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BIG-BANG NUCLEOSYNTHESIS AND THE BARYON DENSITY OF THE UNIVERSE

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Big-bang nucleosynthesis is one of the cornerstones of the standard cosmology. For almost thirty years its predictions have been used to test the big-bang model to within a fraction of a second of the bang. The concordance that exists between the predicted and observed abundances of D, ^{3}He, ^{4}He and ^{7}Li provides important confirmation of the standard cosmology and leads to the most accurate determination of the baryon density, between $1.7\times10^{-31}\,\mathrm{g\,cm^{-3}}$ and $4.1\times10^{-31}\,\mathrm{g\,cm^{-3}}$ (corresponding to between about 1% and 14% of critical density). This measurement of the density of ordinary matter is crucial to almost every aspect of cosmology and is pivotal to the establishment of two dark-matter problems: (i) most of the baryons are dark, and (ii) if the total mass density is greater than about 14% of the critical density as many determinations now indicate, the bulk of the dark matter must be "nonbaryonic," comprised of elementary particles left from the earliest moments. We critically review the present status of primordial nucleosynthesis and discuss future prospects.

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1 Introduction

Because of the extremely high temperatures that existed during the earliest moments it was too hot for nuclei to exist. At around 1 sec the temperature of the Universe cooled to 10^{10} K, and a sequence of events began that led to the synthesis of the light elements D, ^{3}He, ^{4}He and ^{7}Li. The successful predictions of big-bang nucleosynthesis provide the earliest and most stringent test of the big-bang model, and together with the expansion of the Universe and the 2.726 K black-body cosmic background radiation (CBR) are the fundamental observational basis for the standard cosmology.

Big-bang nucleosynthesis began with the pioneering work of Gamow, Alpher, and Herman who believed that all the elements in the periodic table could be produced in the big bang [1]; however, it was soon realized that the lack of stable nuclei of mass 5 and 8 and Coulomb repulsion between highly charged nuclei prevent significant nucleosynthesis beyond ^{7}Li. In 1964, shortly before the discovery of the CBR, Hoyle and Tayler [2] argued that the big bang must produce a large ^{4}He abundance (about 25% by mass) and this could provide the explanation for the high ^{4}He abundance observed in many primitive objects. At about the same time, Zel'dovich realized that a lower temperature for the Universe today implied a greater mass fraction of ^{4}He produced in the big-bang, and concluded that the big-bang model was in trouble. While his reasoning was correct, through a comedy of misunderstandings he mistakenly believed that the primeval mass fraction of ^{4}He was at most 10% and that the temperature of the Universe was less than about 1 K [3].

After the discovery of the CBR by Penzias and Wilson in 1965, detailed calculations of big-bang nucleosynthesis were carried out by Peebles [4] and by Wagoner, Fowler and Hoyle [5]. It soon became clear that, as Hoyle and Tayler had speculated, the origin of the large primeval fraction of ^{4}He was indeed the big-bang, and further, that other light elements were also produced. However, the prevailing wisdom was that D and ^{7}Li were produced primarily during the T Tauri phase of stellar evolution and so were of no cosmological significance [6]. The amount of ^{4}He produced in the big bang is very insensitive to the cosmic baryon—that is, ordinary matter—density (see Fig. 1), and thus it was not possible to reach any conclusions regarding the mean density of ordinary matter.

Since the other light elements are produced in much smaller quantities, ranging from 10^{-5} or so for D and ^{3}He to 10^{-10} for ^{7}Li (see Fig. 1), establishing their big-bang origin was a much more difficult task. Further, it is complicated by the fact that the material we see today has been subjected to more than 10 Gyr of astrophysical processing, the details of which are still not understood completely. However, over the past 25 years the big-bang origin of D, ^{3}He, and ^{7}Li has been established, not only further testing the model, but also enabling an accurate determination of the average density of baryons in the Universe.

First, it was shown that there is no plausible astrophysical site for the production of deuterium [7, 8]; due to its fragility, post big-bang processes only destroy it. Thus, the presently observed deuterium abundance serves as a *lower limit* to the big-bang production. This argument, together with the strong dependence of big-bang deuterium production on the baryon density, led to the realization that D is an excellent "baryometer" [7, 9], and early measurements of the deuterium abundance [10, 11], a few parts in 10^5 relative to hydrogen, established that baryons could not contribute more than about 20% of closure density. This important conclusion still holds today.

which determines the matrix element for all the reactions that interconvert neutrons and protons, and cross sections for nuclear reactions.

As recently as ten years ago the uncertainty in the mean neutron lifetime was significant; at present it is known very precisely: $\tau_n = 889\,\mathrm{sec} \pm 2\,\mathrm{sec}$ [30]. The other cross sections that are required have been measured in the laboratory at energies appropriate for primordial nucleosynthesis (this is in contrast to stellar nucleosynthesis where lab-measured cross sections must be extrapolated to much lower energies). With the exception of ^{7}Li, the uncertainties in cross sections do not result in significant uncertainties in the light-element yields.

Two recent Monte-Carlo studies have quantified the uncertainties in the predicted abundances [29, 31]. Kernan and Krauss [31] ran a suite of 1000 models with input parameters chosen from the probability distributions for the various cross sections and neutron mean lifetime. For a baryon-to-photon ratio of 3×10^{-10} the "two-sigma" range of the abundances found was: $Y_P = 0.239$–0.241; D/H $= 6.7 \times 10^{-5}$–9.0×10^{-5}; ^{3}He/H $= 1.4 \times 10^{-5}$–1.9×10^{-5}; and ^{7}Li/H $= 0.81 \times 10^{-10}$–1.7×10^{-10} (i.e., 950 of the models had abundances within the stated intervals). Here, Y_P is the mass fraction of ^{4}He produced; the other abundances are specified by number relative to hydrogen. Only for ^{7}Li is the uncertainty significant when compared to the uncertainty in the observed abundance. It arises due to three cross sections that are still poorly known: $^3\mathrm{He}+{}^4\mathrm{He} \rightarrow \gamma+{}^7\mathrm{Be}$, $^3\mathrm{H}+{}^4\mathrm{He} \rightarrow \gamma+{}^7\mathrm{Li}$, and $^7\mathrm{Li}+p \rightarrow {}^4\mathrm{He}+{}^4\mathrm{He}$. (In fact, there could be systematic errors in one or more of these cross sections, as the results of different experiments are not consistent with their quoted error flags [29, 31].)

As an aside, the ^{4}He yield is known most accurately, apparently to a precision of better than 1%. For this reason even tiny corrections have become important, and it is difficult to judge whether or not every significant effect has been taken into account. The most recent correction may serve as a guide: finite nucleon-mass effects led to an increase, $\Delta Y_P \simeq +0.001$ [32]. Further, an informal poll of the various nucleosynthesis codes known to us gave results that, with the exception of ^{4}He, fell within the above mentioned Monte-Carlo range; for ^{4}He, the values reported ranged from $Y_P = 0.237$ to $Y_P = 0.241$.

Modifications of the standard scenario have also been investigated, including almost every imaginable possibility [33]: additional light particle species; unstable, massive tau neutrino; decaying particles; variations in the fundamental constants; large neutrino chemical potentials; primeval magnetic fields; and spatial variations in the baryon-to-photon ratio. In most instances the "nonstandard physics" was introduced for the purpose of obtaining a bound or limit based upon primordial nucleosynthesis, e.g., the previous mentioned limit to the number of light neutrino species. In a few cases, however, it was motivated by other considerations.

For example, Witten suggested that if the transition from quark/gluon plasma, which existed prior to about 10^{-5} sec, to hadron matter involved a strongly first-order phase transition the resulting distribution of baryons could be quite inhomogeneous [34], thereby possibly significantly changing the outcome of primordial nucleosynthesis. For a short time, it appeared that such inhomogeneity could lead to a relaxation of the bound to Ω_B, even permitting closure density in baryons [35]. It is now clear that any significant level of inhomogeneity upsets the agreement of the predictions with the observations [36, 37, 38]; moreover, there is now little motivation from particle physics for a strongly first-order quark/hadron phase transition. At present, the only modification involving the known particles that leads to significant changes is the possibility that the tau neutrino has a mass of the order of 1 MeV–30 MeV

[39]. The present laboratory limit to its mass is just above 30 MeV and should be improved enough to clarify this issue soon.

To summarize the theoretical situation; the only compelling scenario for primordial nucleosynthesis is the standard one. Within the standard picture the predictions for the light-element abundances have uncertainties that, with the exception of ^{7}Li, are not significant when compared to the accuracy with which the primeval abundances are known. At present, the comparison between theory and observation turns primarily on the observations, and there, the uncertainties are more difficult to quantify.

3 Confrontation Between Theory and Observation

The predictions of the standard scenario, including "two-sigma" uncertainties based upon our Monte-Carlo calculations are shown in Fig. 1.[1] We now discuss the *inferred* primordial abundances, with emphasis on *inferred*, since one must deduce the primordial abundances of D, ^{3}He, ^{4}He, ^{7}Li from material that has undergone some 10 Gyr of chemical evolution.

3.1 Deuterium and Helium-3

Since deuterium is the most weakly bound, stable nucleus it is easy to destroy and difficult to produce. As discussed earlier, the deuterium abundance observed today provides a lower limit to the big-bang production. The Apollo Solar Wind Composition experiment, which captured solar-wind particles in foils exposed on the moon, and the subsequent analysis by Geiss and Reeves [10] provided the first accurate assessment of the pre-solar D and ^{3}He abundances. Based on these experiments and studies of primitive meteorites, Geiss deduces a pre-solar (i.e., at the time of the formation of the solar system) deuterium abundance [40]

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\odot} = 2.6 \pm 1.0 \times 10^{-5}. \tag{4}$$

This value is consistent with measurements of the deuterium abundance in the local ISM (i.e., within a few hundred pc) made two decades ago by the Copernicus satellite [11], and more recently by the Hubble Space Telescope [41],

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{HST}} = 1.65^{+0.07}_{-0.18} \times 10^{-5}. \tag{5}$$

That the ISM value is slightly lower than the pre-solar abundance is consistent with slow depletion of deuterium with time since the material in the ISM is about 5 Gyr younger than the material from which our solar system was assembled. A sensible lower bound to the primordial deuterium abundance,

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{P} \geq 1.6 \times 10^{-5}, \tag{6}$$

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[1] Our Monte-Carlo calculations are similar to those in Refs. [29, 31] with one exception; we have treated the cross sections for ^{7}Li production differently. For the cross sections where data from two experiments are inconsistent we have used both distributions, alternating between the two.

based on these measurements leads to an upper limit to η of 9×10^{-10}. Because of the rapid variation of the amount of deuterium produced with η, this upper limit is rather insensitive to the exact lower bound adopted for D/H. Further, this argument is very robust because it involves minimal assumptions about galactic chemical evolution, simply that D is only destroyed by stellar processing [8].

It would be nice to exploit the rapid variation of deuterium production to obtain a lower bound to η, based upon the overproduction of deuterium. This cannot be done directly because deuterium is so easily destroyed. However, an equally useful bound can be derived based upon the sum of D + ^{3}He production. Primordial deuterium either resides in the ISM or has been burnt to ^{3}He (via $D + p \rightarrow \gamma + {}^3\mathrm{He}$). A significant fraction of ^{3}He survives stellar processing (in fact, low mass stars are net producers of ^{3}He), and thus an upper bound to the primordial D + ^{3}He abundance can be inferred from present-day measurements with few assumptions. This line of reasoning was introduced by Yang et al. [12] who derived the bound,

$$\left(\frac{{}^3\mathrm{He}+\mathrm{D}}{\mathrm{H}}\right)_p \leq \left(\frac{{}^3\mathrm{He}+\mathrm{D}}{\mathrm{H}}\right)_\odot + \left(g_3^{-1} - 1\right)\left(\frac{{}^3\mathrm{He}}{\mathrm{H}}\right)_\odot , \tag{7}$$

where the ^{3}He survival fraction g_3 was argued to be greater than 25% [42]. (It should be noted that even massive stars, which tend to burn ^{3}He, eject some ^{3}He in their winds.) The bound was improved by taking account of material that has been processed by more than one generation of stars [23, 24]. Both methods lead to similar upper limits to the primordial D + ^{3}He abundance,

$$\left(\frac{\mathrm{D}+{}^3\mathrm{He}}{\mathrm{H}}\right)_p \leq 1.1 \times 10^{-4}, \tag{8}$$

which in turn gives the bound $\eta \geq 2.5 \times 10^{-10}$. Like the upper limit to η based upon deuterium, this lower limit is insensitive to the precise bound to the primeval abundance of D + ^{3}He because of the steep rise of D + ^{3}He production with decreasing η. Together, D and ^{3}He define a concordance interval, $2.5 \times 10^{-10} \leq \eta \leq 9 \times 10^{-10}$.

The theoretical belief that low-mass stars actually increase the D + ^{3}He abundance by producing ^{3}He is supported by the observations of Wilson, Rood and Bania [43]. By using the analogue of the 21 cm hydrogen hyperfine transition for $^3\mathrm{He}^+$ they found $^3\mathrm{He/H} \sim 10^{-3}$ in planetary nebulae. This much additional ^{3}He production agrees with the value predicted by stellar models of Iben and Truran [44]. However, measurements of the ^{3}He abundance by the same method in hot, ionized gas clouds, so called H II regions, vary greatly, from $^3\mathrm{He/H} \sim 1 \times 10^{-5}$ to $^3\mathrm{He/H} \sim 8 \times 10^{-5}$ [45], which suggests that ^{3}He is destroyed by varying degrees [46]. While H II regions are the only place outside the solar system where the ^{3}He abundance can be measured, they are samples of the cosmos dominated by the effects of massive, young stars, which are the most efficient destroyers of ^{3}He, and thus, they do not represent "typical samples" of the cosmos (so far as the chemical evolution of ^{3}He is concerned). In any case, we believe that a ^{3}He survival fraction of 25% or more remains a reasonably conservative estimate as applied to the solar system ^{3}He abundance.

3.2 Helium-4

In two important regards the primordial ^{4}He abundance is the easiest to measure: it is large, around 25% by mass fraction, and the chemical evolution of ^{4}He is straightforward—stars are net producers of ^{4}He. On the other hand, the predicted abundance is most accurately known and varies only logarithmically with η. Thus, measuring the ^{4}He abundance to sufficient accuracy to sharply test the big-bang prediction is just as challenging as determining the other light-element abundances.

Needless to say, since ^{4}He is ubiquitous, its abundance can be measured in many different ways, all of which give values consistent with a primeval mass fraction of around 25%. The most accurate determinations of the primeval ^{4}He abundance rely on measurements of its recombination radiation in low-metallicity H II regions (see Ref. [47] for a detailed discussion of the experimental method). Since stars produce both helium and other heavier elements, contamination due to stellar production should be minimized in metal-poor samples of the Universe. A number of groups have obtained high-quality data for very metal-poor, extragalactic H II regions, which has allowed determination of helium abundances to very good statistical accuracy [48]. Moreover, several independent and detailed analyses of these data sets have been carried out [24, 49, 50]. The quality of the data and the accuracy of the abundance determinations desired are now such that possible systematic errors dominate the error budget, and they are the focus of our attention.

3.2.1 Systematic Effects

The first step in the path to the primordial helium abundance is measuring line strengths of the recombination radiation for hydrogen and helium. Line strengths are then translated into a helium mass fraction by means of theoretical emissivities for both helium and hydrogen and modeling of the H II region. In modeling an H II region spherical symmetry and uniform temperature are assumed, neither of which is an excellent assumption given that a typical H II region is heated by a few massive, young stars near its center. Since the ionization potentials for hydrogen and helium are different, corrections must be made for both neutral and doubly ionized helium. Collisional excitation can be significant, but is not easy to accurately estimate. Stellar absorption by the stars heating the H II region can affect the excitation of the hydrogen and helium in the H II region. Absorption due to intervening dust can also affect the abundance determinations. A summary of our estimate of the systematics, based largely on the discussion of Skillman and Kennicutt [51] and Skillman et al. [52], is given in Table 1. A detailed numerical assessment of some of these effects has recently been carried out by Sasselov and Goldwirth [53], who suggest that the systematic errors may even be slightly larger.

3.2.2 Primordial helium-4 abundance

Even in the most metal-poor H II regions some of the ^{4}He is produced by stars. Since stars also produce the elements beyond ^{4}He (collectively referred to as metals), there should be a direct relationship between metallicity and stellar-produced ^{4}He. Peimbert and Torres-Peimbert [54] pioneered the extrapolation of the helium abundance vs. heavy-element abundance to zero metallicity to infer the primordial ^{4}He abundance. Oxygen, nitrogen, and

Type of correction	Estimate
Line ratios (including dust absorption)	±2%
Emissivities	±2%
Collisional excitation and stellar absorption	±1%
Neutral helium	+2%
Total	+7%,−5%

Table 1: Estimate of systematic errors.

carbon have all been used as indicators of stellar nucleosynthesis and hence the amount of stellar produced ^{4}He. Each has its advantages and disadvantages [55], though the quantitative results are very similar. Recently, Olive and Steigman [50] have performed a detailed statistical analysis of very metal-poor H II regions, and derive a primordial ^{4}He abundance (see Fig. 3)

$$Y_P = 0.232 \pm 0.003^{+0.016}_{-0.012} \tag{9}$$

where their statistical error is quoted first and the systematic error based upon Table 1 appears second. (For reference, their quoted systematic error is ±0.005.)

To summarize, there is undisputed evidence for a large primeval ^{4}He abundance whose only plausible explanation is the big bang. Following Olive and Steigman [50] we take as a reasonable estimate for the primeval mass fraction, $Y_P = 0.221 - 0.243$, which allows for a two-sigma statistical uncertainty and their one-sigma systematic uncertainty. Within the two-sigma theoretical uncertainty, such a primeval mass fraction of ^{4}He is consistent with the big-bang prediction provided $0.8 \times 10^{-10} \leq \eta \leq 4 \times 10^{-10}$. At present, errors are dominated by possible systematic effects; allowing for our higher estimate of systematic error, a primeval ^{4}He mass fraction as low as 0.214, or as high as 0.254, cannot be ruled out with certainty. This extreme range for the primeval ^{4}He abundance is consistent with a much larger interval, $6 \times 10^{-11} \leq \eta \leq 1.5 \times 10^{-9}$, illustrating the exponential sensitivity of η to Y_P.

3.3 Lithium

The study of extremely metal-poor, pop II halo stars has provided the bulk of our knowledge of the light elements beyond ^{4}He. It began with the work of Spite and Spite [13], who measured the ^{7}Li abundance as a function of metallicity (iron abundance) and surface temperature. Much to their surprise they found a "plateau" in the ^{7}Li abundance and established what has become a very strong case for the determination of the primeval ^{7}Li abundance.

The Spite plateau refers to the fact that the ^{7}Li abundance as a function of surface temperature is flat for surface temperatures greater than about 5600K (see Fig. 4). and further that the ^{7}Li abundance for stars with temperatures greater than 5600K as a function of iron abundance is flat for very low iron abundance (Fig. 5). The first plateau gives strong evidence that the stars with the highest surface temperatures are not destroying their ^{7}Li by convective burning since the depth of the convective zone depends upon the surface temperature (for temperatures lower than 5600K the measured ^{7}Li does vary with surface temperature indicating convective burning). The second plateau indicates that any ^{7}Li due to stellar production must be insignificant for the most metal-poor stars since the ^{7}Li abundance is independent of the metal abundance.

The actual value of the ^{7}Li abundance on "the Spite plateau" is subject to several important systematic effects. In particular, model atmospheres used by different authors assume effective surface temperatures, differing by as much as 200 K. Other differences in the model atmospheres. including assumptions made about opacities, also affect the inferred ^{7}Li abundances in a systematic way. These systematic effects explain the main difference between the Spite and Spite abundance, $^7\mathrm{Li/H} = 1.1 \times 10^{-10}$, and the value derived recently by Thorburn [15] from a sample of 90 pop II stars, $^7\mathrm{Li/H} = 1.7 \times 10^{-10}$ (see Figs. 4, 5). Further, Thorburn's data seems to indicate a slight systematic variation of the ^{7}Li abundance with surface temperature, possibly indicating some depletion from a higher primordial value by processes that transport ^{7}Li inward to regions of high enough temperature that it can be burned; e.g., meridonal mixing [56]. However, the amount of depletion is constrained by the relatively narrow spread in ^{7}Li abundance for a wide range of surface temperatures and metallicities. Microscopic diffusion is ruled out by this fact, though stellar models that incorporate rotation, which suppresses microscopic diffusion, can be made consistent with the observations [57].

The case against significant depletion (and hence for a primeval abundance) was further strengthened by the observation of ^{6}Li in a pop II star by Smith, Lambert, and Nissen [58]; Hobbs and Thorburn [59] have detected ^{6}Li in this and another pop II star. Big-bang production of ^{6}Li is negligible and so the ^{6}Li seen was presumably produced by cosmic-ray processes, along with beryllium and boron (as discussed below). Since ^{6}Li is much more fragile than ^{7}Li and yet still survived with an abundance relative to Be and B expected for cosmic-ray production, depletion of ^{7}Li cannot have been very significant [60, 61]. These ^{6}Li measurements allow for a largely model-independent limit to the amount of ^{7}Li depletion, less than about a factor of two.

In summary, based on metal-poor, pop II halo stars we infer a primordial ^{7}Li abundance of

$$\left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_P = 1.4 \pm 0.3^{+1.8}_{-0.4} \times 10^{-10} \tag{10}$$

where the central value is the average of the Spite and Spite and Thorburn determinations, the statistical error is listed first, and the systematic error second. The systematic-error estimate consists of ± 0.4 due to differences in model atmospheres and $+1.4$ to account for possible depletion. In fixing a range for the primordial ^{7}Li abundance it is the systematic error that is most important; accordingly, we use the sum of statistical plus systematic error to derive our estimate for the ^{7}Li abundance, $0.7 \times 10^{-10} \leq {}^7\mathrm{Li/H} \leq 3.5 \times 10^{-10}$. Allowing for the two-sigma theoretical uncertainty, the concordance interval is $1 \times 10^{-10} \leq \eta \leq 6 \times 10^{-10}$. (We note that the 95% confidence range for the ^{7}Li abundance advocated by Thorburn [15] differs only slightly from ours.)

3.4 Beryllium and Boron

While the inhomogeneous variant of big-bang nucleosynthesis motivated by a first-order quark/hadron phase transition cannot alter the basic conclusions, an important question remains, namely, is there an observable signature that can differentiate between the inhomogeneous and the homogeneous models, thereby probing the quark/hadron transition? Several authors [35] argued that the regions with high neutron-to-proton ratio that exist in inhomogeneous models could lead to "leakage" beyond mass 5 and mass 8 and traces of ^{9}Be, ^{10}B, ^{11}B, and possibly even r-process elements (neutron-rich isotopes) could be produced. However, detailed studies by Sato and Terasawa [37] and Thomas et al. [38] have shown that such leakage is negligible when the D, ^{3}He, ^{4}He, and ^{7}Li abundances are consistent with their observed values, with Be/H, B/H $\sim 10^{-18}$

An observational program similar to that of Spite and Spite [13] was begun for beryllium and boron. Recently, both beryllium [62] and boron [63] have been detected in metal-poor, pop II halo stars. The observations indicate that beryllium and boron abundances scale with metallicity, strongly suggesting that their production was not the big bang [64]. The processes that produce the beryllium and boron (and ^{6}Li) seen in younger pop I stars (like our sun) are thought to be cosmic-ray reactions [65]. For Be and B, such reactions involve the breakup of heavy nuclei such as C, N, O, Ne, Mg, Si, S, Ca, and Fe by protons and alpha particles (for lithium in pop II stars, alpha plus alpha fusion reactions are dominant [66]).

3.5 Toward truly primordial abundances

As the reader by now should appreciate, the task of disentangling 10 Gyr of galactic chemical evolution is not an easy one. What are the prospects for determining the light-element abundances in very primitive samples of the Universe (that is, in objects seen at very high red shift)?

Hydrogen clouds at high redshift "backlit" by quasars offer the possibility of measuring the deuterium abundance in very old, very distance, and very primitive samples of the cosmos [67]. These clouds, known as quasar absorption line systems, are "seen" by the absorption features they produce in the quasar spectrum; many are observed to be very metal-poor, indicative of primeval material. There have been many searchs for the deuterium analog of the 1216 Å Lyman-α absorption feature, which is shifted very slightly to the blue, by about 0.33 Å. Recently, Songaila et al. and Carswell et al. [68] announced a possible detection of deuterium in a redshift $z = 3.32$ absorption line system (in the quasar Q0014+813); if it is deuterium, it corresponds to an abundance

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{abs}} = (1.9\text{--}2.5) \times 10^{-4}. \tag{11}$$

Both groups are quick to point out that a single measurement does not constitute a definite detection of deuterium as there is a significant probability ($\sim$ 15%) that the feature seen arises from Lyman-α absorption due to another, smaller hydrogen cloud at slightly lower redshift. At the very least though, their detection provides an important upper limit to the deuterium abundance in this very primitive sample of the cosmos.

Interpreting the detection as an upper bound to the primordial deuterium abundance leads to the constraint $\eta \geq 1.6 \times 10^{-10}$, only slightly less stringent than the previous bound based upon the production of D + ^{3}He. If, on the other hand, it is interpreted as a measurement of the primordial deuterium abundance, then $(\mathrm{D/H})_P \sim 2 \times 10^{-4} \gg [(\mathrm{D} + {}^3\mathrm{He})/\mathrm{H}]_\odot \sim$

4×10^{-5}, which leads to a problem in understanding the observed pre-solar D+^{3}He abundance. Since it is almost certain that D is destroyed by burning to ^{3}He one would expect a much higher D + ^{3}He abundance than has been observed. This could indicate a problem with models of the chemical evolution of ^{3}He, or the interpretation as a deuterium detection [69].

Carswell et al. have studied another quasar at a similar redshift (Q0420-388) and have detected deuterium in an absorption line system at the level of about 2×10^{-5}, with a three-sigma upper limit of 6×10^{-5} [70]. This new observation seems to imply that the previous detection was really due to another small hydrogen cloud. Further, if correct, it fits nicely with the local measurements of D and ^{3}He, and suggests that the astration of D is not great.

The merits of using quasar absorption line systems to obtain the primordial deuterium abundance are clear. The means necessary for such observations are now at hand: large-aperture telescopes with very high-resolution spectrometers, such as the 10 meter Keck telescope used by Songalia et al. With some luck, it should just be a matter of time before the deuterium Lyman-α feature is measured in several such systems. Once it is, and if the abundances are similar, both the reality of the feature and its interpretation as reflecting the primordial D abundance will have been established.

With regard to ^{3}He, one might hope to eventually use the ^{3}He$^+$ hyperfine line to determine the ^{3}He abundance in extragalactic H II regions that are very metal poor. However present technology is only marginally sufficient to observe galactic ^{3}He so it will take time before extragalactic detections are possible.

The ^{4}He abundance has been measured through its absorption lines in a quasar at redshift $z = 2.72$ (HS1700+6414) [71], and, very recently, observations made with the refurbished Hubble Space Telescope have revealed the presence of singly ionized ^{4}He in the intergalactic medium [72]. While both measurements provide important confirmation of a large, primeval ^{4}He abundance in very primitive samples of the cosmos, they lack the precision necessary to sharply test big-bang nucleosynthesis. In that regard, metal-poor extragalactic H II regions provide the most accurate determinations.

Finally, owing to its small abundance, it seems very unlikely that the ^{7}Li abundance can be measured in high-redshift objects, or even in extragalactic stars. On the other hand, the data at hand present a good case for having determined the ^{7}Li abundance in the very oldest stars in our galaxy.

4 Implications and Future Directions

The agreement between the predictions of primordial nucleosynthesis and the inferred primordial abundances is impressive—all the more so when viewed in light of the sharpening of the theoretical predictions and the improvement in the observational data that the past decade has witnessed. Without a doubt, primordial nucleosynthesis provides the most significant test of the standard cosmology—which it passes with flying colors—and leads to the best determination of the density of ordinary matter.

Where do we stand? The data are not yet good enough to single out a value for the baryon-to-photon ratio. However, they are good enough to delineate a very narrow "concordance interval" where the predicted abundances of all four light elements are consistent with their measured values.

The lower limit to the concordance interval hinges primarily upon the D + ^{3}He abundance. Based upon our understanding of the difficulty of efficiently destroying ^{3}He, $\eta = 2.5 \times 10^{-10}$ stands as a reliable lower bound. This lower bound is buttressed by both ^{7}Li—for $\eta \leq 1 \times 10^{-10}$ the predicted ^{7}Li abundance rises above 3.5×10^{-10}—and by the Songaila et al. upper limit to the primitive deuterium abundance—for $\eta \leq 1.6 \times 10^{-10}$ D/H exceeds 2.5×10^{-4}.[2]

The upper limit to the concordance interval derives from ^{4}He, ^{7}Li and D, with the stringency of the limits in that order, but the reliability in the reverse order. Assuming that the primordial mass fraction of ^{4}He is no larger than 0.243, based upon the work of Olive and Steigman [50], then η must be less than 4×10^{-10}. On the other hand, if owing to systematic error Y_P is as large as 0.254, then η could be as large as 1.5×10^{-9}. This illustrates the point mentioned earlier, the upper limit to η depends exponentially upon the upper limit to Y_P,

$$\eta_{\rm max} \simeq 4 \times 10^{-10} \exp[100(Y_P^{\rm max} - 0.243)]. \tag{12}$$

While ^{4}He is arguably the most striking confirmation of big-bang nucleosynthesis, the logarithmic dependence of the ^{4}He mass fraction on η makes it a very poor baryometer.

The uncertainty in our reasonable upper bound to ^{7}Li, $^7{\rm Li/H} \leq 3.5 \times 10^{-10}$, is primarily systematic error associated with possible ^{7}Li depletion in metal-poor, pop II stars. Our upper bound to ^{7}Li implies $\eta \leq 6 \times 10^{-10}$. On the other hand, since the strongest argument against very significant depletion of ^{7}Li in metal-poor, pop II stars is the observation of ^{6}Li, which has only been seen in two stars, very significant depletion of ^{7}Li cannot be ruled out with certainty. Taking as an extreme upper limit, $^7{\rm Li/H} \sim 6 \times 10^{-10}$, corresponding to a factor of four depletion, η could be as large as 9×10^{-10}.

Finally, turning to deuterium; because it is so easily destroyed and lacks a plausible contemporary astrophysical site for its origin, its primordial abundance must be larger than what is seen today: ${\rm D/H} \geq 1.6 \times 10^{-5}$. This implies an upper bound to η of 9×10^{-10}. It seems very difficult to get around this simple argument; moreover, because the abundance of deuterium varies so rapidly with η this bound is insensitive to the precise deuterium abundance assumed.

The difficulty in drawing sharp conclusions from the comparison between predicted and measured primordial abundances—e.g., stating two- or three-sigma limits—is the fact that the dominant uncertainties, primarily in the observations, are not Gaussian statistical errors. Two- or three-sigma limits in the present circumstance simply have no meaning. Instead, we choose to quote a "sensible" and an "extreme" concordance interval for the baryon-to-photon ratio. For the sensible interval we take 2.5×10^{-10} to 6×10^{-10}, supported from below by D+^{3}He overproduction and above by ^{7}Li overproduction. Some have argued that ^{4}He can be used to push the upper limit down to 4×10^{-10}; however, as described, such an upper limit is exponentially sensitive to the uncertainties in the primeval ^{4}He abundance, and thus not very robust.

It is interesting to compare our sensible interval with similar concordance intervals found by Yang et al. [12] in 1984, $4 \times 10^{-10} \leq \eta \leq 7 \times 10^{-10}$, and by Walker et al. [24] in 1991, $2.8 \times 10^{-10} \leq \eta \leq 4 \times 10^{-10}$. The difference between our lower limit and that of Yang et

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[2] Had we used the Carswell et al. [70] upper limit, ${\rm D/H} \leq 6 \times 10^{-5}$, which has yet to be published, the lower bound to η would be very similar to that based upon D + ^{3}He.

al. is the fact that we have allowed for slightly more astration of ^{3}He. The somewhat larger difference between our upper limit and that of Walker et al. involves ^{7}Li: They used the lower Spite and Spite value for the primordial ^{7}Li abundance and did not allow for systematic error. In any case, the fact that the differences between the concordance intervals are small is reassuring.

In setting the extreme range, we take account of of our less than perfect understanding of the chemical evolution of the Universe during the 10 Gyr or so since primordial nucleosynthesis, as well as other possible systematic errors. Though there is no plausible reason for believing that ^{3}He could be astrated significantly, or that the primeval ^{7}Li abundance is significantly different from that seen in halo pop II stars, we do not believe the wider interval of $\eta = 1.6 \times 10^{-10}$ to 9×10^{-10} can be excluded with absolute certainty. Our extreme range derives exclusively from deuterium: the present abundance, $\mathrm{D/H} \gtrsim 1.6 \times 10^{-5}$, and the limit to the primeval abundance, $\mathrm{D/H} \lesssim 2.5 \times 10^{-4}$. Moreover, for such extreme values of η all the light-element abundances are pushed to almost untenable values.

Based upon these concordance intervals—sensible and extreme—we can obtain bounds to the baryonic fraction of critical density, albeit at the expense of additional dependence upon the Hubble constant,

$$\begin{array}{lll}\text{sensible}: & 2.5 \times 10^{-10} \leq \eta \leq 6 \times 10^{-10} & \Rightarrow \quad 0.009 \leq 0.009h^{-2} \leq \Omega_B \leq 0.02h^{-2} \leq 0.14 \\ \text{extreme}: & 1.6 \times 10^{-10} \leq \eta \leq 9 \times 10^{-10} & \Rightarrow \quad 0.006 \leq 0.006h^{-2} \leq \Omega_B \leq 0.03h^{-2} \leq 0.21\end{array}$$

where the outer limits to Ω_B allow for $0.4 \leq h \leq 1$ (see Fig. 6).

The implications of these bounds for cosmology are manifold and very significant. First and foremost, the nucleosynthesis limit is pivotal to the case for both baryonic and nonbaryonic dark matter. The nucleosynthesis determination of the baryonic fraction of critical density taken together with the observational data that indicate that luminous matter contributes much less than 1% of critical density and that the total mass density is greater than 14% of critical density makes the case for these two most pressing problems in cosmology. (The Hubble-constant dependence of the nucleosynthesis limits precludes addressing both problems by simply choosing the right value for the Hubble constant since both the upper and lower limits to Ω_B scale in the same way.)

Second, one can exploit the relatively well known baryon density to estimate the total mass density by using measurements of the ratio of total mass-to-baryonic mass in clusters of galaxies, as determined by recent x-ray studies made using the ROSAT satellite. Assuming that rich clusters like Coma provide a fair sample of the "universal mix" of matter (if some, or all, of the nonbaryonic dark matter is neutrinos of mass 5 eV to 30 eV, this might not be the case) and that the hot, x-ray emitting gas is in virial equilibrium supported against gravity only by its thermal motion, White et al. [73] infer a total mass-to-baryonic mass ratio of $(20 \pm 5)\,h^{3/2}$, which leads to the following estimate for the total mass density:

$$\Omega_0 = \frac{M_{\mathrm{TOT}}(\mathrm{Coma})}{M_B(\mathrm{Coma})}\Omega_B \simeq (0.15 - 0.5)\,h^{-1/2}. \qquad (13)$$

If h is near the lower extreme of current measurements this determination of Ω_0 lends some support to the theoretically attractive notion of a flat Universe (i.e., $\Omega_0 = 1$).

The "cluster-inventory" estimate of Ω_0 is a new and potentially very powerful method for estimating the mean density of the Universe. There are still important systematic sources of error and a key assumption. The key assumption is that the baryons are either in stars (visible matter) or hot, x-ray emitting gas (by a wide margin, the baryons in the hot gas outweigh those in stars). If there is a large amount of baryonic matter hidden in dark stars, then $M_{\rm TOT}/M_B$ would be smaller. On the other hand, essentially all systematic sources of error go in the direction of increasing $M_{\rm TOT}/M_B$. For example, if the hot gas is partially supported by magnetic fields or bulk motion of the gas, then $M_{\rm TOT}$ would be larger. There is some evidence that $M_{\rm TOT}$ has been underestimated: The measurement of the mass of one cluster of galaxies based upon weak-gravitational lensing of galaxies behind the cluster yields a mass than is almost a factor of three larger than that based upon x-ray studies [74]. If the hot gas is clumpy, rather than smooth as is assumed, then the gas mass would be smaller, which also increases $M_{\rm TOT}/M_B$. It is intriguing that a factor of two or three increase in $M_{\rm TOT}/M_B$ would bring the estimate of Ω_0 close to unity. In any case, further study of the x-ray and gravitational lensing data as well as the better x-ray temperatures that the ASCA satellite is now providing should help refine this new technique for estimating the mean density.

While the primary concern of this paper is the baryon density of the Universe, big-bang nucleosynthesis also places an important constraint to the number of light particle species present around the time of nucleosynthesis, usually quantified as a limit to the equivalent number of neutrino species, N_ν. This limit arises because more species lead to additional ^{4}He production [22]. The limit to N_ν relies upon a lower limit to η and an upper limit to Y_P. Using the D + ^{3}He bound to η, $\eta \geq 2.5 \times 10^{-10}$, and our reasonable upper limit to $Y_P \leq 0.243$, it follows that $N_\nu \leq 3.4$.[3] This limit depends upon the upper limit to Y_P. However, in contrast to the upper limit to η based upon Y_P, the dependence is linear, not exponential, $N_\nu \lesssim 3.4 + (Y_P^{\rm max} - 0.243)/0.012$, and so the limit to N_ν is far less sensitive to Y_P than is upper bound to η.

Finally, what does the future hold? We believe that primordial nucleosynthesis is the best method for determining the mean baryon density, and, in that regard, that deuterium is the best baryometer. Not only does the primeval deuterium abundance vary rapidly with the baryon-to-photon ratio (as $\eta^{-1.5}$ in the relevant range), but prospects for measuring its primeval abundance in high-redshift, metal-poor quasar absorption line systems look promising. While the present situation is unsettled, with a reported detection of D/H $\sim 2 \times 10^{-4}$, as well as an upper limit, D/H $\leq 6 \times 10^{-5}$, the situation should improve. A handful of such measurements could establish the primeval D abundance to an accuracy of 10%, which would determine the baryon density to better than 5% (taking account of both the observational and theoretical uncertainties). Because of their weak dependence upon the baryon-to-photon ratio, as well as lingering systematic uncertainties, ^{4}He and ^{7}Li are destined to play a supporting role, albeit a very important one. It is both ironic and satisfying that after twenty years deuterium is still the best baryometer.

More than forty years have passed since Gamow's introduction of the notion of big-bang nucleosynthesis, and thirty years have passed since the cosmic background radiation was discovered. After more than two decades of careful comparison of theory with observation, primordial nucleosynthesis has become the earliest and most important test of the standard

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[3] Kernan and Krauss [31] point out that by using the correlations between the theoretical uncertainties in ^{4}He and D + ^{3}He, one can improve this limit very slightly, by about 0.1 neutrino species, the equivalent of reducing Y_P by about 0.001.

cosmology. Further, it leads to the best measurement of the density of ordinary matter in the Universe and provides a powerful laboratory for studying both the early Universe and fundamental physics.

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Figure Captions

Figure 1: The predictions of big-bang nucleosynthesis. The broken curves indicate the 2σ theoretical uncertainties based upon our Monte-Carlo analysis. The ^{4}He abundance is given as mass fraction; the other abundances are number relative to hydrogen. The boxes indicate the range of baryon-to-photon ratio consistent with the primeval light-element abundances; the ^{4}He box is dotted to remind the reader that ^{4}He has not been used to derive an upper limit to η because of the exponential dependence of such a limit to Y_P (see text). Our sensible concordance range, $2.5 \times 10^{-10} \leq \eta \leq 6 \times 10^{-10}$, comes from D + ^{3}He and ^{7}Li overproduction.

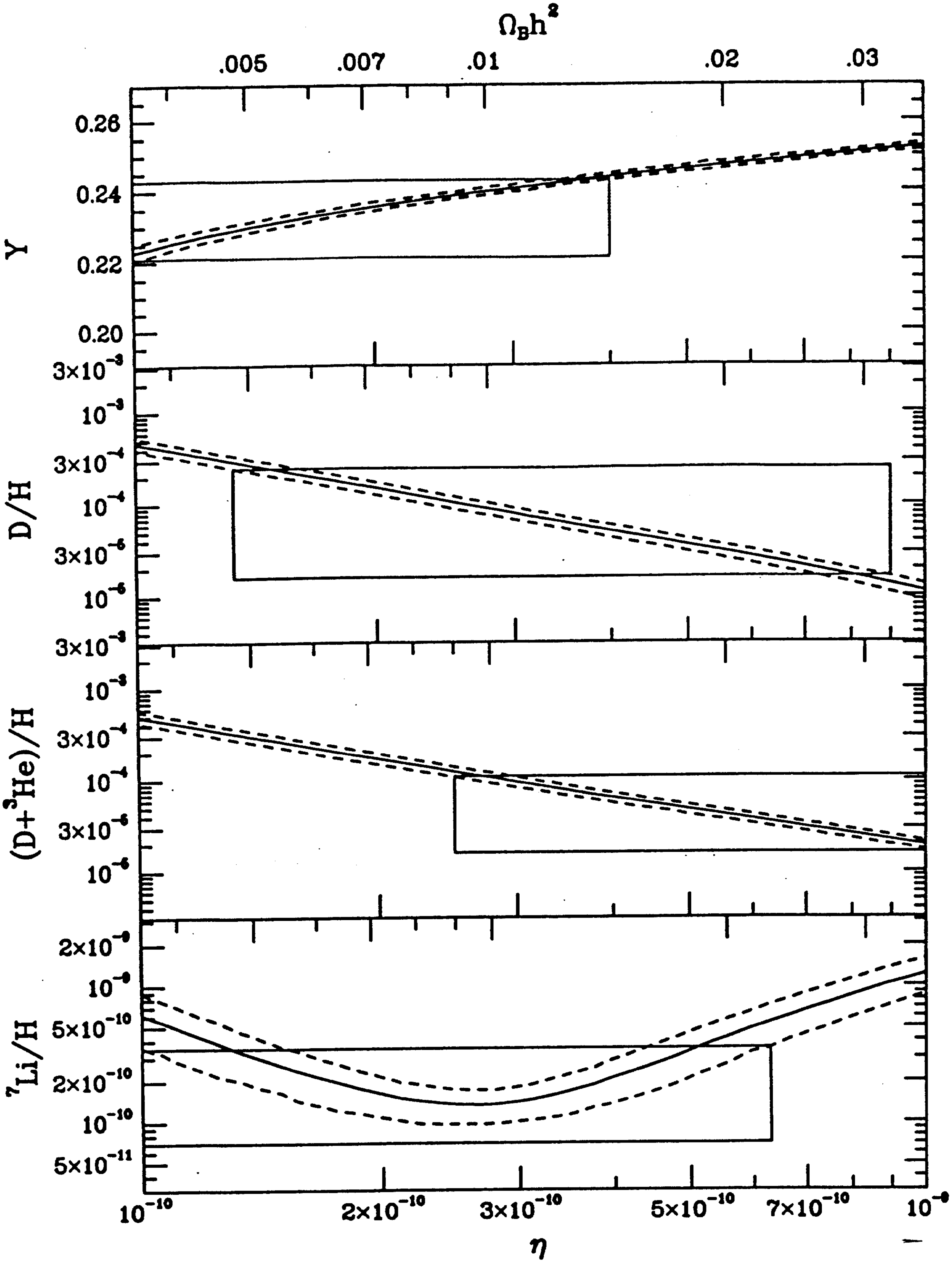
Figure 2: The nuclear reaction network used for big-bang nucleosynthesis; the most important reactions are numbered. The broken boxes for mass 5 and 8 indicate that all nuclides of this mass are very unstable.

Figure 3: The ^{4}He mass fraction vs. nitrogen abundance for very metal-poor, extragalactic H II regions. The solid line is the best fit to the data from the analysis of Olive and Steigman [60]. (In deriving their fit they did not include some of the higher metallicity H II regions).

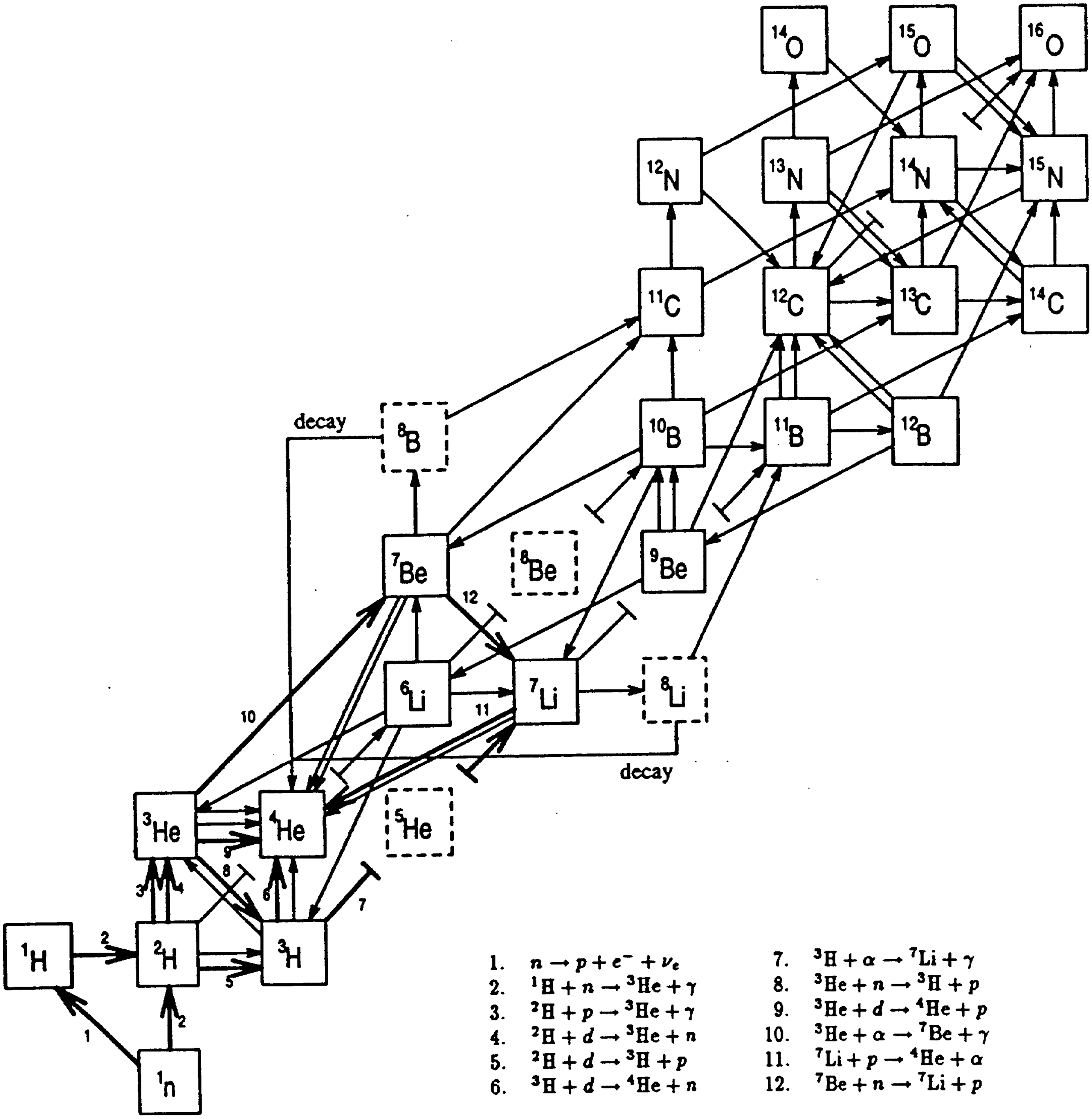
Figure 4: The ^{7}Li abundance as a function of surface temperature for very metal-poor, pop II halo stars. The decreasing ^{7}Li abundance in the stars with lower surface temperatures indicates they have burned some of their ^{7}Li (consistent with the fact that such stars are predicted to have deeper convection zones). The solid and broken lines indicate the Thorburn and Spite plateaus respectively.

Figure 5: The ^{7}Li abundance as a function of iron abundance (relative to that seen in the solar system) for stars with surface temperatures greater than 5600 K. The increase in ^{7}Li abundance seen for the stars with higher iron abundance is indicative of additional ^{7}Li due to cosmic-ray processes and stellar production. The solid and broken lines indicate the Thorburn and Spite plateaus respectively. For comparison, the abundances of beryllium and boron in metal-poor, pop II halo stars are also shown (from Refs. [64]). Unlike the ^{7}Li abundance, the B and Be abundances increase with increasing metal abundance, indicative of post-big-bang production.

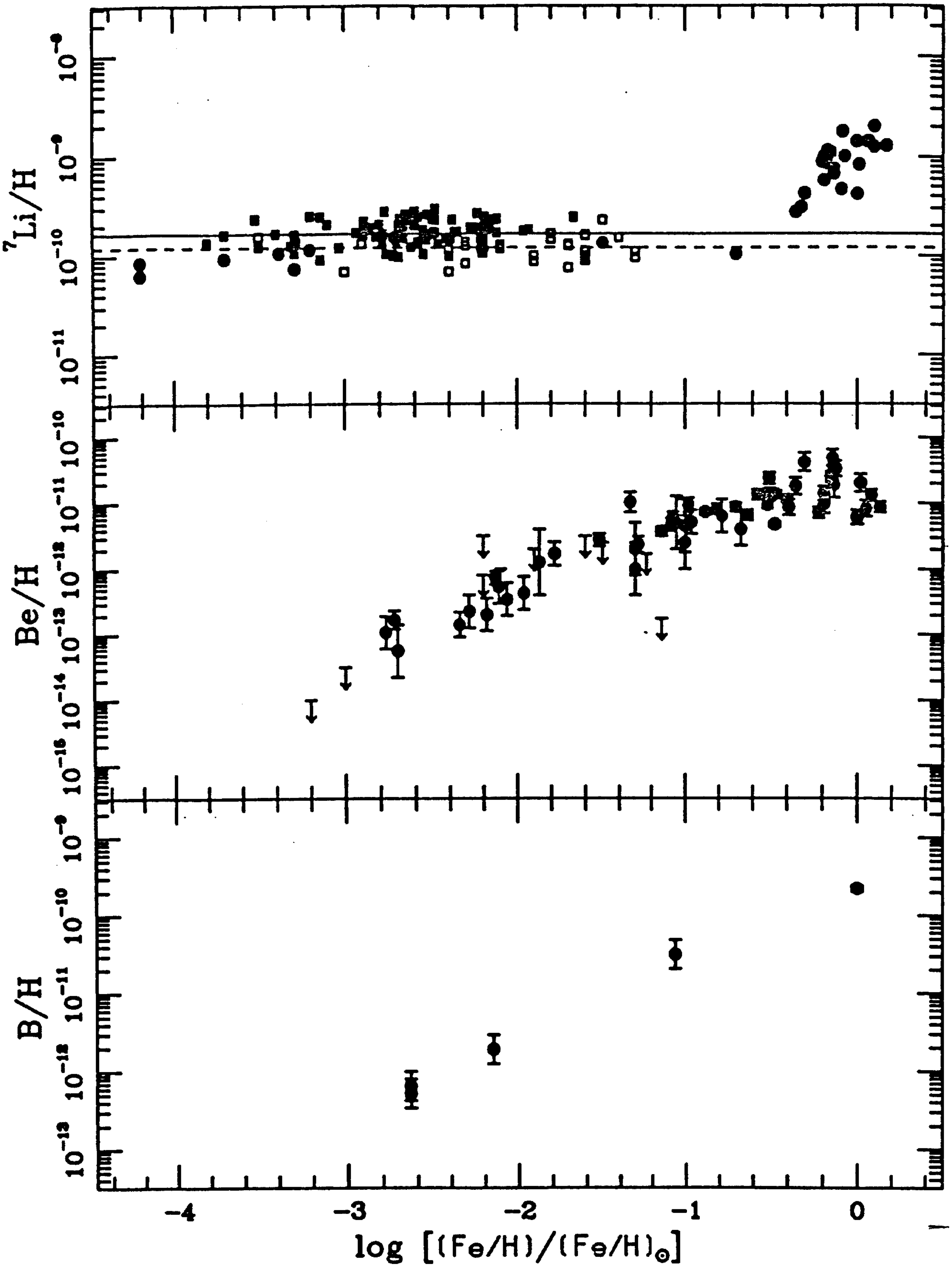
Figure 6: The fraction of critical density contributed by baryons as a function of the Hubble constant for the sensible concordance range of baryon-to-photon ratio (solid) and extreme concordance range (dotted).



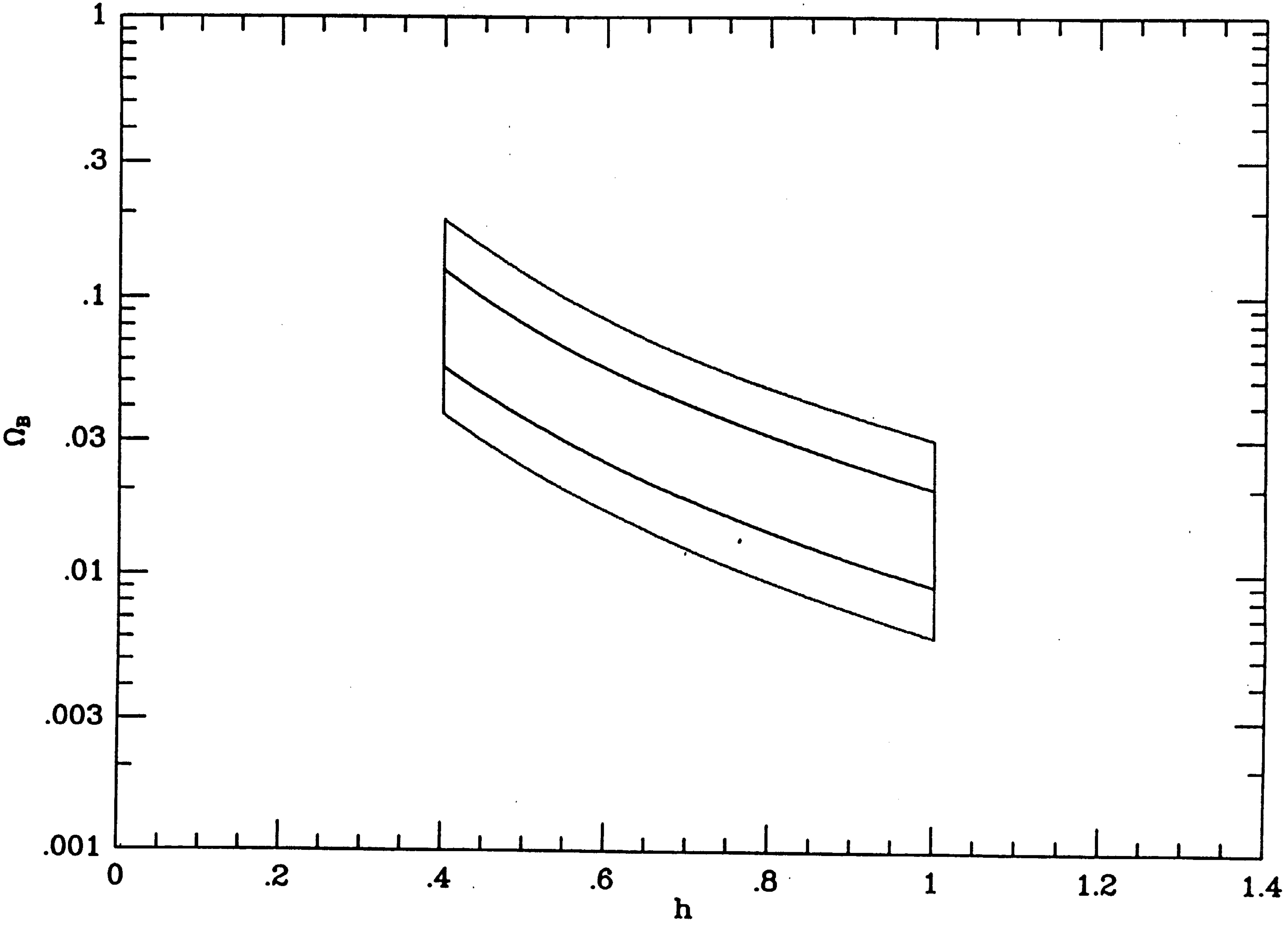
$\Omega_B h^2$
.005
.007
.01
.02
.03
Y
0.26
0.24
0.22
0.20
D/H
3×10^{-3}
10^{-3}
3×10^{-4}
10^{-4}
3×10^{-5}
10^{-5}
$(D+^3He)/H$
3×10^{-3}
10^{-3}
3×10^{-4}
10^{-4}
3×10^{-5}
10^{-5}
$^7Li/H$
2×10^{-9}
10^{-9}
5×10^{-10}
2×10^{-10}
10^{-10}
5×10^{-11}
10^{-10}
2×10^{-10}
3×10^{-10}
5×10^{-10}
7×10^{-10}
10^{-9}
η

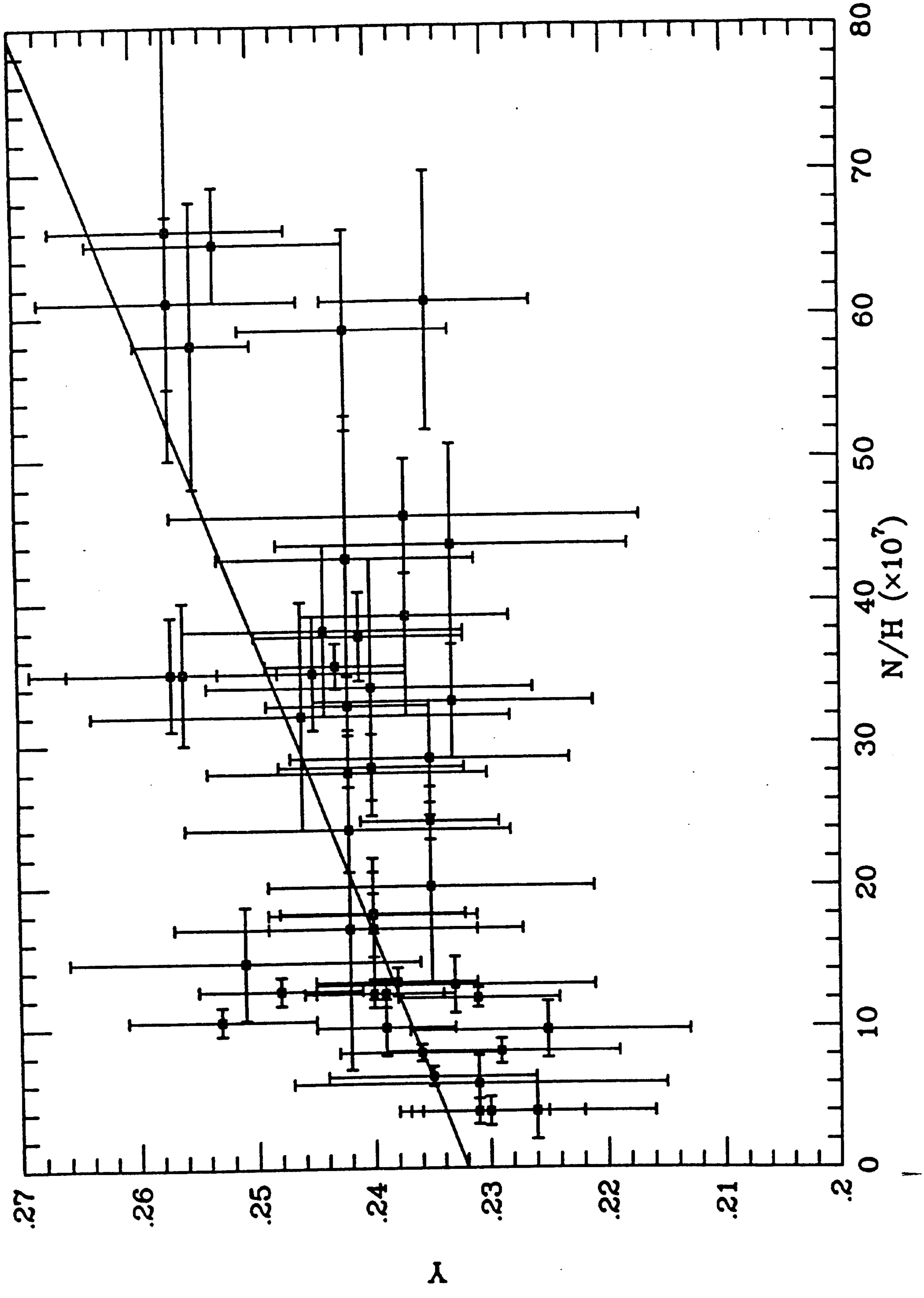


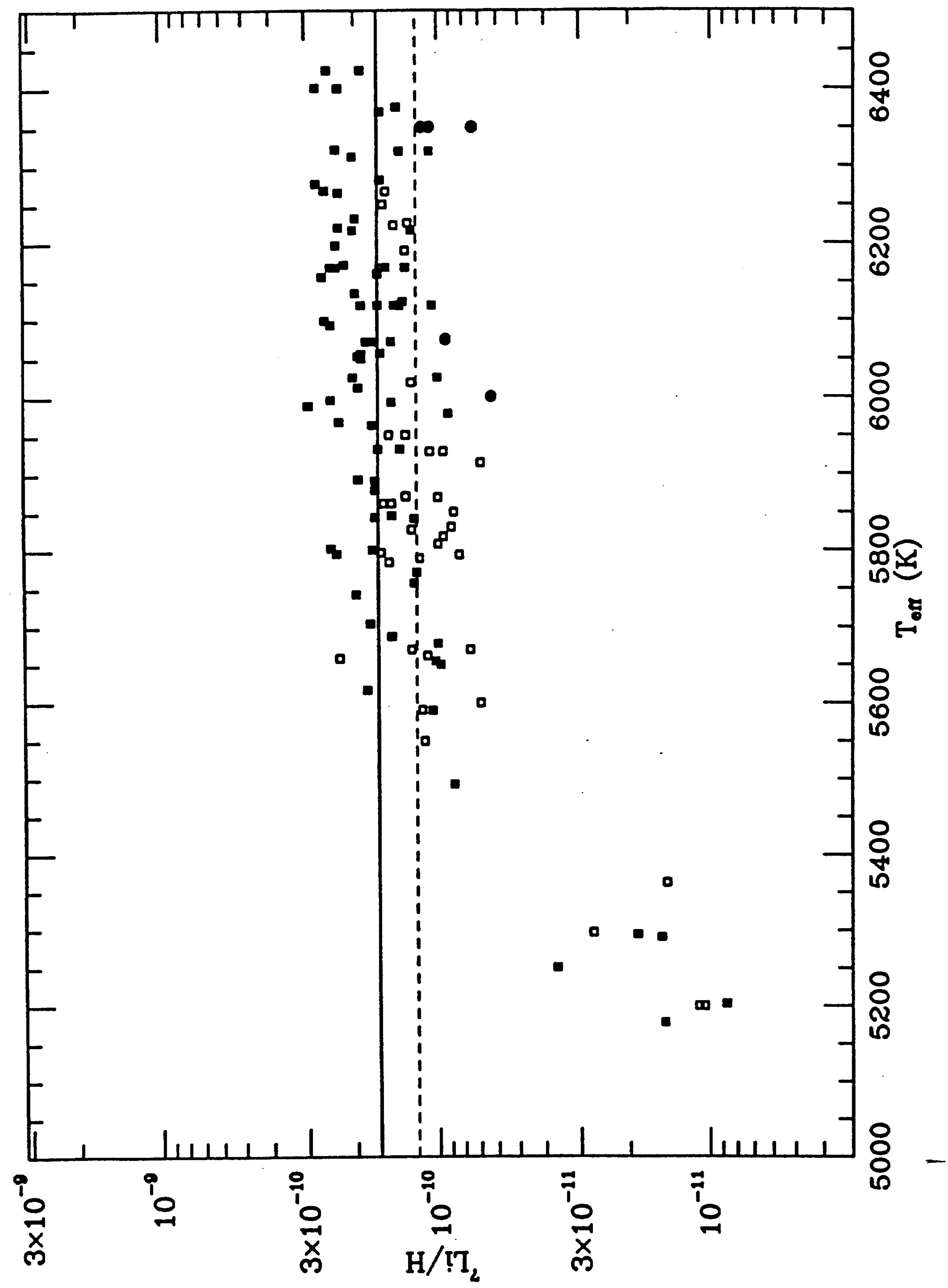
1. $n \rightarrow p + e^- + \nu_e$
2. $^1\mathrm{H} + n \rightarrow {}^3\mathrm{He} + \gamma$
3. $^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$
4. $^2\mathrm{H} + d \rightarrow {}^3\mathrm{He} + n$
5. $^2\mathrm{H} + d \rightarrow {}^3\mathrm{H} + p$
6. $^3\mathrm{H} + d \rightarrow {}^4\mathrm{He} + n$
7. $^3\mathrm{H} + \alpha \rightarrow {}^7\mathrm{Li} + \gamma$
8. $^3\mathrm{He} + n \rightarrow {}^3\mathrm{H} + p$
9. $^3\mathrm{He} + d \rightarrow {}^4\mathrm{He} + p$
10. $^3\mathrm{He} + \alpha \rightarrow {}^7\mathrm{Be} + \gamma$
11. $^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + \alpha$
12. $^7\mathrm{Be} + n \rightarrow {}^7\mathrm{Li} + p$



^{7}Li/H
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Be/H
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
B/H
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
−4
−3
−2
−1
0
log [(Fe/H)/(Fe/H)$_\odot$]


1
.3
.1
.03
.01
.003
.001
Ω_B
0
.2
.4
.6
.8
1
1.2
1.4
h


Y
.27
.26
.25
.24
.23
.22
.21
.2
0
10
20
30
40
50
60
70
80
N/H ($\times 10^7$)


3×10⁻⁹
10⁻⁹
3×10⁻¹⁰
10⁻¹⁰
3×10⁻¹¹
10⁻¹¹
⁷Li/H
5000
5200
5400
5600
5800
6000
6200
6400
T_eff (K)