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LITHIUM IN F STARS OF KNOWN AGE

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ABSTRACT

High spectral resolution and high signal-to-noise ratio Reticon spectra of 25 F stars observed with the Canada-France-Hawaii Telescope are presented. The sample was chosen from the list of solar-type stars of known age by Duncan. Abundances of Fe, Ca, and Li relative to H are determined from equivalent widths and a standard model atmosphere abundance routine. We find that all the stars with well-determined Li abundances fall into the range of log $N(\text{Li}) = 2.0$–3.2. All stars hotter than 6800 K show "initial" Li, $\langle \text{Li/H} \rangle = 1.3 \times 10^{-9}$, while stars cooler than 6300 K show an order-of-magnitude spread in Li content. This spread is shown to be consistent with expected age-dependent depletion of Li in late F and early G stars. Stars with temperatures of 6300–6700 K are depleted by factors of 6–20. The depletion in this temperature range is similar to the pattern of Li depletion with temperature found previously for Hyades mid-F stars. We suggest that the Li content of stars in this narrow range of temperature may be influenced by the presence of nearby companions.

Subject headings: stars: abundances — stars: evolution

I. INTRODUCTION

Thirty-five years ago Greenstein and Richardson (1951) found that the Sun was deficient in Li by a factor of ~ 100 compared to Earth and meteorites. They suggested that slow circulation carried Li atoms to temperatures high enough to destroy them. Herbig (1965) hypothesized that convective destruction of Li occurred on a long time scale, so that Li abundance should be correlated with stellar age. Strong support for this came from his observations of Li in G stars in clusters and from comparisons with Li in T Tau stars.

Wilson *et al.* (1965) made a preliminary study of Li in the two components of F and G visual binaries. A more precise study was done by Wallerstein (1966), who looked at Li in visual binaries to check the Li-age hypothesis of Herbig (1965) with stars that can be dated as miniature clusters. His results were fairly supportive of the Herbig hypothesis. More recently, Duncan (1981) and Soderblom (1982) have found specific Li-age relations for solar-type stars. In this paper we have studied F stars in visual binary systems, from a sample of stars for which Duncan (1984) has determined ages, to investigate whether a Li-age connection can be seen in these somewhat more massive stars.

II. OBSERVATIONS

High spectral resolution, high signal-to-noise ratio spectra of 25 stars were obtained at the Canada-France-Hawaii Telescope on UT 1983 November 18 and 1984 July 6 and December 11 and 12. With the exception of HD 11131B, whose spectrum was obtained with the holographic grating, all stars were observed with the 830 lines mm^{-1} mosaic grating, the f/7.4 coudé camera, and the liquid-nitrogen–cooled Reticon detector with 1872 pixels with dimensions of 15 μm $\times$ 750 μm. The spectra were centered at 6700 Å taken in the first order of the grating. This combination yields 135 Å of spectrum at 0.0723 Å pixel^{-1} or 4.83 Å mm^{-1}. The projected slit width of 21 μm gives a spectral resolution of 0.11 Å at 6700 Å. The visual magnitudes of the stars were 6–8 and exposure times of 10–60 minutes gave signal-to-noise ratios of 200–500. The spectrum of HD 11131B, with the higher resolution holographic grating, covers 55 Å with a dispersion of 0.029 Å pixel^{-1}. The stars observed and their relevant physical parameters (mostly from Duncan 1984) are listed in Table 1.

For each of the nights we took a set of four flat-field exposures at the relevant mean stellar continuum level for each stellar exposure. The appropriate four flat fields were averaged and divided into the stellar exposure to remove the instrumental response. Then a four-channel normalization procedure, which equalizes the total output from each of the four channels, was applied to correct for any remaining nonlinearities. Part of the spectral region covered for four of the stars is shown in Figure 1.

Equivelent widths W_λ were measured by a computer routine for the Li I λ6707 resonance, for the Ca I λ6717 line, and for five Fe I lines in the vicinity. The spectral region is not crowded, and at these high signal-to-noise ratio levels the continuum level is easy to establish. For four of the stars the lines are quite broad, and the weaker lines are difficult to measure with high accuracy. Table 2 gives the measured equivalent widths in the 25 spectra; less certain measures are indicated by a colon after the equivalent width. The second column gives the signal-to-noise ratio of the observed spectrum and indicates which stars have broad lines.

III. ABUNDANCE DETERMINATIONS

A model atmosphere abundance analysis program was used which predicts line profiles and equivalent widths for a given model atmosphere (specified by effective temperature T_{eff} and gravity), microturbulent velocity and other line broadening mechanisms, atomic parameters, and an array of abundances of a given element. We used Kurucz's (1979) model atmospheres and found abundances from five Fe I lines, $\lambda\lambda$6678, 6703, 6705, 6727, and 6750; one Ca I line, λ6717; and Li I or the Li I–Fe I blend λ6707 (calculated with the appropriate Fe/H abundance). Calculations were made with atmospheres

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TABLE 1

CHARACTERISTICS OF STARS OBSERVED

HD	Sp.	M_V	$T_{\rm eff}$ (K)	log g	log Age[a]
4A	F0	0.65	6345	3.01	9.0:
6479A	F3 V	3.08	6686	4.14	9.15
6480B	F6–F7 V	4.06	6107	4.24	9.15P
7345B(b)	F7 V	3.4	5680[b]	4.1	8.95P
7345B(r)			6270[b]		8.95P
11131B	G1 V	4.66	5709	4.24	<8.9P
11973B	G0 V	4.22	5959	4.22	8.95P
14082A	F5 V	4.28	6084	4.32	<9.5
29819A	F2 V	2.16	7016	3.88	9.1
35736A	F2 V	2.75	6470	3.91	9.3
35722B	F5	4.01	5959	4.14	9.3P
48501A	F0	2.29	7095	3.96	9.1
81029A	F0	2.13	7274	3.95	9.05
92855B	F9 V	4.47	5914	4.30	9.1P
126531A	F5 V	2.92	6527	4.01	9.3
137392B	G1 V	...	5920[b]	...	9.0P
146835B	F9 V	4.34	5936	4.26	9.4P
162003A	F5 IV–V	2.99	6504	4.03	9.3
162004B	G0 V	3.89	6107	4.18	9.3P
190779	F5 V	2.73	6345	3.85	9.4
196310A	F0	2.89	6834	4.12	9.1
205811B	F2 V	3.14	6982	4.26	<8.2P
206751A	F2 V	2.59	6834	4.00	9.15
216582B	F5 V	3.13	6330	4.14	9.22P
216606A	F2 V	3.49	6590	4.12	9.22

[a] P, age of primary assumed for secondary.

[b] $T_{\rm eff}$ from $I(\lambda6748)/I(\lambda6750)$, $I(\lambda6748)/I(6752)$, or $W(\lambda6703)/W(\lambda6705)$. For the double-lined spectroscopic binary HD 7345B, the upper $T_{\rm eff}$ is for the blueshifted set of lines and the lower for the redshifted set.

characterized by $T_{\rm eff}$ = 6000, 65000, 7000, and 7500 K for both log g = 4.0 and 4.5 and for the solar ($T_{\rm eff}$ = 5770 K, log g = 4.44) atmosphere. Results for a particular star were interpolated for the appropriate values for log g and $T_{\rm eff}$. See Boesgaard and Tripicco (1986a, hereafter BT) for further details, and that reference and Boesgaard and Lavery (1986) for samples of the resultant curves of growth for a grid of atmospheres. These same curves and same methods were used for this work.

The temperatures and gravities used were primarily those published by Duncan (1984). These temperatures are typically +40 (±75) K hotter than the Hearnshaw (1974) calibration used by BT. For the spectroscopic binary HD 7345B and for HD 137392B, for which Duncan gives no temperature, we used various temperature-sensitive line ratios in the spectral region observed. In addition to the equivalent width ratio of Fe I λ6703 to Fe I λ6705 calibrated by BT, we calibrated two other temperature-sensitive line ratios: I(Cr I λ6748)/(Fe I λ6750) and I(Cr I λ6748)/I(Fe I λ6752). The measured line depth ratios are shown against temperature in Figure 2. The straight lines represent the following relationships:

$$I(\lambda6748)/I(\lambda6750) = 7.80 \times 10^{-4} T_{\rm eff} - 4.38 ,$$

$$I(\lambda6748)/I(\lambda6752) = 1.61 \times 10^{-3} T_{\rm eff} - 8.89 .$$

For the double-lined spectroscopic binary, the measured equivalent widths had to be multiplied by a correction factor based on the temperature and radius, as discussed by BT. The multiplication factors used are given in a footnote to Table 2.

Abundances were found for [Ca/H] and [Fe/H] from a line-

TABLE 2

EQUIVALENT WIDTHS

(mÅ)

HD	S/N	Fe I λ6678	Fe I λ6703	Fe I λ6705	Li I λ6707	Fe I λ6727	Fe I λ6750	Ca I λ6717
4A[a]	190	...	24.:	16.:	132.8	...	95.:	...
6479A	350	86.6	11.9	22.7	≤7.:[b]	30.9	30.7	81.0
6480B	280	95.7	16.9	18.1	51.0	25.3	49.4	84.8
7345B(b)[c]	340	...	11.3	14.8	≤43.:[d]	16.9	22.5	...
7345B(r)[c]		86.7	13.4	≤43.:[d]	88.9	<31.:	...	92.7
11131B	150	...	31.1	39.6	83.6	40.6	...	102.5
11973B	430	...	28.0	41.5	70.7	45.3	63.8	120.0
14082A[a]	350	127.4	23.4	41.1	138.2	45.2	68.0	105.2
29819A[a]	380	...	5.:	16.:	63.6	24.:	...	...
35736A	400	102.0	13.2	26.7	11.9	25.9	44.5	98.0
35722B	380	112.5	20.1	33.9	57.8	32.9	60.4	102.5
48501A	380	...	6.:	21.:	33.7	19.5	22.:	78.7
81029A[a]	370	...	5.:	26.:	29.8	30.9	29.:	90.:
92855B	440	125.6	26.0	37.6	42.5	39.6	60.8	109.9
126531A	380	99.0	10.6	24.8	23.0	22.0	36.3	83.0
137392B	390	125.9	34.7	49.5	89.8	49.3	71.5	128.4
146835B	360	115.6	24.7	35.8	26.4	37.3	62.9	104.4
162003A	500	106.0	14.8	28.0	36.0	31.9	46.4	93.1
162004B	500	113.8	24.0	36.0	69.7	31.4	61.7	113.7
190779	250	96.2	20.:	27.2	10.:[b]	...	40.9	83.:
196310A	250	93.8	12.5	23.9	63.4	25.9	30.1	75.1
205811B	360	92.7	11.8	22.9	66.4	26.0	33.6	77.9
206751A	360	91.7	11.3	22.7	48.:[b]	23.4	33.2	80.8
216582B	300	100.8	14.6	32.5	19.7	30.5	42.9	89.0
216606A	290	...	15.8	28.4	7.:	32.4	43.7	97.5

[a] Broad lines.

[b] Li line contaminated by emission.

[c] Measured W_λ not "corrected" ones; mf(b) = 2.910, mf(r) = 1.524.

[d] The Li I line for the blue component is blended with the Fe I λ6705 line of the red component.

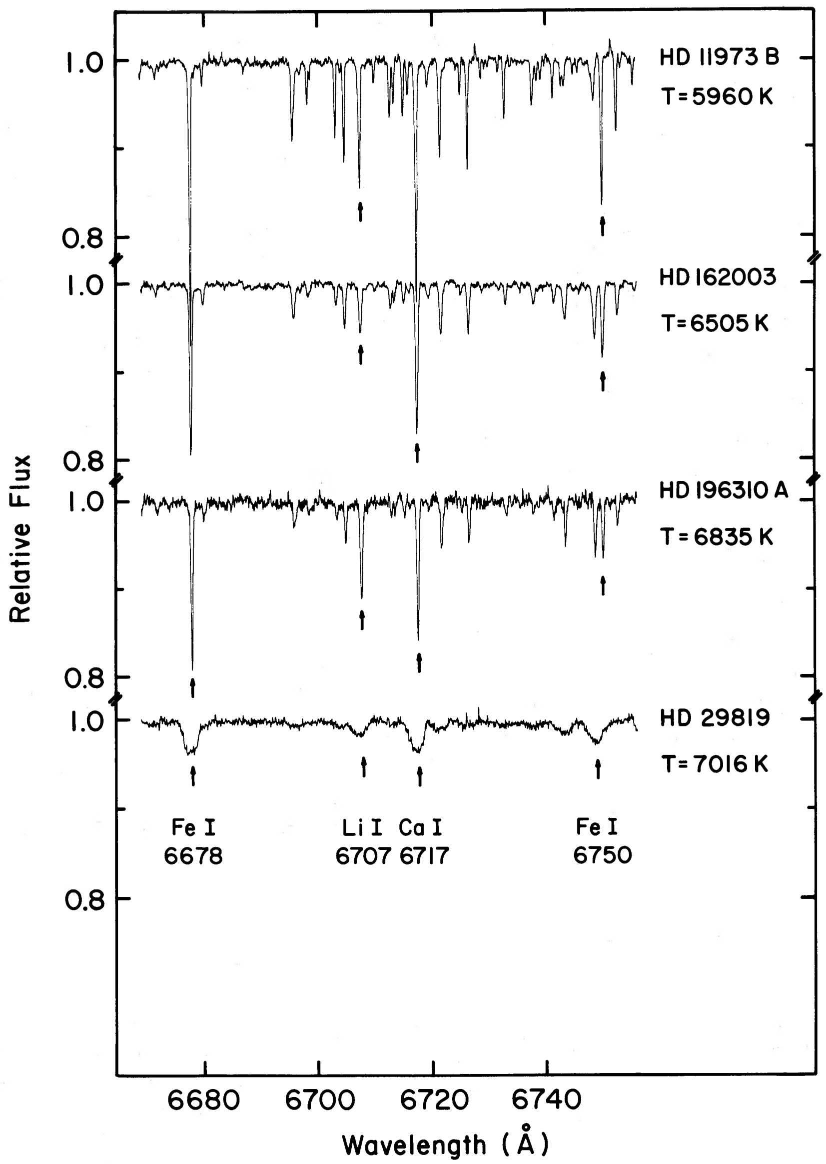

FIG. 1.—Samples of part of the specta in the Li I region, arranged in order of temperature. The lowest is one of the broad-lined stars, HD 29819.

by-line comparison with the solar value. The Li I feature blends with a weak Fe I line, so the Li-Fe blend curves of growth were used (see BT, Figs. 4 and 5). Interpolation was done between Li abundance curves calculated with [Fe/H] = 0.6, −0.3, 0.0, and +0.3. The abundance results are presented in Table 3. The final column gives an indication of the quality of the Li abundance based on the signal-to-noise ratio of the spectrum, the line breadth, and accuracy of the Li I equivalent width measurement.

IV. RESULTS AND INTERPRETATION

With the exception of three stars with uncertain Li abundances, all the stars in this sample show log N(Li) values between 2.0 and 3.2. Figure 3 is an H-R diagram showing the positions of our stars, where the three different symbols correspond to different abundance ranges. All six of the stars hotter than 6800 K have the so-called "cosmic" or initial Li with values of log N(Li) = 2.94–3.26 [where log N(H) = 12.00], or a mean of $\langle \mathrm{Li/H} \rangle = 1.3 \times 10^{-9}$. Most of the stars with the lowest Li abundances [log N(Li) < 2.2] are in the temperature region of 6300–6700 K, where the Hyades F stars show a severe dip in the Li content (Boesgaard and Tripicco 1986*b*). The stars cooler than 6300 K show a spread in Li content of an order of magnitude [log N(Li) = 1.98–3.20] which is typical of late F and early G field stars (e.g., BT; Duncan 1981). This spread in Li has been attributed to a spread in age. In our sample of nine stars with $T_{\mathrm{eff}} < 6300$ K, all the stars (except one) are younger than 2×10^9 yr, and none are depleted by more than an order of magnitude from the initial log N(Li) of 3.0. Both the existence of some depletion and the relatively small amount of it in these rather young stars can be understood in the context of the Li-age relation discussed in earlier studies by Duncan (1981) and BT.

Another way to look at these data is shown in Figure 4, which plots Li abundance against effective temperature. Included in this figure are the Boesgaard and Tripicco (1986*b*) results for the Hyades, shifted by −40 K relative to this sample. Our stars fit the relation we drew in for the Hyades

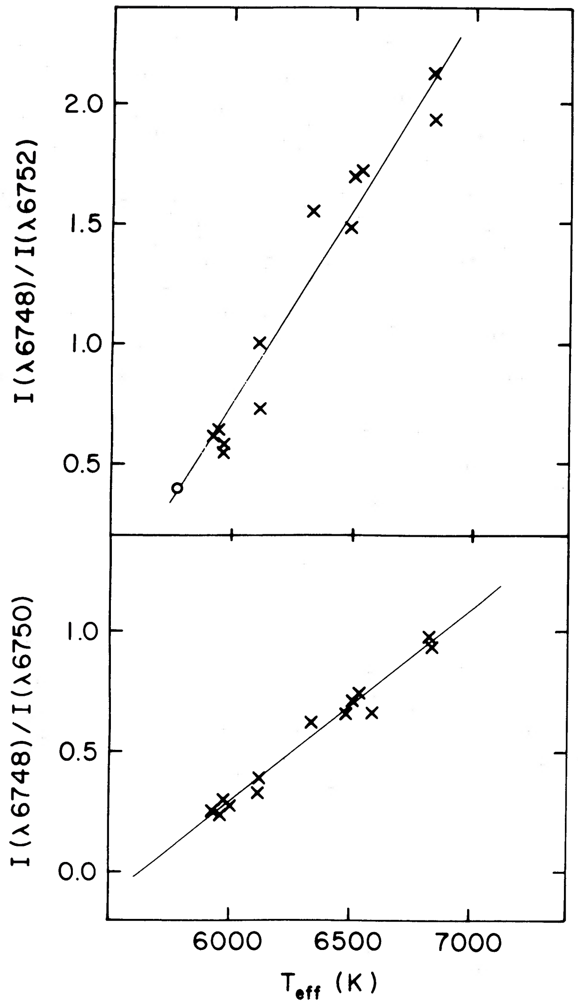

FIG. 2.—Temperature-sensitive line intensity ratio of Cr I λ6748 to Fe I λ6750 or λ6752 features as a function of the temperature found by Duncan (1984). Either line ratio provides a good temperature indicator. These calibrations were used for stars with no Strömgren photometry and for the double-lined spectroscopic binaries.

TABLE 3

ABUNDANCE RESULTS

HD	[Fe/H]	[Ca/H]	log N(Li)	Li Quality[a]
4A	+0.3:	...	3.25	3
6479A	+0.01	+0.01	+1.8:	3
6480A	−0.25	−0.25	2.48	2
7345B(b)	−0.13	...	≤2.7:	2
7435B(r)	+0.1:	...	3.20	2
11131B	−0.16	−0.25	2.48	2
11973B	−0.03	+0.18	2.58	1
14082A	+0.02	+0.02	3.11	1
29819A	0.00	...	3.26	3
35736A	−0.04	+0.17	1.98	2
35722B	−0.19	−0.09	2.43	1
48501A	+0.01	+0.20	2.99	3
81029A	+0.27:	+0.5:	3.00	2
92855B	−0.11	+0.01	2.22	1
126531A	−0.09	−0.04	2.36	2
137392B	+0.05	+0.21	2.67	1
146835B	−0.13	−0.06	1.98	1
162003A	+0.04	+0.11	2.60	1
162004B	−0.08	+0.19	2.66	1
190779	−0.03	−0.14:	1.7:	3
196310A	+0.09	+0.01	3.13	1
205811B	+0.17	+0.12	3.24	2
206751A	+0.07	+0.08	2.94	2
216582B	−0.07	−0.17	2.15	2
216606A	+0.07	+0.20	1.8:	3

[a] Li quality index: 1, excellent; 2, good, OK; 3, noisy, and/or broad lines, and/or cosmic rays.

mid-F star dip quite well. Some scatter in the field binary sample is due to the spread in age. The two oldest stars are those with the least Li at temperatures of 5936 and 6345 K (HD 146835B and HD 190779) at log age = 9.4 or 2.5×10^9 yr. The Hyades stars have ages of $\sim 7 \times 10^8$ yr (Patenaude 1978). By itself the apparent Li dip in the field binaries is not compelling, but in conjunction with the Hyades F stars, the mid-F star dip is quite convincing. Our new stars strengthen the Li plateau at the high-temperature side.

Michaud (1986) presents an explanation for the Hyades dip in Li content in the mid-F stars: Li depletion by as much as an order of magnitude will occur because of downward diffusion, with additional depletion occurring if there is mass loss of $\sim 10^{-14}$ $M_\odot$ yr^{-1}. These phenomena may also account for the Li depletion in the visual binaries in the temperature range 6300–6700 K.

The BT paper is a surveey of Li (and Fe) abundances in 75 F0–F5 field dwarf stars. We point out that about half the field stars studied by BT at the dip temperature (6400–6800 K) have log N(Li) ≈ 3.0, i.e., are undepleted. It is possible that "environment"—a binary companion or a nearby cluster neighbor—affects the mechanism which causes the depletion. One possible contributor to Li depletion is mass loss (Michaud 1986), which may be influenced by the presence of a nearby neighbor. Stellar rotation and stellar structure may also be affected by the presence or formation, or both, of a companion. (Counter to this suggestion, however, is the field star pair γ Vir N and γ Vir S, both of which show undepleted Li, with temperatures of 6695 K and 6795 K respectively.)

Michaud *et al.* (1983) have shown that diffusion accounts well for the surface chemical composition of Am-Fm stars which rotate slowly enough for diffusion to occur. Recently, Abt and Levy (1985) have demonstrated that virtually all Am-Fm stars are members of binary systems: 36% are visual binaries, 29% are double-lined spectroscopic binaries (SB2), and 36% are single-lined spectroscopic binaries. The percent of SB2's is especially high compared to F3–G2 dwarfs. The binary nature of these stars contributes to the fact that they are slow rotators and that, consequently, diffusion can take place. In our sample the stars are members of visual binaries (and one is an SB2 in addition), but all are slow rotators, in accordance with expectations for cooler main-sequence stars. Thus diffusion could take place in them without the need for a fairly distant binary companion (which may or may not contribute to the mutual spindown of the pair). The presence of the companion may contribute to mass loss and may alter the internal stellar structure.

The Li content of a given main-sequence star is presumably a function of mass (or T_{eff}) and age. The Hyades observations show that it is a rather complex function of mass for mid-F stars. In general we would expect that the hot, young F stars would have high Li. There should be a spread in Li for the cool F stars, with the young ones preferentially Li-rich and the older ones somewhat depleted. Figure 5 shows the positions of stars in a temperature-age diagram with different symbols corresponding to the three Li abundance ranges given in Figure 3.

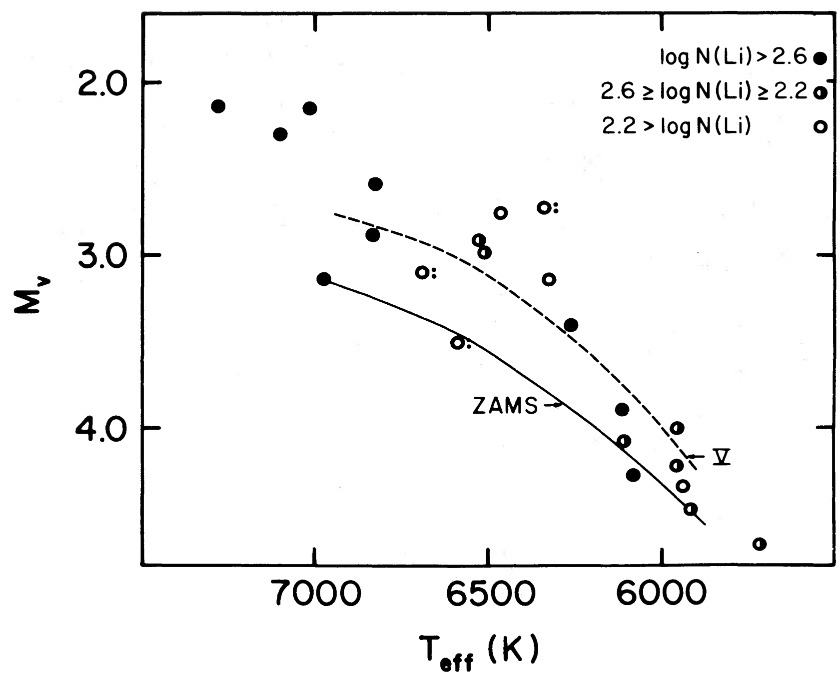

FIG. 3.—Positions of observed stars in H-R diagram. Theoretical zero-age main sequence (ZAMS) is that of VandenBerg (1985) and the dashed line (V) is the observed ZAMS of Crawford (1975). The different symbols indicate the Li content: *filled circles*, stars with "initial" Li; *half-filled circles*, somewhat Li depleted (factors of 3–6); *open circles*, stars whose Li content is about a factor of 10 below the "initial" Li. Colons after symbols mean Li value is uncertain. Three characteristic regions can be found: $T > 6700$ K, all stars have the "initial" Li; $T_{eff} = 6300$–6700 K, Hyades-like Li deficiencies (see text); $T_{eff} < 6300$ K, Li depletion is a function of mass and age.

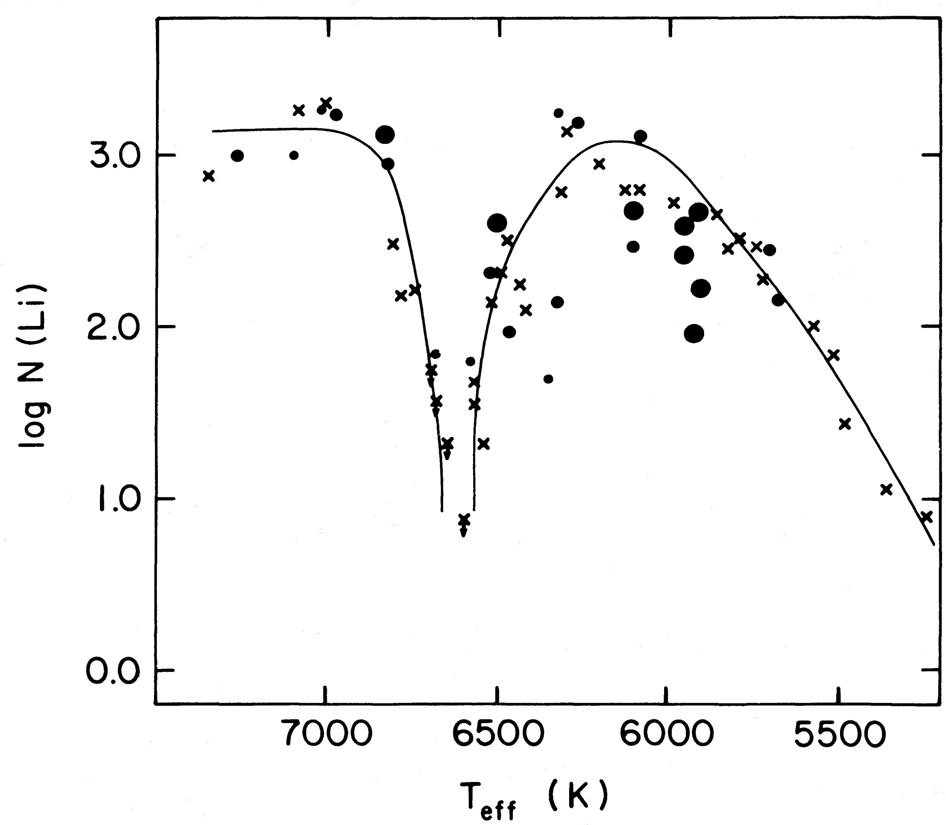

FIG. 4.—Li abundance as log N(Li), where log N(H) = 12.00, vs. effective temperature. *Filled circles*, visual binaries, with size of symbol corresponding to quality of Li abundance: *large*, excellent; *medium*, good; *small*, fair. *Crosses*, Hyades results of Boesgaard and Tripicco (1986*b*) for $T_{eff} > 6200$ K and Cayrel *et al.* (1984) for the cooler stars. The deep, narrow dip in the Hyades between 6400 and 6800 K is verified by these results, and the high-temperature plateau above 6800 K is better defined. The spread in Li content of the binaries near 6000 K can be attributed to a spread in age and the fact that all the stars are older than the Hyades.

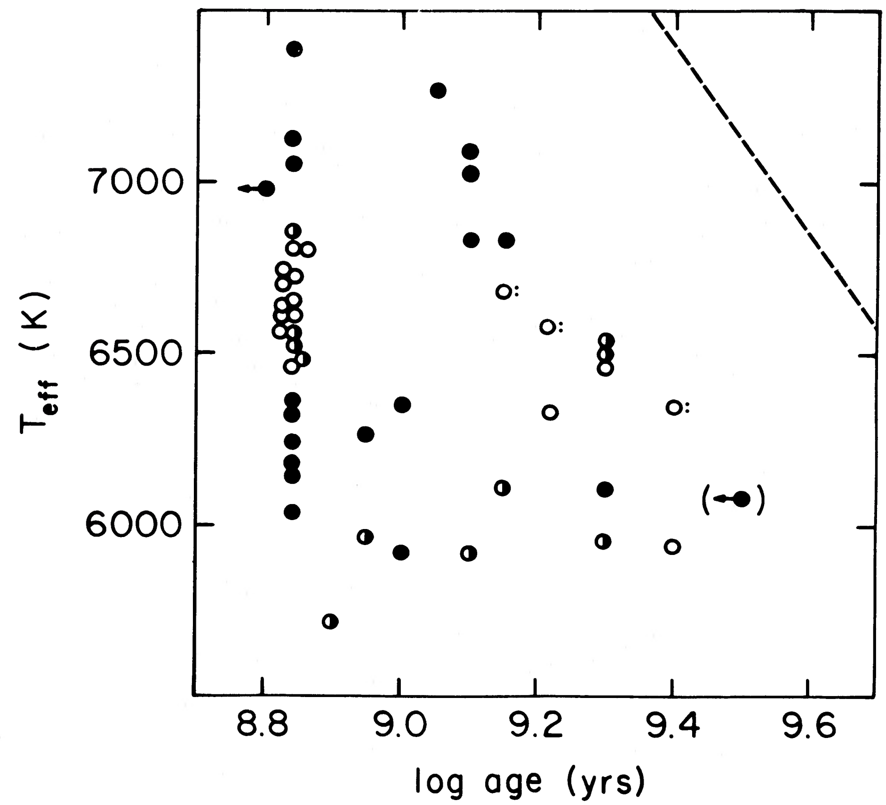

FIG. 5.—Our observed stars in the (T_{eff}, log age)-plane with Li abundance ranges denoted by the same symbols as in Fig. 3. The Hyades stars from Boesgaard and Tripicco (1986*b*) are the series of points in the vertical row at log age = 8.84. The dashed line in the upper right corresponds to the calculated main-sequence lifetime for a given ZAMS temperature (see text). All the young, hot stars in the upper left have the "initial" Li, as do many of the young, cool stars. The cool stars do show an order of magnitude range in Li, related to their age.

The stars in the upper left quadrant hotter than 6800 K and younger than 2×10^9 yr do indeed have the "initial" Li content, log $\langle N(\mathrm{Li}) \rangle = 3.1 \pm 0.1$. And the cooler stars do show a greater range in Li content, with the stars younger than 2 Gyr generally having more Li than those older than 2 Gyr. Positions and Li content of the Hyades stars are shown at log age = 8.84 for comparison. The total main-sequence lifetimes for stars of various temperatures are indicated by the dashed line in the upper left of Figure 5. This calculation is based on Clayton's (1968) formulation for main-sequence lifetime, $\tau_{ms} = 9.24 \times 10^9 (M/M_\odot)/(L/L_\odot)$, with the fraction $X_H = 0.70$ for hydrogen content, of which 12% is converted to He on the main sequence, and on the relations of Allen (1973) between spectral type, effective temperature, mass, and luminosity. Our limited sample suggests that the Li content of F stars conforms to the age-mass expectations and that stars younger than 2 Gyr show a range in Li content of only a factor of 10.

V. SUMMARY

We have determined the Li/H and Fe/H abundances in a sample of F stars in visual binary systems whose ages can be estimated from their evolution off the main sequence or from that of their companion. The six youngest (<2 Gyr), hottest (>6800 K) stars show "initial" Li, $\langle \mathrm{Li/H} \rangle = 1.3 \times 10^9$. Three of the seven youngest, coolest stars also show this initial Li/H. Although severe (factor of 100) Li depletions were not found in these stars, the Li content of some stars were reduced by factors of 6–20. These stars are found in the temperature (mass) range where the Hyades stars show large Li depletions: T_{eff} = 6300–6700 K (Boesgaard and Tripicco (1986*b*), or among the stars cooler than ~6000 K where age-dependent Li depletions are found.

The stars hotter than 6000 K agree with the Li-temperature relation found for the Hyades and confirm the Li dip for the middle F stars. Because this dip is present in the binary and cluster stars, but not in all the field stars, we suggest that the presence of near companions may influence the rotation, internal structure, or mass loss rate that affects the Li depletion.

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