THE ASTROPHYSICAL JOURNAL, 452:L13–L16, 1995 October 10

EVIDENCE OF HIGHER PRIMORDIAL LITHIUM FROM KECK OBSERVATIONS OF M92

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Received 1995 May 17; accepted 1995 June 27

ABSTRACT

Knowledge of the primordial lithium abundance (Li$_p$) tests and constrains models of big bang nucleosynthesis and may have implications for dark matter and the laws of physics. An apparent small dispersion in the Li abundances of field halo dwarfs had been predicted to result from differences in the Li depletion of models with rotationally induced mixing, and would imply a higher Li$_p$ than is observed today in these stars. However, this dispersion could also be explained by differential Galactic Li enrichment (from lower Li$_p$) coupled with a halo age spread and/or incomplete mixing. To differentiate between these possibilities, we have obtained Keck/HIRES observations at $R = 45{,}000$ in one of the oldest and most metal-poor globular clusters, M92, where differential Li enrichment within the cluster is unlikely. We find some evidence for differences in the Li abundances of three otherwise apparently identical M92 subgiants in the Spite Li plateau. We provide evidence against cosmic-ray, supernova, and asymptotic giant branch star Li production as causing these Li differences, and suggest that different stellar surface Li depletion histories in these stars from a higher initial abundance is a more likely explanation (as is also the case for open clusters). This higher initial abundance may have been the Li$_p$, or a combination of Li$_p$ plus significant pre-M92 Galactic Li. Implications are discussed.

Subject headings: early universe — globular clusters: individual (M92) — stars: abundances — stars: evolution — stars: Population II — subdwarfs

1. INTRODUCTION

The value of the primordial Li abundance is still a subject of some controversy. In this Letter we present observations of Li in stars near the turnoff of the globular cluster M92, a sample of old stars of uniform age. This cluster is one of the oldest, most metal-poor, and nearest globulars, with near-zero reddening. The surfaces of unevolved stars in this cluster are expected to contain the primordial Li (plus possibly some precluster Galactic Li), unless this has been altered by stellar processing. Stellar depletion might be expected due to rotationally induced mixing, which (1) could deplete the observed Li plateau in halo field stars by an order of magnitude ("Yale models," Deliyannis 1990; Pinsonneault, Deliyannis, & Demarque 1992; Chaboyer & Demarque 1994) and (2) could act differently in different stars depending on (e.g.) the initial angular momentum of each star. The latter effect would cause a small dispersion in the Li abundances for stars at a given temperature. In fact, such dispersions are clearly observed in the Hyades (Thorburn et al. 1993) and other open clusters (Soderblom et al. 1993a, b, c). Deliyannis, Pinsonneault, & Duncan (1993) and Thorburn (1994) have provided evidence that such a dispersion also exists in the field halo dwarfs, but there it could be due to differential Galactic enrichment plus incomplete mixing and/or a significant age range in the halo. In M92 any real dispersion would more likely be due to stellar depletion from a higher initial abundance.

2. OBSERVATIONS, REDUCTION, AND ANALYSIS

We have chosen three subgiant stars near the turnoff (Fig. 1), since they are brighter than stars right at the turnoff and have a stronger Li line. We have stayed away from the onset of Li dilution (near $B - V \sim 0.57$) as defined by more evolved field halo stars, which reflects the deepening of the convection zone (Deliyannis, Demarque, & Kawaler 1990; Ryan & Deliyannis 1995). Our three stars are photometrically identical and are expected to have nearly identical masses. We also observed a star right at the turnoff, which would also have that same mass.

Observations of the M92 and some halo field stars were obtained on 1994 July 29 using the W. M. Keck telescope with the efficient HIRES echelle spectrograph and a Tektronix 2048^2 CCD. HIRES is described by Vogt et al. (1994). Two instrumental configurations were used: a "red" one covering the range 5695–7960 Å and a "blue" one covering 4480–6770 Å, with gaps between the orders in both cases. Table 1 lists the stars observed, the setup, total exposure time (typically two exposures for M92 stars), empirically determined S/N pixel^{-1} near Li and near Fe lines measured from the final spectra, photometry (from Stetson & Harris 1988 for M92, with 1 σ errors), and [Fe/H] (from Sneden et al. 1991 for M92 and from Deliyannis et al. 1995 for the other stars, based on each of two $T_{\rm eff}$ scales, a "high" one of King 1993 [hereafter K93] and a "low" one of Carney 1983 [hereafter C83]). Exposures of a Th-Ar lamp and ~15 quartz flat-field frames were taken for each setup. Preliminary reductions (overscan removal, trimming, bias subtraction, etc.) were carried out with standard IRAF routines. The flat-field normalization, order tracing, and extraction were performed using the specialized suite of FIGARO echelle reduction routines imported into the IRAF environment at the University of Texas. The positions of several hundred Th-Ar lines were fitted using fourth-order Chebyshev polynomials in both the x and y-directions, with rms residuals ~0.0016 Å. The linearized dispersion at Li I 6708

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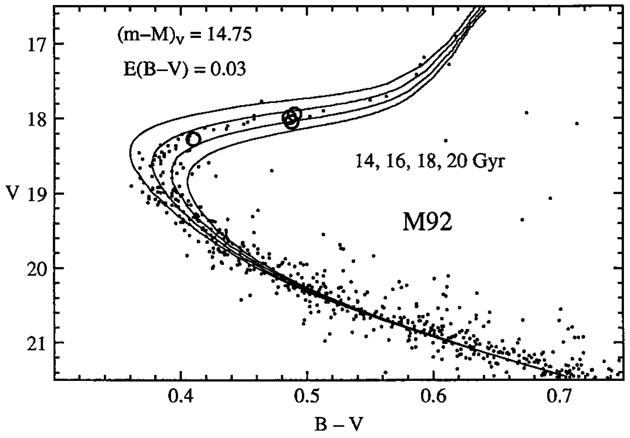

FIG. 1.—Color-magnitude diagram of M92 showing photometry from Stetson & Harris (1988), isochrones from Demarque, Deliyannis, & Sarajedini (1991), and the four program stars (*open circles*).

Å is 0.047 Å pixel^{-1}. The measured FWHM of Th-Ar lines near Li was 3.1–3.2 pixels, corresponding to $R \sim 45,000$. Scattered light removal was carried out using the IRAF package APSCATTER. The large order separation (~100 pixels) compared with the order FWHM (~5 pixels < 1″) implies that scattered light due to order blending is negligible. Global scattered light was negligible (only ~10 DN pixel^{-1}) for HD 140283 and BD +23°3912, and (though unmeasurable) assumed negligible in M92, which might conservatively lead to systematic errors of up to 0.4%. Various internal reflections in HIRES with complex structure and small spatial structure (which were not removed) do not affect the Li region.

Figure 2 shows spectra of the Li region in our four M92 stars, smoothed by a boxcar function of 3 or 5, and Figure 3 shows the four field stars. The spectra have not been corrected to rest wavelength, in order to show (particularly for M92:18 and M92:21) that the apparent features marked correspond to Li 6707.8 Å given the known radial velocity of M92. Other indicators that these stars are true members are (1) their location on the M92 fiducial sequence, (2) their identical Fe I line strengths (see below), and (3) the identical $(V-I)$ colors for Nos. 18 and 21 (0.640 ± 0.006 and 0.636 ± 0.011 [Davis 1995]; Davis's $B-V$ colors of 0.488 ± 0.012 and 0.497 ± 0.003 are also in excellent agreement with those of Stetson & Harris 1988).

Equivalent widths for Li and for four Fe I lines in the range 5200–5450 Å were measured using routines in the IRAF package SPLOT and are reported in Table 2 along with 1 σ photon noise errors (computed using the Cayrel 1988 approximation, assuming a measured FWHM of 6 pixels for Li I and 4 pixels for Fe I), the dominant source of error for the M92 stars. For M92:18 and M92:21, the Li line is securely detected (at the 6.3 σ and 4.8 σ levels, respectively). The equivalent widths appear to be different, by as much as a factor of 2–3 (star 18 lies 3.5 σ above star 21; alternatively, star 21 lies 2.6 σ below star 18; a χ^2 test suggests that there is less than a 2.5% probability of obtaining the measured equivalent widths by chance with the given errors if the real equivalent widths are identical). This is surprising given the similarity of the two stars in their position on the H-R diagram, i.e., in temperature and gravity. In star 46, a Li feature is possibly detected at the 2.5 σ level; this lies 3.2 σ below star 18. (A formal 2 σ upper limit of 22 mÅ for star 46 would lie 3.8 σ below star 18, whereas 3 σ = 33 mÅ would still lie 2.6 σ below star 18.) This, too, is surprising, since this star is also at the same place on the H-R diagram. No clear Li feature is seen in the hotter star, No. 80. A possible feature of 18 mÅ may be present, but this is less than our limiting 2 σ equivalent width of 22 mÅ. The measured Fe I lines were always clearly discernible as lines; in only one case the measured line strength lies just below the 2 σ detection limit. In view of the errors, the Fe I line strengths agree remarkably well in the three M92 subgiants, and, as expected, the Fe I lines are stronger in HD 19445 and BD +23°3912 (Table 2).

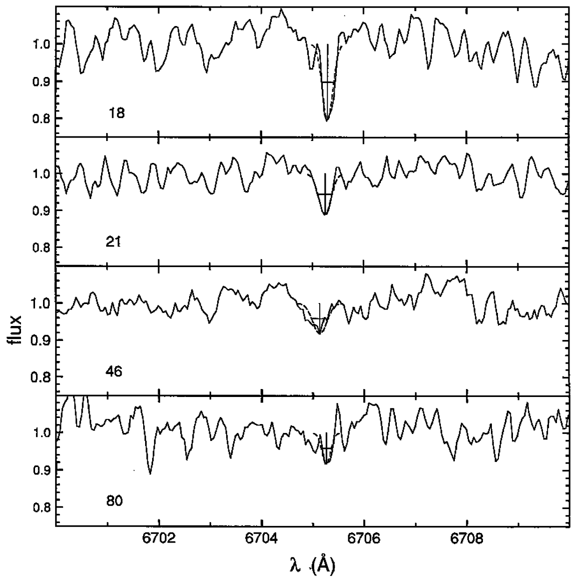

FIG. 2.—Li spectra for the four M92 stars

Figure 4 shows the Li equivalent widths for our M92 stars together with metal-poor field subgiants (in particular, prob-

TABLE 1

OBSERVATIONS AND STELLAR DATA

star (1)	setup (2)	exp (min) (3)	S/N at Li (4)	S/N at Fe (5)	V (6)	B − V (7)	[Fe/H] K93 (8)	[Fe/H] C83 (9)
M92:18......	blue	90	18	12	17.985	0.486 ± 0.016	−2.25	
M92:21......	blue	90	24	17	17.943	0.490 ± 0.006	−2.25	
M92:46......	blue	64	16	7	18.048	0.488 ± 0.025	−2.25	
M92:80......	red	94	17	—	18.278	0.410 ± 0.016	−2.25	
HD 19445...	blue	2.0	355	280	8.05	0.47	−2.01	−2.10
+23:3912....	blue	3.0	320	250	8.88	0.51	−1.41	−1.53
HD 140283.	red	0.5	280	—	7.24	0.49	−2.46	−2.56
+20:3603....	red	7.0	335	—	9.69	0.44	−2.15	−2.22

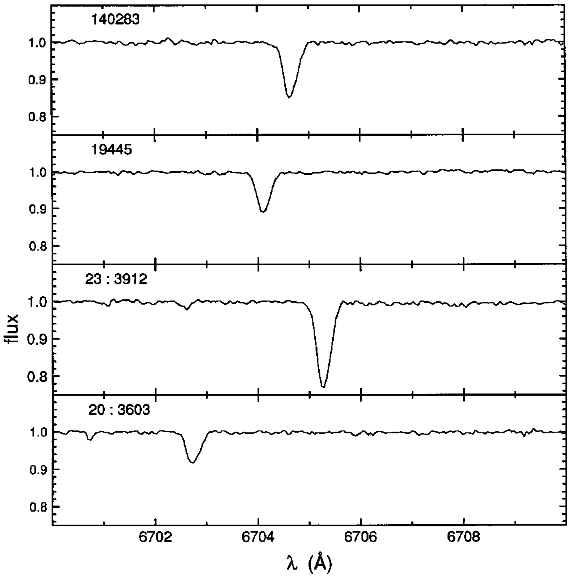

FIG. 3.—Li spectra for the four field halo stars

able subgiants HD 76932, HD 132475, HD 134169, HD 140283, HD 160617, HD 166913, HD 189558, and BD +23°3912, and possible subgiants HD 3567, HD 16031, HD 24289, HD 116064, BD +2°4651, BD +17°4708, G90-3, G18-54, for which subgiant status is suggested by the Strömgren c_0 index using Schuster & Nissen 1989) vs. $T_{\rm eff}$. $T_{\rm eff}$ values are either from Deliyannis et al. (1995; based on $b - y$, $R - I$, and $V - K$ colors, C83 scale) or are approximated similarly. $T_{\rm eff}$ values for the three M92 subgiants have been equated with that of HD 140283 on the basis of their $B - V$ colors,[5] with the small differences (and the $T_{\rm eff}$ for star 80) being based on a $B - V$ calibration to the $T_{\rm eff}$ scale of Deliyannis et al. (1995) from $B - V$ values of stars therein. Errors in $T_{\rm eff}$ shown in Figure 4 are simply the propagated 1 σ errors in $B - V$ (Table 1). Also shown in Figure 4 are field halo dwarfs from Thorburn (1994) with $T_{\rm eff}$ similar to that of the M92 subgiants.[6] Li abundances were derived based on curves of growth for the Li I 6707.8 Å doublet constructed using Kurucz (1992) atmospheres, for each of the K93 and C83 $T_{\rm eff}$ scales used in Deliyannis et al. (1995) [see Table 3 of this Letter; the errors in W(Li) and $T_{\rm eff}$ were propagated to derive $\sigma_{A({\rm Li})}$]; A(Li) is virtually insensitive to the adopted gravity and only marginally sensitive to metallicity ($\xi = 1.5$ was adopted). The differences in W(Li) of the M92 subgiants are reflected in the derived Li abundances.

TABLE 3

LITHIUM ABUNDANCES

star (1)	W(Li) (mÅ) (2)	$T_{\rm eff}$ K93 (3)	σ (4)	A(Li) (5)	σ (6)	$T_{\rm eff}$ C83 (7)	σ (8)	A(Li) (9)	σ (10)
M92:18......	57	5870	70	2.48	0.10	5710	70	2.33	0.09
M92:21......	33	5850	25	2.14	0.13	5690	25	2.00	0.12
M92:46......	28	5860	115	2.05	0.22	5700	115	1.92	0.22
M92:80......	<22	6300	70	<2.25	—	6200	70	<2.18	—
HD 19445...	35.1	5996	52	2.29	0.07	5852	40	2.18	0.06
+23:3912....	77.6	5854	40	2.64	0.06	5691	40	2.50	0.05
HD 140283.	47.5	5847	40	2.31	0.06	5692	40	2.16	0.05
+20:3603....	25.6	6234	76	2.27	0.07	6114	89	2.20	0.08

TABLE 2

MEASURED EQUIVALENT WIDTHS

star (1)	Li I 6708 (2)	σ Li (3)	Fe I 5233 (4)	Fe I 5397 (5)	Fe I 5406 (6)	Fe I 5435 (7)	σ Fe (8)
M92:18......	57	9.1	37	52	43	31	9.5
M92:21......	33	6.9	30	58	47	29	6.7
M92:46......	28	11	35	49	43	28:	16
M92:80......	<18	11	—	—	—	—	—
HD 19445...	35.1	0.48	64	73	75	61	0.41
+23:3912....	77.6	0.53	96	100	99	90	0.46
HD 140283.	47.5	0.62	—	—	—	—	—
+20:3603....	25.6	0.52	—	—	—	—	—

3. DISCUSSION

Evidence is accumulating that the halo Li plateau (Spite & Spite 1982) does not reflect the pristine $\rm Li_p$. Application of various multiple regression methods to the total current field halo *dwarf* sample suggests that (*a*) A(Li) increases slightly with [Fe/H], which could be due to Galactic Li enrichment and/or metallicity-dependent stellar Li depletion, and (*b*) A(Li) increases slightly with $T_{\rm eff}$, reaching a maximum at the turnoff (Ryan et al. 1995). While the second effect clearly illustrates stellar Li depletion at work in plateau dwarfs cooler than the turnoff (and much more severe depletion at lower $T_{\rm eff}$), standard stellar models (no rotation) can match the observations (Deliyannis et al. 1990) with little overall depletion in the plateau ("low" $\rm Li_p$). Some field halo *subgiants* (and M92:18) appear to have higher Li abundances than field halo dwarfs (Fig. 4), consistent with the expectation that subgiants preserve their turnoff abundance from the hot edge of the Li plateau until dilution begins at lower $T_{\rm eff}$ (Deliyannis et al. 1990; Ryan & Deliyannis 1995). Indeed, the A(Li) of M92:18 is marginally higher than previous values for an "average" Li plateau abundance that are often derived (misleadingly) from dwarfs and subgiants mixed together, and that ignore these trends.

Using Keck/HIRES, we have found evidence that the Li

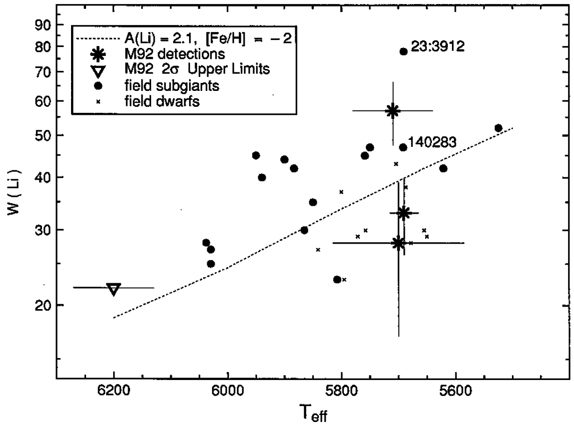

FIG. 4.—Li equivalent widths vs. $T_{\rm eff}$ for field metal-poor subgiants (*filled circles*), the four M92 stars (*asterisks or triangles*), and field metal-poor dwarfs (*small crosses*) with $T_{\rm eff}$ values similar to those of the three M92 subgiants.

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[5] Note that for both M92 and HD 140283, $E(B - V)$ up to about 0.03 is possible.

[6] The $T_{\rm eff}$ values in Thorburn (1994) agree well with those of Deliyannis et al. (1995) using the C83 scale. For nine stars in common (excepting two stars where the two studies disagree on the adopted reddening), the mean difference is −1.2 K (former minus latter).

abundances differ in three otherwise identical subgiants of the old, metal-poor globular cluster M92. Although Galactic Li enrichment might plausibly have occurred (though, we stress, strong evidence in favor of such enrichment remains elusive) as a result of Li produced by (*a*) cosmic rays interacting with the ISM via $\alpha + \alpha$ (e.g., Prantzos, Cassé, & Vangioni-Flam 1993), (*b*) Type II supernovae via the ν-process (Woosley et al. 1990), and (*c*) the ^{7}Be transport process in asymptotic giant branch (AGB) stars (Cameron & Fowler 1971), we argue against these possibilities as sources for the extra Li in M92:18. Uniform age in our three M92 stars argues against $\alpha + \alpha$, while the stars' similar Fe argue against supernova production. Some metal-poor ([Fe/H] ~ -0.5) AGB stars are known to be Li-rich [A(Li) ~ 3] in the Small Magellanic Cloud (SMC) (Smith & Lambert 1990), as is a halo CH subgiant [A(Li) ~ 2.5; Thorburn 1994]; all are very rich in *s*-process elements, with the CH subgiant having supersolar Ba ([Fe/H] $= -2.35$ but [Ba/Fe] $= +2.67$! [Thorburn 1993; McWilliam et al. 1995]). However, all three M92 subgiants seem to have normal and similar Ba II 4554 Å equivalent widths ($\sim$40 mÅ, 2–3 σ detections) lying between those of HD 140283 ($\sim$20 mÅ) and HD 19445 ($\sim$60 mÅ [Zhao & Magain 1990; Gilroy et al. 1988]), as might be expected. In any case, it is clear that M92:18 is not super–Ba-rich [compare with W(Ba) = 225 mÅ in the CH subgiant or 159 mÅ in the Sun] or even just Ba-rich. Limits for other Ba lines also support this. Although these arguments do not definitively exclude the possibility of prestellar Li variations or Li contamination in our M92 stars from the sources discussed here or from other more exotic sources, the high Li in M92:18 more likely points to the action of stellar processes that deplete the surface Li abundance to different degrees, perhaps by a significant total amount such as in the Yale rotational models ("high" Li$_p$). Study of additional elements (C, Na, Al, and others), additional stars, and higher S/N would be desirable.

In standard big bang nucleosynthesis (BBN) "low" Li$_p$ has been thought to provide a concordance of similar constraints for Ω_b as do arguments involving D, ^{3}He, and ^{4}He (Walker et al. 1991; Deliyannis 1994). The inferred Ω_b ($\sim 0.01\ h^{-2}$) is somewhat suggestive of the existence of nonbaryonic dark matter in galactic halos and on larger scales, though far from definitive. However, a wider range of Ω_b is possible. "High" Li$_p$ could allow either a "high" Ω_b or a "low" Ω_b interpretation of standard BBN. "High" Ω_b is possible if we allow for slightly larger values of ^{4}He$_p$ than are usually accepted (but are certainly possible), and relatively low values of H_0 (which would also be consistent with the estimated ages of globular clusters): with this concordance, the inferred Ω_b of 0.1–0.2 would be consistent with $\Omega_{\rm dyn}$ derived for galactic halos and larger scales, and would alleviate the need for nonbaryonic dark matter on those scales. However, assuming traditional values of ^{4}He$_p$ ($\sim$0.23), if D$_p \sim 10^{-4}$, as suggested by recent Keck observations toward a quasar (Songaila et al. 1994), and if the D + ^{3}He constraint is relaxed to lower Ω_b as suggested by mixing on the giant branch (Deliyannis 1994), then concordance is possible at "low" Ω_b ($\sim 0.004\ h^{-2}$). Assuming the validity of standard BBN, then nonbaryonic dark matter would be definitively required. Alternatively, a high Li$_p$ could perhaps be pointing to the action of inhomogeneities (e.g., Mathews et al. 1990; Jedamzik, Fuller, & Matthews, 1994) or other additional physics in BBN (Malaney & Mathews 1993), which could well have *different* implications for dark matter.

We are grateful to James Heasley for kindly providing extremely useful finding charts from his photometry prior to publication, and to Julie Thorburn for kindly communicating her results on the CH subgiant; we also thank James Heasley, Julie Thorburn, and Robert Kraft for useful discussions. Support for this work was provided by NASA through grants HF-1042.01-93A (to C. P. D.) and HF-1046.01-93A (to J. R. K.), awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS5-26555, and by NSF grant AST-9409793 awarded to A. M. B. at the University of Hawaii. We thank the Keck telescope staff, Tom Bida and Barbara Schaffer, for their expert assistance.

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