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DETECTION OF LITHIUM IN THE COOL HALO DWARFS GROOMBRIDGE 1830 AND HD 134439: IMPLICATIONS FOR INTERNAL STELLAR MIXING AND COSMOLOGY

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ABSTRACT

Lithium abundances in halo stars, when interpreted correctly, hold the key to uncovering the primordial Li abundance Li_p. However, whereas standard stellar evolutionary models imply consistency in standard big bang nucleosynthesis (BBN), models with rotationally induced mixing imply a higher Li_p, possibly implying an inconsistency in standard BBN. We report here Li detections in two cool halo dwarfs, Gmb 1830 and HD 134439. These are the coolest and lowest Li detections in halo dwarfs to date, and are consistent with the metallicity dependence of Li depletion in published models. If the recent report of a beryllium deficiency in Gmb 1830 represents a real Be *depletion*, then the rotational models would be favored. We propose tests to reduce critical uncertainties.

Subject headings: early universe — stars: abundances — stars: evolution — stars: interiors — stars: Population II — stars: rotation

1. INTRODUCTION

Lithium is of great importance in the study of stellar interiors and stellar evolution, Galactic chemical evolution, and cosmology. Knowledge of Li_p, the primordial Li abundance, can test models of big bang nucleosynthesis (BBN) and thereby constrains cosmological parameters such as the baryonic density, Ω_b. The key to determining Li_p lies in understanding what processes have modified the Li abundances observed in extreme halo stars. Spite & Spite (1982) and many subsequent studies have shown that halo dwarfs and subgiants with 6300 K $\geq T_{\mathrm{eff}} \geq$ 5600 K exhibit a nearly uniform plateau of Li abundances near $A(\mathrm{Li}) = 12 + \log [N(\mathrm{Li})/N(\mathrm{H})] = 2.1$, and that cooler halo dwarfs and subgiants have depleted their Li relative to the plateau. It is often conjectured that the plateau represents the unaltered Li_p; however, stellar and/or Galactic processing may mean that the average Li abundance observed today in halo stars is *not* the primordial value.

Deliyannis, Demarque, & Kawaler (1990, hereafter DDK) examined the role of stellar evolution in their study of Li depletion in detailed halo standard[6] stellar evolutionary models. These models reproduced both the halo dwarf (Fig. 1) and subgiant observations with little Li depletion in the plateau. The derived Li_p provides similar constraints on Ω_b in standard BBN to those resulting from estimated primordial abundances of the other light elements, yielding a low value for Ω_b. This underlines calls for the existence of nonbaryonic dark matter in galactic halos and larger scales. However, detailed models with rotationally induced mixing resulting from angular momentum loss and transport can significantly deplete the Li (Pinsonneault, Deliyannis, & Demarque 1992), to the extent that Li_p nearer 3.0 would be inferred, inconsistent in standard BBN with current estimates of $^4\mathrm{He}_p$ and thus possibly requiring the inclusion of additional physics in BBN. [However, the value of Ω_b inferred from the higher Li_p, 0.1–0.2, would be consistent with Ω(dyn) inferred for Galactic halos and larger scales, alleviating the need for nonbaryonic dark matter on those scales.] It is clearly important to ascertain which stellar processes might be acting.

Scrutiny of the data in the color–equivalent width plane suggested that the plateau is not completely uniform but that instead there is a small dispersion in the Li abundances at a given T_{eff} (Deliyannis, Pinsonneault, & Duncan 1993), consistent with the rotational models. The dispersion has been confirmed by Thorburn (1994) using a much larger sample of stars. Thorburn (1994) and Norris, Ryan, & Stringfellow (1994) discuss possible roles of Galactic enrichment and stellar depletion in effecting observed Li; the extent to which each has contributed is still unclear.

There currently exist few Li observations in cool (5500 K $\geq T_{\mathrm{eff}}$) halo dwarfs. In this contribution we announce the detection of low abundances of Li in two halo dwarfs several

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[6] We define standard models as those ignoring diffusion, mass loss, rotation, magnetic fields, and other physics not usually included in stellar evolution calculations.

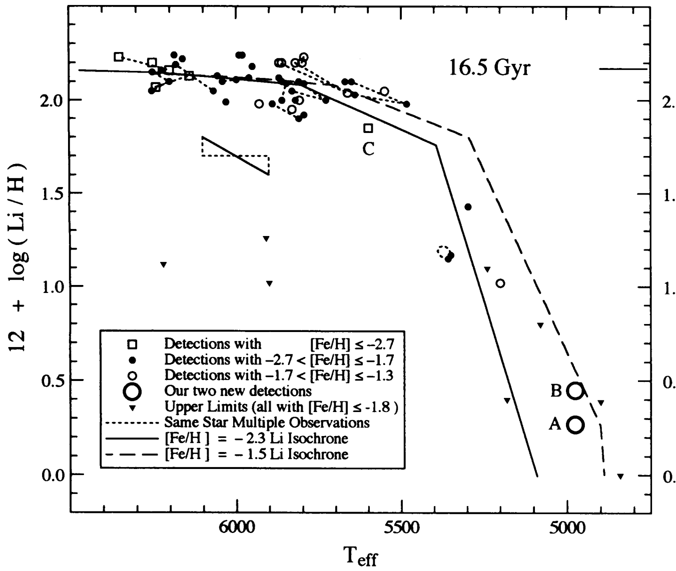

FIG. 1.—Previous observations of Li in halo dwarfs, binned by metallicity, together with our two detections in Gmb 1830 and HD 134439 (*large open circles*). Also shown are two 16.5 Gyr standard Li isochrones, either from DD or computed with the same physics as in DD, with $[Fe/H] = -2.3$ (corresponding to stars represented by open squares and filled circles, i.e., most stars) and -1.5 (the average metallicity of our two cool dwarfs, corresponding to open circles). The error bar shows the effect of a 100 K error in T_{eff} on $A(Li)$. A: Gmb 1830. B: HD 134439; C: G238−30.

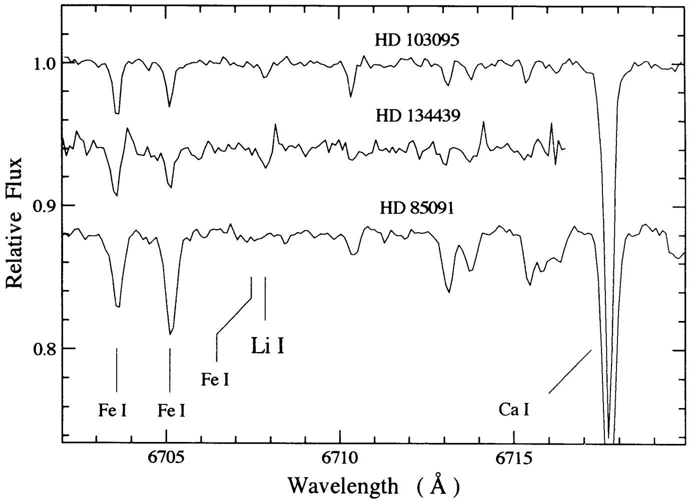

FIG. 2.—Spectra of Gmb 1830, HD 134439, and HD 85091 in the Li 6707.8 Å region. Note the expanded vertical scale.

hundred kelvins cooler than the plateau, Groombridge 1830 (=HD 103095) and HD 134439. The former is especially interesting, since Boesgaard & King (1993, hereafter BK) find that Be is deficient in this star. In standard models, Li survival is not expected in stars that have begun to deplete Be. Gmb 1830 is the nearest halo dwarf and has a well-determined parallax. As a result, it has been the object of numerous studies, and calibrates stellar evolution models used to determine globular cluster ages. Here we argue that this star's light-element abundances could potentially provide a different and critically important insight into stellar interiors, and perhaps cosmology as well.

2. OBSERVATIONS AND ABUNDANCES

Spectra in the region of the Li doublet (6708 Å) were obtained with the Canada-France-Hawaii Telescope in 1991 March, using the coudé spectrograph and CCD to yield 0.095 Å pixel^{-1} at a resolving power (FWHM) of 38,000. (See Beers et al. 1994 for more details.) The data were reduced using IRAF. Lines at the wavelength of the Li doublet were detected in both cool subdwarfs but not in HD 85091 (Fig. 2). The equivalent widths, their 1 σ photon noise errors, and other stellar parameters are given in Table 1. HD 85091 is slightly warmer and more metal-rich than the other two, and the Fe 6707.4 Å line is detected. The upper limit given for its Li equivalent width is the 3 σ photon noise level.

The atmospheric parameters for HD 134439 are based on Peterson & Carney (1979), Laird (1985), and Ryan, Norris, & Bessell (1991). For HD 103095 we used the color-temperature calibrations of Peterson & Carney and of Buser & Kurucz (1992).[7] The uncertainties in T_{eff} are expected to be 50–100 K, which correspond to uncertainties in $A(Li)$ of 0.05–0.11 dex. Li abundances were derived by computing synthetic spectra, measuring the Li equivalent widths on these, and comparing the values with the observed ones (see Norris et al. 1994). The equivalent width uncertainties translate to abundance errors of 0.05 dex, and it is these errors which are given in the table. Our detection in Gmb 1830 supersedes two previous slightly higher upper limits (see DDK).

The absorption seen in the two cooler subdwarfs is certainly due to Li. The wavelength of the absorption feature is *not* consistent with it being the Fe I line at 6707.44 Å, which synthetic spectra showed would not be detectable anyway. Although Brault & Muller (1975) report a CN line of equivalent width 0.3–0.4 mÅ superposed on the solar Li doublet, and the lower T_{eff} values of our stars favor the formation of CN, their low values of [Fe/H] more than compensate for this. A synthetic spectrum showed that the CN line strength in Gmb 1830 would still be only ~0.1 mÅ. Moreover, the CN line at 6707.53 Å, expected at ~0.4 mÅ, is also not detected. Further-

TABLE 1

PROGRAM STARS, ATMOSPHERIC PARAMETERS, AND LITHIUM ABUNDANCES

Star	$B-V$	$R-I$	$b-y$	$E(B-V)$	T_{eff} (K)	log g	[Fe/H]	ξ	Signal-to-Noise Ratio (pixel^{-1})	W (mÅ)	$A(Li)$
HD 103095	0.75	0.47	0.484	0.00	4975	4.5	−1.4	1.0	400	4.0 ± 0.6	0.27 ± 0.06
HD 134439	0.77	0.45	0.484	0.01	4975	4.4	−1.6	1.0	250	6.0 ± 0.7	0.45 ± 0.05
HD 85091	0.61	0.40	...	0.00	5500	4.5	−0.5	1.0	350	<2.0	<0.40

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[7] The spectrophotometric temperature derived by Peterson & Carney (1979) for HD 134439, 4860 K, is 160 K cooler than that derived by feeding its observed $R-I$ and $V-K$ colors back into their color-temperature calibrations. Using their colors and temperature scales, we compute $T_{eff} = 5024$ K, which is in better agreement with the temperatures derived by Laird (1985) and by Ryan et al. (1991). We have adopted $T_{eff} = 4975$ K.

more, in Hyades dwarfs having the same T_{eff} as our two subdwarfs, Thorburn et al. (1993) have placed 3 σ upper limits ranging from 3 to 5 mÅ for *any* line at the Li wavelength; our subdwarfs are 25–40 times more metal-poor, and contaminating lines must be correspondingly weaker. Similarly, there is no feature at the Li position in the spectrum of the stronger lined star HD 85091 (Fig. 2).

3. DISCUSSION

Figure 1 shows the Li abundances compiled in Deliyannis & Demarque (1991, hereafter DD) and DDK, Li from Hobbs & Thorburn (1991), and the cool stars ($T_{\mathrm{eff}} < 5500$ K) of Thorburn (1994), which span $-4.0 \leq [\mathrm{Fe/H}] \leq -1.3$, together with the Li abundances of our two cool dwarfs (*large open circles*); these are the lowest Li abundances yet detected in halo dwarfs.[8] Shown also is the 16.5 Gyr standard Li isochrone of DD for $[\mathrm{Fe/H}] = -2.3$, and one computed here with identical physical assumptions for $[\mathrm{Fe/H}] = -1.5$ (the average metallicity of our two cool dwarfs). We also show three stars with T_{eff} in the range occupied by the plateau but having Li abundances well below it (Hobbs, Welty, & Thorburn 1991; Thorburn 1992), for reasons unknown.

Both standard and rotational models of DD show that Li depletion in cool halo dwarfs depends on metallicity. For $-3.3 < [\mathrm{Fe/H}] < -1.3$, at a given T_{eff} higher [Fe/H] implies higher Li. Our two new cool dwarf detections, the two previous ones, and G238-30 are consistent with this prediction (Fig. 1), as are *all* the upper limits. However, we caution that since cool star depletion is sensitive to opacities, models with improved opacities (e.g., Livermore) will have to be constructed before any strong conclusions can be drawn. DDK and DD also suggested other ways in which models could be improved, and other ways in which cool dwarfs could potentially differentiate between rotational and standard models and perhaps also provide estimates for the age range in the Galactic halo. However the sample is currently too small to address all of these possibilities; more observations are being obtained.

The most interesting aspect of detecting Li in Gmb 1830 is that this star's Be abundance seems to be at least a factor of 2–3 below the mean for a star of its [Fe/H] (Fig. 9 of BK). If this represents a real Be *depletion*, the presence of Li could have serious implications (below). For this reason, we take the conservative position that it would be desirable to reobserve Be in Gmb 1830 at higher resolution and signal-to-noise ratio. It would also be necessary to consider the errors in detail, including an improved understanding of possible line blanketing due to OH in the 3130 Å region.

Assuming the Be deficiency is real and represents stellar depletion, our discovery of Li in Gmb 1830 is at odds with the predictions of standard stellar evolution theory. In standard models, light-element depletion in cool dwarfs occurs at the base of the surface convection zone where Li and Be are both destroyed by (p, α) reactions, but Li at lower temperatures. Any significant destruction of Be would require Li to have been completely obliterated first (DDK; Deliyannis & Pinsonneault 1990). Nonetheless, there are several possible explanations for Gmb 1830 that can be subjected to observational tests:

1. This star might have formed with unusually low Be. If this is true, Be should be "normal" in other stars with similar T_{eff} and Li. Additionally, since Be boron are believed to originate from spallation reactions in the interstellar medium (ISM), and the predicted B/Be (halo) ratio lies robustly in the range 10–15 (Prantzos, Casse, & Vangioni-Flam 1993; Walker et al. 1993), consistent with observations (Duncan, Lambert, & Lemke 1992), a low initial Be abundance should be accompanied by a low B abundance. Conversely, since B is more robust to destruction, high B could indicate Be depletion.

2. It might be envisaged that mass loss has diluted both elements, but we argue against this below. As mass is lost from a model with a reasonably deep convection zone, such as Gmb 1830, its bottom "deepens" beyond the Li and Be preservation boundaries. Both elements can dilute with Li still detectable, as has been proposed for the Sun (e.g., Boothroyd, Sackmann, & Fowler 1991), in which Be is depleted by a factor of 2–3 and Li by 100–200; the similarity in the depletion pattern is striking. However, this mechanism runs afoul of other observations. Using detailed mass-losing stellar evolutionary models, Swenson & Faulkner (1992) argue that depleting the Hyades cool dwarf Li abundances has absurd implications for the initial mass function and for the mass-loss rates themselves. Consequently, we do not embrace mass loss for the Population II case of Gmb 1830 either. Besides, additional oddities would be required in the case of the halo stars (e.g., § V*c* of DDK). Finally, the Li data in halo subgiants flatly contradict mass loss in stars that were at the hot edge of the plateau just a short while ago, because the subgiants provide direct evidence that Li has been preserved in at least most of the ZAMS Li preservation region (and argue against reduction of globular cluster age estimates due to mass loss).

3. The Li and Be depletion seen in Gmb 1830 might be the signature of slow mixing, such as rotationally induced mixing. To illlustrate, suppose that there exists (e.g., at the ZAMS) a region *below* the surface convection zone in which Li is preserved, and thus an even larger one in which Be is preserved due to its higher threshold temperature for nuclear burning. Dilution of the Li- and Be-rich material from higher layers with Li- and Be-poor material from lower layers may occur via slow mixing processes, in such a way as to mimic the Li and Be abundances observed in Gmb 1830. Such processes may explain Li and Be in the Sun (Pinsonneault et al. 1989). If similar mechanisms are at work in halo stars, they could have serious cosmological implications for the inferred Li_p, BBN, and dark matter (see above). However, until the apparent Be deficiency of Gmb 1830 is shown to be Be depletion, any conclusions about mixing and cosmology are likely premature.

4. CONCLUDING REMARKS

The confident determination of Li_p requires more than simply taking the mean plateau value. Beryllium depletion in Gmb 1830, if real, combined with our Li detection, may reflect mixing which could have lowered Li from a higher Li_p value to the observed level of the plateau. However, the detection of ^{6}Li in HD 84937 (Smith, Lambert, & Nissen 1993), if real, restricts how much mixing and depletion of ^{7}Li could have occurred, most likely to no more than about a factor of 5 or so. At minimum, this restricts the allowed parameter range in high ^{7}Li cosmological models, such as inhomogeneous BBN. However, measurements of ^{6}Li are even more challenging than those of Be, and a ^{6}Li detection is now claimed in only one

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[8] We have used published Strömgren photometry to verify that, with the possible exception of LP 625−44 from Thorburn (1994), for which we could not find Strömgren photometry, all plotted stars with $T_{\mathrm{eff}} < 5500$ K are indeed dwarfs, not subgiants. Additionally, we would not expect to find subgiants this cool in a proper-motion catalog.

star. Before any firm conclusions can be drawn, further thorough studies of both elements in halo stars will be required.

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