PRIMORDIAL NUCLEOSYNTHESIS AND DARK MATTER

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The cosmological abundance of nucleons determined from considerations of big bang nucleosynthesis allegedly provides compelling evidence for non-nucleonic dark matter. Recent developments in measurements of primordial light element abundances, in particular deuterium and helium, require reexamination of this important issue. The present situation is uncertain but exciting.

"At this point I would like to make a remark on the present state of observations relevant to cosmology. When a physicist reads a paper by a typical astronomer, he finds an unfamiliar style in the treatment of uncertainties and errors . . . The authors are apparently unwilling to state precisely the odds that their number is correct, although they have pointed out very carefully the many sources of error, and although it is quite clear that the error is a considerable fraction of the number. The evil is that often other cosmologists or astrophysicists take this number without regard to the possible error, treating it as an astronomical observation as accurate as the period of a planet."

Richard Feynmann (1962)[1]

1 Introduction

The focus of this Workshop is the problem of dark matter. It is well established that the dynamics of galaxies and clusters is dominated by unseen matter which contributes $\sim 10-20\%$ of the critical density.[2] In contrast, the luminous (nucleonic) matter in such structures has a density parameter of only [3]

$$\Omega_{\rm N} \simeq 2.2 \times 10^{-3} + 6.1 \times 10^{-4} h^{-1.3} \ , \tag{1}$$

where the first term accounts for the stars and the second for the X-ray emitting gas. Here, $h \equiv H_0/100\,{\rm km\,sec^{-1}\,Mpc^{-1}}$ is the present Hubble parameter. The obvious question is whether the dark matter might also be nucleonic but in the form of say cold compact objects or diffuse gas.[4]

We also recognize a second, indirect, dark matter problem in that the standard Friedmann-Robertson-Walker cosmology must be incredibly fine tuned if the universe does not have exactly the critical density, as would be naturally ensured by an initial De Sitter (inflationary) epoch.[a] Then there must be a substantial amount of matter in some form which is not clustered on the scales

[a] In principle inflation would be consistent with a present day cosmological constant, requiring only that $\Omega_{\rm matter} + \Omega_\Lambda = 1$. However for the two contributions to be comparable today would also require severe fine tuning, hence for consistency we must assume $\Omega_\Lambda = 0$.

probed by dynamical measurements of galaxies or clusters. Indeed studies [5] of non-Hubble velocity flows on larger scales indicate that $\Omega > 0.3$ and recent attempts [6] to measure the large-scale curvature of space-time using Type I SN as 'standard candles' find $\Omega > 0.5$. Finally, degree-scale measurements of the cosmic microwave background (CMB) anisotropy [7] provide preliminary evidence of a 'Doppler peak' at the position expected for a critical density universe.

Recently there has been considerable progress on the first dark matter problem through searches [8] for microlensing which indicate [9] that $\approx 40\%$ of the dark matter in the halo of our Galaxy is in the form of compact, presumably nucleonic, objects of mass $\sim 0.1 - 1\,\mathrm{M}_{\odot}$. Given the plethora of exotic particle candidates for the dark matter in extensions of physics beyond the Standard Model [10] and the increasing number of experimental efforts at their direct detection, it is clearly crucial to establish whether there really is any hard evidence for non-nucleonic dark matter. It is here that considerations of Big Bang nucleosynthesis (BBN) play a crucial role since the abundances of the light elements provide a limit on the abundance of nucleons [b] in *any* form. This limit on Ω_{N} has also become relevant to the indirect dark matter problem because of *ROSAT* X-ray observations which reveal rather large nucleon fractions in clusters of galaxies. For example in the *Coma* cluster,[11]

$$f_{\mathrm{N}} \equiv \frac{M_{\mathrm{N}}}{M_{\mathrm{tot}}} \geq 0.009 + 0.05\,h^{-3/2}\ , \tag{2}$$

where the first term accounts for the stellar matter within the Abell radius of $r_{\mathrm{A}} \approx 1.5\,h^{-1}$ Mpc and the second for the X-ray emitting gas. Hydrodynamical simulations of cluster formation in a CDM universe find that cooling and other dissipative effects could have enhanced f_{N} within r_{A} by a factor of at most $\Upsilon \approx 1.4$ over the global average.[11] Since the global density parameter is just $\Omega = \Upsilon(\Omega_{\mathrm{N}}/f_{\mathrm{N}})$, we see that $\Omega = 1$ would be permitted only if $\Omega_{\mathrm{N}} \gtrsim 0.1$.

Although these are well known issues they have become somewhat controversial of late since the quoted limit on Ω_{N} has varied depending on how different authors have inferred the primordial elemental abundances from their present values, using models of galactic chemical evolution. In fact some authors [12] have gone so far as to question the consistency of standard BBN itself. We have argued elsewhere [13] that there is *no* such crisis if a conservative view is taken of observational errors. Physicists are often puzzled that such very different conclusions can be drawn on the basis of (presumably) the same observational data. The words of Feynmann [1] quoted above appear to be as relevant today as when they were spoken 34 years ago!

[b] We distinguish between nucleons and baryons since there may well be baryonic dark matter (e.g. strange quark nuggets, black holes) which does not participate in BBN.

2 Big Bang Nucleosynthesis

The physics of BBN is well understood [14] and in recent years the uncertainties in the input nuclear reaction cross-sections and the neutron lifetime have been included in the computer code using Monte Carlo methods, thus accounting for all correlated effects.[15,16] As shown in figure 1, the ^{4}He abundance is known to within $\pm 0.5\%$,[c] but the D and ^{3}He abundances have a $\pm 15\%$ uncertainty, while the ^{7}Li abundance is uncertain to within $\pm 60\%$. There are of course many possibilities for departures from the standard model, e.g. an inhomogeneous nucleon distribution or non-zero neutrino chemical potentials.[19] However recent developments in our understanding of cosmological phase transitions and lepto/baryogenesis [20] do not motivate such non-standard scenarios and moreover they are highly constrained by the observational data. It is therefore reasonable to adopt the standard picture which has only two unknown parameters, viz. the nucleon-to-photon ratio, $\eta \equiv n_{\rm N}/n_\gamma \simeq 2.72\times10^{-8}\Omega_{\rm N}h^2(T_0/2.73\,{\rm K})^{-3}$, and the effective number of massless, 2-component neutrinos, N_ν.[d] The latter determines the expansion rate of the universe (hence the free neutron abundance when nucleosynthesis begins) while the former determines the rates of nuclear reactions (which synthesize essentially all neutrons into ^{4}He nuclei, leaving behind small traces of D, ^{3}He and ^{7}Li). Therefore the ^{4}He abundance increases proportionally as N_ν but only logarithmically as η while the other elemental abundances are strongly dependent on η, as seen in figure 1.

The essential problem in attempting to compare the theoretical predictions with observational data is that the primordial abundances have been significantly altered during the lifetime of the universe through nuclear processing in stars and other galactic chemical evolution effects.[21] The most stable nucleus, ^{4}He, grows in abundance with time since it is always created in stars, while D, the most weakly bound, is always destroyed. The history of ^{3}He and ^{7}Li is more complicated since these elements may be both destroyed and created. To avoid uncertain corrections, it is neccessary to measure abundances in the most primordial material available and the recent development of large telescopes and CCD imaging technology have led to significant progress in the field. We present the key results and recent developments below and refer for more details to a recent review.[17]

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[c]However small corrections to the ^{4}He abundance for finite temperature effects [17] may not have quite stabilized yet [18] so there *could* be a comparable systematic uncertainty.

[d]The number of left-handed doublet neutrinos is known to be 3 from *LEP*, but we must allow for the possibility that there are other relativistic particles (e.g. singlet neutrinos) which may contribute to the energy density, and parametrize their contribution in terms of an effective N_ν. We do not entertain the possibility that the ν_τ is unstable and decays before BBN as this is ruled out experimentally if the decays are into known particles.[17]

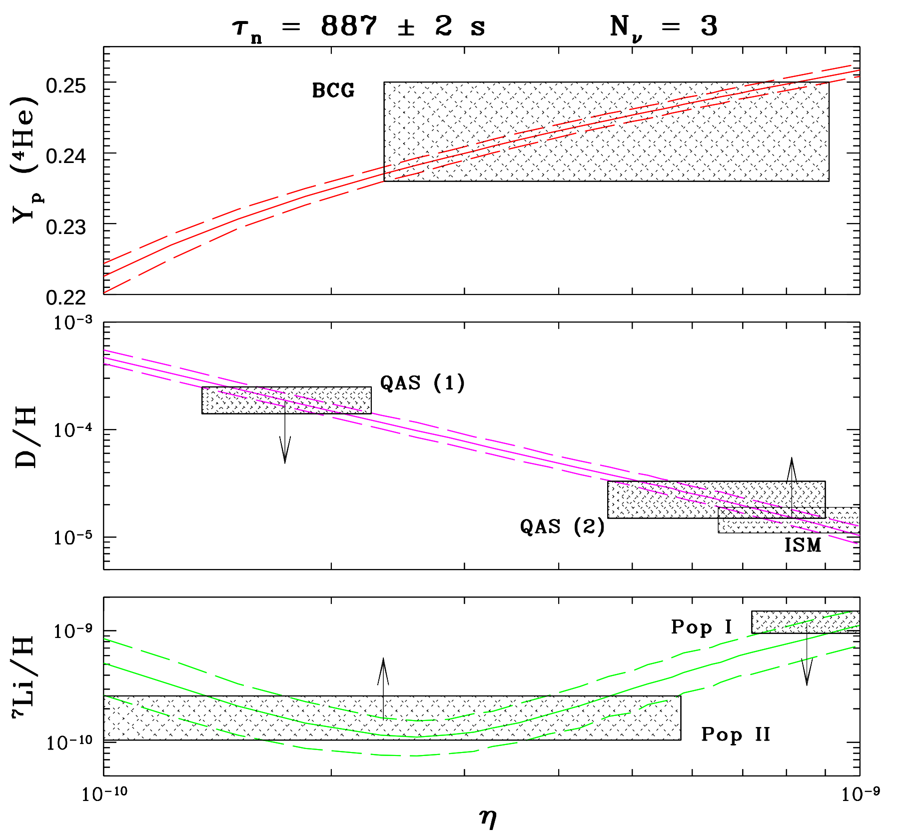

Figure 1: Predicted light element abundances for the Standard Model (with $N_\nu = 3$ neutrino species) versus the nucleon-to-photon ratio η.[13] The 95% c.l. limits determined by Monte Carlo reflect the uncertainties in all input nuclear cross-sections and the neutron lifetime. Rectangles indicate the various observational determinations and associated '95% c.l.' bounds. The ^{4}He abundance is obtained from observations of metal-poor blue compact galaxies by linear extrapolation to zero metallicity;[28] the upper bound is reliable, the lower one less so. Both the D abundance measurements [44,50] in quasar absorption systems are shown; the higher value is interpreted as an upper bound. Also shown is the abundance in the interstellar medium [31] which provides a reliable lower bound. The ^{7}Li abundance as measured in the hottest, most metal-poor halo stars [55], as well as in disk stars [58] is shown and interpreted as providing, respectively, reliable lower and upper bounds on its primordial value. GIven these uncertainties, the Standard Model is presently consistent with observations for η in the range $\sim (2-9) \times 10^{-10}$.

2.1 Helium-4

To determine the primordial ^{4}He mass fraction, $Y_{\rm p}$, we must allow for stellar helium production through its correlation with elements which are made only in stars. This is best done by studying recombination lines from H II regions in blue compact galaxies (BCGs) where relatively little stellar activity has occured, as evidenced by their low 'metal' abundance. The data set of Pagel *et al* [22] gathered from 33 selected objects indicated a primordial abundance of $Y_{\rm p}(^4{\rm He}) = 0.228 \pm 0.005$ (with an estimated systematic error of ± 0.005.) As shown in figure 2(a) this is obtained by linear extrapolation to zero metal abundance in a plot of the measured helium abundance against that of oxygen and nitrogen. A similar result was obtained for another set of 11 BCGs by Skillman *et al*.[23] Olive and Steigman [24] made a fit to a selected subset of the combined data and quoted

$$Y_{\rm p}(^4{\rm He}) = 0.232 \pm 0.003 \text{ (stat)} \pm 0.005 \text{ (syst)} \ . \tag{3}$$

However, it has been argued that the systematic error may be significantly larger than the value estimated above.[25] A particular issue is the input atomic physics used to extract the abundance from the measured line strengths. The point is that the He I line intensities deviate from the pure recombination values, due mainly to collisional excitation from the metastable 2^3S state. To correct for this, the physical conditions, in particular the electron density, in the H II regions must be accurately known. This is best done by simultaneously measuring several lines and determining the corrections self-consistently by demanding that all line ratios have their recombination values after correction. Izotov *et al* [28] have recently done this in a study of 27 objects, using data on 4 different lines (including the triplet line $\lambda 7065$). They used the updated emissivities of Smits [27] which are $\approx 50\%$ higher for this line than those of Brocklehurst [26], which were used in previous work. As shown in figure 2(b) they find a higher intercept of $Y_{\rm p}(^4{\rm He}) = 0.243 \pm 0.003$, with a smaller dispersion of the data points in their regression plots. Moreover the derived slope, ${\rm d}Y/{\rm d}Z \approx 1.7 \pm 0.9$, is smaller than the value of 6.1 ± 2.1 found earlier,[22] in better agreement with general theoretical expectations. Izotov *et al* argue that other possible systematic effects (in particular corrections for fluorescent enhancement in the $\lambda 7065$ line) cannot alter $Y_{\rm p}$ by more than ± 0.001 so that

$$Y_{\rm p}(^4{\rm He}) = 0.243 \pm 0.003 \text{ (stat)} \pm 0.001 \text{ (syst)} \ . \tag{4}$$

This value is presently controversial; for example in his talk [29] at this meeting, Keith Olive criticized their use of the $\lambda 7065$ line in view of its sensitivity to collisional excitation. However if it is excluded the correction for collisional

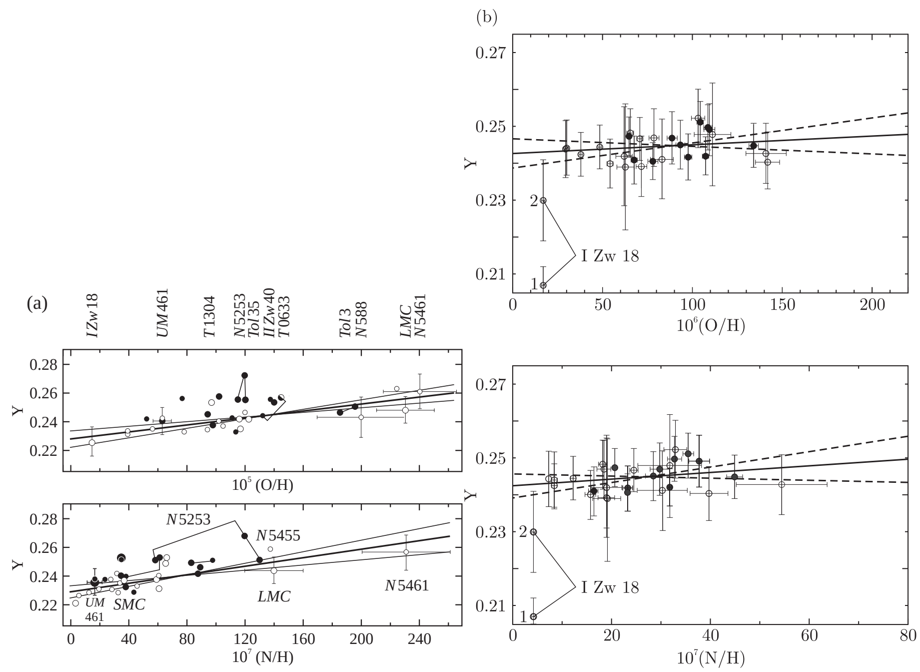

Figure 2: Regressions of the helium mass fraction against the oxygen and nitrogen abundances in extragalactic low-metallicity H II regions, with (filled circles) and without (open circles) broad Wolf-Rayet features. Panel (a) shows abundances for 33 objects obtained using the Brocklehurst emissivities,[22] with the maximum-likelihood linear fits (with $\pm 1\sigma$ limits) for the latter category. Panel (b) shows abundances for 27 objects obtained using the Smits emissivities,[28] along with the maximum-likelihood linear fits (with $\pm 1\sigma$ limits).

enhancement would depend, as in previous work, on more uncertain estimates of the electron density from nebular S II emission lines! I recall the admonishment of Zeldovich that "Observations should be analyzed by astronomers and not by theoretical physicists".[30] However I agree with Olive that the Izotov *et al* result is higher because of dropping the lowest metallicity galaxy *I Zw 18* from their sample (see figure 2(b)). They did so on account of its anomalously low He I line intensities, said to be caused by underlying stellar and interstellar absorption; whether this is justified or not is for other *observers* to decide. I maintain that while more work is neccessary to settle this issue, it would be *conservative* at this time to allow for the possibility that the upper bound to $Y_{\mathrm{p}}(^4\mathrm{He})$ is 0.25 rather than 0.24. The lower bound is less certain since the *linear* extrapolation to zero metallicity is purely empirical.

2.2 *Deuterium and Helium-3*

Deuterium is detected in the local interstellar medium through its ultraviolet absorption lines in stellar spectra but, as expected for a fragile element, its abundance shows a large scatter, $\mathrm{D/H} \approx (0.2 - 4) \times 10^{-5}$, suggesting localized abundance fluctuations and/or systematic errors. McCullough [31] finds that after discarding some unreliable measurements, the 7 *IUE* and 14 *Copernicus* measurements along the cleanest lines of sight (towards hot stars within about 1 kpc) are all consistent with an interstellar abundance of

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{ISM}} = 1.5 \pm 0.2 \times 10^{-5} \ . \tag{5}$$

Recently the *HST* has provided a more accurate measurement of $\mathrm{D/H} = 1.60 \pm 0.09\,(\mathrm{stat})^{+0.05}_{-0.10}\,(\mathrm{syst}) \times 10^{-5}$ towards the star *Capella* at 12.5 kpc.[32] However since the Lyman-α line (of hydrogen) is severely saturated even towards such a nearby star, such observations, although precise, cannot test whether there are real spatial variations in the interstellar deuterium abundance. It has been argued [33] that there are no important astrophysical sources of deuterium and observational attempts to detect signs of deuterium synthesis in the Galaxy have so far not contradicted this belief.[34] Then the lowest D abundance observed today provides a reliable lower bound to the primordial abundance, viz. $(\mathrm{D/H})_{\mathrm{p}} > 1.1 \times 10^{-5}$.

There are similar large fluctuations in the abundance of ^{3}He which has been detected through its radio recombination line in a dozen galactic H II regions. The values measured by Balser *et al*[35] range over

$$\left(\frac{^3\mathrm{He}}{\mathrm{H}}\right)_{\mathrm{H\,II}} \sim (1 - 4) \times 10^{-5} \ . \tag{6}$$

It has also been detected [36] with a large abundance ($^3\mathrm{He/H} \approx 10^{-3}$) in the planetary nebula *NGC3242*, in accord with the theoretical expectation [37] that it is created in low mass stars. However the galactic observations find the highest ^{3}He abundances in the outer Galaxy where stellar activity is *less* than in the inner Galaxy. While regions with high abundances do lie preferentially in the Perseus spiral arm, there are large source-to-source variations which do not correlate with stellar activity.[35] Thus these measurements do not provide any reliable cosmological input.

Yang *et al* [38] had suggested that the uncertainties in determining the primordial abundances of D and ^{3}He may be circumvented by considering their *sum*. They argued that since D is burnt in stars to ^{3}He, a fraction g_3 of which survives stellar processing, the primordial abundances may be related to the abundances later in time through the inequality

$$\left(\frac{\mathrm{D}+{}^3\mathrm{He}}{\mathrm{H}}\right)_{\mathrm{p}} < \left(\frac{\mathrm{D}+{}^3\mathrm{He}}{\mathrm{H}}\right) + \left(\frac{1}{g_3}-1\right)\left(\frac{{}^3\mathrm{He}}{\mathrm{H}}\right) \ . \tag{7}$$

As reviewed by Geiss,[39] the terms on the rhs may be determined at the time of formation of the Solar system, 4.6 Gyr ago. The abundance of ^{3}He in the Solar wind, deduced from studies of gas-rich meteorites, lunar rocks and metal foils exposed on lunar missions, may be identified with the sum of the pre-Solar abundances of ^{3}He and D (which was burnt to ^{3}He in the Sun), while the smallest ^{3}He abundance found in carbonaceous chondrites, which are believed to reflect the composition of the pre-Solar nebula, may be identified with the pre-Solar abundance of ^{3}He alone. For example, Walker *et al* [40] obtained

$$1.3\times10^{-5} \lesssim \left(\frac{{}^3\mathrm{He}}{\mathrm{H}}\right)_{\odot} \lesssim 1.8\times10^{-5} \ , \quad 3.3\times10^{-5} \lesssim \left(\frac{\mathrm{D}+{}^3\mathrm{He}}{\mathrm{H}}\right)_{\odot} \lesssim 4.9\times10^{-5}. \tag{8}$$

These authors also interpreted a study [37] on the survival of ^{3}He in stars to imply the lower limit $g_3 \gtrsim 0.25$. Using these values yields the bound [38,40]

$$\left(\frac{\mathrm{D}+{}^3\mathrm{He}}{\mathrm{H}}\right)_{\mathrm{p}} \lesssim 10^{-4} \ , \tag{9}$$

which is essentially a bound on primordial D alone since it is relevant only at small η where the relative abundance of ^{3}He is negligible.

There are however several reasons to distrust the above bound, from which a stringent lower limit on η has been deduced.[38,40,15,41] First, it is not clear if the Solar system abundances provide a representative measure at all, given that observations of ^{3}He elsewhere in the Galaxy reveal unexplained source-to-source variations. Indeed the pre-Solar abundance of ^{3}He is *less* than some of the present day interstellar values. Second, the survival fraction of ^{3}He may have been overestimated since there may be net *destruction* of ^{3}He in low mass stars through the same mixing process which appears to be needed to explain other observations, e.g. the ^{12}C/^{13}C ratio.[42] In fact a recent measurement using *Ulysses* finds that $^3\mathrm{He}/^4\mathrm{He} = 2.2^{+0.7}_{-0.6}\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}) \times 10^{-4}$ in the local interstellar cloud, rather close to the value of $1.5 \pm 0.3 \times 10^{-4}$ in the pre-solar nebula, demonstrating that the ^{3}He abundance has hardly increased since the formation of the Solar system.[43]

It is obviously crucial to detect deuterium outside the Solar system and the nearby interstellar medium in order to get at its primordial abundance and also, of course, to establish its cosmological origin. Astronomers have attempted to measure Lyman-series absorption lines of deuterium in the spectra of distant quasars, due to foreground intergalactic clouds made of primordial unprocessed material. Problems arise in studying such quasar absorption systems (QAS) because of possible confusion with neighbouring absorption lines of hydrogen and multi-component velocity structure in the clouds. The advent of large aperture ground-based telescopes, e.g. the 10-mt *Keck Telescope*, has provided the required sensitivity and spectral resolution, leading to several detections. Songaila *et al* [44] find

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QAS(1)}} \approx (1.9 - 2.5) \times 10^{-4} \ , \tag{10}$$

in a chemically unevolved cloud at $z = 3.32$ along the line of sight to the quasar *Q0014+813*, and note that there is a 3% probability of the absorption feature being a misidentified Ly-α line of hydrogen. Further observations by Rugers and Hogan [45] have resolved D lines at $z = 3.320482$ and $z = 3.320790$, thus eliminating the possibility of such confusion; the measured abundances in the two clouds are, respectively, $\mathrm{D/H} = 10^{-3.73\pm0.12}$ and $10^{-3.72\pm0.09}$ (where the errors are *not* gaussian). An independent lower limit of $\mathrm{D/H} \geq 1.3 \times 10^{-4}$(95% c.l.) is also set on their sum from the Lyman limit opacity. Recently, these authors have detected $\mathrm{D/H} = 1.9^{+0.6}_{-0.9} \times 10^{-4}$ in another QAS at $z = 2.797957$ towards the same quasar; The errors are higher because the D feature is saturated, even so a 95% c.l. lower limit of $\mathrm{D/H} > 0.7 \times 10^{-4}$ is obtained.[46] There have been other, less definitive, observations of QAS consistent with this abundance, e.g. $\mathrm{D/H} \lesssim 1.5 \times 10^{-4}$ at $z = 4.672$ towards *BR1202-0725*,[47] and $\mathrm{D/H} \lesssim 10^{-3.9\pm0.4}$ at $z = 3.08$ towards *Q0420-388*.[48] However, very recently, Tytler and collaborators have found much lower values in QAS at $z = 3.572$ towards *Q1937-1009*[49] and at $z = 2.504$ towards *Q1009+2956*;[50] their average abundance is

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QAS(2)}} = 2.4 \pm 0.3 \ (\mathrm{stat}) \pm 0.3 \ (\mathrm{syst}) \times 10^{-5} \ . \tag{11}$$

Since the Lyman-α line (of hydrogen) is saturated in these objects, the D abundance must be derived from a cloud model, with associated uncertainties.[51] A recent independent measurement [52] of the H I density in the cloud towards *Q1937-1009* raises the deuterium abundance to $\mathrm{D/H} \gtrsim 4\times10^{-5}$. The situation is clearly volatile at the moment! We adopt the *conservative* viewpoint that the 'ceiling' to the D measurements in QAS provides a reliable upper bound to its primordial abundance, viz. $(\mathrm{D/H})_{\mathrm{P}} < 2.5 \times 10^{-4}$.

2.3 Lithium-7

Lithium is observed in both halo (Pop II) and disk (Pop I) stars, with widely differing abundances.[53] For Pop I stars in open clusters with ages up to 10 Gyr, the observed abundances range upto $^7\mathrm{Li/H} \sim 10^{-9}$. However in the older Pop II halo dwarfs, Spite and Spite[54] observed the abundance to be ≈ 10 times lower and, for high temperatures and low metallicity, nearly independent of the stellar temperature and the metal abundance. This has been used to argue that the Pop II abundance reflects the primordial value in the gas from which the stars formed, with the higher abundance in the younger Pop I stars created subsequently. For example Walker *et al*[40] took the primordial abundance to be an weighted average of the data for 35 stars, $(^7\mathrm{Li/H})_\mathrm{p} = 10^{-9.92 \pm 0.07}$(95% c.l.). However Thorburn[55] finds a weak trend of increasing ^{7}Li abundance with both increasing temperature and increasing metallicity in a larger sample of 80 stars. The elements beryllium and boron are also observed in similar stars, correlated with the metallicity and in the ratio $\mathrm{B/Be} \approx 10$, which indicates that they were produced by galactic cosmic ray spallation rather than being primordial.[56] This should have also made $\approx 35\%$ of the observed ^{7}Li. The primordial abundance can then be identified[55] with the average value in the hottest, most metal-poor stars, viz.

$$\left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_\mathrm{p}^\mathrm{II} = 10^{-9.78 \pm 0.20}\ (95\%\ \mathrm{c.l.})\ . \tag{12}$$

However Molaro *et al*[57] do not find any correlation with the temperature or metallicity in another sample of 24 halo dwarfs using different modelling of the stellar atmospheres. The abundance they obtain is fortuitously identical to that given above but this does highlight the systematic uncertainties involved. Moreover there are several Pop II halo dwarfs which have *no* detectable lithium.[55] This suggests that the primordial ^{7}Li abundance may instead be the Pop I value which has been depleted down to (and occasionally, below) the level in Pop II stars, for example through turbulent mixing driven by stellar rotation. Stellar modelling shows that the primordial abundance can then be as high as[58]

$$\left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_\mathrm{p}^\mathrm{I} = 10^{-8.92 \pm 0.1}. \tag{13}$$

An argument against such severe depletion is that ^{6}Li, an even more fragile isotope, has been detected[59] in one of the hottest known Pop II stars with $(^6\mathrm{Li}/^7\mathrm{Li})^\mathrm{II} = 0.05 \pm 0.02$. However it is possible, e.g. through mass loss by stellar winds, for ^{7}Li to be depleted without depleting ^{6}Li; the preferred primordial abundance would then be the upper envelope of the Pop II value.[60]

3 Theory versus observations

In figure 1 we show that the standard model with $N_\nu = 3$ is consistent with these observations over a wide range of $\eta \sim (2-9)\times 10^{-10}$. The value of η will be close to its minimum allowed value if the high D abundance in QAS (eq.10) and the Pop II ^{7}Li abundance (eq.12) are primordial, while it will be close to its maximum allowed value if instead the low D abundance in QAS (eq.11) and the Pop I ^{7}Li abundance (eq.13) are primordial. Of course a value of η in between is also possible, given the systematic uncertainties in these abundance determinations.[61,13] At present, only the ^{4}He abundance inferred from BCGs is reasonably established to be primordial and even here we can only trust its upper, not lower, bound, given the empirical linear extrapolation to zero metallicity. Thus to be *conservative* we can only determine the *upper* limits on the parameters N_ν and η corresponding to the reliable bounds, $Y_{\rm p}(^4{\rm He}) < 0.25$ (eq.4), $\mathrm{D/H} > 1.1 \times 10^{-5}$ (eq.5) and $^7\mathrm{Li/H} < 1.5 \times 10^{-9}$ (eq.13), taking into account uncertainties in the nuclear cross-sections and the neutron lifetime by Monte Carlo methods. This exercise finds [13]

$$N_\nu^{\rm max} = 3.75 + 78\ (Y_{\rm p}^{\rm max} - 0.240), \tag{14}$$

i.e. upto 1.5 additional neutrino species are allowed for η at its lowest allowed value. Conversely, for $N_\nu = 3$,

$$\eta^{\rm max} = [3.28 + 216.4\,(Y_{\rm p}^{\rm max} - 0.240) + 34521\,(Y_{\rm p}^{\rm max} - 0.240)^2] \times 10^{-10}, \tag{15}$$

so that $\eta = 8.9 \times 10^{-10} \Rightarrow \Omega_{\rm N} = 0.033h^{-2}$ is the maximum allowed value.

The "crisis" in BBN identified by Hata *et al* [12] essentially arose because they used a chemical evolution model, normalized to Solar system abundances and convolved with BBN predictions, to infer that the *primordial* abundances were, $\mathrm{D/H} = 3.5^{+2.7}_{-1.8}\times 10^{-5}$ and $^3\mathrm{He/H} = 1.2\pm 0.3\times 10^{-5}$ at 95% c.l.. This picks out a high value of $\eta \approx 4.4 \times 10^{-10}$ which would imply, for $N_\nu = 3$, a higher abundance of ^{4}He than their adopted value (3). These authors found that concordance requires $N_\nu = 2.1 \pm 0.3$ and suggested various exotic possibilities to achieve this. They also noted that the crisis evaporates if the systematic uncertainty in the estimate (3) of $Y_{\rm p}(^4{\rm He})$ has been underestimated or if the extent to which ^{3}He survives stellar processing has been overestimated. As we have seen there are observational grounds for both suppositions. Overall it is clear that abundances derived from chemical evolution arguments are suspect and we should only consider direct observational limits. This is now accepted even by authors who previously used such arguments to derive bounds such as the one in eq.(9) on $\mathrm{D} + {}^3\mathrm{He}$, which implies a lower limit of $\eta \gtrsim 2.5 \times 10^{-10}$

leading to the much advertised [40,41] constraint $N_\nu \lesssim 3.4$.[e] Some of them have indeed conceded [61,62] that such arguments were not reliable.

What then are the implications for the nature of the dark matter?[17] For many years it has been stated [38,40,15,41] on the basis of the bound (9) on $\mathrm{D} + {}^3\mathrm{He}$ combined with the upper bound from (3) on ${}^4\mathrm{He}$ that BBN determines the nucleon density to be $\Omega_\mathrm{N} \approx 0.011 \pm 0.0015 h^{-2}$. It was argued that this is significantly higher than the value obtained from direct observations of luminous matter, suggesting that most nucleons are dark and, in particular, that much of the dark matter in galactic halos which contribute [2] $\Omega \approx 0.05 h^{-1}$ may be nucleonic. However if the indications of a high primordial D abundance (eq.10) are correct then as shown in figure 3 the implied lower value of $\Omega_\mathrm{N} \simeq 0.0059 \pm 0.0011\, h^{-2}$ is closer to its observational lower limit (for high values of h), leaving little room for the halo dark matter to be nucleonic. Conversely, if the primordial D abundance is actually low (eq.11) then the corresponding value of $\Omega_\mathrm{N} = 0.023 \pm 0.0032\, h^{-2}$ would suggest that the opposite is the case. The results from gravitational microlensing searches [8] allow both possibilities at present and are unlikely to provide a definitive resolution.

More interesting is the comparison with clusters of galaxies which are observed to have a large nucleonic fraction (eq.2). If $\Omega = 1$, then as shown in figure 3, the *Coma* observations can be consistent with standard BBN only for a low deuterium abundance (and low values of h). In fact observations of large-scale structure and CMB anisotropy do favour high Ω_N and low h for a critical density universe dominated by cold dark matter.[63] Conversely if the deuterium abundance is actually high, then to achieve consistency would require $\Omega \approx 0.2$, which is, admittedly, consistent with all dynamic measurements.[2] The dark matter in *Coma* and other clusters would then be comparable to that in the individual galactic halos. However this is not yet a firm argument for $\Omega < 1$ since gravitational lensing observations suggest that the assumption of hydrostatic equilibrium underestimates the total cluster mass;[64] for example there may be sources of non-thermal pressure such as magnetic fields and cosmic rays which would lower the inferred thermal pressure of the X-ray emitting plasma.[65] Note that in either case, most of the matter in the universe *must* be non-nucleonic, although not neccessarily present in our Galactic halo where it can be searched for by direct experimental means.

The present situation is confusing but it has focussed attention on systematic errors in measurements of elemental abundances and made it evident that chemical evolution models are uncertain and results based on them are not to be trusted. Within a decade Ω_N is expected to be known independently

[e]When correlations between the different elemental yields are taken into account, the actual limit coorresponding to these bounds is even more stringent,[16] $N_\nu < 3.04$!

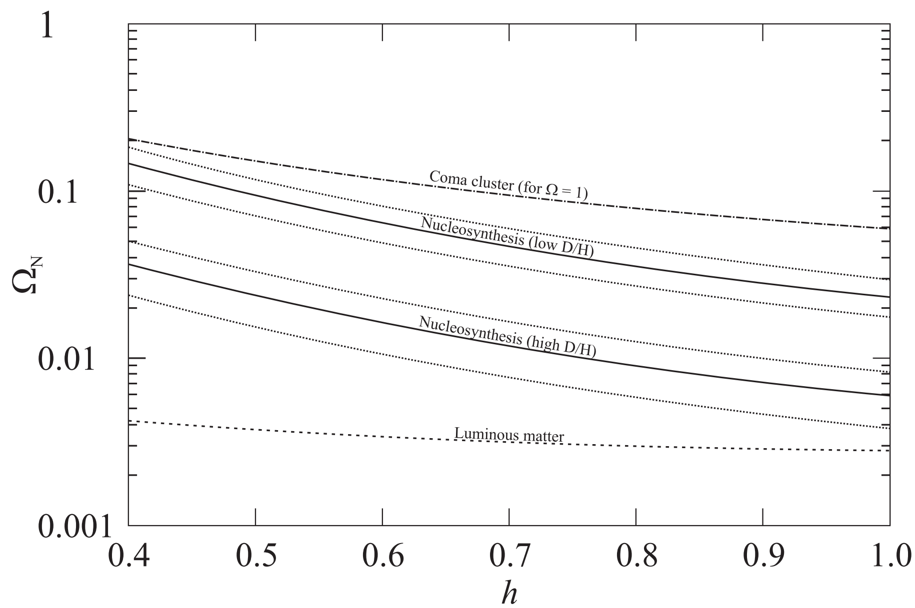

Figure 3: The cosmological density parameter in nucleons as a function of the Hubble parameter.[17] The full lines (with dotted '2σ' error bands) show the standard BBN values according as whether the primordial D abundance is taken to be the high value [44] or the low value [50] measured in QAS. The dashed line is the lower limit from an audit [3] of luminous matter in the universe. The dot-dashed line indicates the value deduced [11] from the observed luminous matter in the *Coma* cluster for $\Omega = 1$; it should be lowered by a factor of Ω^{-1} for $\Omega < 1$.

to within a few per cent through measurement of the height of the Doppler peak in the CMB angular power spectrum.[7] Nevertheless precise measurement of light element abundances is still crucial because primordial nucleosynthesis provides an unique probe of physical conditions, for example the particle content, in the early universe. The challenge for observers is to be ready by then to perform an unprecedented consistency check of the Standard Models of cosmology and particle physics, and perhaps to even glimpse what lies beyond.

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References

1. R.P. Feynmann, F.B. Morinigo and W.G. Wagner, *Feynmann Lectures on Gravitation* (Addison-Wesley, 1995) p.179.
2. J. Binney and S. Tremaine, *Galactic Dynamics* (Princeton University Press, 1987).
3. M. Persic and P. Salucci, *Mon. Not. R. Astr. Soc.* **258**, 14p (1992).
4. B.J. Carr *Annu. Rev. Astron. Astrophys.* **32**, 531 (1994).
5. A. Dekel, *Annu. Rev. Astron. Astrophys.* **32**, 371 (1994).
6. S. Perlmutter *et al*, astro-ph/9608192.
7. D. Scott and G.F. Smoot, *Phys. Rev.* D **54**, 118 (1996).
8. C. Alcock *et al*, astro-ph/9606165.
9. W. Evans, *these proceedings* (astro-ph/9611161).
10. R.N. Mohapatra, *these proceedings.*
11. S.D.M. White *et al*, *Nature* **366**, 429 (1993).
12. N. Hata *et al*, *Phys. Rev. Lett.* **75**, 3977 (1995).
13. P.J. Kernan and S. Sarkar, *Phys. Rev.* D **54**, 3681 (1996).
14. R.V. Wagoner, W.A. Fowler and F. Hoyle, *Astrophys. J.* **148**, 3 (1967).
15. M.S. Smith, L.H. Kawano and R.A. Malaney, *Astrophys. J. Suppl.* **85**, 219 (1993).
16. P.J. Kernan and L.M. Krauss, *Phys. Rev. Lett.* **72**, 3309 (1994);
    L.M. Krauss and P.J. Kernan, *Phys. Lett.* B **347**, 347 (1995).
17. S. Sarkar, *Rep. Prog. Phys.* **59**, 1493 (1996).
18. R.F. Sawyer, *Phys. Rev.* D **53**, 4232 (1996).
19. R.A. Malaney and G.J. Mathews, *Phys. Rep.* **229**, 145 (1993).
20. V.A. Rubakov V A and M.E. Shaposhnikov, hep-ph/9603208.
21. A.M. Boesgaard and G. Steigman, *Annu. Rev. Astron. Astrophys.* **23**, 919 (1985).
22. B.E.J. Pagel *et al*, *Mon. Not. R. Astr. Soc.* **255**, 325 (1992).
23. E. Skillman *et al*, *Ann. N. Y. Acad. Sci.* **688**, 739 (1993).
24. K.A. Olive and G. Steigman, *Astrophys. J. Suppl.* **97**, 49 (1995).
25. K. Davidson and T.D. Kinman, *Astrophys. J. Suppl.* **58**, 321 (1985);
    G. Shields, in *13th Texas Symp. on Relativistic Astrophysics*, ed. P. Ulmer (World Scientific, Singapore, 1987) p.192;
    D. Sasselov and D.S. Goldwirth, *Astrophys. J.* **444**, L5 (1995).
26. M. Brocklehurst, *Mon. Not. R. Astr. Soc.* **157**, 211 (1972).
27. D.P. Smits, *Mon. Not. R. Astr. Soc.* **278**, 683 (1996).
28. Y.I. Izotov, T.X. Thuan and V.A. Lipovetsky, *Astrophys. J.* **435**, 647 (1994), *Astrophys. J. Suppl.* submitted (1996).
29. K.A. Olive, *these proceedings.*

30. Ya.B. Zeldovich, *Adv. Astron. Astrophys.* **3**, 241 (1965).
31. P.R. McCullough, *Astrophys. J.* **390**, 213 (1992).
32. J.L. Linsky *et al*, *Astrophys. J.* **402**, 694 (1993), **451**, 335 (1995).
33. R. Epstein, J. Lattimer and D.N. Schramm, *Nature* **263**, 198 (1976).
34. J.M. Pasachoff and A. Vidal-Madjar, *Comm. Astrophys.* **14**, 61 (1989).
35. D.S. Balser *et al*, *Astrophys. J.* **430**, 667 (1994).
36. R.T. Rood, T.M. Bania and T.L. Wilson, *Nature* **355**, 618 (1992)
37. D.S.P. Dearborn, D.N. Schramm and G. Steigman, *Astrophys. J.* **302**, 35 (1986).
38. J. Yang *et al*, *Astrophys. J.* **281**, 493 (1984).
39. J. Geiss, in *Origin and Evolution of the Elements*, ed. N. Prantzos *et al*(Cambridge University Press, 1993) p.89.
40. T.P. Walker *et al*, *Astrophys. J.* **376**, 51 (1991).
41. C.J. Copi, D.N. Schramm and M.S. Turner, *Science*, **267**, 192 (1995).
42. C.J. Hogan, *Astrophys. J.* **441**, L17 (1995).
43. G. Gloeckler and J. Geiss, *Nature* **381**, 210 (1996).
44. A. Songaila *et al*, *Nature* **368**, 599 (1994).
45. M. Rugers and C.J. Hogan, *Astrophys. J.* **459**, L1 (1996),
46. M. Rugers and C.J. Hogan, *Astron. J.* **111**, 2135 (1996).
47. E.J. Wampler *et al*, *Astron. Astrophys.* **316**, 33 (1996).
48. R.F. Carswell *et al*, *Mon. Not. R. Astr. Soc.* **278**, 506 (1996).
49. D. Tytler, X. Fan and S. Burles, *Nature* **381**, 207 (1996).
50. S. Burles and D. Tytler, astro-ph/9603070.
51. E.J. Wampler, *Nature* **383**, 308 (1996).
52. A. Songaila, E.J. Wampler and L.L. Cowie, astro-ph/9611143.
53. G. Michaud and P. Charbonneau, *Space Sci. Rev.* **57**, 1 (1992).
54. F. Spite and M. Spite, *Astron. Astrophys.* **115**, 357 (1982).
55. J.A. Thorburn, *Astrophys. J.* **421**, 318 (1994).
56. G. Gilmore *et al*, *Nature* **357**, 379 (1992).
57. P. Molaro, F. Primas and P. Bonifacio, *Astron. Astrophys.* **295**,L47 (1995).
58. B. Chaboyer and P. Demarque, *Astrophys. J.* **433**, 510 (1994).
59. V. Smith, D. Lambert and P. Nissen, *Astrophys. J.* **408**, 262 (1992).
60. S. Vauclair and C. Charbonnel, *Astron. Astrophys.* **295**, 715 (1995).
61. C.J. Copi, D.N. Schramm and M.S. Turner, *Phys. Rev. Lett.* **75**, 3981 (1995), hep-ph/9606059.
62. B.D. Fields *et al*, *New Astronomy* **1**, 77 (1996).
63. A.R. Liddle, *these proceedings* (astro-ph/9610215)
64. X-P. Wu and L-Z. Fang, *Astrophys. J.* **467**, L45 (1996).
65. G. Steigman and J.E. Felten *Space Sci. Rev.* **74**, 245 (1995).