THE ASTROPHYSICAL JOURNAL, 370:L89–L93, 1991 April 1

LITHIUM IN THE MOST EXTREME HALO STARS; TRENDS WITH METALLICITY

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Received 1990 October 9; accepted 1991 January 4

ABSTRACT

We have constructed a grid of extremely metal-poor stellar evolutionary tracks ($Z = 10^{-5}$) to compare the predicted lithium abundance depletion to observations of the lithium abundance in correspondingly metal-poor stars ([Fe/H] = −3.3), and, combined with an earlier work (Deliyannis, Demarque, & Kawaler) to investigate trends of lithium isochrones with metal abundance. Lithium abundances in the most extreme halo stars hint at the possibility of a small downward slope toward lower $T_{\rm eff}$ in the flat Li-$T_{\rm eff}$ relation (the Spite lithium plateau) observed in slightly less extreme stars; the models also predict this. In the cool star region of the Li-$T_{\rm eff}$ plane, higher metallicity lithium isochrones are cooler at fixed lithium abundance, consistent with the observations. Current data thus agree well with the lithium trends from standard models, but more observations are required for a thorough testing. We also discuss a reversal in trends for higher metallicity, which results (at a given $T_{\rm eff}$) in the existence of a maximum lithium abundance for some intermediate metallicity. Comments are made on the effects of diffusion and rotation.

Subject headings: stars: abundances — stars: evolution — stars: interiors — stars: low-mass — stars: Population II — stars: weak-line

1. INTRODUCTION

Lithium is uniquely important in big bang cosmology because, contrary to other elements synthesized during big bang nucleosynthesis (BBN), knowledge of its primordial abundance can (in the standard model of BBN) by itself delimit both a lower and an upper limit on the baryon-to-photon ratio, and hence the baryon density in the universe (Ω_b; e.g., Yang et al. 1984; Deliyannis et al. 1989a; Krauss & Romanelli 1990). There is also the possibility that of the primordial light element abundances, knowledge of $[\rm Li]_{prim}$ might be the most accessible (see Deliyannis, Pinsonneault, & Demarque 1991 for more details; see footnote 2 for notation)[2]. Much progress was made toward obtaining an estimate of $[\rm Li]_{prim}$ by the discovery of lithium in the atmospheres of old halo stars (Spite & Spite 1982). The lithium abundances of chemically and kinematically extreme halo dwarfs ("group A" stars as defined by Deliyannis, Demarque, & Kawaler 1990, hereafter DDK) exhibit the striking properties of a uniform plateau for stars ranging over 800 K in $T_{\rm eff}$ and over a factor of 25 in metallicity, and progressively smaller abundance for cooler dwarfs. These properties were repeatedly confirmed in subsequent studies (see Fig. 1 for a list). Less extreme stars exhibit a dispersion about the Li plateau which may be due to variable local Galactic Li enrichment and/or more complex stellar Li depletion processes applying to more metal-rich stars.

More recent studies have explored the ^{7}Li (hereafter simply "Li") abundance in stars with an even smaller content of heavy elements ([Fe/H] < −2.7. DDK reserved analysis of these stars for the present study on metallicity trends and thus did not include them in their group A sample; for clarity, we shall refer to these as "new" group A stars). Because such stars are likely to have been even less contaminated by non–big bang sources of lithium, their initial abundance would be an even better reflection of the primordial lithium abundance (see also § 6.2 in Deliyannis 1990). To date three such stars have been observed (Spite et al. 1987; Rebolo, Beckman, & Molaro 1987; and Hobbs & Pilachowski 1988), and while they generally fall on the same Spite plateau of lithium abundances as do the group A stars, they also hint at some rather interesting subtle differences. Unfortunately, stars of such extreme metal deficiency are rare relative to the other group A stars; thus, on average, they are also fainter.

The purpose of this *Letter* is to discuss the properties of these stars in the context of standard lithium isochrones of sufficiently low metallicity ($Z = 10^{-5}$, which corresponds to [Fe/H] = −3.3 in our models) that we have constructed for this purpose. These isochrones are basically an extension of the work of DDK for $Z = 10^{-3}$ and $Z = 10^{-4}$, and they have been calculated with the same standard assumptions and physical input. We find that lithium isochrones in the metallicity range $Z = 10^{-5}$ to $Z = 10^{-3}$ predict observable trends in the lithium abundance that could provide a test of the theory of lithium depletion during stellar evolution. Specific observational tests are proposed. Predictions about the behavior of intermediate metallicity stars ($10^{-3} \le Z \le 2 \times 10^{-2}$) are also proposed to test and constrain the theory.

2. THE OBSERVATIONS

The lithium observations of the three new group A stars are summarized in Table 1. The spectral lines are weaker in these stars; in fact, the lithium line is the only discernible feature in the spectra of Spite et al. (1987) and Rebolo et al. (1987). The metallicity, $T_{\rm eff}$, and lithium abundances are somewhat more uncertain than those listed for the other group A stars in Table 5 of DDK. Note also that at 5600 K, G238-30 provides a valuable observation in a region of the plateau that is sparsely populated, and where the isochrones of DDK depart from being flat. A plot of the new group A stars against the other

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[2] Abundances are given by number relative to hydrogen on a logarithmic scale where hydrogen is 12 and are represented by notation "[X]"; i.e., $[X] \equiv 12 + \log (N_X/N_H)$. We also employ the usual notation for relating abundances to solar values: $[X/H] = \log (X/H)_* - \log (X/H)_\odot$.

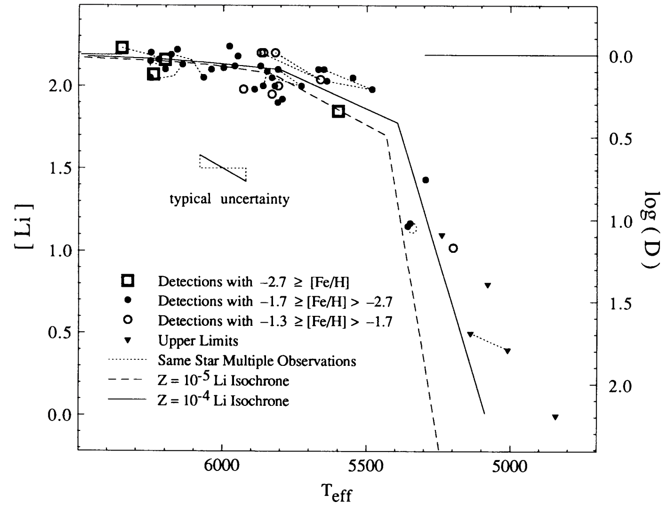

FIG. 1.—The new group A dwarfs (*square symbols*) compared with the other group A dwarfs. The two stars G64-12 and BD 3°740 fall right on top of the plateau near the hot edge. G238-30, located near the sparsely populated cool edge of the plateau, appears to have a lithium abundance that is lower than any other plateau star. The group A data are compiled in Table 5 of DDK and are from Spite & Spite (1982); Spite, Maillard, & Spite (1984); Spite & Spite (1986); Boesgaard (1985); Hobbs & Duncan (1987); Rebolo, Molaro, & Beckman (1988). See Table 1 for the new group A star data. Note that a typical relative uncertainty of up to ± 100 K in $T_{\rm eff}$ results in an uncertainty of up to ± 0.07 dex in the determination of [Li].

For comparison with theory, also shown are two 16.5 Gyr isochrones (with $\alpha = 1.5$): $Z = 10^{-5}$ for the new group A stars and $Z = 10^{-4}$ for the other group A stars. A weighted least-squares fit for the latter yields an initial abundance of 2.17; the $Z = 10^{-5}$ isochrone is assigned the same initial value. Note that the low lithium abundance of G238-30 near the cool edge of the plateau is consistent with the downward sloping of the isochrones in that region and the fact that the $Z = 10^{-5}$ isochrone lies below the $Z = 10^{-4}$ isochrone there.

group A stars (Fig. 1) shows the following:

1. *G238−30 has a lithium abundance that appears to be lower than any other plateau star.*

2. G64−12, *one of the hottest plateau stars*, has a lithium abundance at the level of or slightly higher than the plateau (depending on the $T_{\rm eff}$ adopted), and BD 3°740 falls on the plateau.

3. Inclusion of these two stars in the group A sample hints that the "plateau" might have a small but nonzero slope. (The possibility of a slope was also noted by Rebolo et al. 1987 and Rebolo, Molaro, & Beckman 1988).

3. THEORY AND COMPARISON WITH OBSERVATION

We follow the same procedure outlined in DDK in constructing the new $Z = 10^{-5}$ isochrones. For each of $Z = 10^{-3}$ and $Z = 10^{-4}$, DDK found that progressively lower masses destroy progressively more lithium. For a more detailed description of the theory, see DDK.

3.1. *The* $Z = 10^{-5}$ *Lithium Isochrones*

Where does a $Z = 10^{-5}$ lithium isochrone fall relative to a $Z = 10^{-4}$ isochrone? Two factors determine the relative location of the isochrones: the relative amount of lithium burning at each mass, and the relative $T_{\rm eff}$ of each mass. For all relevant masses, the $Z = 10^{-5}$ models burn more lithium than do the $Z = 10^{-4}$ models. This is reflected by the slightly higher T_b and ρ_b attained by each $Z = 10^{-5}$ mass (Fig. 2; differences between $Z = 10^{-4}$ and $Z = 10^{-3}$ model pairs of the same mass are more striking). Furthermore, the effective temperature of a $Z = 10^{-5}$ model is higher than that of the $Z = 10^{-4}$ model of equal mass. Therefore, a $Z = 10^{-5}$ lithium isochrone simply lies below (and/or to the left of) the corresponding $Z = 10^{-4}$ isochrone in all relevant portions of the [Li]-$T_{\rm eff}$ plane.

Figure 1 shows all Group A dwarfs together with a $Z = 10^{-4}$ and a $Z = 10^{-5}$ 16.5 Gyr isochrone. The $Z = 10^{-4}$ isochrone (which represents a midrange metallicity) has been fitted to the Li detections using a weighted least-squares fit, assuming uncertainties as given by the observers of (0.1, 0.2) for (plateau star, cool star) and those listed in Table 1 for the new group A stars (see Appendix A, § III(*a*) of DDK for a more detailed discussion of the uncertainties). This yields an initial abundance of 2.17, a reduced χ^2 of 1.03, and a probability $P(\chi^2/\nu)$ of 0.45 of obtaining a higher χ^2. The last two numbers are very close to what one expects ($\chi^2 = 1$ and $P[\chi^2/\nu] = 0.5$) from an ideal fitting function. It is worth emphasizing that, if the uncertainties are represented accurately, then the $Z = 10^{-4}$ lithium isochrone is very close to being a best possible fitting function. Figure 1 shows that it reproduces in detail the morphology of the observations, from the depletion in the cool stars to the possible slope in the "plateau," all the way to the hot edge of the plateau. Such good fitting from standard models constrains models that include more complex physics but which have poorer-fitting lithium isochrones.

The $Z = 10^{-5}$ isochrone has been assigned the same initial value; there is then good agreement between theory and observation. In particular, G238-30 is located near the right edge of the plateau (at 5600 K) and slightly below it; indeed, this is

TABLE 1

OBSERVED PROPERTIES OF NEW GROUP A STARS

Star	[Fe/H]	Reference	$T_{\rm eff}$	Reference	[Li]	σ[a]	Reference
G64-12	−3.5	CP	∼6200	SSPC, C	2.16	0.18	SSPC
			6350	RBM, CP	2.23	0.2	RBM
			6400–6435[b]	CP2			
G238-30	−3.0	C	5600	C	1.85	0.1	SSPC
BD 3°740[c]	−2.9	HP	6240	HP	2.07	0.19	HP

[a] Inferred or quoted uncertainty.

[b] This range has not been plotted in Fig. 1. For G64-12, Rebolo et al. 1987 find $\Delta T_{\rm eff} = 100$ K implies Δ[Li] = 0.07 dex; thus, for this range in $T_{\rm eff}$, we expect [Li] ∼ 2.28.

[c] Although DDK have already used BD 3°740 as a group A star on account of the data of Rebolo et al. 1988, the detailed analysis of HP suggest that it may be as metal-poor as indicated here. We thus consider this possibility by including it here with the other two new group A stars, and we use here the data of HP on this star.

REFERENCES.—CP, CP2, Carney & Peterson 1981a, b; SSPC, Spite et al. 1987; RBM, Rebolo et al. 1987; C, Carney, quoted in SSPC; HP, Hobbs & Pilachowski 1988.

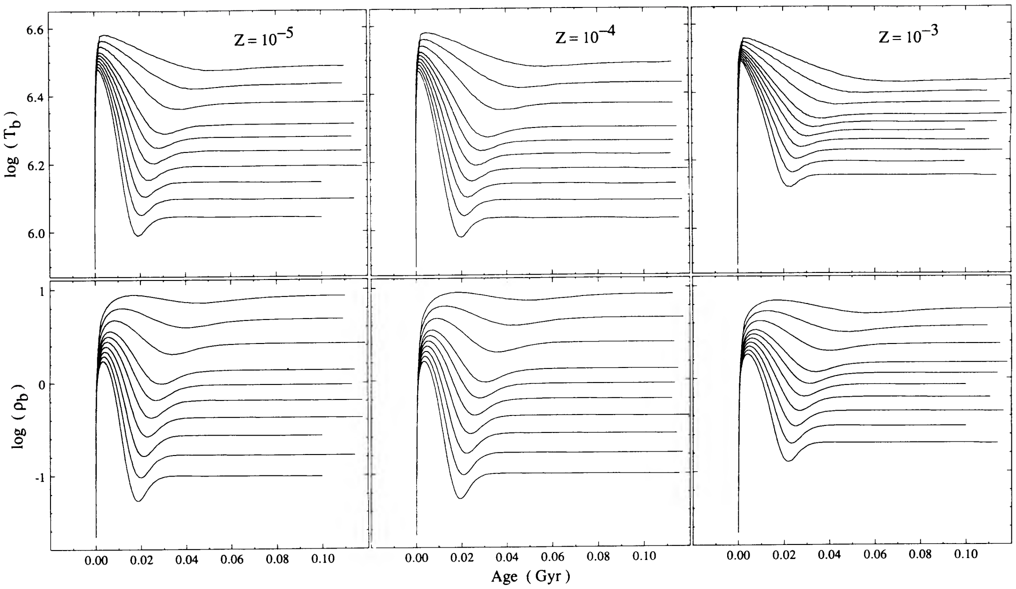

FIG. 2.—Evolution of the T_b (in K) and ρ_b (in g cm^{-3}) curves during the pre–main sequence. The masses are (*top to bottom*) 0.50, 0.55, 0.60, 0.65, 0.675, 0.70, 0.725, 0.75, 0.775, and 0.80 $M_\odot$. Note that, fot a given value of α, each $Z = 10^{-5}$ curve (both T_b and ρ_b) is just slightly higher than the $Z = 10^{-4}$ curve of corresponding mass. However, when comparing $Z = 10^{-4}$ to $Z = 10^{-3}$, there exists a transition mass above which the $Z = 10^{-4}$ curves are higher and below which the $Z = 10^{-3}$ are higher. These trends are reflected in the amount of lithium burning experienced by each track, where tracks with higher T_b and ρ_b experience more burning.

where both isochrones begin to slope downward. Furthermore, its location slightly below the plateau at that temperature is consistent with the $Z = 10^{-5}$ isochrone being below the $Z = 10^{-4}$ isochrone there. The other two stars are in excellent agreement with the isochrones at the hot edge of the plateau.

For a given mass, the turnoff age is nearly identical for $10^{-5} \leq Z \leq 10^{-3}$, but the radius is smaller for smaller Z. Thus, for a given mass and age, at the hot edge of the Spite plateau, a $Z = 10^{-5}$ model is about 50 K hotter than a $Z = 10^{-4}$ model, which is about 200 K hotter than a $Z = 10^{-3}$ model. The observations are consistent with such a trend (Fig. 1). Therefore, the most metal-poor stars define the morphology of the hot side of the Spite plateau. This is particularly important in constraining models that include microscopic diffusion, which currently generate Li isochrones with an excessive amount of curvature (see discussion in Deliyannis & Demarque 1991a), and in constraining any associated reduction in globular cluster age estimates.

3.2. *Trends with Metallicity for Cool Stars*

For sufficiently small masses ($\lesssim 0.60\ M_\odot$), the same trend that holds between the $Z = 10^{-5}$ and $Z = 10^{-4}$ isochrones also holds between the $Z = 10^{-4}$ and $Z = 10^{-3}$ isochrones. Thus, for $T_{\rm eff}$ lower than the cool edge of the Li plateau, the $Z = 10^{-4}$ isochrone is located below the $Z = 10^{-3}$ isochrone (Fig. 3). As the models evolve from 10 to 20 Gyr, the three isochrones maintain their order, and the distance between them remains approximately fixed (Fig. 3).

Therefore, a larger sample of cool star detections would serve to test the theory. The qualitative agreement between this predicted pattern and the observations is already encouraging. For example, in Fig. 1 the only cool star of sufficiently high metallicity to correspond to the $Z = 10^{-3}$ isochrone (*open circle*) is located to the right of the $Z = 10^4$ cool star detections (*solid circles*).

However, a more thorough test of the theory requires a sample that is sufficiently large so that intrinsic patterns can be clearly separated from complicating factors and noise. One such possible complication is that for cool stars, [Li] is more difficult to determine reliably than for plateau stars. Another complication is that possible differences in age from star to star might blur some of the predicted Z-dependence (e.g. superpose the 10 and 20 Gyr isochrones of Fig. 3). Nevertheless, a large sample might allow average trends at each metallicity to be discerned. A uniform-aged sample would alleviate the second complication; unfortunately, stars in such a sample (globular cluster) are much too faint for current technology. However, many cool field halo stars are being discovered in

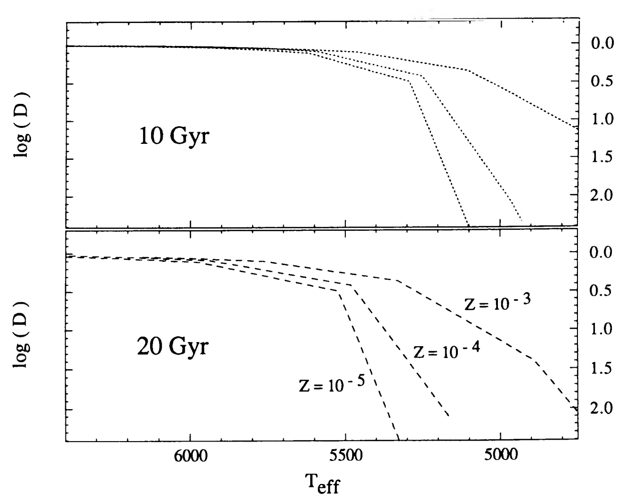

FIG. 3.—A comparison of standard ^{7}Li destruction isochrones of different metallicity at ages 10 and 20 Gyr. The separation between pairs of isochrones stays roughly constant in time; this provides an observational test for the theory.

new surveys (e.g., Beers, Preston, & Schectman 1985; Carney et al. 1990; Ryan 1989; Schuster & Nissen 1989). Although observing Li in most of these stars would be difficult (e.g., see SS86 for the capabilities of CFHT in this regard), these surveys do provide some appropriate cool stars for which Li detections can probably be obtained. Furthermore, existing upper limits in group A cool stars can perhaps be improved upon.

It is conceivable that a sufficiently large sample of cool star detections might also reveal departures from the standard stellar evolutionary scenario. For example, internal stellar rotation might be important. It has been shown (§ 9 in Deliyannis 1990; Pinsonneault, Deliyannis, & Demarque 1991a) that low surface rotation velocities at turnoff can be reconciled with high surface velocities on the horizontal branch only if halo dwarfs develop a sharp differential rotation that allows them to retain a sufficiently large reservoir of internal angular momentum. The rotational models do so naturally, although the effect is not large enough to affect the ages of globular clusters (Deliyannis, Demarque, & Pinsonneault 1989b). However, these models also result in rotationally induced mixing that could produce significantly depleted Li isochrones; these isochrones fit the data acceptably (§ 9 in Deliyannis 1990; Pinsonneault, Deliyannis, & Demarque 1991b). The implications for cosmology are important: while a low primordial abundance as derived from standard stellar models strongly supports the standard model of BBN, a high abundance as derived from rotational stellar models would suggest that there is an inconsistency in standard BBN (Deliyannis et al. 1991). For the cool stars, a test of rotation is provided by the separation between pairs of isochrones of different Z, which is similar to the standard case, but is slightly blurred because of the dependence of the Li depletion on the distribution in initial stellar angular momenta (J_0). If such blurring is observed and can be separated from other possible causes of blurring, it might at least in part support the rotational scenario. For a large sample of plateau stars, the Li dependence on J_0 manifests itself as a dispersion (of up to a factor of about 2) in the lithium abundances. The new surveys can provide such a large sample; however, if some dispersion is discovered, it might be difficult to discern whether it is due to rotation or to other causes, such as variable local Galactic Li enrichment (e.g., § 7 in Deliyannis 1990).

The ordering of the isochrones of different metallicity in the cool star region is predicted by several stellar evolutionary scenarios: standard, diffusive, and rotational. What if future observations no longer support such ordering? Because the ordering becomes reversed at higher metallicity (§ 3.3), this may be an indication that the metallicity scale of halo stars is underestimated. Indeed, suggestions have been made (e.g., Bikmaev, Bobritskij, & Sakhibullin 1990) that this may be so on the basis of non–LTE atmosphere analyses. If this were true, age estimates for the globular clusters might be reduced. Thus, Li observations in cool halo dwarfs might provide an important test of the metallicity scale for metal-poor stars.

3.3. *The Reversal of Metallicity Trends at Higher Metallicities*

The predicted pattern for cool star models (of higher Li abundance for higher Z at fixed $T_{\rm eff}$ for $T_{\rm eff} < 5500$ K) *does not hold* at high metallicities: solar metallicity models are more depleted.[3]

Therefore, for $5500 \geq T_{\rm eff} \geq 4500$ K (*the lowest* $T_{\rm eff}$ *considered in our models*), *at a given* $T_{\rm eff}$, *main-sequence age, and* α, [Li] *is a nonlinear function of* Z. *In particular, there exists a* Z_m *in the range* $0.001 < Z_m < 0.02$ *at which the lithium abundance is a maximum.* Searching observationally for such a pattern would both test and constrain the theory.

Nonlinearities are also found beyond the ranges indicated above, and Z_m is a function of $T_{\rm eff}$: for $T_{\rm eff} > 5500$ K, a reversal in the metallicity trend is evident even in low-metallicity models. The phenomenology can be understood in terms of the two factors mentioned above: the relative amount of lithium burning of each mass in a pair of isochrones of different metallicity (which is a nonlinear function of mass; for example, compare in Fig. 2 the T_b and ρ_b curves for $Z = 10^{-4}$ vs. $Z = 10^{-3}$), and the relative $T_{\rm eff}$ of each mass. A more complete discussion of the nonlinear interaction of these two factors is given in Deliyannis and Demarque (1991b) in the context of a discussion on depletion of the isotope ^{6}Li in halo dwarfs, where it plays a critical role. However, because differences in a pair of ^{7}Li isochrones are minute on an absolute scale in the plateau region, these complexities have no significant observable consequences for ^{7}Li.

4. SUMMARY

We have proposed several observational tests for the theory of lithium depletion as a function of metallicity (from standard stellar models as well as more complex ones). The lithium abundances in very extreme halo dwarf models fall on the Spite plateau; observations in the most metal poor stars will better define the morphology of the hot edge of the plateau. Toward cooler $T_{\rm eff}$, as a function of $T_{\rm eff}$, depletion relative to the plateau is more severe for lower metallicity halo models. Below 5500 K, a reversal occurs at higher metallicity so that at a given $T_{\rm eff}$, there exists a Z_m in the range $0.001 < Z_m < 0.02$ at which the lithium abundance is a maximum; the value is model-dependent, so the theory can be tested and constrained by new observations. These tests are urgently needed for guiding the further refinement of stellar evolution theory and for defining more precisely the implications for big bang cosmology.

This research has been supported by NASA grants NAGW-777 and NAGW-778.

[3] Furthermore, the Population I stars themselves are even more depleted than the models, as it is generally agreed upon that standard Population I models underestimate the Li depletion observed in Population I stars. A similar relative behavior of isochrones with different metallicity is also found when considering internal stellar rotation (see § 9 in Deliyannis 1990).

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