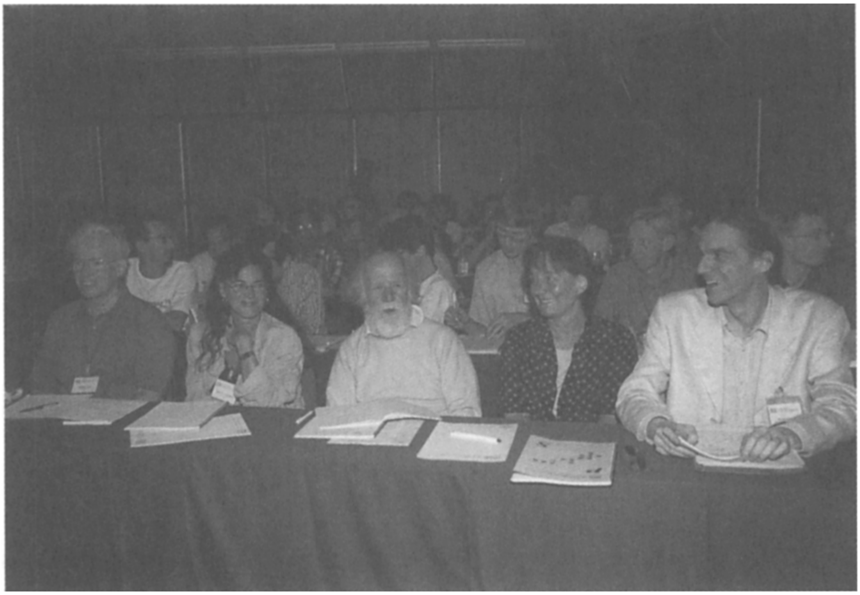
ABUNDANCES OF D, ^{3}He AND ^{4}He



Hebert Reeves making a pertinent and humorous comment, in the good company of Gary Steigman, Francesca Matteucci, Sylvie Vauclair, and Etienne Parizot.

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Measurements of The Primordial D/H Abundance Towards Quasars

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Abstract.

Big Bang Nucleosynthesis (BBN) is the synthesis of the light nuclei, Deuterium (D or ^{2}H), ^{3}He, ^{4}He and ^{7}Li during the first few minutes of the universe. In this review we concentrate on recent data which give the primordial deuterium (D) abundance.

We have measured the primordial D/H in gas with very nearly primordial abundances. We use the Lyman series absorption lines seen in the spectra of quasars. We have measured D/H towards three QSOs, while a fourth gives a consistent upper limit. All QSO spectra are consistent with a single value for D/H: $3.325^{+0.22}_{-0.25} \times 10^{-5}$. From about 1994 – 1996, there was much discussion of the possibility that some QSOs show much higher D/H, but the best such example was shown to be contaminated by H, and no other no convincing examples have been found. Since high D/H should be much easier to detect, and hence it must be extremely rare or non-existent.

The new D/H measurements give the most accurate value for the baryon to photon ratio, η, and hence the cosmological baryon density: $\Omega_b = 0.0190 \pm 0.0009$ (1σ) 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.

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 (Turner 1999).

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, $\eta \equiv n_b/n_\gamma$ (Kolb & Turner 1990). 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. Reeves et al 1973; Wagoner 1973) 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 $\Omega_b = 0.0190 \pm 0.0009$ (1σ) – a 5% error, and there have been improved measurements of the other nuclei.

2. 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 state of the art today (1 σ) is about 3% for Y_p, 10% for D/H and 8% for ^{7}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 $z \simeq 6$, we find heavy elements from stars in most gas. Although we expect that large volumes of the intergalactic medium (IGM) remain primordial today (Gnedin & Ostriker 1997), 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 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.

2.1. From Observed to Primordial Abundances

Even when heavy element abundances are low, it is difficult to prove that abundances are primordial. For deuterium, we can make the following 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 local 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. Reeves et al. 1973; Jedamzik & Fuller 1995), we should be observing primordial D/H in the quasar absorbers.

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. We will now discuss observations of each of the nuclei, and especially D, in more detail.

3. Deuterium in quasar spectra

The abundance of deuterium (D or ^{2}H) is the most sensitive measure of the baryon density (Wagoner 1973). No known processes make significant D, because it is so fragile (Reeves et al. 1973; Epstein et al. 1976; Boyd et al. 1989; Jedamzik & Fuller 1997). 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 complication 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 has about 1000 times the effect of 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 (Tytler, Fan, & Burles 1996), 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 (Audouze 1986). 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 (Vidal-Madjar & Gry 1984).

Reeves, Audouze, Fowler & Schramm (1973) 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 $7 \pm 3 \times 10^{-5}$.

Deuterium has been measured in the ISM for many years, but only recently have we been able to measure primordial D/H, in QSO spectra. The first measurement of D in interstellar gas was reported in 1973 using DCN (jefferts, Penzias, & Wilson 1973). In 1973 Vidal-Madjar and colleagues proposed using the Lyman series absorption lines (Vidal-Madjar & Gry 1984) to measure the the column density of neutral atomic D I, and this was done with great success in the ISM using ultraviolet spectra from the Copernicus satellite from 1973 – 1982. Adams (1976) 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 (Webb et al. 1991), but the task proved too difficult for 4-m class telescopes (Chaffee et al. 1985; Chaffee et al. 1986; Carswell et al. 1994). The high SNR QSO spectra obtained with the HIRES echelle spectrograph (Vogt et al. 1994) on the W.M. Keck 10-m telescope provided the breakthrough.

The primordial D/H is now well established from the spectra of four QSOs obtained by our group using the HIRES spectrograph: first, 1937–1009 (Tytler, Fan, & Burles 1996; Burles & Tytler 1998a); second, 1009+2956 (Burles & Tytler 1998b); third, 0130–4021 (Kirkman et al. 2000), and fourth, HS 0105+1619 (O'Meara et al. 2000). We give some of the parameters associated with these measurements in Table 1.

Table 1. Parameters for the D/H Measurements

QSO	z_{dh}	$\log N_{HI}$ (cm^{-2})	$\log n_{H\ I}/n_H$	b(D) (km s^{-1})	[C/H]
Q1937-1009 [a]	3.572	17.86 ± 0.02	$-2.35, -2.29$	14.0 ± 1.0	$-3.0, -2.1$
Q1009+2956 [a]	2.504	17.39 ± 0.06	$-2.97, -2.84$	15.7 ± 2.1	$-2.8, -3.0$
Q0130-4021	2.799	16.66 ± 0.02	-3.4	$16 - 23$	≤ -2.6 [b]
Q0105+1619	2.536	19.41 ± 0.02	0.8	9.4 ± 0.4	-2.0 [c]

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[a] We list the parameters for each of the two components, where available.

[b] Abundances are for Si.

[c] Abundance is a measurement for O, and an upper limit for C, Al, Fe and Si.

The third case, Q0130–4021, is 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 D/H. Indeed, the spectra of all three QSOs are inconsistent with high D/H.

The fourth quasar, HS 0105+1619, gives the most secure measurement of D/H to date, because the absorption system has a simple, one component, velocity structure, and the N(H I) is high, giving strong absorption lines, including four lines of D and numerous very narrow metal lines which show that the absorption is produced by D and is not significantly contaminated with H.

The result agrees with our prior measurements in three other QSOs, and reduces the best value for the primordial D/H, from all QSOs, by 2.0%. The best estimate of the baryon density is then also almost unchanged, and becomes much more secure because these QSOs sample different directions in the universe, and the measurement conditions differ substantially, because the H I column densities differ by a factor of 240, and the fraction of the gas which is neutral varies over 3 orders of magnitude.

There remains uncertainty over a case at $z_{abs} = 0.701$ towards quasar PG 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 kms^{-1} than those from Keck. Webb et al. (1997a, 1997b) assumed a single hydrogen component and found $\mathrm{D/H} = 25 \pm 5 \times 10^{-5}$. This is the best case for a significantly different value for D/H, but it is not convincing. Levshakov et al. (1998) allow for non-Gaussian velocities and find $\mathrm{D/H} \sim 4.4 \times 10^{-5}$, while Tytler et al. (1999) 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 fully consistent with the usual D/H.

Recently Molaro et al. (1999) claimed that D/H might be measured and 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 Figure 1 (panels a and b) shows that there is a tiny difference between $\mathrm{D/H} = 1.5 \times 10^{-5}$ 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. (2000) 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. (1994), who reported an upper limit of $\mathrm{D/H} < 25 \times 10^{-5}$ in the $z_{abs} = 3.32$ Lyman limit system (LLS) towards quasar 0014+813. Using different spectra, Carswell et al. (1994) 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 (Burles, Kirkman, & Tytler 1999) 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 ± 2 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 ($\mathrm{D/H} \simeq 0$) 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 the current best value for the primordial: D/H $\sim 3.3 \pm 0.2 \times 10^{-5}$. Three quasars (1937–1009, 1009+2956 & HS 0105+1619) are inconsistent with D/H $\geq 5 \times 10^{-5}$, and the third (0130–4021) is inconsistent with D/H $\geq 6.7 \times 10^{-5}$. Most quasar spectra allow much higher D/H, because we lack spectra of sufficient quality to distinguish D from H, or because the D is contaminated by H and the spectra provide no useful information.

3.1. 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. (1998) 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 (Vangiono-Flam & Cassé 1995; Timmes et al. 1997; Scully et al. 1997; Olive 1999b), 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. (1998) 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% (Jedamzik & Fuller 1997).

4. Is there spatial variation in D/H towards quasars?

It seems highly likely that we are measuring the primordial D/H in the QSO spectra.

Are there other places where D is much larger than we observe? All quasar spectra are consistent with a single 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 the usual D. Since we have not found any convincing examples, high D must be very rare. If D were ten times the usual value, the D line would be ten 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 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_{HI} needed to detect the usual D/H. Such absorbers are about 40 – 60 times more common than those needed to show the usual D/H, and hence we should have found tens of excellent examples.

4.1. Conclusions from D/H from quasars

Most agree that D is providing the most accurate and reliable value for η (Schramm & Turner 1998). The prior concern, (Olive 1999b; Audouze 1998), that some quasar absorbers might show much higher values of D/H, is now assuaged by the continuing lack of any secure examples, and the measurement of the usual D/H towards HS 0105+1619.

The weighted mean D/H from three QSOs 1937–1009, 1009+2956 and HS 0105+1619 measured by our group, including Scott Burles & Xiao-Ming Fan: (Burles & Tytler 1998a; Burles & Tytler 1998b; Kirkman et al. 2000; Burles & Tytler 1997; O'Meara et al. 2000)

- $\log \mathrm{D/H} = -4.478 \pm 0.031$ (7% error)
- $\mathrm{D/H} = 3.325^{+0.22}_{-0.25} \times 10^{-5}$,

which is 2.0% lower than our previous best estimate prior to HS 0105+1619. The value and its error are still dominated by the measurement from Q1937–1009, which gave half the errors of Q1009+2956 & HS 0105+1619.

This best primordial D/H value, together with over 50 years of theoretical work and laboratory measurements of reaction rates, leads to the following values for cosmological parameters:

- $\mathrm{D/H} = 3.325^{+0.22}_{-0.25} \times 10^{-5}$ (from the spectra of three quasars)
- $\eta = 5.2 \pm 0.3 \times 10^{-10}$ (from SBBN and D/H)
- $Y_p = 0.2464 \pm 0.0007$ (mass fraction of ^{4}He, from SBBN and D/H)

- ^{7}Li/H $= 3.46^{+0.55}_{-0.48} \times 10^{-10}$ (from SBBN and D/H)
- $n_\gamma = 411.7 \pm 1.8$ photons cm^{-3} (photon density, from the CMB temperature)
- $\rho_b = 3.57 \pm 0.17 \times 10^{-31}$gcm^{-3} (baryon density, from the photon density and η, 0.22 ± 0.01 H atoms m^{-3} today)
- $\Omega_b h^2 = 0.01897 \pm 0.00091$ (baryon density, in units of the critical density ρ_c, 4.8% error)
- Ω_b= 0.039 ± 0.002 for $h = 0.7$
- $N_\nu < 3.20$ (number of neutrino species, from SBBN, D/H and Y_p data).

Here the photon density is from the COBE (Fixen et al. 1996) measurement of the CMB temperature, $T = 2.728 \pm 0.004$ K, and the neutrino limit from Burles et al. (1999). In the past we have often quoted 95% confidence intervals, but now, the agreement between the D/H obtained for three QSOs gives us more confidence that we have approximately the right magnitude for the errors, and hence, in this paper, we quote 1σ errors.

The η and Ω_b from D/H are considered both the most reliable and the most accurate, because the observation of D is straightforward, given sufficient telescope time. The measurement of D/H from spectra is relatively simple, again provided the data are adequate, and the D/H observed is likely the primordial value.

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