety of methods [119], we get $\Omega_b \simeq 0.03$, with factor of two errors. These Ω_b estimates are lower limits, since there might be additional unobserved baryons.

5.3. Local dark baryonic matter

The baryon density estimated in the Lyα forest at $z \simeq 3$ and in local clusters of galaxies are both similar to that from SBBN using low D/H. This implies that there is little dark baryonic matter in the universe [120]. 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 [121], 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 Ω_b) of baryonic MACHOS.

5.4. Simulations of the formation of galaxies

Ostriker (private communication) notes that the Ω_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).

5.5. 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 Ω_b, with large errors, however dramatic improvements are imminent, and future constraints may approach or exceed the accuracy of Ω_b from SBBN [122,123].

6. Conclusion

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 η 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 Ω_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 [93].

At redshifts $z \simeq 3$ the baryons are present and observed in IGM with an abundance similar to Ω_b. Hence there was no 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.

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