Big Bang Nucleosynthesis

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Abstract

The precision of measurements in modern cosmology has made huge strides in recent years, with measurements of the cosmic microwave background and the determination of the Hubble constant now rivaling the level of precision of the predictions of big bang nucleosynthesis. However, these results are not necessarily consistent with the predictions of the Standard Model of big bang nucleosynthesis. Reconciling these discrepancies may require extensions of the basic tenets of the model, and possibly of the reaction rates that determine the big bang abundances.

1 Introduction

Modern cosmology has established convincingly that our universe began roughly fifteen billion years ago as a hot dense fireball. The linch pins upon which this is based are 1) the universal expansion, 2) the 2.7 K microwave background radiation, and 3) big bang nucleosynthesis (BBN). The universal expansion is based on Hubble's law, which states that the velocity of recession of distant objects is proportional to their distance from us. Although this "law" has been known for many decades, only recently has the Hubble constant, the inverse of which gives the age of the universe, been determined to better than a factor of two (see, *e.g.*, Graham *et al.* [1], Tonry *et al.* [2]). Most recently this has been measured using Type Ia (non-core-collapse) supernovae as standard candles. These observations [3] not only measured the Hubble constant, but strongly suggest that there exists a vacuum energy, or cosmological constant, reducing the upper limit on the baryonic matter in the universe to about 30% of its critical density. The background radiation, produced from the photons in the primordial fireball, was found, using the COBE satellite, to be described by a black body radiation curve to incredible precision [4], [5]. However, data from the BOOMERANG [6], [7] and MAXIMA-1 [8], [9] experiments exhibit some interesting effects that may be difficult to explain. BBN, which synthesized light nuclei from the protons and neutrons produced in the big bang, will be described in detail below.

Following our universe's initial instant, the big bang fireball grew (see, *e.g.*, Walker *et al.* [10], Yang *et al.* [11]), possibly very rapidly in the initial instant, and cooled. After roughly 10^{-5} s had elapsed, the quark-gluon plasma that had existed up to that point had cooled enough to allow a phase transition in which the quarks combined into baryons, although the details by which this occurred are not yet well understood. Indeed, if that phase transition was first order, it would have produced a universe with a lumpy baryon distribution or, if it were second order, a smooth baryon distribution. We will see below that this could have impacted the abundances of the nuclides produced in BBN. The primordial plasma also contained between 10^9 and 10^{10} times as many photons as baryons, and numerous leptons and their corresponding antiparticles.

At a somewhat later time, *e.g.*, t = 10^{-2} s, the temperature was still high enough, T = 10^{11}K, that protons and neutrons would be comparable in number, and would be kept in equilibrium by the interactions with the (much more numerous) leptons that also existed in the primordial soup [10], [11]. The leptons were kept in thermal equilibrium by neutral current weak interactions

$$e^+ + e^- \leftrightarrow \nu_i + \bar{\nu}_i \tag{1}$$

where the subscript i refers to e-, μ-, or τ-neutrinos. The interactions that kept the baryons in equilibrium with the leptons are

$$p + e^- \leftrightarrow n + \nu_e \tag{2}$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e \tag{3}$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e \tag{4}$$

However, the slight mass difference between the proton and the neutron (the neutron is more massive by $\Delta = 1.293$ MeV) made it easier to convert neutrons into protons than the reverse, and the proton density (p) began to exceed that of the neutrons (n), *i.e.*,

$$(n)/(p) = exp(-\Delta/kT). \tag{5}$$

At a slightly lower temperature, the equilibrium condition of eqs. 2 to 4 could no longer be maintained, as the universal expansion rate exceeded the rate at which neutrinos could interact. This occurred for T = $4 \mathrm{x} 10^{10}$ K for μ- and τ-neutrinos, and about T = $2 \mathrm{x} 10^{10}$ for e-neutrinos (because both neutral- and charged-current interactions occur for ν_e's and $\bar{\nu}_e$'s at these energies).

As the temperature dropped slightly more, the neutrinos "decoupled", and the reactions in equations 2 and 3 proceeded only to the right. This temperature, though, was still sufficient to produce copius numbers of electron-positron pairs. However, at a slightly later time, $\sim$ a second and a temperature of about 10^9 K, the number of high-energy photons became insufficient to sustain pair production, and the positrons annihilated with electrons. The neutron-proton ratio at this freezeout temperature, T_F, was

$$(n)_F/(p)_F = exp(-\Delta/kT_F), \tag{6}$$

giving about 13% neutrons and 87% protons in the universe. Of course, a free neutron is unstable; it decays to a proton with a lifetime of 889 $\pm$ 2.1 s [12], although the effect of this on the BBN abundances is not large.

2 Standard Model of Big Bang Nucleosynthesis

As the universe expanded and cooled, protons and neutrons interacted, and could, briefly, form deuterons. However, the temperature was high enough that each resulting deuteron was immediately broken up into its constituent proton and neutron by high-energy photons until the temperature dropped to slightly less than 10^9 K. At that point BBN began. The following reactions, then, resulted in the nuclides produced in the big bang:

$$p + n \rightarrow d + \gamma \tag{7}$$

$$d + p \rightarrow \ ^3He + \gamma \tag{8}$$

$$^3He + n \rightarrow \ ^4He + \gamma \ or \ ^3He + d \rightarrow \ ^4He + p \tag{9}$$

$$d + n \rightarrow \ ^3H + \gamma \tag{10}$$

$$^3H + p \rightarrow \ ^4He + \gamma \ or \ ^3H + d \rightarrow \ ^4He + n \tag{11}$$

Also mediating the relative strengths of the two pathways was the reaction

$$^3H + p \leftrightarrow ^3 He + n \tag{12}$$

Note that there are two ways to get from ^{3}He to ^{4}He and from ^{3}H to ^{4}He. These will compete because, although the ^{3}He(d,p)^{4}He cross section is larger than that for ^{3}He(n,γ)^{4}He at the temperatures at which BBN occurs, there are many less deuterons to initiate the former reaction than there are neutrons to initiate the latter.

The neutron abundance, about 12% of baryons during BBN, can be tracked through BBN's three or so minutes. Virtually all of these combine with the more abundant protons to form ^{4}He. Thus the ratio of ^{4}He to ^{1}H from BBN represents a very basic test of our understanding of the processes that occurred then; the amount of ^{4}He in material that is thought to have been processed only in the big bang should be 24% by mass. A major effort by astronomers has been directed toward determining this value. Since "metals", to astronomers all elements heavier than helium, are produced in stars, astronomers can use the "metallicity" of a star to determine how close to the big bang the material of which it is made was produced. Thus the most metal poor stars are the ones to which the astronomers turn for measuring BBN abundances. In the case of ^{4}He, there are several features that complicate the observations; these have also been dealt with in a variety of ways, some by selecting the objects to be observed and others by correcting the observed abundances. The value found is about 0.23, significantly less [13], [14] than 0.24. A recent study [15] found a higher value, in better agreement with prediction, but the final resolution of this conflict has yet to occur. However, the observational and theoretical values are certainly in qualitative agreement, and may be within uncertainties when systematic effects are fully included. Note that the primordial ^{4}He abundance would be lowered if very much ^{2}H or ^{3}He were produced; their values are nonzero, but are much smaller than the ^{4}He abundance.

The "Standard Model" (SM) of BBN, in which it is assumed that the baryon distribution was homogeneous and isotropic during that period, is described by one parameter, η, the baryon to photon ratio. The predicted ^{4}He value could be reduced to the observed 0.23 value, as the ratio of the ^{4}He to the ^{1}H abundances does vary slowly with that parameter (see Fig. 1). However, the ^{4}He abundance is not so useful in determining η. By contrast, ^{2}H and ^{3}He are also produced in BBN; their abundances are considerably more sensitive to η than is that of ^{4}He. ^{3}He is both produced and destroyed in stellar burning, so its primordial value is difficult to determine from those observed. ^{2}H should have a well defined primordial value, as it is only destroyed in stars. Its value is as indicated in Fig. 1. However, there are other "primordial" values [16], [17] of ^{2}H that are about an order of magnitude larger than that shown in Fig. 1. It does not appear to be possible to explain these within plausible models of galactic chemical evolution (see, *e.g.* Tosi *et al.* [18]). However, recent work suggests that the high values might have resulted from creation of ^{2}H via interactions of jets and clouds that may have occurred after galaxies formed [19]. Unfortunately, the value determined for η from the primordial ^{2}H value is not in agreement with that determined from primordial ^{4}He [14] (see Fig. 1). Another nuclide, ^{7}Li is also produced (see below) in BBN, but it cannot resolve the difficulty, as its allowed value could agree with either the ^{4}He or the ^{2}H value. The determination of the primordial abundance of ^{7}Li has some difficult questions associated with stellar processing (see, e.g., Deliyannis and Pinsonneault [20]), although these do not affect the above qualitative statement. Indeed, as can be seen in Fig. 1, the qualitative agreement is remarkable; the theoretical big bang abundances do track the abundances of the four primordial nuclides over the ten orders of magnitude they span.

It should be noted, though, that there are some interesting questions that impinge on the SM. An observed diffuse x-ray glow [21] also determines a baryon density; this suggests a value that is significantly higher than the BBN value derived with the SM. Some of the complexities of this situation have been elucidated by Steigman, Hata, and Felten [22]. Furthermore, recent results from BOOMERANG [6], [7] and MAXIMA-1 [8], [9] appear to indicate more problems for the SM [23]. Specifically, the BOOMERANG data suggest an Ω_b of 0.05 and MAXIMA-1 a value of 0.07, both appreciably larger than the upper limit of $\Omega_b = 0.02$ determined from the SM.

3 Inhomogeneous Models of Big Bang Nucleosynthesis

There is another parametrization, however, that does not assume a homogeneous universe, but a lumpy one at the time of BBN. While the nuclear reactions that synthesize ^{2}H, ^{3}He, and ^{4}He are essentially the same in either model, some reaction possibilities exist in the Inhomogeneous Models (IMs) that do not exist in the SM that can increase the abundance of ^{7}Li and vastly increase the abundances of heavier nuclides. Unfortunately, these models have several more parameters than does the SM, so are much less aesthetically appealing. However, the difficulties with the SM have forced cosmologists to reexamine BBN in the hope of understanding the differences that exist between theory and observation. Ironically, the predictions of the IMs differ only in detail from those of the SM. One important difference, though, is that the IMs do allow a higher Ω_b, up to 0.10, than do the SMs [24].

The nucleus ^{7}Li can be produced in observable amounts in either model. The reactions that produce it are

$$^3H + \ ^4He \rightarrow \ ^7Li + \gamma \tag{13}$$

or

$$^3He + \ ^4He \rightarrow \ ^7Be + \gamma \tag{14}$$

$$^7Be + e^- \rightarrow \ ^7Li + \nu_e \tag{15}$$

The β-decay of ^{7}Be does not occur until much later than the period of BBN, as it occurs by electron capture, and the ^{7}Be remained fully ionized in the

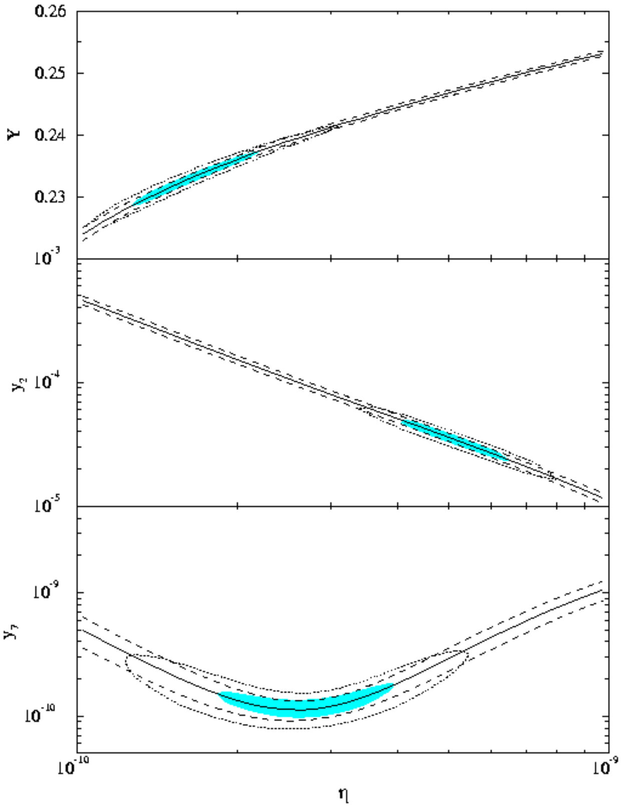

Fig. 1. Abundances of the light nuclides from the SM of BBN, with uncertainties (dashed lines), as a function of η, the baryon to photon ratio. Y is the ^{4}He mass fraction, and y_2 and y_7 are the number densities, relative to H, of deuterium and ^{7}Li respectively. Also indicated are the regions constrained by observations at the 68% (shaded regions) and 95% confidence limits. The best representation of the observed big bang abundances occurs at a density of a few percent of the critical density. From Hata *et al.* (1995).

rare environment following BBN until the time of recombination several hundred thousand years later. None the less, it will ultimately contribute to the observed ^{7}Li abundance.

It may also be possible to produce some slightly heavier nuclides in BBN, although not in appreciable (*i.e.*, measurable) abundances in the SM. In the IMs [25], [26], [27], though, the universe would have developed into two regions, one high-density, the result of an early first order phase transition (see, *e.g.* Malaney and Mathews [28]), and the other low-density, in the region in between. The high-density regions would have quickly become proton-rich, as the neutrons would diffuse out of them much more rapidly than would the protons. This, in turn, would have produced a neutron-rich region in the intervening space. The result of this bifurcation would have been that the nuclear reactions that took place in the low-density regions passed through the nuclei slightly to the neutron-rich side of stability, and would have produced some interesting abundances for nuclei heavier than ^{7}Li. The primary reaction pathway that promoted nuclei beyond mass 7 u would have been

$$^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B(n,\gamma)^{12}B(\beta)^{12}C(n,\gamma)^{13}C(... \tag{16}$$

Curiously this reaction sequence would have had little effect on the ultimate abundance of ^{11}B, as its value at the end of BBN would have depended on reactions that did not involve ^{8}Li (the ^{8}Li, $T_{1/2} = 0.84$ s, would all have decayed by then). However, this sequence could have synthesized significant abundances of nuclei heavier than ^{12}C. Thus the ^{8}Li(α,n)^{11}B cross section would be crucial to production of nuclides heavier than ^{12}C. Its cross section was measured, directly (see Gu *et al.* [29]) using an ^{8}Li radioactive nuclear beam, and indirectly in several experiments (see, *e.g.*, Boyd, Paradellis, and Rolfs [30]). However, a recent direct determination (Mizoi *et al.* [31]) got a different result; further measurements, perhaps using different detection techniques, will be required to finally determine this cross section. In any event, its determination certainly documents the difficulties of applying indirect approaches. Another reaction that could be important is ^{7}Li(^{3}H,n)^{9}Be, by which appreciable amounts of ^{9}Be could have been made in the low-density, neutron-rich regions [32], [33]. Unfortunately, even that amount would still be below observational limits, although the data are approaching the abundance for ^{9}Be that is predicted for some of the IM parameter space. The value predicted in the SM, however, is many orders of magnitude below present observational levels. Because the ^{8}Li abundance is so important to predictions of heavy nuclide abundances in the IMs, reactions that destroy it, such as ^{8}Li(d,t)^{7}Li and ^{8}Li(d,p)^{9}Li, can also be important; these have been studied with an ^{8}Li radioactive nuclear beam [34].

It would be of interest, though, if some nuclides more massive than ^{9}Be and ^{11}B were found to have observable abundances in very low metallicity stars. The elements from sodium to silicon represent cases in which astronomers can achieve high sensitivity at low abundances, so these might be the focus of future efforts. Unfortunately, this requires measurements of cross sections on short-lived nuclides. The path of BBN in the IMs passes primarily through unstable nuclei that are one to three neutrons to the right of stability. Branch points may exist at masses 15 u and 18 u from the following sequences:

$$^{12}C(n,\gamma)^{13}C(n,\gamma)^{14}C(n,\gamma)^{15}C \ ? \tag{17}$$

^{15}C could either β-decay to ^{15}N, and quickly be returned to ^{12}C by a (p,α) reaction, or it could capture another neutron to make ^{16}C. If it did the latter, it would have bypassed that branch point, and moved on to heavier nuclei. Then the following reaction sequence then would become important:

$$^{15}C(n,\gamma)^{16}C(\beta^-)^{16}N(n,\gamma)^{17}N(n,\gamma)^{18}N\ ? \tag{18}$$

As discussed by Applegate, Hogan, and Scherrer [25], Kajino Mathews, and Fuller [35], and Rauscher *et al.* [36], ^{18}N could β-decay to ^{18}O, then returned to ^{15}N by a (p,α) reaction, and to ^{12}C by a second (p,α) reaction, or it might undergo ^{18}O(n,γ). However, if the ^{18}N captured a neutron, then it would go on to ^{19}N and, subsequently, to heavier nuclides. Even before getting to ^{18}N, however, ^{17}N might undergo β-decay to ^{17}O, in which case the ^{17}O(n,α)^{14}C cycling reaction would become important [25], [35], [36].

To understand these branch points, one needs to know the cross sections for the ^{15}C(n,γ)^{16}C and ^{18}N(n,γ)^{19}N reactions, both of which are virtually impossible to measure. However, at least two modes of attack are available to learn about the neutron capture cross sections. The first involves use of β-delayed neutron emission and β-decay itself to study states that might be important to these processes. Ozawa *et al.* [37] searched for β-delayed neutron emission of ^{19}C to states in ^{19}N just above the n+^{18}N threshold. Such states could provide resonance contributions to the reaction rate for the ^{18}N(n,γ) reaction. Unfortunately, β-decays are very selective, so this type of experiment is definitive only if states are observed. Another possibility is the use of (d,p) reactions on beams of ^{15}C and ^{18}N to observe transitions to both bound states and to states just above the threshold. The former would give a reasonably good estimate of the (n,γ) direct capture reaction rate, while the latter would determine the existence and some of the parameters of resonance states that might allow calculation of the (n,γ) resonance capture reaction rate. This is a difficult experiment with end-of-the-20th-century technology, although one experiment of this type has been performed [38]. The next generation radioactive nuclear beam facilities should make such experiments considerably easier, and more likely to produce the results necessary to calculate the reaction rates for the reactions that are important to BBN.

It should be noted that the IMs do allow an expansion of the possible range of η over which representation of the observed primordial abundances can be achieved [41] and at sufficiently large η values that the x-ray data can be accommodated. However, they do so at the price of addition of many parameters to the description of BBN. Other solutions have been discussed as possible cures of the crisis in the BBN abundances, such as neutrino degeneracy (see, *e.g.*, Olive *et al.* [40], Kajino and Orito [41], Kohri, Kawasaki, and Sato [39], Orito *et al.* [42]), which can result in lowering the predicted ^{4}He abundance to a value that agrees with present observed values.

4 Conclusions

Although the theoretical description of BBN can be said, at best, to have an uneasy agreement with the observational data, the qualitative agreement that exists over ten orders of magnitude in abundance is stunning. Thus any discrepancies are not likely to reflect on the general description of the big bang, but rather on details that may lead to important new physics. The challenge to nuclear astrohysicists with access to radioactive nuclear beam facilities is enormous, but should lead to exciting new results in the near future.

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