Primordial Lithium and the Standard Model(s)

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(Received 31 January 1989)

We present the results of new theoretical work on surface ^{7}Li and ^{6}Li evolution in the oldest halo stars along with a new and refined analysis of the predicted primordial lithium abundance resulting from big-bang nucleosynthesis. This allows us to determine the constraints which can be imposed upon cosmology using primordial lithium and both standard big-bang and stellar-evolution models. This leads to a constraint on the baryon density today of $0.0044 < \Omega_b h^2 < 0.025$ (where the Hubble constant is $100h$ km sec^{-1} Mpc^{-1}), and impose limitations on alternative nucleosynthesis scenarios.

PACS numbers: 98.80.Ft, 97.10.Cv

The deduced primordial abundance of lithium provides a sensitive probe of cosmological theory when compared with the predictions of standard big-bang nucleosynthesis (BBN). Because the predicted primordial abundance is not a monotonic function of baryon-to-photon ratio η, Li can by itself provide both upper and lower limits on the baryon density in the Universe today, Ω_b. Moreover, the Li abundance is very sensitive to variations of the standard big-bang production scenario. Yet the theoretical, experimental, and observational factors in a critical comparison of theory and data have all been fraught with uncertainty, limiting our ability to test the BBN model. In this Letter we address these issues.

First we present new theoretical results on surface Li evolution in old halo stars which allow us to estimate solidly the actual prestellar Li abundance. These results employ the most comprehensive numerical analysis to date of halo star evolution. Next, we determine the uncertainties associated with BBN by incorporating current experimental data, and their uncertainties, in a Monte Carlo analysis. Our results allow us to derive stringent constraints in the context of standard BBN and stellar-evolution models on the cosmological parameters affecting Li production, *complete with confidence limits.* Most significant among these is Ω_b. The presently allowed range, from primordial Li alone, neither rules out nor requires baryonic dark matter in galactic halos. Also, our analysis of ^{6}Li in halo stars suggests ways to test nonstandard BBN models.

(1) Prior to 1982, it was generally believed that the primordial abundance of ^{7}Li by number was in the range 3.0–3.3 (on a logarithmic scale where the abundance of hydrogen is 12) as observed in the (younger) galactic disk stars. The pioneering observations of Li abundances in (older) halo stars by Spite and Spite[1] challenged this belief because of the striking distribution of the stellar Li content as a function of $T_{\rm eff}$: at the hotter end a *uniform* plateau ranging 800 K in $T_{\rm eff}$ at about 2.1, and then decreasing Li with decreasing $T_{\rm eff}$. This surprising result has since been confirmed by many studies.[2,3] The flatness of the Li plateau led the Spites to conjecture that it must be undepleted, and thus represents the primordial value. This implies enrichment of ^{7}Li by over a factor of 10 during galactic evolution to account for the higher abundances seen in disk stars. Alternately, adopting 3.3 as primordial would require depleting *all* plateau halo stars *uniformly* by over a factor of 10. Theoretical attempts to achieve this uniform depletion have had to appeal to *ad hoc* physical modeling,[4] shown to be implausible by a study[5] of the rotational and surface Li history of solar-type disk stars.

Our new evolutionary sequences for halo stars reproduce the observed Li abundances of the halo stars within the context of stellar-evolution theory using completely standard assumptions and input physics. We begin by (i) selecting the oldest component of halo stars, and (ii) separating these into a main-sequence group (dwarfs) and a post-main-sequence group (see Ref. 6 for further details). A comprehensive grid of evolutionary sequences spans the relevant ranges in chemical composition, mass, age, and other stellar parameters. Each sequence describes continuously the evolution of halo stars from the contracting pre-main-sequence phase to the giant branch. Because of the high sensitivity of the surface Li abundance to internal processes, special attention is paid to numerical accuracy. The processes taken into account include the following: depletion by nuclear destruction during the pre-main sequence and the early main sequence; possible depletion by gravitational settling diffusion (a nonstandard mechanism) in the late main sequence followed by enrichment caused by early post-main-sequence dredge-up; and, finally, subgiant and early giant depletion by dilution. The relative importance of each of these processes is very sensitive to stellar parameters, leading to a wide dispersion of surface Li for stars that undergo significant depletion.

We construct ^{7}Li isochrones, i.e., curves of Li vs $T_{\rm eff}$ for a given age (and composition and mixing length parameter α), where each $T_{\rm eff}$ value represents a different mass. The main-sequence isochrones (Fig. 1) confirm the conclusion that the plateau stars are essentially undepleted. Fits of the theoretical curves to the data are

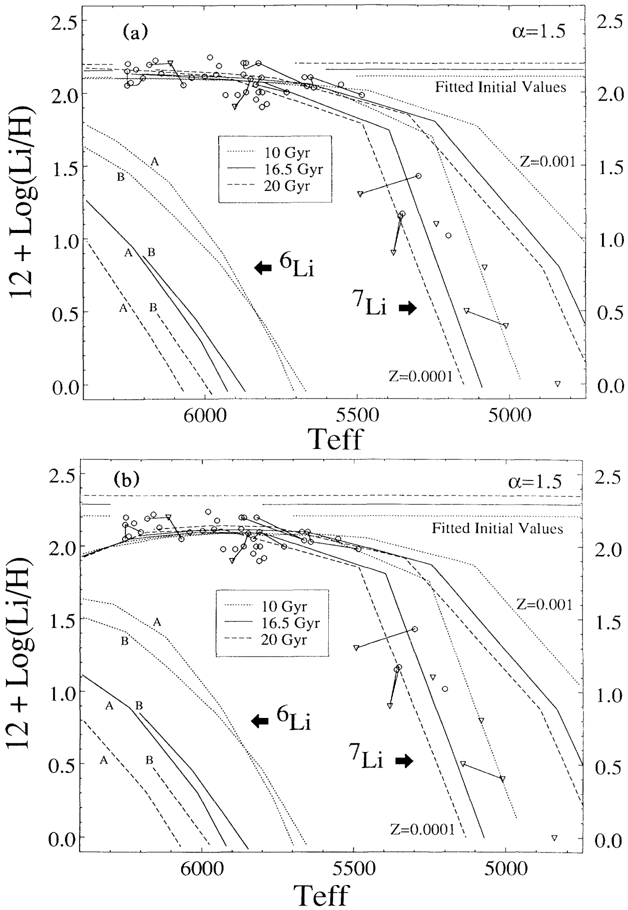

FIG. 1. (a) Li abundance by number (relative to H) vs stellar surface temperature. A pair of standard ^{7}Li isochrones with $Z=(0.0001,0.001)$ of given α is used to bracket the stars. Observations are shown by circles (detections) and triangles (upper limits). Multiple observations are connected by solid lines. The ^{6}Li isochrones assume $^6\mathrm{Li}/^7\mathrm{Li}=1$ initially. A and B refer to $Z=0.0001$ and 0.001, respectively. (b) Same as (a), but including diffusion.

described in Table I. The best fits give ages that agree well with those of the oldest globular clusters, and also with the turnoff age of the stars considered here. Post-main-sequence isochrones with the same parameters also best fit the Li abundances of the (few) evolved stars.

To estimate uncertainties in the initial Li abundance of the halo stars, we performed χ^2 tests in fitting the isochrones. Variations were constrained by assuming that (a) these stars have ages between 10 and 20 Gyr, (b) $1.1 \leq \alpha \leq 1.5$ as calibrated to the Sun and other stars, (c) the uncertainty in the Li abundance of the plateau stars is 0.1–0.2 as indicated by the observers, and (d) the cool stars have larger uncertainty, but less than 0.4 for stars in which Li has been observed (see also Ref. 6). Fits for parameters in this range yielding 95% (2σ) confidence levels or less were considered acceptable, leading to initial values of $2.17^{+0.04}_{-0.13}$ (2σ) for standard isochrones and $2.31^{+0.05}_{-0.17}$ (2σ) for isochrones that include diffusion, leading to an overall initial value of $2.24^{+0.12}_{-0.20}$ (2σ). The main theoretical uncertainty resides in the role of diffusion and rotation.[5,6] Note that the initial Li abundance of the observed halo stars broadly samples that of the protogalaxy.

Several arguments[7,8] suggest that the Li abundance remained unaltered between BBN and the formation of the halo stars. Also, the observed Li abundance stayed constant while stellar metallicity Z increased by almost 3 orders of magnitude to 10^{-3}.[9] Therefore our derived Li values are likely to reflect accurately the primordial abundance. Of those intermediate Z (therefore probably intermediate age) stars that are likely nondepleters of ^{7}Li according to stellar-evolution arguments, most have observed Li between 2.2 and 3.0. This provides strong evidence for galactic Li enrichment.[7] Cosmic rays could have produced ^{7}Li (^{6}Li, ^{9}Be, and ^{10,11}B) before the formation of halo stars; the upper limit of B in HD 140283 (Ref. 10) implies a maximum spallogenic contamination of 4% ^{7}Li and 2% ^{6}Li in the halo stars.

The level of ^{6}Li contamination in the observed abundance has not been determined. There may be[11] reasonable stellar parameters that generate combined ^{6}Li-^{7}Li isochrones that are consistent with the current halo Li observations and that contain a detectable ^{6}Li abundance. Since standard BBN predicts negligible ^{6}Li production, the discovery of a pattern of ^{6}Li in halo stars would be a signature of some nonstandard process. In Fig. 1 we also display ^{6}Li isochrones assuming ^{6}Li and ^{7}Li were produced with equal primordial abundances.[12]

(2) Alone among the light elements the predicted BBN curve of Li/H vs η has a minimum in a physically interesting range.[13] In principle, this makes it possible to set both upper and lower limits on η using just Li, removing any dependence upon uncertainties associated with the other light elements. Unfortunately, because the calculated primordial abundance of Li in standard BBN is so small (i.e., $\mathrm{Li/H} \sim 10^{-10}$), the level of Li production is more sensitive than the other light elements to uncertainties in nuclear reaction rates. Compounding this, the Li-related cross sections have traditionally been among the most poorly measured.

Several factors lead us to reconsider the uncertainties associated with Li production, and indeed all of BBN[14]: (i) The results described above indicated that a reliable estimate of the actual primordial abundance might be in hand; (ii) a new version of Wagoner's BBN code,[15] developed by Kawano,[16] extend the number of reactions considered and allowed for easy variation of fundamental input parameters; (iii) as stressed in Ref. 17, several nuclear reactions relevant to Li have been remeasured; (iv) while estimates of the effect of varying individual reactions on the final Li abundance have been made,[13,18] we consider here the effect of simultaneously incorporating all current reaction uncertainties.

TABLE I. Sample fits for isochrone pairs $Z=(0.001, 0.0001)$ of given α. Each fit is characterized by χ^2 and initial Li abundance C, using logarithmic uncertainties in Li (plateau star, cool star observation, and cool star upper limit) with the following weights: (1), (0.1,0.4,0.4); (2), (0.2,0.4,0.4); (3), (0.2,0.4,1.0). Acceptable fits are those with χ^2 in the range 29–69 for 49 degrees of freedom. S and D represent standard and diffusion isochrones, respectively.

			(1)		(2)		(3)	
	α	Age	C	χ^2	C	χ^2	C	χ^2
S	1.1	10	2.080	78	2.040	53	2.068	33
S	1.1	16	2.102	57	2.075	34	2.089	27
S	1.1	20	2.120	49	2.103	27	2.110	20
D	1.1	10	2.270	193	2.223	94	2.243	105
D	1.1	16	2.349	199	2.313	81	2.319	118
D	1.1	20	2.393	199	2.366	73	2.368	93
S	1.5	10	2.106	57	2.077	35	2.098	25
S	1.5	16	2.152	48	2.142	25	2.146	18
S	1.5	20	2.197	54	2.199	29	2.209	73
D	1.5	10	2.206	74	2.174	42	2.192	33
D	1.5	16	2.287	57	2.273	28	2.274	22
D	1.5	20	2.349	56	2.347	29	2.356	50

We examined the available data associated with six of the most important reactions related to Li production in BBN. For each of the three[19] reactions for which new data have appeared, we amalgamated all the data to estimate new rates and uncertainties (see Ref. 14 for further details). The only reaction whose mean cross section we changed from earlier quoted values used in BBN calculations is ^{3}H$(\alpha,\gamma)^7$Li. By relating this reaction to the better measured mirror reaction ^{3}He$(\alpha,\gamma)^7$Be, its energy dependence can be estimated,[20] and an astrophysical S factor extracted. The new value we determine, based on a weighted average of three different experiments,[21] is 11.2 ± 0.25 keV b.[14] The mean value is larger than quoted in Ref. 13 but smaller than that used in Ref. 17, while the 2σ value just encompasses both. The reaction ^{7}Li$(p,\alpha)^4$He has also been remeasured, yielding a smaller S factor than previously estimated.[22] We use an uncertainty here which is characteristic of the overall cross section at energies more relevant for BBN, where the data have smaller errors.[14]

The minimum in the BBN predicted Li abundance occurs because direct ^{7}Li is a decreasing function of η, while ^{7}Be (which eventually decays to ^{7}Li) is an increasing function of η. Varying each reaction can have different effects for different values of η (see Table II). Increases in those which create (destroy) Li increase (decrease) the abundance at low η, and increases in those which create (destroy) Be increase (decrease) the abundance at high η. In certain cases we increased the 1σ error to overlap the results of different experiments.[14] In addition, the neutron half-life has recently undergone revision. We use the value 10.35 ± 0.12 min.[14,23]

TABLE II. Shown are the 1σ uncertainties used in our analysis of nine BBN reactions, along with a description of the qualitative effect of increasing each reaction on the remnant Li abundance, and the range of η for which this effect is most relevant (i.e., high $\eta=10^{-9}$ and low $\eta=10^{-10}$).

Reaction	1σ uncertainty (%)	Effect of increase on Li
$p(n,\gamma)d$	10	Decrease at low η; increase at high η
$d(p,\gamma)^3$He	16	Increase at high η
$d(d,n)^3$He	10	Increase at high η
$d(d,p)t$	10	Increase at low η
^{3}He$(\alpha,\gamma)^7$Be	6	Increase at high η
$t(d,n)^4$He	10	Decrease at low η
$t(\alpha,\gamma)^7$Li	17.5	Increase at low η
^{7}Be$(n,p)^7$Li	20	Decrease at high η
^{7}Li$(p,\alpha)^4$He	8	Decrease at low η

To incorporate these results into new Li estimates, we revised the BBN code[16] for a Monte Carlo analysis. Each of the parameters in the BBN calculation was randomly varied with a Gaussian weight with width given by the uncertainties listed in Table II. We made 2000 runs at each of 20 values of η. We bracketed a range where 66% of the Li abundances fell to define 1σ limits; with poorer statistics ($\pm5\%$) we defined 2σ limits within which 95% of the results fell. These results are shown in Fig. 2, which also shows the limits on the Li abundance from our halo star analysis.

Even if Li astration were relevant for the halo stars, any astration would be more efficient for D. Hence, *assuming no D enrichment after BBN,* an upper limit on Li/D using $\mathrm{Li}_{\mathrm{pre\,halo}}(\mathrm{max})$ and $\mathrm{D/H}_{\mathrm{pre\,solar}} > 10^{-5}$ (Ref. 13) should give an upper limit on the primordial Li/D ratio.[13] The BBN prediction for this ratio, with uncertainties, is shown in Fig. 3, along with the upper limit.

(3) From Fig. 2, the allowed range of η is $(1.2\text{–}6.4)\times10^{-10}$ at the 2σ level. The limit we derive on η translates into a bound $0.0044 < \Omega_b h^2 < 0.025$, using the relation $\Omega_b = 3.53\times10^{-3}h^{-2}(T_0/2.7\ \mathrm{K})^3(\eta/10^{-10})$.[13] Here the Hubble constant is given as $100h$ km sec^{-1}Mpc^{-1}, and T_0 is the temperature of the microwave background today, measured, assuming no distortion, to be $T_0 = 2.770\pm0.012$ K.[24] Even for $h=\frac{1}{2}$, this is marginally consistent with either no baryonic dark matter, or all the dark matter in galactic halos being baryonic. The lower bound could be increased using arguments about the primordial abundance of D+^{3}He. The Li/D analysis (Fig. 3) gives a larger upper bound: $\eta < 8\times10^{-10}$, $\Omega_b h^2 < 0.03$. If future dynamical measurements can establish that $\Omega_b > 0.15$, then nonbaryonic dark matter will be required for consistency with the standard BBN model. Given a possible high-frequency microwave excess, the actual microwave temperature may be as low as 2.6 K.[25] In this case, the above limits would be reduced by at least 15%. (Note also that the

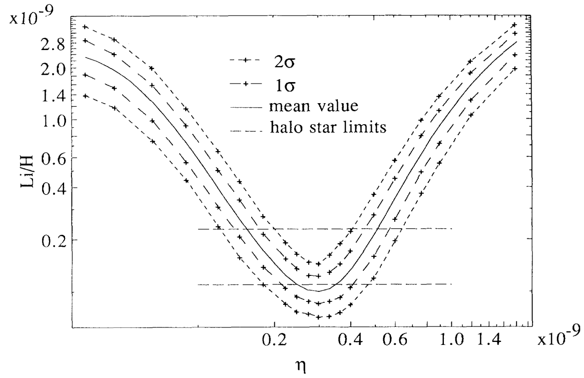

FIG. 2. Predicted primordial abundance of ^{7}Li/H, showing mean value, and 1σ and 2σ upper and lower limits. Also shown are 2σ limits on primordial abundance as inferred from halo star analysis.

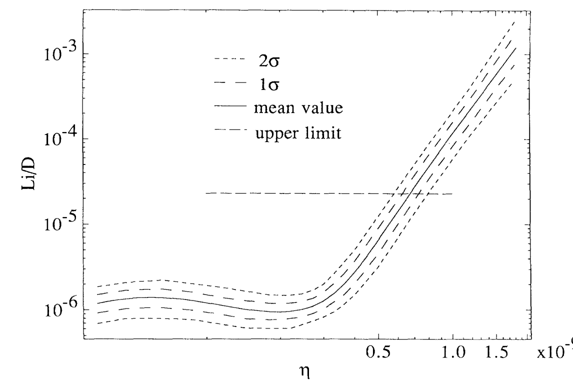

FIG. 3. Predicted primordial abundance of ^{7}Li/D, showing mean value, and 1σ and 2σ upper and lower limits. Also shown is an upper limit on this ratio using $D/H_{\rm pre\,solar} > 10^{-5}$ (Ref. 13) and $Li_{\rm pre\,halo}$(max) derived here.

lower bound on η from Li alone allows at least five neutrino species to be consistent with a primordial He abundance less than 25%.)

It is encouraging that the stellar evolution analysis yields a primordial abundance in such good agreement with the BBN predictions. Nevertheless, if some nonstandard BBN scenario occurred, and if it produced $^6\text{Li}/^7\text{Li} \gtrsim 1$, it can be probed through observations at the hot end of the Spite plateau (see Fig. 1).

Our analysis underscores the importance of both refining experimental input into BBN calculations, and of improving observations and theory of halo stars. If the uncertainties in both areas can be reduced, Li could provide an even tighter bound on the baryon density today, resolving the question of the need for nonbaryonic dark matter in galactic halos.

Much of this research was done while L.M.K. and P.R. were at the Institute of Theoretical Physics (ITP) in Santa Barbara. We acknowledge their support. We thank G. Da Costa, D. Duncan, L. Hobbs, L. Kawano, P. Parker, D. Schramm, and M. Turner for helpful conversations and suggestions. This research was supported in part by grants from the DOE, NASA, and the NSF.

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