

Measuring the baryon content of the universe: BBN vs CMB

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Abstract The relic abundance of baryons — the only form of stable matter whose existence we are certain of — is a crucial parameter for many cosmological processes, as well as material evidence that there is new physics beyond the Standard Model. We discuss recent determinations of the cosmological baryon density from analysis of the abundances of light elements synthesised at the end of “the first three minutes”, and from the observed temperature anisotropies imprinted on small angular-scales in the cosmic microwave background when the universe was $\sim 10^5$ yr old.

0.1 Introduction

Beginning as an uniformly distributed plasma in the radiation-dominated era, baryons are now distributed in a hierarchy of structures, from galaxies to superclusters, which have formed through gravitational collapse and constitute the familiar visible universe. Although it is recognised that baryons are a dynamically unimportant component, outweighed by the dark matter that actually holds such structures together, they constitute the only form of stable matter which we know about and can study directly. Nevertheless their cosmological origin is a mystery, even harder to fathom than that of the much more dominant dark matter. This is not always appreciated, particularly by those who think of baryons as familiar ‘ordinary’ stuff, as opposed to the ‘exotic’ particles that particle theorists dream up such as supersymmetric neutralinos. However it follows from elementary kinetic theory [1] that the relic abundance of massive particles (and anti-particles) which were in thermal equilibrium in the early universe is proportional to the inverse of their (velocity-averaged) self-annihilation cross-section: $\Omega_x h^2 \sim 3 \times 10^{-10} \text{GeV}^{-2} / \langle \sigma v \rangle_{x\bar{x}}$. Thus strongly interacting particles such as baryons should barely have survived self-annihilations ($\Omega_B h^2 \sim 10^{-11} \Rightarrow n_B/n_\gamma \sim 10^{-18}$), while weakly interacting particles such as stable neutralinos, if they exist, should naturally have a present density which is dynamically important ($\Omega_\chi h^2 \sim 0.1$). Since n_B/n_γ is actually found to be of $\mathcal{O}(10^{-10})$ today, with no evidence for antimatter, it is thus *necessary* to postulate that there was an initial excess of quarks over anti-quarks by about 1 part in 10^9 , before baryons and anti-baryons first formed following the QCD confinement transition at ~ 0.2 GeV and

began to annihilate. As Sakharov first noted, to create this baryon asymmetry of the universe (BAU) requires new physics, specifically the violation of baryon number, as well as of C and CP , together with departure from thermal equilibrium to provide an arrow of time. Whereas all these ingredients may in principle be available in the Standard $SU(3)\otimes SU(2)\otimes U(1)$ Model (SM) cosmology [2], in practice it has not proved possible to generate the required BAU with SM dynamics, essentially because the LEP bound on the Higgs mass precludes a strong enough first-order electroweak symmetry breaking phase transition. There is still hope that this may prove possible in supersymmetric extensions of the SM, which moreover may have new sources of CP violation [3]. There is also the novel possibility that the BAU may be linked to the smallness of neutrino masses since the source for both of them may be lepton number violating dynamics at energies close to the GUT scale [4]. Of course the source of the BAU may be some totally different mechanism, e.g. the Affleck-Dine mechanism in supergravity [5], and there is no guarantee that we will necessarily ever be able to link it directly to laboratory physics. All this makes it quite clear that the existence of ‘ordinary’ matter today is far more mysterious in principle than that of dark ‘exotic’ matter. Our very existence *requires* that there is exciting new physics to be discovered beyond the Standard Model!

My task here is to review recent determinations of the baryon density of the universe which is not only of fundamental significance as discussed above, but also an important parameter for crucial cosmological processes, in particular for Big Bang nucleosynthesis (BBN) of the light elements at $t \sim 10^2$ s [6], and for the decoupling of the cosmic microwave background (CMB) when the universe turns neutral at $t \sim 10^5$ yr [7]. It has been recognised for some years that the primordial abundance of a fragile element such as deuterium, whose only source is BBN, serves as a sensitive probe of the baryon density [8]. More recently it has been noted that the temperature fluctuations imprinted on the CMB at small angular scales by acoustic oscillations of the coupled photon-baryon plasma during (re)combination [9] enable an independent determination of the baryon density from CMB sky maps [10]. Recent observations of light element abundances (particularly the deuterium abundance in quasar absorption systems at high redshift), as well as of sub-degree scale temperature fluctuations in the CMB, have allowed a comparison of these two independent methods. After some initial problems, the two determinations are now believed to be in good agreement, and moreover consistent with estimates of the baryon content of the high redshift Lyman- α ‘forest’ [11], leading some cosmologists to declare this a triumph for “precision cosmology”. This may however be premature because there still remain major observational uncertainties on the BBN side, while cosmological parameter extraction from the CMB requires important assumptions, particularly concerning *the nature and spectral shape of the primordial density perturbations*. It is undoubtedly impressive that the standard cosmological model [1] (extended to include the standard model of structure formation from scale-free adiabatic initial density perturbations) has passed an important consistency check. However since cosmologists are no longer starved of data, it would seem more appropriate to abandon the untested assumptions of the model and begin to confront a more sophisticated paradigm, rather than exult in having achieved agreement between different model-dependent determinations to within a factor of ~ 2 . I will therefore emphasise the loopholes in the present approaches to determination of the baryon density in the hope that this will motivate observers to rule out such “non-standard” possibilities. Only then would we really be justified in calling it the ‘standard model’ of cosmology.

0.2 Big bang nucleosynthesis and the baryon density

There have been many discussions of how the baryon density influences the synthesis of the light elements [12]; here we follow a recent summary [13]. BBN is sensitive to physical conditions in the early radiation-dominated era at temperatures $T \lesssim 1$ MeV, corresponding to an age $\gtrsim 1$ s. At higher temperatures, weak interactions were in thermal equilibrium, thus fixing the ratio of the neutron and proton number densities to be $n/p = e^{-Q/T}$, where $Q = 1.293$ MeV is the neutron-proton mass difference. As the temperature dropped, the neutron-proton inter-conversion rate, $\Gamma_{n \leftrightarrow p} \sim G_F^2 T^5$, fell faster than the Hubble expansion rate, $H \sim \sqrt{g_* G_N} T^2$, where g_* counts the number of relativistic particle species determining the energy density in radiation. This resulted in breaking of chemical equilibrium (“freeze-out”) at $T_{\text{fr}} \sim (g_* G_N / G_F^4)^{1/6} \simeq 1$ MeV. The neutron fraction at this time, $n/p = e^{-Q/T_{\text{fr}}} \simeq 1/6$ is thus sensitive to every known physical interaction, since Q is determined by both strong and electromagnetic interactions while T_{fr} depends on the weak as well as gravitational interactions. Moreover it is sensitive to the Hubble expansion rate, affording e.g. a probe of the number of relativistic neutrino species. After freeze-out the neutrons were free to β -decay so the neutron fraction dropped to $\simeq 1/7$ by the time nuclear reactions began. The rates of these reactions depend on the density of baryons (strictly speaking, *nucleons*), which is usually normalised to the blackbody photon density as $\eta \equiv n_B/n_\gamma$. As we shall see, all the light-element abundances can be explained with $\eta_{10} \equiv \eta \div 10^{-10}$ in the range 2.6–6.2.

The nucleosynthesis chain begins with the formation of deuterium in the process $p(n, \gamma)\text{D}$. However, photo-dissociation by the high number density of photons delays production of deuterium (and other complex nuclei) until well after T drops below the binding energy of deuterium, $\Delta_{\text{D}} = 2.23$ MeV. The quantity $\eta^{-1} e^{-\Delta_{\text{D}}/T}$, i.e. the number of photons per baryon above the deuterium photo-dissociation threshold, falls below unity at $T \simeq 0.1$ MeV; nuclei can then begin to form without being immediately photo-dissociated again. Only 2-body reactions such as $\text{D}(p, \gamma)^3\text{He}$, $^3\text{He}(\text{D}, p)^4\text{He}$, are important because the density is rather low at this time — about the density of water! Nearly all the surviving neutrons when nucleosynthesis begins end up bound in the most stable light element ^4He . Heavier nuclei do not form in any significant quantity both because of the absence of stable nuclei with mass number 5 or 8 (which impedes nucleosynthesis via $n^4\text{He}$, $p^4\text{He}$ or $^4\text{He}^4\text{He}$ reactions) and the large Coulomb barriers for reactions such as $\text{T}(^4\text{He}, \gamma)^7\text{Li}$ and $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$. Hence the primordial mass fraction of ^4He , conventionally referred to as Y_{p} , can be estimated by the simple counting argument

$$Y_{\text{p}} = \frac{2(n/p)}{1 + n/p} \simeq 0.25. \quad (1)$$

There is little sensitivity here to the actual nuclear reaction rates, which are however important in determining the other “left-over” abundances: D and ^3He at the level of a few times 10^{-5} by number relative to H, and $^7\text{Li}/\text{H}$ at the level of about 10^{-10} . The experimental parameter most important in determining Y_{p} is the neutron lifetime, τ_n , which normalises (the inverse of) $\Gamma_{n \leftrightarrow p}$. The experimental uncertainty in τ_n used to be a source of concern but has recently been reduced substantially: $\tau_n = 885.7 \pm 0.8$ s.

The predicted elemental abundances, calculated using the (publicly available [14]) Wagoner code [6, 15], are shown in Fig. 1 as a function of η_{10} . The ^4He curve includes small corrections due to radiative processes at zero and finite temperature, non-

equilibrium neutrino heating during e^\pm annihilation, and finite nucleon mass effects [16, 17]; the range reflects primarily the 1σ uncertainty in the neutron lifetime. The spread in the curves for D, ^3He and ^7Li corresponds to the 1σ uncertainties in nuclear cross sections estimated by Monte Carlo methods [18]; polynomial fits to the predicted abundances and the error correlation matrix have been given [19]. Recently the input nuclear data have been carefully reassessed [20, 21], leading to improved precision in the abundance predictions. The boxes in Fig.1 show the observationally inferred primordial abundances with their associated uncertainties, as discussed below.

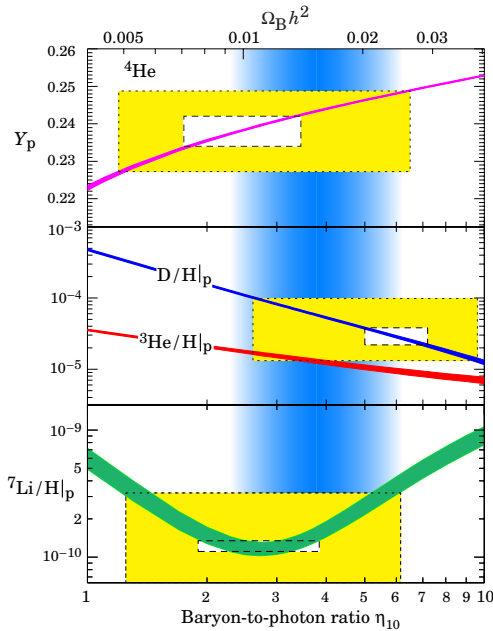


Figure 1: The primordial abundances of ^4He , D, ^3He and ^7Li as predicted by the standard BBN model compared to observations — smaller boxes: 2σ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors added in quadrature (from Ref.[13]).

0.2.1 Primordial light element abundances

BBN theory predicts the universal abundances of D, ^3He , ^4He and ^7Li , which are essentially determined by $t \sim 180$ s (although some reactions continue for several hours). Abundances are however observed at much later epochs, after stellar nucleosynthesis has already commenced. The ejected remains of this stellar processing can alter the light element abundances from their primordial values, but also produce heavy elements such as C, N, O, and Fe (“metals”). Thus one seeks astrophysical sites with low metal abundances, in order to measure light element abundances which are closer to primordial.

We observe ^4He in clouds of ionized hydrogen (H II regions), the most metal-poor of which are in dwarf blue compact galaxies (BCGs). There is now a large body of data on ^4He and C, N, O in these systems [22, 23]. These data confirm that the small

stellar contribution to helium is positively correlated with metal production (see Fig.2); extrapolating to zero metallicity gives the primordial ^4He abundance [24]:

$$Y_p = 0.238 \pm 0.002 \pm 0.005 . \quad (2)$$

Here and throughout, the first error is statistical, and the second is an estimate of the systematic uncertainty. The latter clearly dominates, and is based on the scatter in different analyses of the physical properties of the H II regions [22, 23, 25, 26]. Other extrapolations to zero metallicity give $Y_p = 0.244 \pm 0.002$ [23], and $Y_p = 0.235 \pm 0.003$ [27], while the average in the 5 most metal-poor objects is $Y_p = 0.238 \pm 0.003$ [28]. The value in Eq.(2), shown in Fig.1, is consistent with all these determinations.

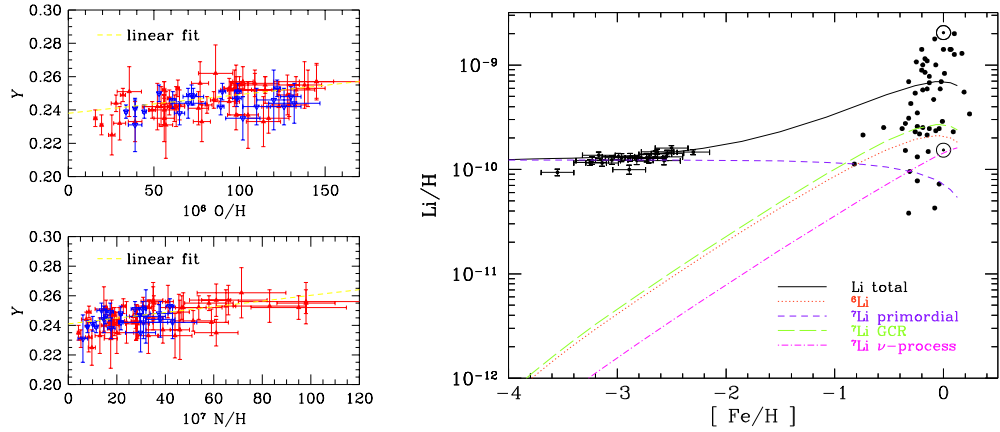


Figure 2: The primordial abundances of ^4He (from Ref.[24]) and of ^7Li (from Ref.[33]), inferred from the observed abundances in, respectively, BCGs and Pop II stars.

The systems best suited for Li observations are hot, metal-poor stars belonging to the halo population (Pop II) of our Galaxy. Observations have long shown that Li does not vary significantly in such stars having metallicities $\lesssim 1/30$ of solar — the “Spite plateau” [29, 30]. Recent precision data suggest a small but significant correlation between Li and Fe [31] which can be understood as the result of Li production from cosmic rays [32]. Extrapolating to zero metallicity (see Fig.2) one arrives at a primordial value [33]

$$\text{Li/H}|_p = (1.23 \pm 0.06^{+0.68+0.56}_{-0.32}) \times 10^{-10} . \quad (3)$$

The last error is our estimate of the maximum upward correction necessary to allow for possible destruction of Li in Pop II stars, due to e.g. mixing of the outer layers with the hotter interior [34, 35]. Such processes can be constrained by the absence of significant scatter in the Li-Fe correlation plot [30, 31], and through observations of the even more fragile isotope ^6Li [32].

In recent years, high-resolution spectra have revealed the presence of D in quasar absorption systems (QAS) at high-redshift, via its isotope-shifted Lyman- α absorption [36, 37, 38, 39, 40, 41]. It is believed that there are no astrophysical sources of deuterium [42], so any measurement of D/H provides a lower limit to the primordial abundance and

thus an upper limit on η ; for example, the local interstellar value of $D/H = (1.5 \pm 0.1) \times 10^{-5}$ [43] requires $\eta_{10} \leq 9$. Early reports of $D/H > 10^{-4}$ towards 2 quasars (Q0014+813 [36] and PG1718+4807 [38]) have been undermined by later analyses [44, 45]. Three high quality observations yield $D/H = (3.3 \pm 0.3) \times 10^{-5}$ (PKS1937-1009), $(4.0 \pm 0.7) \times 10^{-5}$ (Q1009+2956), and $(2.5 \pm 0.2) \times 10^{-5}$ (HS0105+1619); their average value

$$D/H = (3.0 \pm 0.4) \times 10^{-5} \quad (4)$$

has been widely promoted as *the* primordial abundance [39]. However the χ^2 for this average is 7.1 implying that systematic uncertainties have been underestimated, or that there is real dispersion in the abundance. Other values have been reported in different (damped Lyman- α) systems which have a higher column density of neutral H, viz. $D/H = (2.24 \pm 0.67) \times 10^{-5}$ (Q0347-3819) [40] and $D/H = (1.65 \pm 0.35) \times 10^{-5}$ (Q2206-199) [41]. Moreover, allowing for a more complex velocity structure than assumed in these analyses raises the inferred abundance by upto $\sim 50\%$ [47]. Even the ISM value of D/H now shows unexpected scatter of a factor of 2 [49]. All this may indicate significant processing of the D abundance even at high redshift, as indicated in Fig.3 [48]. Given these uncertainties, we conservatively bound the primordial abundance with an upper limit set by the non-detection of D absorption in a high-redshift system (Q0130-4021) [46], and the lower limit set by the local interstellar value [43], both at 2σ :

$$1.3 \times 10^{-5} < D/H|_p < 9.7 \times 10^{-5}. \quad (5)$$

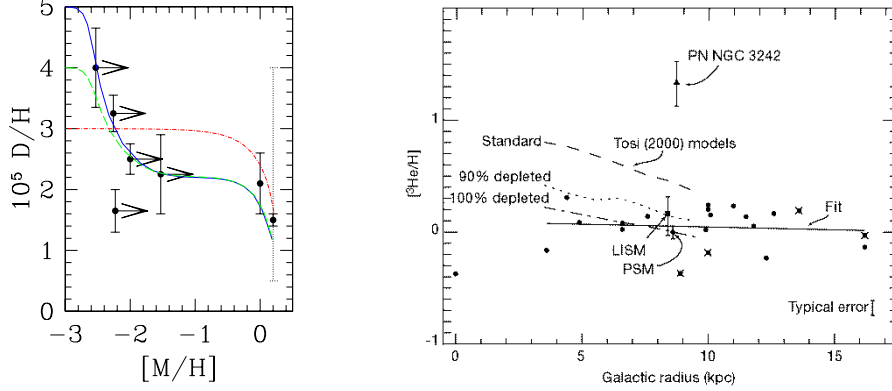


Figure 3: Chemical evolution models compared to the observed abundance of D in QAS and in the ISM (from Ref.[48]), and of ^3He in galactic HII regions (from Ref.[50]).

For ^3He , the only observations available are in the Solar system and (high-metallicity) H II regions in our Galaxy [50]. This makes inference of the primordial abundance difficult, a problem compounded by the fact that stellar nucleosynthesis models for ^3He are in conflict with observations [51]. Such conflicts can perhaps be resolved if a large fraction of low mass stars destroy ^3He by internal mixing driven by stellar rotation, consistent with the observed $^{12}\text{C}/^{13}\text{C}$ ratios [52]. The observed abundance ‘plateau’ in H II regions (see Fig.3) then implies a limit on the primordial value of $^3\text{He}/\text{H} < (1.9 \pm 0.6) \times 10^{-5}$ [50], which is consistent with the other constraints we discuss.

0.2.2 The baryon density from standard (and non-standard) BBN

The observationally *inferred* light element abundances can now be used to assess standard BBN for which the only free parameter is the baryon-to-photon ratio η . (The implications of non-standard physics for BBN will be considered shortly.) The overlap in the η ranges spanned by the larger boxes in Fig.1 indicates overall concordance. More quantitatively, accounting for theoretical uncertainties as well as the statistical and systematic errors in observations, there is acceptable agreement among the abundances when [13]

$$2.6 \leq \eta_{10} \leq 6.2 . \quad (6)$$

However the agreement is far less satisfactory if we use only the quoted statistical errors in the observations. As seen in Fig.1, ${}^4\text{He}$ and ${}^7\text{Li}$ are consistent with each other but favor a value of η which is lower by $\sim 2\sigma$ from the value $\eta_{10} = 5.9 \pm 0.4$ indicated by the D abundance (4). Additional studies are required to clarify if this discrepancy is real.

The broad concordance range (6) provides a measure of the baryon content of the universe. With n_γ fixed by the present CMB temperature $T_0 = 2.725 \pm 0.001$ K, the baryonic fraction of the critical density is $\Omega_B = \rho_B/\rho_{\text{crit}} \simeq \eta_{10} h^{-2}/274$ (where $h \equiv H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is the present Hubble parameter), so that

$$0.0095 \leq \Omega_B h^2 \leq 0.023 , \quad (7)$$

For comparison, if the D abundance in Eq.(4) is indeed its primordial value then the implied baryon density is at the upper end of the (95% c.l.) range quoted above:

$$\Omega_B h^2 = 0.020 \pm 0.0015 . \quad (8)$$

In either case since $\Omega_B \ll 1$, baryons cannot close the universe. Furthermore, the cosmic density of (optically) luminous matter is $\Omega_{\text{lum}} \simeq 0.0024 h^{-1}$ [53], so that $\Omega_B \gg \Omega_{\text{lum}}$; most baryons are optically dark, probably in the form of a $\sim 10^6$ K X-ray emitting intergalactic medium [54]. Finally, given that $\Omega_M \gtrsim 0.3$, we infer that most matter in the universe is not only dark but also takes some non-baryonic (more precisely, non-nucleonic) form.

The above limits hold for the standard BBN model and one can ask to what extent they can be modified if plausible changes are made to the model. For example if there is an initial excess of electron neutrinos over antineutrinos then $n - p$ equilibrium is shifted in favour of less neutrons, leading to less ${}^4\text{He}$. However the accompanying increase in the relativistic energy density speeds up the expansion rate and increases the n/p ratio at freeze-out, leading to more ${}^4\text{He}$, although this effect is smaller. For neutrinos of other flavours which do not participate in nuclear reactions only the latter effect was presumed to operate, allowing the possibility of balancing a small chemical potential in ν_e by a much larger chemical potential in $\nu_{\mu,\tau}$, and thus substantially enlarging the concordance range of η_{10} [55]. However the recent recognition from Solar and atmospheric neutrino experiments that the different flavours are maximally mixed no longer permits such a hierarchy of chemical potentials [56], thus ruling out this possible loophole. Another possible change to standard BBN is to allow inhomogeneities in the baryon distribution, created e.g. during the QCD (de)confinement transition. If the characteristic inhomogeneity scale exceeds the neutron diffusion scale during BBN, then increasing the average value of η increases the synthesised abundances such that the observational limits essentially rule out such inhomogeneities. However fluctuations in η

on smaller scales will result in neutrons escaping from the high density regions leading to spatial variations in the n/p ratio which might allow the upper limit to η to be raised substantially [57]. Recent calculations show that D and ^4He can indeed be matched even when η is raised by a factor of ~ 2 by suitably tuning the amplitude and scale of the fluctuations, but this results in unacceptable overproduction of ^7Li [58]. A variant on the above possibility is to allow for regions of antimatter which annihilate during or even after BBN (possible if baryogenesis occurs e.g. through the late decay of a coherently oscillating scalar field); however the ^7Li abundance again restricts the possibility of raising the limit on η substantially [59]. Finally the synthesised abundances can be altered if a relic massive particle decays during or after BBN generating electromagnetic and hadronic showers in the radiation-dominated plasma. Interestingly enough the processed yields of D, ^4He and ^7Li can then be made to match the observations even for a universe closed by baryons [60], however the production of ^6Li is excessive and argues against this possibility. In summary the conservative range of baryon density (7) inferred from standard BBN appears to be reasonably robust; although non-standard possibilities cannot be definitively ruled out altogether, they have at least been examined in some detail and tests devised to constrain them. This contrasts with the rather simple-minded manner in which parameters have been extracted from CMB observations as discussed below.

0.3 The baryon density from the CMB

The BBN prediction for the cosmic baryon density can be tested through precision measurements of CMB temperature fluctuations on angular scales smaller than the horizon at last scattering [9]. The amplitudes of the acoustic peaks in the CMB angular power spectrum provide an independent measure of η [10]. Creation (or even ‘destruction’) of photons between BBN and CMB decoupling can distort the CMB spectrum, so there cannot be a significant change in η between BBN and CMB decoupling [61]. Thus comparison of the two measurements is a key test for the standard cosmology; agreement would provide e.g. a superb probe of galactic chemical evolution [62], while disagreement would require revision of the standard picture.

However as with other cosmological parameter determinations from CMB data, the derived η_{CMB} depends on the adopted ‘priors’, in particular the assumed nature of primordial density perturbations. The standard expectation from simple inflationary models is for an adiabatic perturbation with a spectrum that is close to the ‘Harrison-Zeldovich’ scale-invariant form [63]. However it is perhaps not widely appreciated that there is no *physical* basis for such ‘simple’ models! In order to obtain the required extremely flat potential for the inflaton it is essential to invoke supergravity to protect against radiative corrections; in such models inflation must occur far below the Planck scale and it is quite natural for the spectrum to be significantly ‘tilted’ below scale-invariance [64] or even have sharp features at particular scales [65]. As seen in Fig.4, the baryon density inferred from the CMB data is sensitive to the assumed spectral slope n_s even if a scale-free spectrum is assumed; agreement with the BBN value (7) does *require* a significant tilt [66]. Another way to have less power on small scales in order to match the CMB data with the BBN baryon density is by having a ‘step’ in the spectrum at a scale of $\sim 50h^{-1}$ Mpc (as was suggested by an analysis of galaxy clustering on the APM catalogue); this too compromises the “precision cosmology” programme by dramatically altering the inferred cosmological parameters such as the matter density and the cosmological constant [67].

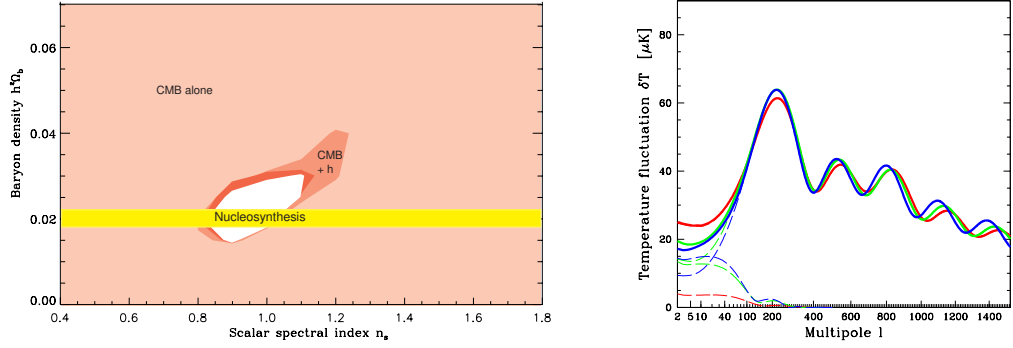


Figure 4: Fits to a compendium of CMB data (assuming adiabatic primordial density perturbations) which demonstrate the inherent ‘degeneracies’ in parameter space. The left panel shows how the inferred baryon density increases with the adopted (power-law) spectral index. The right panel shows 3 models which fit the data equally well but have different values of (from top to bottom) $\Omega_B h^2 = 0.02$ (red), 0.03 (green) and 0.04 (blue); the increase in the baryon density is compensated by decreasing the amount of dark matter, while increasing the dark energy content and the spectral index (from Ref.[66]).

It is in this light that the much advertised [68] agreement between the BBN baryon density (8) and the value $\Omega_B h^2 = 0.022^{+0.004}_{-0.003}$ inferred from the new BOOMERanG [69] and DASI [70] data, should be evaluated.¹ Removal of the degeneracies referred to above will primarily require *independent* measures of the primordial density perturbation spectrum from studies of large-scale structure (LSS), as has been attempted recently using data from the 2dFGRS survey [73]. However such analyses still assume that the primordial density perturbation is *scale-free* — present data cannot either confirm or rule out possible features in the spectrum [74], the presence of which can however significantly alter the extracted cosmological parameters [67] (if restrictive ‘priors’ are not imposed, e.g. on h). Moreover the normalisation of the primordial scalar perturbation at large-scales to the COBE data remains uncertain due to the possible contribution of gravitational waves generated during inflation (shown as the decaying dashed lines in Fig.4).

Even more dramatic changes to the values inferred from the CMB data are possible if there are isocurvature modes present; the most general cosmological perturbation can in fact contain four such modes — in baryons, dark matter and (two in) neutrinos [75]. As shown in Fig.5, a fit to the data *assuming* the BBN value of the baryon density does not allow a significant admixture of isocurvature modes; conversely if such modes are in fact dominant then the baryon density required to fit the data is much larger [76]. To distinguish experimentally between isocurvature and adiabatic perturbations will require careful measurements of the CMB polarisation which will be possible with the forthcoming PLANCK surveyor [77].

¹Note that MAXIMA-1 initially reported $\Omega_B h^2 = 0.033 \pm 0.006$ but a later (frequentist) analysis finds $\Omega_B h^2 = 0.026 \pm^{+0.010}_{-0.006}$ [71]. Observations at very small angles by the CBI suggest a much smaller value $\Omega_B h^2 \sim 0.009$ but the uncertainties are large enough to allow consistency with the other results [72].

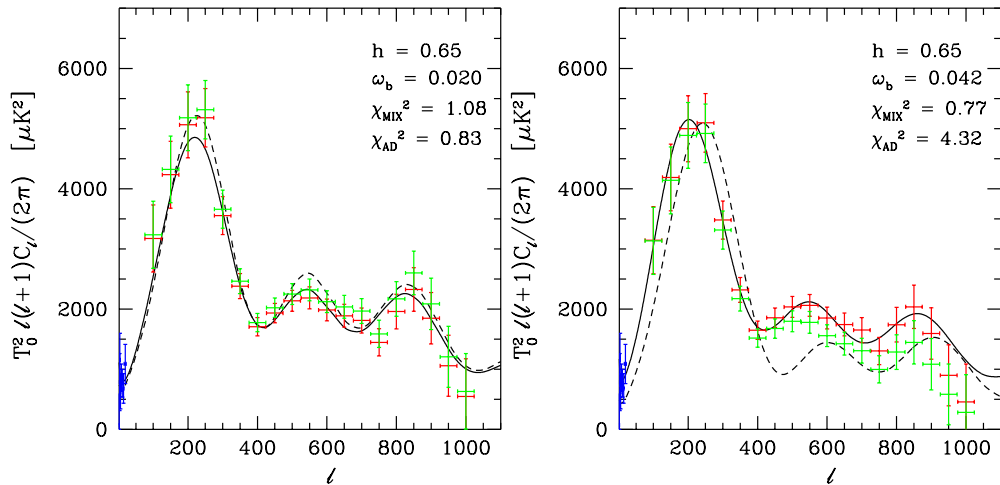


Figure 5: Fits to the CMB data assuming purely adiabatic perturbations (dashed line) and mixed perturbations with 12% isocurvature content (solid line), adopting the baryon density $\omega_B = \Omega_B h^2 = 0.02$ indicated by BBN (left panel), and a value twice as large (right panel); note that the adiabatic case is now a poor fit but the mixed case (with 69% isocurvature component) is quite acceptable (from Ref.[76]).

0.4 Discussion

It is clear that we are still some way away from establishing rigorously that the baryon density inferred from CMB data equals the value required by BBN. Nevertheless the fact that the two values are within a factor ~ 2 of each other is encouraging and has focussed welcome attention on deeper issues. Foremost among these is our fundamental ignorance concerning the nature and spectrum of the primordial density perturbations. The prediction from ‘non-baroque’ models of inflation is of a purely adiabatic, nearly scale-invariant perturbation. While the CMB and LSS data are, within present uncertainties, consistent with this, it would be extremely surprising if future precision data continued to support this naive model. The physics of inflation lies beyond the Standard Model and general expectations, while necessarily speculative, are of a much richer phenomenology. Observationally, the breaking point may well come from observations and modelling of the Lyman- α forest which yield an independent measure of the baryon density [11, 78]; a recent study [79] finds a value of $\Omega_B h^2 = 0.045 \pm 0.008$ if the ionising UV background is as intense as is indicated by observations of Lyman break galaxies [80]. Further such measurements will soon provide a true consistency check of the current paradigm. Perhaps one day we will even have precision cosmology!

0.5 Acknowledgements

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Bibliography

- [1] J. Bernstein, *Kinetic Theory in the Expanding Universe* (Cambridge University Press, 1988).
- [2] V.A. Rubakov & M.E. Shaposhnikov, Phys. Usp. **39**, 461 (1996).
- [3] M. Quiros, Nucl. Phys. Proc. Suppl. **101**, 401 (2001).
- [4] W. Büchmüller & M. Plümacher, Int. J. Mod. Phys. **A15**, 5047 (2000).
- [5] A. Riotto & M. Trodden, Ann. Rev. Nucl. Part. Sci. **49** 35 (1999).
- [6] R.V. Wagoner, W.A. Fowler & F. Hoyle, Astrophys. J. **148**, 3 (1967); R.V. Wagoner, Astrophys. J. **179**, 343 (1973).
- [7] J. Silk, Astrophys. J. **151**, 459 (1968); P.J.E. Peebles & J.T. Yu, Astrophys. J. **162**, 815 (1970); A.G. Doroshkevich, Ya B. Zeldovich & R.A. Sunyaev, Sov. Astron. **22**, 523 (1978).
- [8] H. Reeves, J. Audouze, W.A. Fowler & D.N. Schramm, Astrophys. J. **179**, 909 (1973).
- [9] W. Hu & N. Sugiyama, Phys. Rev. **D51**, 2599 (1995), Astrophys. J. **444**, 489 (1995), **471**, 542 (1996); For a review see, W. Hu and S. Dodelson, [astro-ph/0110414](#).
- [10] J.R. Bond, *et al*, Phys. Rev. Lett. **72**, 13 (1994); G. Jungman, M. Kamionkowski, A. Kosowsky & D.N. Spergel, Phys. Rev. **D54**, 1332 (1996).
- [11] D. Weinberg, J. Miralda-Escudé, L. Hernquist & N. Katz, Astrophys. J. **490**, 564 (1997); Y. Zhang *et al*, Astrophys. J. **496**, 63 (1998).
- [12] For recent detailed reviews, see R.A. Malaney & G.J. Mathews, Phys. Rep. **229**, 145 (1993); S. Sarkar, Rep. Prog. Phys. **59**, 1493 (1996); K.A. Olive, G. Steigman & T.P. Walker, Phys. Rep. **333**, 389 (2000).
- [13] B.D. Fields & S. Sarkar, BBN review on 2001 web update (<http://pdg.lbl.gov/>) of the *Review of Particle Properties*, D.E. Groom *et al*, Eur. Phys. J. **C15**, 1 (2000).
- [14] <http://www-thphys.physics.ox.ac.uk/users/SubirSarkar/bbn.html>.
- [15] L. Kawano, FERMILAB-PUB-92/04-A.
- [16] R. Lopez & M.S. Turner, Phys. Rev. **D56**, 3191 (1997), **D59**, 103502 (1999).

- [17] S. Esposito, G. Mangano, G. Miele & O. Pisanti, Nucl. Phys. **B568**, 421 (2000).
- [18] M.S. Smith, L.H. Kawano & R.A. Malaney, Astrophys. J. Suppl. **85**, 219 (1993).
- [19] G. Fiorentini, E. Lisi, S. Sarkar & F. Villante, Phys. Rev. **D58**, 063506 (1998); E. Lisi, S. Sarkar & F. Villante, Phys. Rev. **D59**, 123520 (1999).
- [20] K.M. Nollett & S. Burles, Phys. Rev. **D61**, 123505 (2000); K.M. Nollett, S. Burles & M.S. Turner, Astrophys. J. **552**, L1 (2001).
- [21] R.H. Cyburt, B.D. Fields & K.A. Olive, New Astron. **6**, 215 (2001).
- [22] B.E.J. Pagel, E.A. Simonson, R.J. Terlevich & M. Edmunds, Mon. Not. R. Astr. Soc. **255**, 325 (1992).
- [23] Y.I. Izotov & T.X. Thuan, Astrophys. J. **500**, 188 (1998); Y.I. Izotov *et al*, Astrophys. J. **527**, 757 (1999).
- [24] B.D. Fields & K.A. Olive, Astrophys. J. **506**, 177 (1998).
- [25] K.A. Olive & E. Skillman New Astron. **6**, 119 (2001).
- [26] D. Sauer & K. Jedamzik, Astron. Astrophys. **381**, 361 (2002).
- [27] M. Peimbert, A. Peimbert & M.T. Ruiz, Astrophys. J. **541**, 688 (2000).
- [28] A. Peimbert, M. Peimbert & V. Luridiana, Astrophys. J. **565**, 668 (2002).
- [29] M. Spite & F. Spite, Nature **297**, 483 (1982); L.M. Hobbs & D. Duncan, Astron. J. **317**, 796 (1987); J.A. Thorburn, Astrophys. J. **412**, 318 (1994).
- [30] P. Bonifacio & P. Molaro, Mon. Not. R. Astr. Soc. **285**, 847 (1997).
- [31] S.G. Ryan, J.E. Norris & T.C. Beers, Astrophys. J. **523**, 654 (1999).
- [32] E. Vangioni-Flam *et al*, New Astron. **4**, 245 (1999).
- [33] S.G. Ryan *et al*, Astrophys. J. **530**, L57 (2000).
- [34] M.H. Pinsonneault *et al*, Astrophys. J. **527**, 180 (1999).
- [35] S. Vauclair & C. Charbonnel, Astrophys. J. **502**, 372 (1998).
- [36] A. Songaila, L.L. Cowie, C. Hogan & M. Rugers, Nature **368**, 599 (1994).
- [37] S. Burles & D. Tytler, Astrophys. J. **499**, 699 (1998), **507**, 732 (1998).
- [38] J.K. Webb *et al*, Nature **388**, 250 (1997).
- [39] J.M. O'Meara *et al*, Astrophys. J. **552**, 718 (2001).
- [40] S. D'Odorico, M. Dessauges-Zavadsky & P. Molaro, Astron. Astrophys. **368**, L21 (2001).
- [41] M. Pettini & D. Bowen, Astrophys. J. **560**, 41 (2001).

- [42] R.I. Epstein, J. M. Lattimer & D.N. Schramm, *Nature* **263**, 198 (1976).
- [43] J. Linsky, *Space Sci. Rev.* **84**, 285 (1998).
- [44] S. Burles, D. Kirkman & D. Tytler, *Astrophys. J.* **519**, 18 (1999).
- [45] D. Kirkman *et al*, *Astrophys. J.* **559**, 23 (2001).
- [46] D. Kirkman *et al*, *Astrophys. J.* **529**, 655 (2000).
- [47] S.A. Levshakov, W.H. Kegel & F. Takahara, *Astrophys. J.* **499**, L1 (1998); S.A. Levshakov *et al*, *Astrophys. J.* **565**, 696 (2002).
- [48] B.D. Fields *et al*, *Astrophys. J.* **563**, 653 (2002).
- [49] G. Sonneborn *et al*, *Astrophys. J.* **545**, 277 (2000).
- [50] D.S. Balser, T.M. Bania, R.T. Rood & T.L. Wilson, *Astrophys. J.* **510**, 759 (1999); T.M. Bania, R.T. Rood & D.S. Balser, *Nature*, **415**, 54 (2002).
- [51] D.S.P. Dearborn, G. Steigman & M. Tosi, *Astrophys. J.* **465**, 887 (1996); K.A. Olive *et al*, *Astrophys. J.* **479**, 752 (1997); D. Galli *et al*, *Astrophys. J.* **477**, 218 (1997).
- [52] C. Charbonnel, *Space Sci. Rev.* **84**, 199 (1998).
- [53] M. Fukugita, C.J. Hogan & P.J.E. Peebles, *Astrophys. J.* **503**, 518 (1998).
- [54] R. Cen & J.P. Ostriker, *Astrophys. J.* **514**, 1 (1999).
- [55] H.-S. Kang & G. Steigman, *Nucl. Phys.* **B372**, 494 (1992).
- [56] A.D. Dolgov *et al*, [hep-ph/0201287](#).
- [57] J.H. Applegate, C. Hogan & R.J. Scherrer, *Phys. Rev.* **D35**, 1151 (1987).
- [58] K. Kainulainen, H. Kurki-Suonio & E. Sihvola, *Phys. Rev.* **D59**, 083505 (1999); K. Jedamzik & J.B. Rehm, *Phys. Rev.* **D64**, 023510 (2001).
- [59] J.B. Rehm & K. Jedamzik, *Phys. Rev. Lett.* **81**, 3307 (1998); H. Kurki-Suonio & E. Sihvola, *Phys. Rev.* **D62**, 103508 (2000).
- [60] S. Dimopoulos, R. Esmailzadeh, G.D. Starkman & L.J. Hall, *Astrophys. J.* **330**, 545 (1988); see also, K. Jedamzik, *Phys. Rev. Lett.* **84**, 3248 (2000).
- [61] M. Birkel & S. Sarkar, *Phys. Lett.* **B408**, 59 (1997); W. Hu & J. Silk, *Phys. Rev.* **D48**, 485 (1993).
- [62] R.H. Cyburt, B.D. Fields & K.A. Olive, *Astropart. Phys.* **17**, 87 (2002).
- [63] A.R. Liddle & D.H. Lyth, *Cosmological Inflation & Large-Scale Structure* (Cambridge University press, 2000).
- [64] G.G. Ross & S. Sarkar, *Nucl. Phys.* **B461**, 597 (1996); J. Adams, G.G. Ross & S. Sarkar, *Phys. Lett.* **B391**, 271 (1997).

- [65] J. Adams, G.G. Ross & S. Sarkar, Nucl. Phys. **B503**, 405 (1997); J. Lesgourgues, Nucl. Phys. **B582**, 593 (2000); T. Kanazawa, M. Kawasaki, T. Yanagida, Phys. Lett. **B482**, 174 (2000); M. Yamaguchi, Phys. Rev. **D64**, 063502 (2001).
- [66] X. Wang, M. Tegmark & M. Zaldarriaga, [astro-ph/0105091](#); M. Tegmark, M. Zaldarriaga & A.J.S. Hamilton, Phys. Rev. **D63**, 043007 (2001).
- [67] J. Barriga, E. Gaztanaga, M.G. Santos & S. Sarkar, Mon. Not. R. Astr. Soc. **324**, 977 (2001).
- [68] see e.g., A. Melchiorri, these Proceedings.
- [69] P. de Bernadis *et al*, Astrophys. J. **564**, 559 (2002).
- [70] C. Pryke *et al*, Astrophys. J. **568**, 46 (2002).
- [71] R. Stompor *et al*, Astrophys. J. **561**, L7 (2001); M.E. Abroe *et al*, [astro-ph/0111010](#).
- [72] S. Padin *et al*, Astrophys. J. **549**, L1 (2001).
- [73] G. Efstathiou *et al*, Mon. Not. R. Astron. Soc **33**, L29 (2002).
- [74] O. Elgaroy, M. Gramann & O. Lahav, [astro-ph/0111208](#).
- [75] M. Bucher, K. Moodley & N. Turok, Phys. Rev. **D62**, 083508 (2000), [astro-ph/0007360](#).
- [76] R. Trotta, A. Riazuelo & R. Dürer, Phys. Rev. Lett. **87**, 231301 (2001).
- [77] K. Enqvist and H. Kurku-Suonio, Phys. Rev. **D61**, 043002 (2000); M. Bucher, K. Moodley & N. Turok, Phys. Rev. Lett. **87**, 191301, (2001).
- [78] H. Bi & A.F. Davidsen, Astrophys. J. **479**, 523 (1997); T. Theuns, A. Leonard, J. Schaye & G. Efstathiou, Mon. Not. R. Astron. Soc. **303**, L58 (1999); M.G. Haehnelt, P. Madau, R. Kudritzki & F. Haardt, Astrophys. J. **549**, L151 (2001); T. Roy Choudhury, R. Srianand & T. Padmanabhan, Astrophys. J. **559**, 29 (2001).
- [79] L. Hui, Z. Haiman, M. Zaldarriaga & T. Alexander, Astrophys. J. **564**, 525 (2002).
- [80] C.C. Steidel, M. Pettini & K.L. Adelberger, Astrophys. J. **546**, 665 (2001).