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Light Element Nucleosynthesis

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The early universe was hot and dense behaving as a cosmic nuclear reactor during the first 20 min of its evolution. It was, however, a 'defective' nuclear reactor, expanding and cooling very rapidly. As a result, only a handful of the lightest nuclides were synthesized before the density and temperature dropped too low for the nuclear reaction rates to compete with the universal expansion rate (see UNIVERSE: THERMAL HISTORY). After hydrogen (^{1}H $\equiv$ protons) the next most abundant element to emerge from the Big Bang is helium (^{4}He $\equiv$ alpha particles). Isotopes of these nuclides (deuterium and helium-3) are the next most abundant primordially. Then there is a large gap to the much lower abundance of lithium-7. The relative abundances of all other primordially-produced nuclei are very low, much smaller than their locally observed (or, currently observable) abundances. After a brief description of the early evolution of the universe emphasizing those aspects most relevant to primordial, or 'big bang' nucleosynthesis (BBN), the predicted abundances of the light nuclides will be presented as a function of the one 'free' parameter (in the simplest, 'standard' model: SBBN), the nucleon (or 'baryon') abundance. Then, each element will be considered in turn in a confrontation between the predictions of SBBN and the observational data. At present (summer 1999) there is remarkable agreement between the SBBN predictions of the abundances of four nuclides (D, ^{3}He, ^{4}He and ^{7}Li) and their primordial abundances inferred from the observations. However, there are some hints that this concordance of the hot big bang model may be imperfect, so we will also explore some variations on the theme of the standard model with regard to their modifications of the predicted primordial abundances of the light elements.

In the simplest, standard, hot big bang model the currently observed large-scale isotropy and homogeneity of the universe is assumed to apply during earlier epochs in its evolution (see COSMOLOGY: STANDARD MODEL). Given the currently observed universal expansion and the matter and radiation (CBR: 'cosmic background radiation', the 2.7 K 'black body radiation') content, it is a straightforward application of classical physics to extrapolate back to earlier epochs in the history of the universe (see COSMIC MICROWAVE BACKGROUND). At a time of order 0.1 s after the expansion began the universe was filled with a hot, dense plasma of particles. The most abundant were photons, electron–positron pairs, particle–antiparticle pairs of all known 'flavors' of neutrinos (ν_e, ν_μ and ν_τ) and trace amounts of neutrons and protons ('nucleons' or 'baryons'). At such early times the thermal energy of these particles was very high, of order a few MeV. With the exception of the nucleons, it is known or assumed that all the other particles present were extremely relativistic at this time. Given their high energies (and velocities close to, or exactly equal to, the speed of light) and high densities, the electroweak interactions among these particles were sufficiently rapid to have established thermal equilibrium. As a result, the numbers and distributions (of momentum and energy) of all these particles are accurately predicted by well-known physics.

Nucleosynthesis in the early universe

The primordial yields of light elements are determined by the competition between the expansion rate of the universe (the Hubble parameter H) and the rates of the weak and nuclear reactions (see HUBBLE CONSTANT). It is the weak interaction, interconverting neutrons and protons, that largely determines the amount of ^{4}He which may be synthesized, while detailed nuclear reaction rates regulate the production (and destruction) of the other light elements. In the standard model of cosmology the early expansion rate is fixed by the total energy density ρ,

$$H^2 = 8\pi G\rho/3 \tag{1}$$

where G is Newton's gravitational constant. In the standard model of particle physics the early energy density is dominated by the lightest, relativistic particles. For the epoch when the universe is a few tenths of a second old and older, and the temperature is less than a few MeV,

$$\rho = \rho_\gamma + \rho_e + N_\nu \rho_\nu \tag{2}$$

where ρ_γ, ρ_e and ρ_ν are the energy densities in photons, electrons and positrons, and massless neutrinos and antineutrinos (one species), respectively; N_ν is the number of massless (or, very light: $m_\nu \ll 1$ MeV) neutrino species which, in standard BBN, is exactly 3. In considering variations on the theme of the standard model, it is useful to allow N_ν to differ from 3 to account for the presence of 'new' particles and/or any suppression of the standard particles (e.g. if the τ neutrino should have a large mass). Since the energy density in relativistic particles scales as the fourth power of the temperature, the early expansion rate scales as the square of the temperature with a coefficient that depends on the number of different relativistic species. The more such species, the faster the universe expands, the earlier (higher temperature) will the weak and nuclear reactions drop out of equilibrium. It is useful to write the total energy density in terms of the photon energy density and g, the equivalent number of relativistic degrees of freedom (i.e. helicity states, modulo the different contributions to the energy density from fermions and bosons),

$$\rho \equiv (g/2)\rho_\gamma. \tag{3}$$

In the standard model at $T \sim 1$ MeV, $g_{SM} = 43/4$. Account may be taken of additional degrees of freedom by comparing their contribution to ρ with that of one additional light neutrino species:

$$\Delta\rho \equiv \rho_{TOT} - \rho_{SM} \equiv \Delta N_\nu \rho_\nu. \tag{4}$$

If the early energy density deviates from that of the standard model, the early expansion rate (or, equivalently, the age at a fixed temperature) will change as well. The 'speed-up' factor $\xi \equiv H/H_{\rm SM}$ may be related to ΔN_ν by

$$\xi = (\rho/\rho_{\rm SM})^{1/2} = (1 + 7\,\Delta N_\nu/43)^{1/2}. \quad (5)$$

As we will see shortly, the ^{4}He abundance is very sensitive to the early expansion rate while the abundances of the other light nuclides depend mainly on the nuclear reaction rates which scale with the nucleon (baryon) density. Since the baryon density is always changing as the universe expands, it is convenient to distinguish between models with different baryon densities using a dimensionless parameter which either is conserved or, changes in a known and calculable fashion. From the very early universe until now the number of baryons in a comoving volume has been preserved and the same is roughly true for photons since the end of BBN. Therefore, the ratio of number densities of baryons ($n_{\rm B}$) and photons (n_γ) provides just such a measure of the universal baryon abundance:

$$\eta \equiv (n_{\rm B}/n_\gamma)_0 \qquad \eta_{10} \equiv 10^{10}\eta. \quad (6)$$

The universal density of photons at present (throughout this article the present epoch is indicated by the subscript '0') is dominated by those in the CBR (for $T_0 = 2.73$ K, $n_{\gamma 0} = 412$ cm^{-3}) so that the baryon density parameter $\Omega_{\rm B} \equiv (\rho_{\rm B}/\rho_{\rm c})_0$, the ratio of the present baryon density ($\rho_{\rm B}$) to the present critical density ($\rho_{\rm c}$), may be related to η and the present value of the Hubble parameter $H_0 \equiv 100h$ km s^{-1} Mpc^{-1},

$$\eta_{10} = 273\Omega_{\rm B}h^2. \quad (7)$$

It should be noted that prior to electron–positron annihilation there were fewer photons in every comoving volume (by a factor very close to 4/11); this is automatically accounted for in all numerical BBN codes. It is simply a matter of consensus and convenience that the baryon abundance is quoted in terms of its present value.

In SBBN (i.e. $N_\nu = 3$) the abundances of the light nuclides synthesized primordially depend on only one 'free' parameter, η. SBBN is thus 'overconstrained' since one value (or, a narrow range of values set by the observational and theoretical reaction rate uncertainties) of η must account consistently for the primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li. At the same time this value or range of η must be consistent with current estimates of (or, bounds to) the present baryon density. For these reasons BBN is one of the key pillars supporting the edifice of the standard model of cosmology and it is the only one which offers a glimpse of the earliest evolution of the universe. In the following we will first identify the key landmarks in the first 20 min in the evolution of the universe in order to identify the physical processes responsible for determining the primordial abundances of the light nuclides. Then, after presenting the SBBN predictions (as a function of η; see figure 1) we will review the current status of the observational data, as well as the

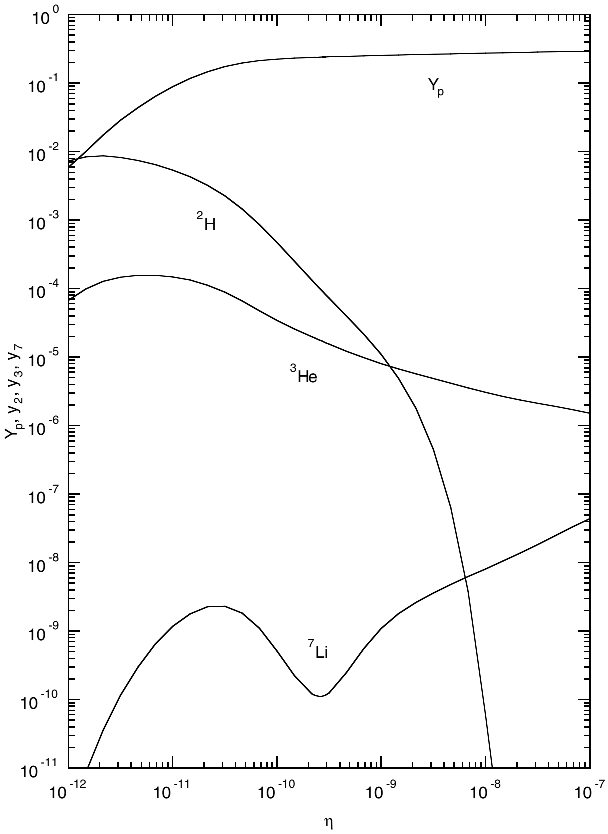

Figure 1. The predicted primordial abundances as a function of η. $Y_{\rm P}$ is the ^{4}He mass fraction while $y_{\rm 2P}$, $y_{\rm 3P}$, $y_{\rm 7P}$ are the number density ratios to hydrogen of D, ^{3}He and ^{4}He respectively.

steps necessary in order to go from 'here and now' to 'there and then' when using the data to infer the true primordial abundances. Then we will be in a position to assess the consistency of the standard model.

Weak equilibrium and the ^{4}He abundance

Consider now those early epochs when the universe was only a few tenths of a second old and the radiation filling it was at a temperature (thermal energy) of a few MeV. According to the standard model, at those early times the universe was a hot, dense 'soup' of relativistic particles (photons, e$^\pm$ pairs, three 'flavors' (e, μ, τ) of neutrino–antineutrino pairs) along with a trace amount (at the level of a few parts in 10^{10}) of neutrons and protons. At such high temperatures and densities both the weak and the nuclear reaction rates are sufficiently rapid (compared with the early universe expansion rate) that all particles have come to equilibrium. A key consequence of equilibrium is that the earlier history of the evolution of the universe is irrelevant for an understanding of BBN. When the temperature drops below a few MeV the weakly interacting neutrinos effectively decouple from the photons and e$^\pm$ pairs, but they still play an important role in regulating the neutron-to-proton ratio.

At high temperatures, neutrons and protons are continuously interconverting via the weak interactions: $n + e^+ \leftrightarrow p + \bar{\nu}_e$, $n + \nu_e \leftrightarrow p + e^-$, and $n \leftrightarrow p + e^- + \bar{\nu}_e$. When the interconversion rate is faster than the expansion rate, the neutron-to-proton ratio tracks its equilibrium value, decreasing exponentially with temperature ($n/p = e^{-\Delta m/T}$, where $\Delta m = 1.29$ MeV is the neutron–proton mass difference). A comparison of the weak rates with the universal expansion rate reveals that equilibrium may be maintained until the temperature drops below ~0.8 MeV. When the interconversion rate becomes less than the expansion rate, the n/p ratio effectively 'freezes out' (at a value of ≈1/6), thereafter decreasing slowly, mainly as a result of free neutron decay.

Although n/p freeze-out occurs at a temperature below the deuterium binding energy, $E_B = 2.2$ MeV, the first link in the nucleosynthetic chain, $p + n \rightarrow D + \gamma$, is ineffective in jump-starting BBN since the photodestruction rate of deuterium ($\propto n_\gamma\, e^{-E_B/T}$) is much larger than the deuterium production rate ($\propto n_B$) owing to the very large universal photon-to-baryon ratio ($\gtrsim 10^9$). Thus, the universe must 'wait' until there are so few sufficiently energetic photons that deuterium becomes effectively stable against photodissociation. This occurs for temperatures $\gtrsim$80 keV, at which time neutrons are rapidly incorporated into ^{4}He with an efficiency of 99.99%. This efficiency is driven by the tight binding of the ^{4}He nucleus, along with the roadblock to further nucleosynthesis imposed by the absence of a stable nucleus at mass 5. By this time ($T \gtrsim 80$ keV), the n/p ratio has dropped to ~1/7, and simple counting (2 neutrons in every ^{4}He nucleus) yields an estimated primordial ^{4}He mass fraction

$$Y_P \approx \frac{2(n/p)}{1 + n/p} \approx 0.25. \qquad (8)$$

As a result of its large binding energy and the gap at mass 5, the primordial abundance of ^{4}He is relatively insensitive to the nuclear reaction rates and, therefore, to the baryon abundance (η). As may be seen in figure 1, while η varies by orders of magnitude, the predicted ^{4}He mass fraction, Y_p, changes by factors of only a few. Indeed, for $1 \le \eta_{10} \le 10$, $0.22 \le Y_P \le 0.25$. As may be seen in figures 1 and 2, there is a very slight increase in Y_p with η. This is mainly due to BBN beginning earlier, when there are more neutrons available to form ^{4}He, if the baryon-to-photon ratio is higher. The increase in Y_p with η is logarithmic; over most of the interesting range in η, $\Delta Y_p \approx 0.01\, \Delta\eta/\eta$.

The ^{4}He abundance is, however, sensitive to the competition between the universal expansion rate (H) and the weak interaction rate (interconverting neutrons and protons). If the early universe should expand faster than predicted for the standard model, the weak interactions will drop out of equilibrium earlier, at a higher temperature, when the n/p ratio is higher. In this case, more neutrons will be available to be incorporated into ^{4}He and Y_p will increase. Numerical calculations show that, for a modest speed-up ($\Delta N_\nu \lesssim 1$), $\Delta Y_p \approx 0.013\, \Delta N_\nu$. Hence, constraints on Y_p (and η) lead directly to bounds on ΔN_ν and on particle physics beyond the standard model [1].

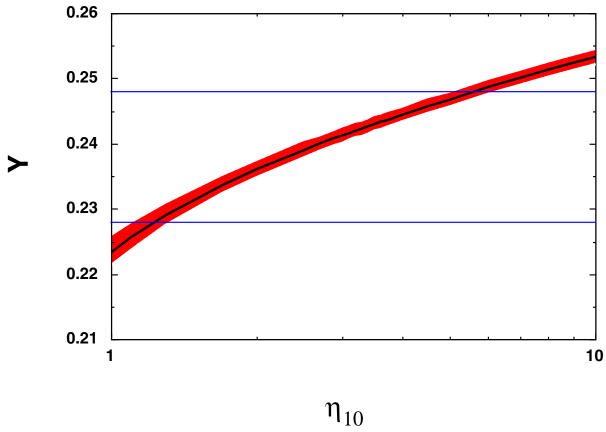

Figure 2. The predicted ^{4}He abundance (solid curve) and the 2σ theoretical uncertainty [2]. The horizontal lines show the range indicated by the observational data.

It should be noted that the uncertainty in the BBN-predicted mass fraction of ^{4}He is very small and almost entirely dominated by the (small) uncertainty in the n–p interconversion rates. These rates may be 'normalized' through the neutron lifetime, τ_n, whose current standard value is 887 ± 2 s (actually, 886.7 ± 1.9 s). To very good accuracy, a 1 s uncertainty in τ_n corresponds to an uncertainty in Y_p of order 2×10^{-4}. At this tiny level of uncertainty it is important to include finite-mass, zero- and finite-temperature radiative corrections, and Coulomb corrections to the weak rates. However, within the last few years it has emerged that the largest error in the BBN-prediction of Y_p was due to a too large time-step in the numerical code. With this now under control, it is estimated that the residual theoretical uncertainty (in addition to that from the uncertainty in τ_n) is of the order of 2 parts in 10^4. Indeed, a comparison of two major, independent BBN codes reveals agreement in the predicted values of Y_p to 0.0001 ± 0.0001 over the entire range $1 \le \eta_{10} \le 10$. In figure 2 is shown the BBN-predicted ^{4}He mass fraction, Y_p, as a function of η; the thickness of the band is the $\pm 2\sigma$ theoretical uncertainty. For $\eta_{10} \gtrsim 2$ the 1σ theoretical uncertainty in Y_p is $\lesssim 6 \times 10^{-4}$. As we will soon see, the current observational uncertainties in Y_p are much larger (see, also, figure 2).

Deuterium—the ideal baryometer

As may be seen in figure 1, the deuterium abundance (the ratio, by number, of deuterium to hydrogen: hereinafter, $(D/H)_P \equiv y_{2P}$) is a monotonic, rapidly decreasing function of the baryon abundance η. The reason for this behavior is easily understood. Once BBN begins in earnest, when the temperature drops below ~80 keV, D is rapidly burned to ^{3}H, ^{3}He and ^{4}He. The higher the baryon abundance, the faster the burning and the less D survives. For η_{10} in the 'interesting' range 1–10, y_{2P} decreases with the ~1.6

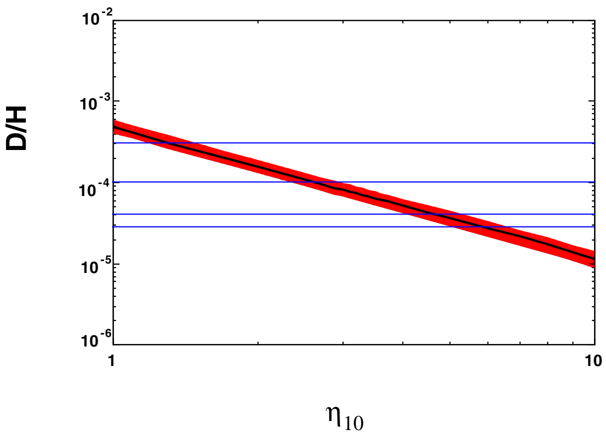

Figure 3. The predicted D/H abundance (solid curve) and the 2σ theoretical uncertainty [2]. The horizontal lines show the range indicated by the observational data for both high D/H (upper two lines) and low D/H (lower two lines).

power of η. As a result, a 10% error in y_{2P} corresponds to only a 6% error in η. This strong dependence of y_{2P} on η_{10}, combined with the simplicity of the evolution of D/H in the epochs following BBN, is responsible for the unique role of deuterium as a baryometer [3]. Because almost all the relevant reaction cross sections are measured in the laboratory at energies comparable with those of BBN, the theoretical uncertainties in the BBN-predicted abundance of deuterium is quite small, 8–10% for most of the interesting η range shown in figure 3.

Deuterium and helium-4 are complementary, forming the crucial link in testing the consistency of BBN in the standard model. While the primordial D abundance is very sensitive to the baryon density, the primordial ^{4}He abundance is relatively insensitive to η. Deuterium provides a bound on the universal baryon density while helium-4 constrains the early expansion rate of the universe, offering bounds on particle physics beyond the standard model.

Helium-3—complicated evolution

As may be seen in figure 1, the predicted primordial abundance of ^{3}He behaves similarly to that of D, decreasing monotonically with η. Again, the reason is the same: ^{3}He is being burned to the more tightly bound nucleus ^{4}He. The higher the nucleon abundance, the faster the burning and the less ^{3}He survives. In contrast to the behavior of D/H versus η, the decrease of ^{3}He/H with increasing η is much slower. This is simply a reflection of the much tighter binding of ^{3}He compared with D. Although the BBN predictions for the abundance of ^{3}He have similarly small uncertainties (8–10%) to those of D, it is much more difficult to exploit the observations of ^{3}He to test and constrain BBN. The complication is the evolutionary history of the ^{3}He abundance since BBN.

Although any deuterium cycled through stars is burned to ^{3}He during the stars' pre-main-sequence evolution, ^{3}He will survive in the cooler stellar exteriors while being destroyed in the hotter interiors. For the more abundant lower-mass stars which are cooler, a larger fraction of prestellar ^{3}He (along with the ^{3}He produced from prestellar D) survives. Indeed, for sufficiently low-mass stars (less than a few solar masses) incomplete burning actually leads to a buildup of newly synthesized ^{3}He (to be contrasted with the prestellar D and ^{3}He) which may—or may not—be returned to the interstellar medium. In fact, some PLANETARY NEBULAE are observed to be highly enriched in ^{3}He. So, the evolution of ^{3}He is complex with stellar destruction competing with primordial and stellar production. Indeed, if all low-mass stars were as prolific producers of ^{3}He as indicated by some planetary nebulae, the solar system and local interstellar medium abundances of ^{3}He should far exceed those inferred from observations. Thus, at least some low-mass stars must be net destroyers of ^{3}He. Given this necessarily complex and uncertain picture of production, destruction and survival, it is difficult to use current observational data to infer the primordial abundance of ^{3}He. Unless and until ^{3}He is observed in high-redshift (i.e. early universe), low-metallicity (i.e. nearly unevolved) systems, it will provide only a weak check on the consistency of BBN.

Lithium-7– the lithium valley

The trend of the BBN-predicted primordial abundance of lithium (almost entirely ^{7}Li) with η is more 'interesting' than that of the other light nuclides (see figures 1 and 4). The 'lithium valley', centered near $\eta_{10} \approx 2$–3, is the result of the competition between production and destruction in the two paths to mass 7 synthesis. At relatively low baryon abundance ($\eta_{10} \lesssim 2$) mass 7 is mainly synthesized as ^{7}Li via $^3H + {}^4He \to {}^7Li + \gamma$. As the baryon abundance increases at low η, ^{7}Li is destroyed rapidly by (p, γ)2α reactions, hence the decrease in $(Li/H)_P \equiv y_{7P}$ with increasing η seen (at low η) in figures 1 and 4. Were this the only route to primordial synthesis of mass 7, this monotonic trend would continue, similar to those for D and ^{3}He. However, mass 7 may also be synthesized via $^3He + {}^4He \to {}^7Be + \gamma$. The ^{7}Be will later capture an electron to become ^{7}Li. This channel is very important because it is much easier to destroy ^{7}Li than ^{7}Be. As a result, for relatively high baryon abundance ($\eta_{10} \gtrsim 3$) the latter channel dominates mass 7 production and y_{7P} increases with increasing η.

As may been seen in figure 4, the BBN-predicted uncertainties for y_{7P} are much larger than those for D, ^{3}He or ^{4}He. In the interval $1 \le \eta_{10} \le 10$ the 1σ uncertainties are typically ~20%, although in a narrow range of η near the bottom of the 'valley' they are somewhat smaller (~12–15%).

From here and now to there and then

To test the consistency of SBBN requires that we confront the predictions with the primordial abundances of the light nuclides which, however, are not observed but, rather, are inferred from observations. The path from the observational data to the primordial abundances is long

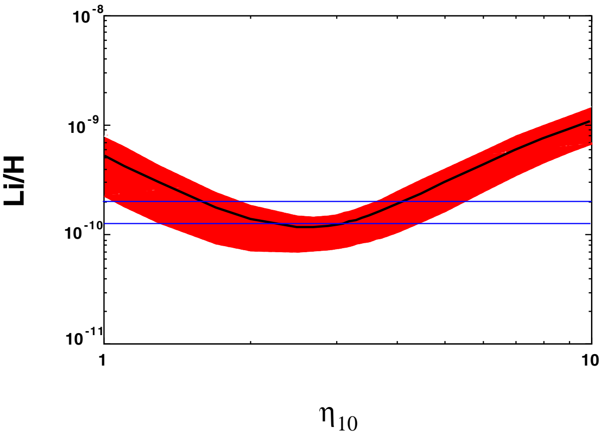

Figure 4. The predicted ^{7}Li abundance (solid curve) and the 2σ theoretical uncertainty [2]. The horizontal lines show the range indicated by the observational data.

and twisted and often fraught with peril. In addition to the usual statistical and systematic uncertainties, it is crucial to forge a connection from 'here and now' to 'there and then', i.e. to relate the derived abundances to their primordial values. It is indeed fortunate that each of the key elements is observed in different astrophysical sites using very different astronomical techniques. Also, the corrections for chemical evolution differ among them and, even more important, they can be minimized. For example, deuterium (and hydrogen) is mainly observed in cool, neutral gas (so-called H I REGIONS) via UV absorption from the atomic ground state (the Lyman series), while radio telescopes allow helium-3 to be studied utilizing the analog of the hydrogen 21 cm line for singly ionized ^{3}He in regions of hot, ionized gas (so called H II regions). Helium-4 is probed using the emission from its optical recombination lines formed in H II regions. In contrast, lithium is observed in the absorption spectra of warm, low-mass halo stars. With such different sites, with the mix of absorption–emission, and with the variety of telescopes and different detectors involved, the possibility of correlated errors biasing the comparison with the predictions of BBN is unlikely. This favorable situation extends to the obligatory evolutionary corrections. For example, although until recently observations of deuterium were limited to the solar system and the Galaxy, mandating uncertain evolutionary corrections to infer the pregalactic abundance, the Keck and HUBBLE SPACE TELESCOPES have begun to open the window to deuterium in high-redshift, low-metallicity, nearly primordial regions (Lyman-α clouds). Observations of ^{4}He in chemically unevolved, low-metallicity ($\sim$1/50 of solar) extragalactic H II regions permit the evolutionary correction to be reduced to the level of the statistical uncertainties. The abundances of lithium inferred from observations of the very metal-poor halo stars (one-thousandth of solar abundance and even lower) require almost no correction for chemical evolution. On the other hand, as noted earlier, the status of helium-3 is in contrast to that of the other light elements. For this reason, ^{3}He will not be used quantitatively in this article.

The currently very favorable observational and evolutionary situation for the nuclides produced during BBN is counterbalanced by the likely presence of systematic errors in the path from observations to primordial abundances. By their very nature, such errors are difficult—if not impossible—to quantify. In the key case of deuterium there is a very limited set of the most useful data. As a result, and although cosmological abundance determinations have taken their place in the current 'precision' era of cosmology, it is far from clear that the present abundance determinations are truly 'accurate'. Thus, the usual *caveat emptor* applies to any conclusions drawn from the subsequent comparison between the predictions and the data. With this caution in mind the current status of the data will be surveyed in order to infer 'reasonable' ranges for the primordial abundances of the key light elements.

Deuterium

Since deuterium is completely burned away whenever it is cycled through stars, and there are no astrophysical sites capable of producing deuterium in anywhere near its observed abundance [3], any D abundance derived from observational data provides a lower bound to its primordial abundance. Thus, without having to correct for Galactic evolution, the 'here-and-now' deuterium abundance inferred from UV observations along 12 lines of sight in the local interstellar medium (LISM) bounds the 'there-and-then' primordial abundance from below ($(D/H)_P \geq (D/H)_{LISM} = (1.5 \pm 0.1) \times 10^{-5}$). As may be seen from figures 1 and 2, any lower bound to primordial D will provide an upper bound to the baryon-to-photon ratio [4].

Solar system observations of ^{3}He permit an independent, albeit indirect, determination of the pre-solar-system deuterium abundance [5]. This estimate of the Galactic abundance some 4.5 Gyr ago, while somewhat higher than the LISM value, has a larger uncertainty ($D/H = (2.1 \pm 0.5) \times 10^{-5}$ [6]). Within the uncertainty it is consistent with the LISM value suggesting there has been only modest destruction of deuterium in the last 4.5 Gyr. There is also a recent measurement of deuterium in the atmosphere of Jupiter using the Galileo Probe Mass Spectrometer [7] ($D/H = (2.6 \pm 0.7) \times 10^{-5}$ (see GALILEO MISSION TO JUPITER)).

To further exploit the solar system and/or LISM deuterium determinations to constrain or estimate the primordial abundance would require corrections for the Galactic evolution of D; see GALACTIC EVOLUTION. Although the simplicity of the evolution of deuterium (it is only destroyed) suggests that such correction might be very nearly independent of the details of specific chemical evolution models, large differences remain between different estimates. It is therefore fortunate that data on D/H in high-redshift (nearly primordial), low-metallicity (nearly unevolved) Lyman-α absorbers have become available in recent years [8, 9]. It is expected that such systems still retain their original, primordial deuterium, undiluted by the deuterium-depleted debris of any significant stellar evolution. That is the good news. The bad news is that, at present, D abundance determinations are claimed for only three such systems, and that the abundances inferred for two of them (along with a limit to the abundance for a third) appear to be inconsistent with the abundance estimated for the remaining one. Here we have a prime illustration of 'precise', but possibly inaccurate, cosmological data. Indeed, there is a serious obstacle inherent to using absorption spectra to measure the deuterium abundance since the isotope-shifted deuterium absorption lines are indistinguishable from the corresponding lines in suitably velocity-shifted (-81 km s^{-1}) hydrogen. Such 'interlopers' may have been responsible for some of the early claims [8] of a 'high' deuterium abundance [10]. Indeed, an interloper may be responsible for the one surviving high-D claim [11]. At present it seems that only three good candidates for nearly primordial deuterium have emerged from ground- and space-based observations. It may be premature to constrain cosmology on the basis of such sparse data. Nonetheless, the two 'low-D' systems suggest a primordial deuterium abundance consistent with estimates of the pre-Galactic value inferred from LISM and solar system data ($(\mathrm{D/H})_\mathrm{P} = (3.4 \pm 0.25) \times 10^{-5}$ [12]). To illustrate the confrontation of cosmological theory with observational data, this D abundance will be adopted in the following. However, the consequences of choosing the 'high-D' abundance ($(\mathrm{D/H})_\mathrm{P} = (20 \pm 5) \times 10^{-5}$ [11]) will also be discussed.

Helium-4

As the second most abundant nuclide in the universe (after hydrogen), the abundance of ^{4}He can be determined to high accuracy at sites throughout the universe. However, as stars evolve they burn hydrogen to helium and the ^{4}He in the debris of STELLAR EVOLUTION contaminates any primordial ^{4}He. Since any attempt to correct for stellar evolution will be inherently uncertain, it is sensible to concentrate on the data from low-metallicity sites. Extragalactic regions of hot, ionized gas (H II regions) provide such sites, where the helium is revealed via emission lines formed when singly and doubly ionized helium recombines. As with deuterium, current data provide ambiguous estimates of the primordial helium abundance. Since the differences ($\Delta Y = 0.010$) are larger than the statistical uncertainties ($\lesssim \pm 0.003$), systematic errors probably dominate. Among the currently most likely sources of such errors are uncertain corrections for collisional excitation in helium, uncertain corrections for unseen neutral helium and/or hydrogen, and underlying stellar absorption (leading to an underestimate of the true strength of the helium emission lines). In contrast, since the most metal poor of the observed regions have metallicities of order 1/50–1/30 of solar, the extrapolation from the lowest-metallicity regions to truly primordial introduces an uncertainty no larger than the statistical error.

Using published data [13, 14] for 40 low-metallicity regions, one group [15] finds $Y_\mathrm{P} = 0.234 \pm 0.003$. In contrast, from an independent data set of 45 low-metallicity regions another group [16] infers $Y_\mathrm{P} = 0.244 \pm 0.002$. Clearly, these results are statistically inconsistent. It is crucial that high priority be assigned to further H II region observations to estimate or avoid the systematic errors. Until then, since the error budget for Y_P is probably dominated by systematic rather than statistical uncertainties, in what follows a generous range for Y_p will be adopted: $0.228 \le Y_\mathrm{P} \le 0.248$.

Lithium-7

Cosmologically interesting lithium is observed in the spectra of nearly 100 very metal poor halo stars [17, 18] (see GALACTIC METAL-POOR HALO). These stars are so metal poor they provide a sample of more nearly primordial material than anything observed anywhere else in the universe; the most metal-poor among them have heavy-element abundances less than one-thousandth of the solar metallicity. However, these halo stars are also the oldest objects in the Galaxy and, as such, have had the most time to modify their surface abundances. So, even though any correction for Galactic evolution modifying their lithium abundances may be smaller than the statistical uncertainties of a given measurement, the systematic uncertainty associated with the dilution and/or destruction of surface lithium in these very old stars could dominate the error budget. There could be additional errors associated with the modeling of the surface layers of these cool, low-metallicity, low-mass stars needed to derive abundances from absorption-line spectra. It is also possible that some of the Li observed in these stars is non-primordial (e.g. that some of the observed Li may have been produced post-BBN by spallation reactions (the breakup of C, N and O nuclei into nuclei of Li, Be and B) or fusion reactions ($\alpha + \alpha$ to form ^{6}Li and ^{7}Li) in cosmic-ray collisions with gas in the ISM). In a recent analysis [19], it is argued that as much as $\sim$0.2 dex of the observed lithium abundance, $A(\mathrm{Li}) \equiv 12 + \log(\mathrm{Li/H})$, could be post-primordial in origin.

The very large data set of lithium abundances measured in the warmer ($T > 5800$ K), more metal-poor ($[\mathrm{Fe/H}] < -1.3$) halo stars defines a plateau (the 'Spite-plateau' [17]) in the lithium abundance–metallicity plane. Depending on the choice of stellar-temperature scale and stellar atmosphere model, the abundance level of the plateau is $A(\mathrm{Li}) = 2.2 \pm 0.1$, with very little dispersion in abundances around this plateau value. The small dispersion provides an important constraint on models which attempt to connect the present surface lithium abundances in these stars to the original lithium abundance in the gas out of which these stars were formed some 10–15 Gyr ago. 'Standard' (i.e. non-rotating) stellar models predict almost no lithium depletion and, therefore, are consistent with no dispersion about the Spite plateau. Although early work on mixing in models of rotating stars was very uncertain, recently stellar models have been constructed which reproduce the angular momentum evolution observed for the much younger, low-mass open cluster stars. These models have been applied to the study of lithium depletion in main sequence halo stars. A well-defined lithium plateau with modest scatter and a small population of 'outliers' (overdepleted stars), consistent with the current data, is predicted for depletion factors between 0.2 dex and 0.4 dex [20].

To err on the side of caution, a generous range for the plateau abundance, $2.1 \leq A(\mathrm{Li}) \leq 2.3$, is adopted. If depletion is absent, this range is consistent with the primordial lithium 'valley' (see figure 4). For depletion $\geq$0.2 dex, the consistent primordial lithium abundances bifurcate and move up into the 'foothills', although a non-negligible contribution from post-BBN lithium could move the primordial abundance back down again (figure 4).

Confrontation of theory with data

In the context of the 'standard' model (three families of massless, or light, two-component neutrinos), the predictions of BBN (SBBN) depend on only one free parameter, the nucleon-to-photon ratio η. The key test of the standard, hot, big bang cosmology is to assess whether there exists a unique value or range of η for which the predictions of the primordial abundances are consistent with the light-element abundances inferred from the observational data. From a statistical point of view it might be preferable to perform a simultaneous fit of the inferred primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li to the SBBN predictions. In this manner the 'best fit' η, along with its probability distribution may be found, and the 'goodness of fit' assessed [21]. However, since systematic uncertainties most likely dominate observational errors at present, the value of this approach is compromised. An alternative approach is adopted here.

As emphasized earlier, deuterium is an ideal baryometer. As a first step the primordial abundance of deuterium inferred from observations at high redshift will be compared with the SBBN prediction to identify a consistent range for η. Then, given this range, the SBBN abundances of ^{4}He and ^{7}Li are predicted and these are compared with the corresponding primordial abundances derived from the observational data. The challenge is to see whether the D-identified range for η leads to consistent predictions for ^{4}He and ^{7}Li. Recall that, because of its complicated evolutionary history, it is difficult to use ^{3}He to test and constrain SBBN. Furthermore, another consistency test is to compare the SBBN-inferred η range with the present baryon density derived from non-BBN observations and theory. Is our model for the very early evolution of the universe consistent with the present universe?

From the two well-observed, high-redshift absorption line systems with 'low D', the estimate adopted for the primordial D abundance is $(\mathrm{D/H})_\mathrm{P} = (2.9 - 4.0) \times 10^{-5}$ (see figure 3). Also shown for comparison in figure 3 is the allowed range of the primordial deuterium abundance suggested by the 'high-D' abundance inferred from observations of one lower-redshift absorption-line system. With allowance for the $\sim$8% uncertainty in the theoretically predicted abundance, the favored range (low D) for η is quite narrow: $\eta_{10} = 5.1 \pm 0.36$. It is clear from figure 4 that, for the baryon abundance in this range, the BBN-predicted lithium abundance is entirely consistent with the Spite plateau value, even if the plateau were raised by $\sim$0.2 dex to allow for modest stellar destruction–dilution or lowered by a similar amount owing to post-BBN production. For this narrow range in η the predicted ^{4}He mass fraction varies very little. For $\eta_{10} \approx 5$, $\Delta Y_\mathrm{p} \approx 0.010\,\Delta\eta/\eta$, so that, including the error in the predicted abundance, $Y_\mathrm{p} = 0.247 \pm 0.001$. As may be verified from figure 2, this is within (albeit at the high end of) the range allowed by the data from the low-metallicity, extragalactic H II regions. Given the current uncertainties in the primordial abundances, SBBN is consistent with 'low-D, high-η'.

The significance of this concordance cannot be underestimated. A glance at figure 1 provides a reminder of the enormous ranges for the predicted primordial abundances. That the simplest hot, big bang cosmological model can account for ('predict') three independent abundances (four with ^{3}He; although ^{3}He has not been employed in this comparison, its predicted abundance is consistent with extant observational data) by adjusting only one free parameter (η) is a striking success. The theory, which is in principle falsifiable, has passed the test. It need not have. Indeed, future observational data coupled to better understanding of systematic errors may provide new challenges. For example, if in the future it should be determined that the primordial helium mass fraction were lower than $Y_\mathrm{p} = 0.245$, this would be inconsistent (within the errors) with the 'low-D, high-η' range derived above. Similarly, if the best estimate for the D-determined η range changed, the comparison performed above should be repeated. With this in mind, what of the 'high-D, low-η' range which has been set aside in the current comparison?

If, in contrast to the deuterium abundance adopted above, the true value were higher, $(\mathrm{D/H})_\mathrm{P} = (10\text{–}30) \times 10^{-5}$, the SBBN-favored range in η would be lower (see figure 3). Accounting for the $\sim$8% uncertainty in the theoretically predicted abundance, $\eta_{10} = 1.7 \pm 0.28$. Inspection of figures 2–4 reveals that, as long as $\eta_{10} \gtrsim 1.1$–1.3, consistency with ^{4}He and ^{7}Li can be obtained. Hence, for 'high D' as well, the standard model passes the key cosmological test.

Comparison of BBN with non-BBN baryon density estimates

Having established the internal consistency of primordial nucleosynthesis in the standard model, it is necessary to proceed to the next key test. Does the nucleon abundance inferred from processes which occurred during the first thousand seconds of the evolution of the universe agree with estimates–bounds to the nucleon density in the present universe?

It is a daunting task to attempt to inventory the baryons in the universe. Since many (most?) baryons may be 'dark', such approaches can best set lower bounds to the present ratio of baryons to photons. One such estimate [22] suggests a very weak lower bound on η of $\eta_{10} \geq 0.25$, entirely consistent with the BBN estimates above. Others [23] have used more subjective (although cautious) estimates of the uncertainties, finding a much higher lower bound to the global budget of baryons: $\eta_{10} \geq 1.5$, which is still consistent with the 'low-η' range identified using the high-D results.

A possible challenge to the 'low-η' case comes from an analysis [24] which employed observational constraints on the Hubble parameter, the age of the universe, the structure-formation 'shape' parameter and the x-ray cluster gas fraction to provide non-BBN constraints on the present density of baryons, finding that $\eta_{10} \geq 5$ may be favored over $\eta_{10} \leq 2$. Even so, a significant low-η, high-D range still survives.

Cosmology constrains particle physics

Limits on particle physics beyond its standard model are mostly sensitive to the bounds imposed on the ^{4}He abundance (see also STANDARD MODEL OF PARTICLE PHYSICS). As described earlier, the ^{4}He abundance is predominantly determined by the neutron-to-proton ratio just prior to nucleosynthesis. This ratio is determined by the competition between the weak interaction rates and the universal expansion rate. The latter can be modified from its standard model prediction by the presence of 'new' particles beyond those known or expected on the basis of the standard model of particle physics. For example, additional neutrino 'flavors' ($\Delta N_\nu > 0$), or other new particles, would increase the total energy density of the universe, thus increasing the expansion rate (see equations (4) and (5)), leaving more neutrons to form more ^{4}He. For ΔN_ν sufficiently small, the predicted primordial helium abundance scales nearly linearly with ΔN_ν: $\Delta Y \approx 0.013\,\Delta N_\nu$. As a result, an upper bound to $Y_{\rm P}$ coupled with a lower bound to η (since $Y_{\rm P}$ increases with increasing baryon abundance) will lead to an upper bound to ΔN_ν and a constraint on particle physics [1].

The constraints on $N_\nu = 3 + \Delta N_\nu$ as a function of the baryon-to-photon ratio η are shown in figure 5. For 'low D, high η' there is little room for any 'extra' particles: $\Delta N_\nu \lesssim 0.3$. This would eliminate a new neutrino flavor ($\Delta N_\nu = 1$) or a new scalar particle ($\Delta N_\nu = 4/7$) provided they were massless or light ($m \ll 1$ MeV) and interacted at least as strongly as the 'ordinary' neutrinos. In contrast, much weaker constraints are found for 'high D, low η' where N_ν as large as 5 ($\Delta N_\nu \leq 2$) may be allowed (see figure 5).

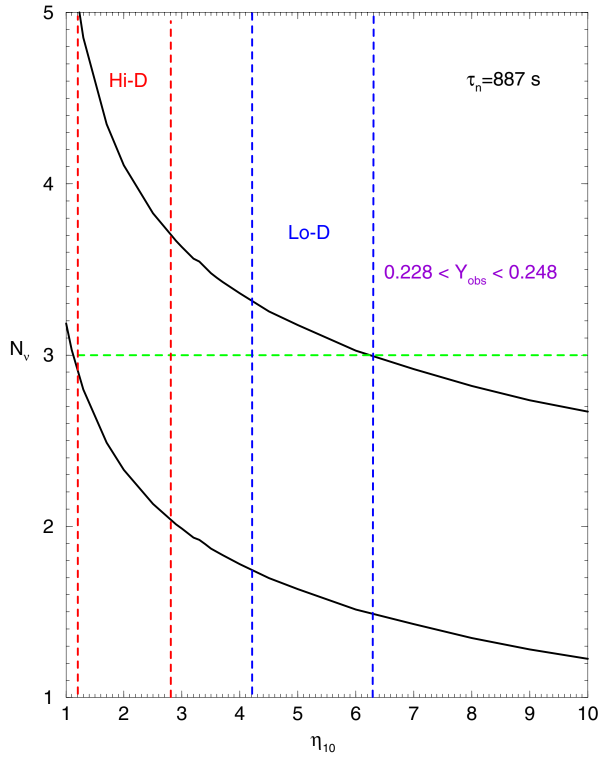

Figure 5. The number of equivalent massless neutrinos $N_\nu \equiv 3 + \Delta N_\nu$ (see equation (4)) as a function of η. The region allowed by an assumed primordial ^{4}He mass fraction in the range 0.228–0.248 lies between the two solid curves. The vertical bands bounded by the dashed lines show generous bounds on η from 'high' and 'low' deuterium.

Summary

The standard, hot, big bang cosmological model is simple (assuming isotropy, homogeneity, Newtonian–Einsteinian gravity, standard particle physics, etc) and, probably, simplistic. In broad brush it offers a remarkably successful framework for understanding observations of the present and recent universe. It may seem hubris to expect that this model could provide a realistic description of the universe during the first 20 min or so in its evolution when the temperature and density were enormously larger than today. According to the standard model, during these first 20 min the entire universe was a nuclear reactor, turning neutrons and protons into the light nuclides. This prediction presents the opportunity to use observations here and now to test the theory there and then. As described in this article, SBBN predicts observable primordial abundances for just four light nuclides, D, ^{3}He, ^{4}He and ^{7}Li, as a function of only one adjustable parameter, η, the nucleon-to-photon ratio, which is a measure of the universal baryon abundance. Even though it is currently difficult to use the extant observational data to bound the primordial abundance of ^{3}He, SBBN is still overconstrained, yielding three predicted abundances for one free parameter. Furthermore, the baryon density inferred from SBBN must be consistent with that derived from observations of the present universe. Given the many possibilities that SBBN could be falsified by the empirical data, it is a remarkable success of the standard model that there is consistency between theory and observations provided that there are a few billion photons (most of them in the 2.7 K CBR) for every neutron or proton (nucleon) in the universe.

This success establishes primordial nucleosynthesis as one of the main pillars of our standard model of cosmology, providing the only probe of the physical universe during its very early evolution. Alternative theories of gravity and/or particle physics must now be tested against the impressive success of SBBN.

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