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LITHIUM, AGE, AND METALLICITY IN OPEN CLUSTERS

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ABSTRACT

It is shown that a strong relationship exists between Li abundance and age for stars in the temperature region 5950–6350 K. The relation is derived from mean Li abundances in eight open clusters ranging in age from 5×10^7 to 8×10^9 yr. The Li declines exponentially with $t^{-0.3}$. It is suggested that in this temperature regime that simple microscopic diffusion is the cause of the Li depletion. It is possible that there is a metallicity term in the relation such that higher metallicity clusters with deeper convection zones have less Li depletion, while lower metallicity clusters undergo greater depletion. This is consistent with expectations from diffusion theory. Furthermore, the halo stars, with even lower metallicity and shallower convection zones, would have more diffusion and more Li depletion; this is in agreement with recent theoretical work.

Subject headings: abundances — clusters: open — diffusion — stars: abundances — stars: evolution

1. INTRODUCTION

The distinct pattern in the Li-temperature profile seen in the Hyades first discovered by Boesgaard & Tripicco (1986a) is seen in other Galactic clusters as well (Boesgaard 1987; Pilachowski & Hobbs 1988; Boesgaard, Budge, & Burck 1988a). There are large Li deficiencies in the temperature region 6400–6800 K. Plausible explanations for this Li "chasm" includes microscopic diffusion (Michaud 1986), meridional circulation plus diffusion (Charbonneau & Michaud 1988), and turbulent diffusion induced by rotation (Vauclair 1986).

Michaud's (1986) proposal is that the Li depletions in the mid-F stars were caused by microscopic diffusion of Li atoms below the convection zone. The downward acceleration of gravity is greater than the upward radiative acceleration on the ionized Li atoms which causes a chemical separation to take place and Li to diffuse downward. The calculations show that the effect would be the greatest just at the temperatures at the center of the observed gap. Toward cooler temperatures, the convection zone deepens and the number of Li atoms in the reservoir is greater, so diffusion has not had time to modify the Li abundance during the lifetime of the Hyades. Within the gap itself, the time scale for diffusion is fairly long so that the effect could be seen in stars the age of the Hyades, but not at the age of the Pleiades. Michaud speculates that in younger clusters the gap would be shallower and narrower, and, in the absence of evolutionary effects, the gap would be wider and deeper in older clusters. The Pleiades with no gap (Boesgaard, Budge, & Ramsay 1988b; Pilachowski, Booth, & Hobbs 1987) at the age of 7×10^7 yr seems to confirm this picture of diffusion. And in M67 subgiants at 5×10^9 yr, Balachandran (1990) has shown that more Li depletion has occurred than can be accounted for by dilution in the subgiant phase and has suggested that the F star gap in this cluster was wider and deeper. Michaud (1986) has discussed the effects of mass loss and has estimated that for a mass loss rate of 10^{-15} $M_\odot$ yr^{-1}, there would be no effect at $T \sim 6500$ K, but for $T > 6700$ mass loss would reduce the Li content making a better match for the depth of the Li deficiencies in the gap.

Figure 1 shows the Li-temperature profile for the Hyades; observational results are taken from Boesgaard & Tripicco (1986a), Boesgaard & Budge (1988), and Cayrel et al. (1984). The various regions are labeled according to the processes which affect Li. The hottest F dwarfs seem to have the "initial" Li that the cluster was born with; this same value is found in the young clusters Pleiades and α Per (Boesgaard et al. 1988b; Pilachowski et al. 1988) and in the hottest F field stars (Boesgaard and Tripicco 1986b). (But note, however, that Michaud indicates that mass loss must have occurred at $T > 6900$ K to correct for model predictions of an increase in Li there.) In the mid-F star region is the Li gap, due to microscopic diffusion (plus mass loss) in its original form by Michaud, or including the effects caused by stellar rotation as described by Charbonneau & Michaud (1988) and Vauclair (1988a). On the cool side of this Li gap, the combination of decreasing rotation and increasing convection zone depth reduces the Li depletion. The region of this profile just on the cool side of this gap, and just warmer than the strong depletions in the G dwarfs (5950–6350 K), is the domain where the dominant depletion cause must be microscopic diffusion. Compared to the stars in the Li gap, these stars are slow rotators so diffusion can occur, unaffected by meridional circulation. The convection zones (CZs) are deep enough so that diffusion is slow, but not so deep that the diffusion time scale is longer than the lifetime of a main sequence star. Compared to the cooler stars, the CZ is not so deep that nuclear destruction can deplete Li at the bottom of the CZ. For the cooler G stars the CZs deepen so that the span is shortened between the bottom of the CZ and the region where the temperature is hot enough for Li destruction by (*p*, α) reactions. Here sub–convection zone turbulence and convective overshoot can aid in transporting Li to the region of destruction.

By looking at stars in the temperature domain of microscopic diffusion at 5950–6350 K, then, we can put strong constraints on diffusion theory. For eight Galactic clusters there are Li observations with stars with temperatures between 5950 and 6350 K. For those clusters the mean Li can be determined. Table 1 lists the Li abundance for the stars used to find the

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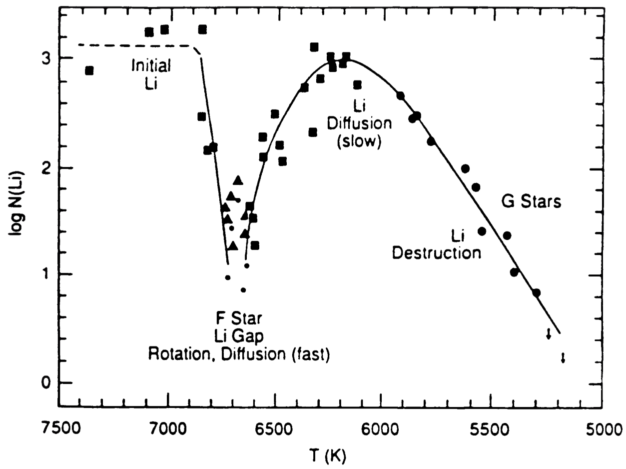

FIG. 1.—The Li-temperature profile for the Hyades F and G dwarfs. Squares are from Boesgaard & Tripicco (1986b) and Boesgaard & Budge (1988); the filled circles are the G star data from Cayrel et al. (1984). Triangles represent upper limits on the Li abundance, but the small dots represent alternative upper limits from a Li-Fe blend synthesis. The small arrows are upper limits for two G stars. The various regions on this profile are labeled.

mean in each cluster. (For Pleiades and α Per, there is no Li dip, and all stars seem to have similar Li abundances so more stars could be used to find the mean Li.) The means were taken of the Li/H values, not logs. The data are taken from Boesgaard et al. (1988b) for α Per and Pleiades, from Boesgaard et al. (1988a) for UMa, from Boesgaard (1987) for Coma, from Boesgaard & Tripicco (1986a) and Boesgaard & Budge (1988) for Hyades, from Hobbs & Pilachowski (1986) for NGC 752, and from Hobbs & Pilachowski (1988) for M67 and NGC 188.

2. AGE DEPENDENCE

From the mean Li/H values from the temperature region 5950–6350 K, we can measure the time scale of microscopic diffusion by comparing Li depletions in clusters of different ages. The results for the eight open clusters are plotted as a function of age in Figure 2 (see also Table 2). The points in this log–log plot can be represented by a straight line:

$$\log N(\mathrm{Li}) = -0.30 \log \mathrm{age}\ (\mathrm{yr}) + 5.33 ,$$

where log N(Li) is on the scale with log N(H) = 12.00. In these late-F stars, affected primarily by diffusion, the Li abundance declines according to a $t^{-0.3}$ relation. For comparison, recall that for G stars in clusters Skumanich (1972) showed that the

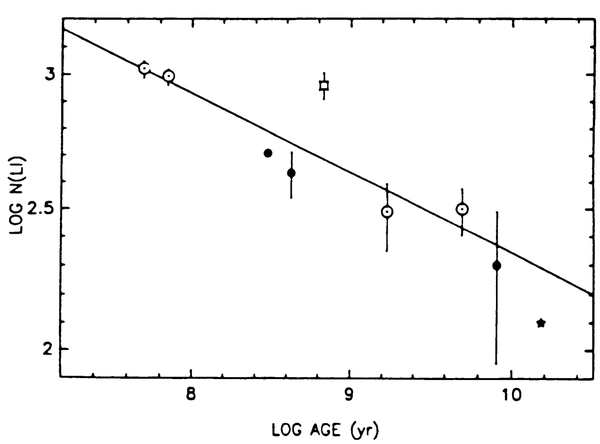

FIG. 2.—The log of the mean values of Li/H for stars in the 5950–6350 K region in eight different clusters as a function of cluster age. From the left the clusters are α Per, Pleiades, UMa, Coma, Hyades, NGC 752, M67, and NGC 188. The straight line is a fit to the solar metallicity clusters indicated by solar (⊙) symbols. The higher metallicity Hyades (*open square*) falls above the line, while the lower metallicity clusters (*filled circles*) fall below the line. The error bars are the errors of the mean Li/H from the stars in the temperature range 5950–6350 K. The star in the lower right represents the halo stars.

TABLE 1

STARS USED FOR MEAN CLUSTER LITHIUM DETERMINATION

Cluster	Star	log N(Li)
α Per	He 490	3.06
	He 361	3.03
	He 135	3.04
	He 799	2.93
Pleiades	Hz 338	3.09
	Hz 470	3.18
	Hz 530	3.06
	Hz 1766	2.90
	Hz 1122	3.07
	Hz 1139	2.89
	Hz 1132	2.81
	Hz 25	2.88
	Hz 233	2.98
	Hz 1200	2.97
	Hz 164	2.88
	Hz 1726	3.08
	Hz 627	2.98
	Hz 1613	3.04
	Hz 1856	2.86
UMa	HR 7451	2.70
	ϕ^2 Cet	2.73
	HD 151044	2.72
	HR 8170	2.65
	HD 94686b	2.72
	HD 94686r	2.72
Coma Tr	90	2.56
	162	2.48
	92	2.52
	58	2.58
	53	2.92
	97	2.84
	76	2.16
	65	2.53
Hyades	VB 121	3.13
	VB 77	2.35
	VB 19	2.85
	VB 61	3.04
	VB 48	2.95
	VB 65	2.98
	VB 62	3.03
	VB 59	2.79
NGC 752	H258	2.2
	H185	2.5
	H237	2.4
	H229	2.7
M67	I-11	2.5
	I-9	2.4
	III-22	2.0
	III-43	2.5
	I-20	2.7
	I-29	2.6
NGC 188	I-101	2.3
	I-17	2.3
	I-71	2.3

TABLE 2

CLUSTER AGES AND ⟨N(Li)⟩ VALUES

Cluster	log Age (yr)	log ⟨N(Li)⟩ (H = 12.00)	n	Actual T Range (K)	Error/$(N-1)^{1/2}$ in Li (H = 12.00)
α Per	7.70	3.02	4	6700–6800	2.99–3.04
Pleiades	7.85	2.99	15	6000–6850	2.96–3.02
UMa	8.48	2.71	6	6000–6240	2.69–2.72
Coma	8.63	2.63	8	5985–6350	2.54–2.71
Hyades	8.83	2.96	8	6100–6370	2.91–3.00
NGC 752	9.23	2.49	4	5955–6240	2.35–2.59
M67	9.70	2.50	6	6000–6255	2.40–2.57
NGC 188	9.91	2.30	3	5915–6000	1.95–2.49
Halo	10.18	2.1	...	...	...

characteristics of rotation, chromospheric activity, and Li abundance decline according to $t^{-0.5}$ relation.

3. METALLICITY DEPENDENCE

In Figure 2 the line is the best fit through all the points. However, the points that fall below the line are those clusters that are slightly metal deficient, UMa, Coma, and NGC 188, and the cluster point that falls above the line is for the metal-enhanced Hyades (Boesgaard 1989; Hobbs, Thorburn, & Rodriguez-Bell 1990). Thus the figure shows a possible effect due to metallicity in the Li diffusion-age relation. The straight line from the solar metallicity clusters (*circled dots*) including the metallicity term is given by

$$\log N(\mathrm{Li}) = -0.29 \log \mathrm{age}\ (\mathrm{yr}) + 5.27 + 1.40\ [\mathrm{Fe/H}]\ .$$

The surface convection zones in metal-rich stars are thicker than those in metal-poor stars. The most important parameter which influences the time scale for diffusion is the mass of the convection zone; the greater the convection zone, the greater the time scale for diffusion to be effective. The effects of diffusion cannot be seen readily when there is a larger total supply of Li atoms in the more massive convection zone. The differences in metallicity in the clusters in Figure 2 are small, but the effects on Li are in the direction expected by diffusion theory (Deliyannis, Demarque, & Kawaler 1990; Proffitt & Michaud 1990).

The halo stars also fit in with this picture. Because they have lower metallicity, diffusion would have a greater effect on their Li abundance in this temperature range. The models of Proffitt & Michaud (1990) show that the initial Population II star Li abundance was log N(Li) = 2.4–2.5 which has now been reduced to the 2.1 which is observed today.

4. CONCLUSIONS

A rather tight relationship exists between Li and age in the temperature region 5950–6350 K with the Li abundance declining as $t^{-0.3}$. The cause of the depletion is probably diffusion, and this relation puts constraints on the diffusion time scale.

Age is the primary parameter determining the Li depletion, but there may be a metallicity effect, too. Lower metallicity stars have shallower convection zones at the same temperature which allows Li atoms to diffuse out of the convection zone in shorter times.

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REFERENCES

Balachandran, S. 1990, in Cool Stars, Stellar Systems, and the Sun, ed. G. Wallerstein (ASP Conf. Ser., 9), p. 357
Boesgaard, A. M. 1987, ApJ, 321, 967
———. 1989, ApJ, 336, 798
Boesgaard, A. M., & Budge, K. G. 1988, ApJ, 332, 410
Boesgaard, A. M., Budge, K. G., & Burck, E. E. 1988a, ApJ, 326, 749
Boesgaard, A. M., Budge, K. G., & Ramsay, M. E. 1988b, ApJ, 327, 389
Boesgaard, A. M., & Tripicco, M. J. 1986a, ApJ, 302, L49
———. 1986b, ApJ, 303, 724
Charbonneau, P., & Michaud, G. 1988, ApJ, 334, 746
Cayrel, R., Cayrel de Strobel, G., Campbell, B., & Däppen, W. 1984, ApJ, 283, 205
Deliyannis, C., Demarque, P., & Kawaler, S. D. 1990, ApJS, 73, 21
Hobbs, L. M., & Pilachowski, C. A. 1986, ApJ, 309, L17
———. 1988, ApJ, 334, 734
Hobbs, L. M., Thorburn, J. A., & Rodriguez-Bell, T. 1990, AJ, 100, 710
Michaud, G. 1986, ApJ, 302, 650
Pilachowski, C., Booth, J., & Hobbs, L. M. 1987, PASP, 99, 1288
Pilachowski, C., and Hobbs, L. M. 1988, PASP, 100, 336
Proffitt, C. R., & Michaud, G. 1990, preprint
Skumanich, A. 1972, ApJ, 171, 565
Vauclair, S. 1988, ApJ, 335, 971