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THE EVOLUTION OF THE LITHIUM ABUNDANCES OF SOLAR-TYPE STARS. VIII. M67 (NGC 2682)

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ABSTRACT

We have used the HIRES spectrograph on the Keck 10 m telescope to obtain echelle spectra of 25 solar-type stars in the old open cluster M67 (NGC 2682) and have used these spectra to derive lithium abundances. This cluster, which has approximately the same age and composition as the Sun, shows a pattern of Li depletion different from either the Pleiades or the Hyades. At $M \lesssim 1\ M_\odot$, M67 is more Li depleted than the Hyades. For $\sim 1\ M_\odot$ stars, M67 shows a significant spread in Li, with about two-thirds of the stars being Li-rich and the remainder Li-poor. The data are consistent with M67 having the same initial Li abundance as the initial solar abundance. This is further evidence that Li depletion in solar-type stars occurs during their main-sequence lifetimes, although at a slower rate than pre–main-sequence depletion. These M67 observations also indicate that a 1 $M_\odot$ star at the Sun's age can have an Li abundance within a range of ~ 1 dex, and that the Sun is not necessarily representative of all stars of its mass, age, and composition.

Key words: open clusters and associations: general — stars: abundances — stars: evolution — stars: late-type — stars: rotation

1. INTRODUCTION

Low-mass stars ($M \lesssim 1\ M_\odot$) undergo significant depletion of their surface lithium because convection carries material to a depth where the temperature is high enough ($T \gtrsim 2.5$ MK) to destroy Li either during pre–main-sequence evolution or while the stars are on the main sequence. The degree of depletion will depend on the temperature reached and how long that temperature is maintained. Standard stellar models predict that stars less massive than the Sun should show Li depletion that increases with decreasing mass, while main-sequence stars more massive than the Sun should show little or no depletion. Very low mass objects ($M < 0.06\ M_\odot$) should not suffer depletion at all, because their central temperature never reaches 2.5 MK, even though those stars are fully convective.

This paper is the eighth in a series about the Li abundances of solar-type stars. Soderblom et al. (1990, hereafter Paper I) provided the rationale for this program as a whole. Our most recent publication, Paper VII (Jones, Fischer, & Soderblom 1997), gives an overview of the Li depletion problem with a large reference list. Recent reviews with extensive references include Pinsonneault (1994), Strom (1994), Balachandran (1994), and Martín (1997). Briefly, our aim is to use high-quality data for large samples of stars in nearby clusters to fully describe and delineate the constraints that observations place on models of the decline of the surface Li abundance with age for solar-type stars.

The current observational picture is confusing. Cool young stars have a large spread in Li abundance at a given temperature, well in excess of the errors, and the spread is temperature dependent. For example, the Pleiades, with an age ~ 100 Myr, shows a large spread in Li abundance at a given temperature for stars less massive than the Sun (Soderblom et al. 1993b, hereafter Paper III; García Lopéz, Rebolo, & Martín 1994). Higher Li abundances appear to be correlated with rapid rotation, although there are exceptions. In the older cluster NGC 1039 (M34; 250 Myr), the spread in Li is less, but the correlation of high Li with high rotation remains (Paper VII). The lower bound of Li abundance versus $T_{\rm eff}$ appears to be the same in both clusters. NGC 6475, at an age of 220 Myr, shows an Li abundance pattern very much like that of NGC 1039 (James & Jeffries 1997). In both the older Hyades and Praesepe clusters (age ~ 700 Myr) there are marked depletions of Li in low-mass stars compared with the Pleiades or NGC 1039, and the spread in Li abundance is less in the older clusters (Thorburn et al. 1993; Soderblom et al. 1993a, hereafter Paper IV; see Fig. 4 below).

These observations indicate that cool stars arrive on the zero-age main sequence (ZAMS) with a spread in Li abundance at a given temperature and that the spread is connected with rotation. These observations give support to the models of pre–main-evolution by Martín & Claret (1996). The observations also suggest that during their main-sequence lifetimes, stars deplete Li at a rate that depends on their mass and angular momentum loss, so that both the Li abundances and surface rotation rates converge by the age of the Hyades. Thus the observations also give support to models with rotationally induced mixing on the main sequence (Pinsonneault, Kawaler, & Demarque 1990; Chaboyer, Demarque, & Pinsonneault 1995). However, this naive picture does not take into account the different metallicities of the Pleiades and Hyades or other possible effects.

Observations of clusters older than the Hyades are few. The available observations of M67 and NGC 752 show significantly more Li depletion than the Hyades and Praesepe (Hobbs & Pilachowski 1986a; Hobbs & Pilachowski 1986b; Spite et al. 1987; García Lopéz, Rebolo, & Beckman 1988; Pilachowski & Hobbs 1988; Balachandran 1995, Pasquini, Randich, & Pallavicini 1997). In the case of M67, there is evidence of a significant spread in Li abundance

(Pasquini et al. 1997). To try to disentangle the effects of age and metallicity, we decided to improve upon the existing observations of solar-mass stars in M67. This cluster has nearly solar metallicity, close to that of the Pleiades and NGC 1039, and is of nearly solar age. The use of HIRES on the Keck 10 m telescope allows a significant number of stars to be observed at a high signal-to-noise ratio (S/N) in a reasonable observing time.

M67 is one of the most studied open clusters, and there have been numerous publications on its membership, metallicity, and age. Montgomery, Marschall, & Janes (1993) give an extensive discussion and review of previous work. The earlier proper-motion membership estimates of Ebbighausen (1940), van Maanen (1942), and Murray, Corban, & Allchorn (1965) have been supplanted by the newer studies of Sanders (1977), Girard et al. (1989), and Zhao et al. (1993). These newer astrometric studies are highly precise and provide a list of nearly certain members. Broadband *UBV* photometry of M67 was obtained by Johnson & Sandage (1955), Eggen & Sandage (1964), and Racine (1971). More recently, Montgomery et al. (1993) have published extensive CCD *UBVI* photometry of the central $\frac{1}{2}^\circ$ of M67 to $V = 20$. Hobbs & Thorburn (1991) derive an abundance that is near solar ($[\mathrm{Fe/H}] = -0.04 \pm 0.12$) from high-dispersion spectroscopy, and an age of $\tau = 5.2 \pm 1.0$ Gyr, found by comparing the limiting turnoff temperature with theoretical isochrones. Our preliminary determination of [Fe/H], to be discussed elsewhere (Fischer et al. 1999), gives a slightly more metal-poor value, $[\mathrm{Fe/H}] = -0.10 \pm 0.03$. Dinescu & Demarque (1995) derive an age of 4 ± 0.5 Gyr by fitting the theoretical isochrones to the color-magnitude diagram. We will assume here that M67 is close to solar metallicity and age.

2. OBSERVATIONS AND ANALYSIS

The most easily observed spectroscopic feature of Li is a resonance doublet of neutral ^{7}Li at wavelengths of 6707.761 and 6707.912 Å. The corresponding doublet of ^{6}Li is at 6707.921 and 6708.072 Å, but the abundance of ^{6}Li is very low compared with ^{7}Li, and ^{6}Li is essentially unobservable in normal stellar photospheres. Lines arising from the first excited state at wavelengths of 8126.5 and 6103.5 Å have also been observed in stellar spectra, but they are much weaker than the λ6708 doublet. Li II, in most situations the dominant ionization state, has a first excited state $\sim$60 eV above the ground state, and its lines are completely unobservable.

Our aim in this program was to observe solar-mass stars in M67 that are near the main sequence. In particular, we wanted to avoid the problems of some previous investigations that observed evolved stars at the turnoff having the same T_{eff} but different masses. Unless account is taken of the evolutionary state, as was done by Balachandran (1995), a spread of Li abundance at a given T_{eff} may only reflect a spread in Li abundance as a function of mass. We therefore selected stars having proper-motion membership probabilities that are high (Sanders 1977), and having magnitudes and colors (Johnson & Sandage 1955; Eggen & Sandage 1964; Racine 1971; Montgomery et al. 1993) that placed them near the cluster main sequence. The observed dereddened colors [$(B-V)_0$; see below] ranged from 0.60 to 0.74, corresponding to T_{eff} from 6160 to 5480 K. The *V* magnitudes ranged from 13.70 to 14.87. Most of the earlier Li observations in M67 (with the exception of Pasquini et al. 1997) were either of evolved stars or of stars that fall within our temperature range but above the main sequence. Figure 1 shows a color-magnitude diagram for M67 stars near our temperature and luminosity range, with the stars previously observed for Li indicated by open squares, and the stars observed here with open circles.

Most of our observations were obtained on 1996 February 29 and March 1 UT using the HIRES spectrograph (Vogt 1992) on the Keck 10 m telescope. We also observed two stars with HIRES with the Keck on 1996 December 5 UT and four stars on 1998 January 8 and 9 UT. The detector was a Tektronix 2048 × 2048 CCD having 24 μm pixels. We used the "B2" slit decker, which yielded a projected slit height of 7″ (36.6 pixels) and a projected slit width of 0″.574 (2 pixels), yielding a resolving power of 60,000. The wavelength region of our spectra extended from $\sim$6300 to $\sim$8700 Å, split into 16 orders, with each order covering approximately 100 Å; i.e., our spectra are not fully sampled in wavelength and have small interorder gaps. The echelle tilt was chosen so that most features of interest are included in the wavelength regions sampled by our CCD. The integration times averaged 30 minutes, which gave a typical S/N of $\sim$60–100.

We reduced the data in a manner similar to that used by Soderblom et al. (1993d, hereafter SSHJ) and in Soderblom et al. (1993b, hereafter Paper III) and Paper VII, using IRAF version 2.10.4, including the NOAO.IMRED.ECHELLE package for flat-fielding, scattered light removal, extraction of the orders, and wavelength calibration (using a ThAr lamp). Figure 2 shows the reduced spectra of our stars in the vicinity of the Li λ6708 feature. We note that there are bad columns on the CCD, corresponding to wavelengths $\sim$6712 Å, that we have artificially removed because there are no neighboring lines that would be affected, and one near $\sim$6703.6 Å that we have left alone because it lies near an Fe I line and tends to play havoc with that line profile.

Equivalent widths of the Li λ6708 feature were measured using both Gaussian profile fitting and with an integrated flux method. No significant differences in equivalent widths were found for the two methods. The region around the Li line also contains several other weak features (Paper III;

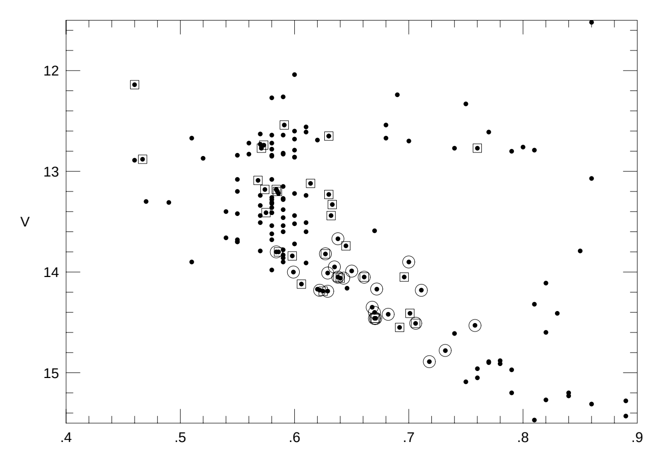

FIG. 1.—Color-magnitude diagram of highly probable M67 members. The stars observed here for Li are indicated by open circles, while stars previously observed are indicated by open squares. Note that the colors here have not been dereddened.

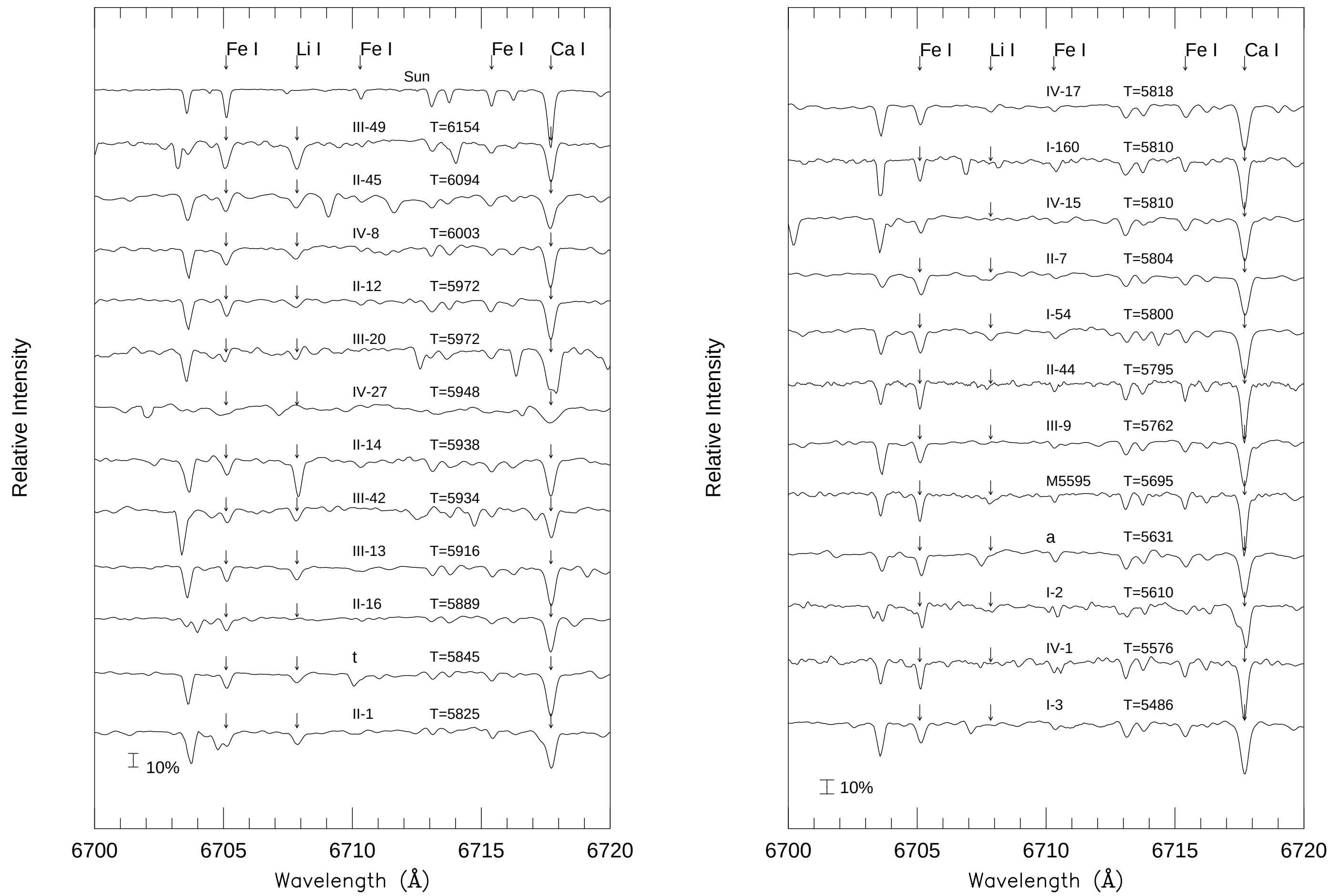

FIG. 2*a* FIG. 2*b*

FIG. 2.—Montage of spectra near 6708 Å for (*a*) the hotter stars observed and (*b*) the cooler M67 stars observed

King et al. 1997; Lambert, Smith, & Heath 1993; Thorburn et al. 1993). The strongest is at 6707.441 Å, most likely due to Fe I, and the HIRES spectrograph resolves this feature in stars with $v \sin i \lesssim 15$ km s^{-1}. For faster rotators, the Gaussian fit was made to the red side of the absorption line. None of our stars were rotating fast enough to demand other methods of deblending this feature, and thus our equivalent widths (and derived abundances and upper limits) do not contain a contribution from the 6707.441 Å feature. We did not attempt to take into account other very weak features due possibly to CN, V I, Cr I, and Ce II.

The uncertainty in the measurement of Li equivalent width depends on several factors, such as S/N, temperature of the star, rotational velocity, and line strength. The temperatures of the stars in this program are high enough that continuum placement is straightforward, the lines are all fairly strong, and the rotational velocities are low. We estimate an uncertainty of about 10% in our Li equivalent width measurements, based on several independent measurements of the Li line in each star, as well as previous experience with HIRES spectra of similar stars and S/N.

Effective temperatures were determined from colors in the same manner as for the Pleiades (SSHJ). We first transformed the observed $(V-I)_K$ of Montgomery et al. (1993) to $B-V$. Over the limited color range involved, this transformation is linear. To obtain the constants of the transformation we used all high-probability cluster members in the magnitude range 13.7 to 16.0, with the result

$$B-V = 1.0146(V-I) - 0.108 .$$

This transformed color was then averaged with the observed $B-V$, and the average corrected for a reddening of $E_{B-V} = 0.05$ to give a mean $(B-V)_0$. Effective temperatures were then determined from the relationship

$$T_{\rm eff} = 1808(B-V)_0^2 - 6103(B-V)_0 + 8899$$

(SSHJ). The main source of accidental error in our method is error in the photometry. For stars with $B-V$ around 0.6, an error in the color of 0.01 magnitude translates into an error of $T_{\rm eff}$ of 40 K.

We used our method to determine temperatures for stars observed in other investigations, and the agreement between our temperatures and those by the original investigators is excellent. There are 28 stars for which both Pasquini et al. (1997) and we determined effective temperatures, with a mean difference (our temperatures minus Pasquini et al. temperatures) of 7 K and an rms scatter of 43 K. Similarly, the comparison with Spite et al. yields a mean difference of -8 K and a scatter of 43 K for six stars, and with Hobbs & Pilachowski (1986a) the mean difference is -6 K with a scatter of 45 K for seven stars. The largest difference is with García Lopéz et al. (1988), where the mean difference is 36 K and a scatter of 97 K for seven stars.

For consistency, the Li abundances for the program stars were obtained from the same curve of growth (COG) as in our previous analysis, given in Table 2 of Paper III. The error in the derived abundances include contributions from errors in the equivalent widths, errors in the temperatures, and errors in the COG. As discussed above, we estimate the errors in our equivalent widths to be on the order of 10% for stars with detections. For the range of temperatures and equivalent widths covered by our observations, an error of 10% in equivalent width corresponds to an error in Li abundance of roughly 0.05 dex. From the discussion above, the accidental errors in our temperature scale are likely to be of the order of 50 K, again corresponding to an error in Li abundance of about 0.05 dex.

The numbering system for stars in M67 can be confusing. Johnson & Sandage (1955) used the numbering system of Fagerholm (1906), adding letters for stars not listed in that reference. Eggen & Sandage (1964) extended that numbering system using roman numerals for sectors and Arabic numerals within the sector, a scheme continued by Racine (1971). In a proper-motion survey, Sanders (1977) introduced a new numbering system for the 1866 stars that he measured, although the numbering system goes from 1 to 2316 since not all numbers were used. Montgomery et al. (1993) introduced a new system with numbers starting at 5001. Thus it is possible for a star to have three independent designations. Here we give all these designations for each star that we observed (Table 1). Column (1) gives the number from Johnson & Sandage (1955), Eggen & Sandage (1964), or Racine (1971); column (2) the Sanders (1971) identification; and column (3) the Montgomery et al. (1993) identification. Column (4) lists the V magnitude; column (5) the dereddened color $(B-V)_0$; column (6) the derived effective temperature; column (7) the observed equivalent width of Li $\lambda 6708$; column (8) the derived Li abundance on a scale where $\log N(\mathrm{H}) = 12$; and column (9) the observed radial velocity.

Star I-2 is a double-lined spectroscopic binary. We have estimated the equivalent widths and abundances for both components by using the depths of two iron lines at 6726.6 and 6752.7 Å to estimate the continuum contributions of each star, measuring the equivalent widths of the two Li lines and normalizing them by the calculated continuum contributions. The results are listed in Table 1. We used these equivalent widths to calculate the abundances of each star, assuming that they both had the same temperature, which was given by the observed $B-V$. These are the abundances listed in Table 1.

Star IV-27 appears peculiar. It has a very discrepant radial velocity, and its lines appear to be rotationally broadened. Unfortunately, its high radial velocity moved the Li line onto a bad column, making the abundance determination uncertain. There is no indication that the star is a double-lined binary. Its high radial velocity would indicate nonmembership, but both Sanders (1977) and Girard et al. (1989) give the star a high membership probability based on proper motions, and its position in the cluster color-magnitude diagram also supports membership. We retain IV-27 in our sample because we have no sound reason to reject it, but we cannot explain all its properties.

In Table 2 we present other information drawn from the literature (Hobbs & Pilachowski 1986b; Spite et al. 1987; García Lopéz et al. 1988; Pasquini et al. 1997). We do not list in Table 2 the observations of Balachandran (1995),

TABLE 1

New Observations of Lithium in M67

ID (1)	Sandage (2)	Montgomery (3)	V (mag) (4)	$(B-V)_0$ (mag) (5)	T_{eff} (K) (6)	$\mathrm{EW}_{\lambda 6708}$ (mÅ) (7)	$\log N(\mathrm{Li})$ (8)	v_{rad} (km s^{-1}) (9)
a	2213	5517	14.87	0.668	5631	<12	<1.47	33.8
t	1064	5718	14.04	0.611	5845	34	2.14	32.7
I-2a........	1014	5788	14.18	0.673	5610	22	1.73	36.2
I-2b........	1014	5788	14.18	0.673	5610	44	2.02	27.0
I-3	1012	5777	14.52	0.708	5486	<7	<1.08	36.5
I-54........	969	5705	14.18	0.622	5800	31	2.07	33.5
I-160	958	...	14.46	0.620	5810	<10	<1.56	34.7
II-1	1011	5844	13.82	0.617	5825	39	2.18	25.4
II-7	1255	5995	14.49	0.621	5804	25	1.96	34.0
II-12.......	1248	5963	14.22	0.579	5972	31	2.23	32.7
II-14.......	1252	6073	14.07	0.588	5938	44	2.35	29.1
II-16.......	1247	6010	14.04	0.600	5889	<5	<1.32	17.4
II-44.......	1457	6254	13.90	0.624	5795	<8	<1.44	33.4
II-45.......	1453	6267	13.96	0.549	6094	57	2.55	32.8
III-9	1048	5829	14.41	0.632	5762	<4	<1.11	33.0
III-13......	1283	5873	14.11	0.593	5916	49	2.38	33.3
III-20......	1287	5917	14.03	0.579	5972	36	2.28	36.3
III-42......	1314	5932	13.70	0.588	5934	40	2.30	46.0
III-49......	1300	6060	13.75	0.534	6154	94	2.94	49.3
IV-1	1041	5807	14.72	0.682	5576	<3	<0.79	33.3
IV-8	1033	5567	14.16	0.572	6003	43	2.40	32.2
IV-15......	1050	5639	14.29	0.620	5810	<4	<1.15	37.4
IV-17......	1057	5683	14.30	0.618	5818	16	1.75	34.5
IV-27......	1070	5671	13.90	0.585	5948	<3:	<1.15:	103.4
	963	5595	14.51	0.650	5695	23	1.83	27.8

TABLE 2

OTHER M67 DATA

ID (1)	Sandage (2)	Montgomery (3)	V (mag) (4)	$(B-V)_0$(mag) (5)	T_{eff} (K) (6)	$EW_{\lambda 6708}$ (mÅ) (7)	log N(Li) (8)	log $N(\mathrm{Li})_c$ (9)	Source (10)
t	1064	5718	14.04	0.611	5845	49	2.32	2.22	P
f-111	986	5624	12.73	0.523	6202	<21	<2.24	<2.04	G
f-119	1045	5654	12.54	0.548	6098	80	2.82	2.82	D
f-119a	1045	5654	12.54	0.548	6098	144	3.24	3.19	P
f-119b	1045	5654	12.54	0.548	6098	110	3.02	2.97	P
f-124	997	5667	12.13	0.410	6700	<19	<2.61	<2.46	G
f-125	1075	5692	13.84	0.529	6178	58	2.70	2.63	P
f-127	995	5675	12.76	0.521	6210	20	2.22	2.01	G
f-128	2205	5679	13.14	0.534	6156	<28	<2.34	<2.19	G
f-129	988	...	13.18	0.534	6153	<12	<1.94	<1.48	P
	988	...	13.18	0.534	6153	<12	<1.94	<1.50	G
f-130	2204	5688	12.89	0.417	6668	<17	<2.53	<2.36	G
f-132	976	5695	13.10	0.564	6031	<25	<2.18	<1.99	G
	976	5695	13.10	0.564	6031	<13	<1.87	<1.42	P
I-9	994	5716	13.18	0.535	6151	38	2.47	2.37	H
I-11	998	5610	13.06	0.518	6223	45	2.60	2.52	H
I-19	991	5485	14.56	0.642	5727	<12	<1.56	<0.80	H
I-20	990	5464	13.43	0.525	6191	67	2.79	2.72	H
I-29	758	5334	13.49	0.582	5958	55	2.48	2.39	S
I-46	746	5261	14.38	0.656	5672	<13	<1.54	<0.87	H
I-48	747	5414	14.05	0.646	5708	<15	<1.65	<1.16	H
I-51	982	5776	14.12	0.561	6043	<12	<1.85	<1.33	P
I-160	958	...	14.46	0.620	5810	<30	<2.07	<1.89	S
	958	...	14.46	0.620	5810	<22	<1.92	<1.66	P
II-1	1011	5844	13.82	0.617	5825	47	2.28	2.18	P
II-4	1260	5937	14.19	0.582	5960	44	2.37	2.27	P
II-7	1255	5995	14.49	0.621	5804	<12	<1.63	<0.95	P
II-13	1256	6039	13.67	0.595	5907	<15	<1.83	<1.42	S
	1256	6039	13.67	0.595	5907	12	1.73	1.13	H
II-14	1252	6073	14.07	0.587	5938	45	2.36	2.26	P
III-13	1283	5873	14.11	0.593	5916	32	2.19	2.04	P
III-22	1292	5961	13.20	0.580	5968	19	1.99	1.72	S
III-42	1314	5932	13.70	0.588	5934	63	2.53	2.45	S
III-43	1092	5838	13.31	0.583	5954	49	2.42	2.33	S
IV-35	1055	5471	13.80	0.543	6116	45	2.51	2.43	P
	963	5595	14.51	0.650	5695	27	1.91	1.69	P

NOTES.—The sources for the data are (G) García López et al. 1988; (H) Hobbs and Pilachowski 1986b; (S) Spite et al. 1987; (D) Deliyannis et al. 1994; (P) Pasquini et al. 1997.

because her objects were more massive evolved stars that are now giants or subgiants. They are the stars that would have been in or near the "lithium chasm" when on the main sequence, and were observed by Balachandran to obtain information about the chasm in an old cluster, a problem we do not address here. To be consistent with our results, we rederived abundances for the stars in Table 2 from the published equivalent widths in the same manner as for the stars in Table 1.

The feature at 6707.44 Å has been included in the equivalent widths in the above publications (although Spite et al. 1987 and Pasquini et al. 1997 do take account of the feature in their abundance determinations). One can make an empirical correction for the effect this feature has on the Li equivalent width as a function of color (Paper III) and derive an abundance from the corrected equivalent width. Soderblom et al. (1993c, hereafter Paper II) gives the correction as $20(B-V) - 3$ mÅ. For stars with moderately strong lines, the correction to the equivalent width and, hence, the Li abundance are small. However, particularly for the cooler stars, the effect on the abundance is large for stars with small equivalent widths, or low upper limits, making the derived abundances (or upper limits) highly uncertain. For example, for a star of temperature 5700 K the correction to the equivalent width is 10 mÅ. For a star of this temperature with an upper limit of 15 mÅ, the corrected equivalent width of 5 mÅ is comparable to the error of measurement and to the error of the correction. For this reason the upper limits in Table 2 derived from the corrected equivalent widths are highly uncertain, and in the discussion below we are conservative, taking for the upper limits the uncorrected abundances listed in Table 2.

We have seven stars in common with Pasquini et al. (1997) and two in common with Spite et al. (1987). For the six stars that had actual detections in both data sets, the mean difference between our derived Li abundance and theirs is -0.02 dex, with an rms scatter of 0.17 dex. Much of this scatter is due to the different temperatures used. If we compare the Li abundances we derive from their equivalent width, the mean difference is 0.03 dex with an rms scatter of 0.13 dex. There is one discrepant star, II-7. We determined an equivalent width of 25 mÅ for this star, giving an abun-

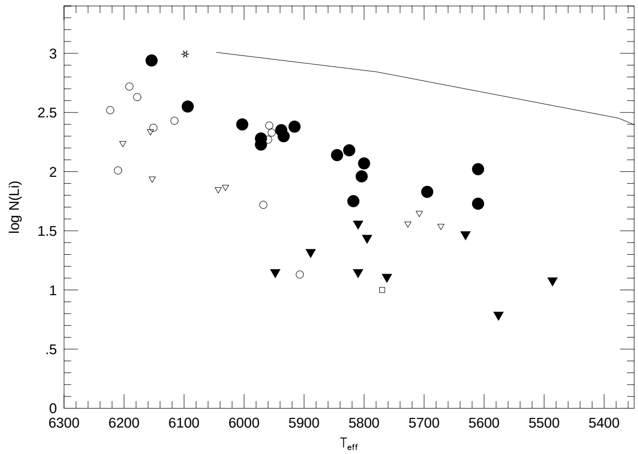

FIG. 3.—Li abundance vs. effective temperature. The solid line is a prediction of Li depletion from the standard models for solar metallicity and an age of 4.5 Gyr. The filled symbols are our observations, and the open symbols the observations of others. Circles are detections, and triangles upper limits. The asterisk is the mean of the three determinations of the abundance of the tidally locked binary f-119. The open square is the Sun. The upper limits for observations other than our own are uncorrected for the feature at 6707.441 Å.

dance of 1.96, while Pasquini et al. determined an upper limit to the equivalent width of 12 mÅ and an upper limit to the abundance of 1.08.

In Table 2, column (1) gives the number from Johnson & Sandage (1955), Eggen & Sandage (1964), or Racine (1971); column (2) the Sanders (1971) identification; and column (3) the Montgomery et al. (1993) identification. Column (4) lists the V magnitude; column (5) the dereddened color $(B-V)_0$; column (6) the derived effective temperature; column (7) the observed equivalent width (in mÅ) of Li λ6708; column (8) the derived Li abundance on a scale where $\log N(\mathrm{H}) = 12$ without a correction for the feature at λ6707.44; column (9) the derived Li abundance with a correction; and column (10) the source of the equivalent width.

Deliyannis et al. (1994) derived abundances for both components of one tidally locked binary in M67 (Sanders 1045 = MMJ 5654 = f-119). The components of this binary are nearly identical. Deliyannis et al. derived abundances under several assumptions about the temperature differences, but the effects were minor. Here we adopt their case 1 (identical components with the equivalent width equal to the mean of the two components), but with temperature and abundance rederived by us. This abundance is listed in Table 2. Pasquini et al. (1997) also observed this star, and we list their observations for the separate components.

Figure 3 shows our derived abundances versus effective temperature. The solid line is a prediction of Li depletion from a standard model (not including rotation, mass loss, or diffusion) for solar metallicity and an age of 4.5 Gyr (M. Pinsonneault 1997, private communication). In Figure 3, the solid symbols are our observations and the open symbols the observations of others. Circles are detections, and triangles upper limits. We have plotted the uncorrected abundances from Table 2. The asterisk is the mean of the three determinations of the abundance of the tidally locked binary f-119.

3. DISCUSSION

3.1. *Comparison with Other Clusters and Models*

In the discussion below, we make an implicit assumption that the differences in Li abundance between the clusters we compare are due to age and metallicity, i.e., that they form an evolutionary sequence. This is certainly the simplest assumption to make, but one should not dismiss the possibility that the differences are wholly or partly due to initial conditions or environment. This assumption will be testable as data collect for more clusters. The similarity between the Hyades and Praesepe, between NGC 1039 and NGC 6475, and between the Pleiades and α Per argues in favor of an evolutionary sequence.

Figure 4 shows the Li abundances for the Pleiades, NGC 1039, the Hyades, and M67 as a function of temperature. The solid line in each case is a standard-model prediction of Li depletion for the age and metallicity of the cluster from Pinsonneault (1997, private communication), assuming an initial Li abundance of $\log N(\mathrm{Li}) = 3.32$. We assume solar metallicity for the Pleiades, M34, and M67. The two lines for the Hyades are for metallicities of 0.10 and 0.20. Again, by "standard model" we mean a model without rotation, mass loss, or diffusion. The curve for M67 is consistent with that cluster having formed with an initial $\log N(\mathrm{Li}) \sim 3.2$. We note that much of the major differences at cool temperatures between the standard models for the Pleiades and

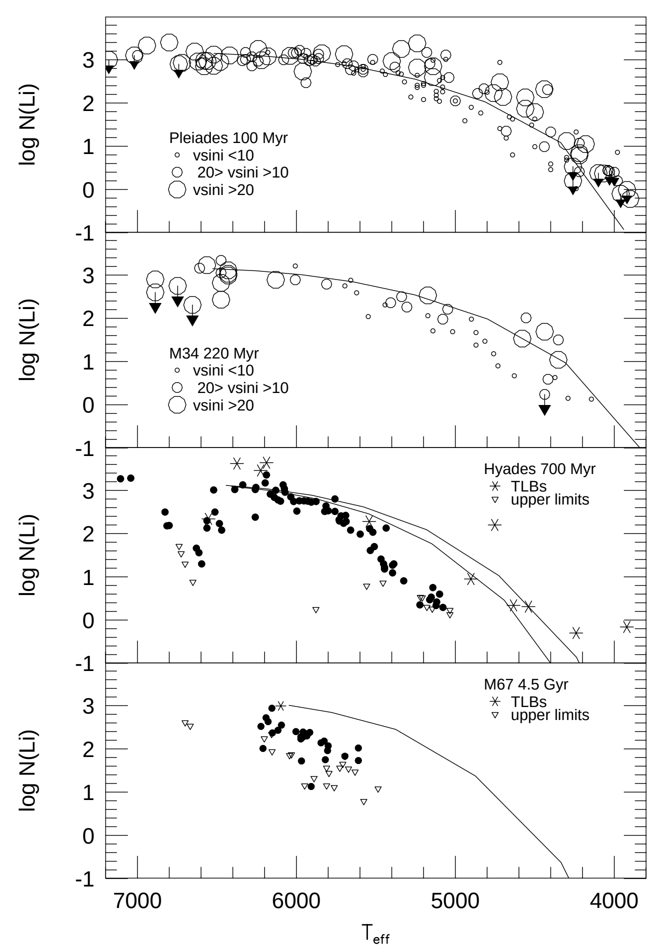

FIG. 4.—Montage of observations of Li abundance vs. effective temperature for clusters of different ages. The sources for the data are listed in the text.

NGC 1039, on the one hand, and the Hyades, on the other, are due to metallicity.

The youngest cluster in Figure 4, the Pleiades, shows a large spread in Li abundance at temperatures between 5600 and 4200 K (Paper III), corresponding to masses between about 1.0 and 0.65 $M_\odot$. Moreover, there appears to be a correlation between Li abundance and rotation. The somewhat older cluster NGC 1039 (Paper VII) shows less of a spread in Li abundance in this temperature range, but the correlation with rotation persists. The much older stars in the Hyades in this temperature range have much less Li than the younger clusters, but as noted above, we believe that this is primarily a metallicity effect; also, the spread in Li abundance is less, as discussed in Paper VII. No stars have been observed in the much older M67 in this temperature range, but the trend in Figure 3 would suggest that Li is so depleted as to be essentially unobservable.

If we look at the temperature range between 5600 and 6200 K (the temperature range spanned by the M67 observations), the overall pattern of Li depletion in the Pleiades and NGC 1039 agrees fairly closely with the standard model. As discussed in Paper VII, the stars in the Pleiades and NGC 1039 in this temperature range show a spread that is entirely accounted for by measurement errors. Over this range, the abundance of the Hyades stars falls slightly below the standard model, and there is a small but significant spread in Li abundance that is greater than the measurement errors (Thorburn et al. 1993). In M67, the stars in this temperature range show significant Li depletion with respect to the standard model, and the spread in Li abundance is greater than 1 dex. This is much larger than the spread in the Hyades over this temperature range. It is also much larger than estimates of the external errors determined from intercomparison of the different investigations.

Assuming an evolutionary sequence, the implication of Figure 4 is that main-sequence Li depletion takes place for stars in this mass range. However, perhaps the most striking feature of Figure 3 and Figure 4 is the large spread in Li abundance at a given temperature in M67. We note that there are detections, as well as upper limits, over almost all of the temperature range observed, and the spread in Li is at least a factor of 10 at all temperatures. This is the same temperature range over which neither the Pleiades nor NGC 1039 show any scatter, and scatter in the Hyades is small. The implication is that whatever the mechanism driving main-sequence Li depletion, it is not only highly mass dependent, but also depends on a second parameter, which, as discussed below, is most likely angular momentum loss. Also, this second parameter influences Li depletion relatively late in the star's life.

The observational scenario we presented in Paper VII is that stars arrive on the main sequence with an overall depletion pattern approximating the standard model but, for the cooler stars, with a spread in Li abundance that is correlated with surface rotation. As the stars spin down, the Li is depleted, with the most rapidly rotating stars both losing angular momentum and depleting Li at a higher rate than the more slowly rotating stars.

There is some theoretical support for this scenario. Models by Martín & Claret (1996) show a spread in Li abundance at a given mass for ZAMS stars due to different initial angular momentum, with the faster rotating stars arriving on the main sequence with more lithium. Main-sequence Li depletion due to angular momentum loss finds support from several investigators (Pinsonneault et al. 1990; Charbonnel et al. 1994; Zahn 1994; Chaboyer et al. 1995). Since main-sequence depletion takes place, the overall pattern of depletion will fall below the standard model as the cluster ages and stars lose angular momentum. Moreover, given the initial spread in Li abundance and its correlation with rotation, the models predict an initial convergence in both rotational velocities and Li abundance as the cluster ages. However, the timescales for convergence in Li and rotation need not be the same, since the mechanisms are likely very different. If the stars continue to lose angular momentum after the initial convergence in Li abundance, there can be a divergence again as the faster rotators continue to slow down and the Li abundance of the faster rotators falls below that of the slow rotators.

Observations in M67 give additional insight into main-sequence Li depletion. In M67, 5 times older than the Hyades, even solar-mass stars are significantly depleted, and there is a large spread in Li abundance at $\sim 1\ M_\odot$. Although not as compelling as for the lower mass stars, there is observational evidence that Li depletion for these stars is being driven by angular momentum loss. One piece of evidence is the Li-rich, short-period, tidally locked binary (SPTLB) f-119. As discussed in Paper I, Deliyannis et al. (1994), Zahn (1994), and Paper VII, SPTLBs will not spin down the same way that single stars do, because of the huge reservoir of angular momentum available in the orbit, and one expects them to undergo less Li depletion than other stars. Although not as persuasive, the ratio of Li-rich to Li-poor stars near 1 $M_\odot$ in M67 reflects inversely the ratio of slow to fast rotators in the Pleiades. This is consistent with both clusters having the same initial angular momentum distribution, with the older M67 fast rotators having lost both their angular momentum and their Li.

3.2. *Galactic Enrichment and the Primordial* Li *Abundance*

The discussion in § 3.1 gives support to a scenario in which main-sequence Li depletion in stars near solar metallicity is driven by angular momentum loss. The Yale evolutionary models provide a framework for this scenario. The naive expectation is that old stars should show a spread in Li abundance if they had an initial spread in angular momentum. The spread in Li abundance seen in M67 supports this view. In this section we discuss the implication this scenario has for halo Li abundances.

Halo stars in the temperature range 6200 to 5500 K show a nearly uniform (but see below) Li abundance of 2.2, the so-called Spite plateau (Spite & Spite 1982; Spite & Spite 1984). Standard models of low-metallicity stars in this temperature range show neither pre–main-sequence nor main-sequence Li depletion. Acceptance of these models at face would imply (1) the Li abundance of the plateau stars is close to the primordial abundance, with obvious cosmological implications, and (2) there has been a Galactic enrichment of Li by a factor of about 10 over the life of the Galaxy.

If we accept the view that the Spite-plateau Li abundance is close to the primordial abundance, then we are forced to explain why disk stars undergo main-sequence depletion and halo stars do not. We can think of three explanations: (1) Halo stars formed with little initial angular momentum, so there was no Li depletion driven by angular momentum loss. We find this explanation ad hoc and unsatisfactory. (2) Main-sequence Li depletion is driven not only by angular momentum loss, but also by metallicity; i.e., stars of low metallicity but high initial angular momentum do not deplete Li like high-metallicity stars with comparable levels of high initial angular momentum. This explanation receives little theoretical support (Chaboyer & Demarque 1994). (3) Our assumption that the clusters discussed above form an evolutionary sequence is incorrect *and* the theoretical models that predict main-sequence Li depletion due to angular momentum loss are wrong. Although possible, we think the evidence points in the opposite direction.

The observations of stars on the Spite plateau are not inconsistent with their having undergone substantial Li depletion. These stars do show a dispersion in Li abundance greater than the measurement errors (Ryan & Deliyannis 1998; Thorburn 1994), including some stars with severe Li depletion (Hobbs, Welty, & Thorburn 1991; Norris et al. 1997) and some stars with significant Li overabundance (King et al. 1996; Ryan & Deliyannis 1995). Chaboyer & Demarque (1994) argue that models with rotational mixing, a reasonable spread in initial angular momentum, and an initial Li abundance of near $\log N(\mathrm{Li}) = 3$ can reproduce the Spite plateau observations.

4. CONCLUSIONS

Both the Pleiades and M67 have essentially solar composition, and the dramatic difference in the run of Li versus T_{eff} for the two clusters clearly shows that solar-type stars deplete Li while on the main sequence. Moreover, a comparison of M67 with young ZAMS stars, such as those in the Ursa Major group (Paper II), shows that this main-sequence Li depletion continues at a steady pace and does not all happen early on.

Pasquini et al. (1997) have already noted that the spread in Li in M67 reinforces the inadequacies of Li as an age indicator, a point made by others as well (Soderblom 1988). To put it another way, M67 shows us that an ensemble of stars with the same age and composition as the Sun can have very different surface Li abundances. Therefore in at least this one humble respect the Sun is not necessarily a representative star. Modest though it is, this represents the first evidence that the Sun cannot necessarily be taken as a completely typical star for its mass, age, and composition.

In what underlying way is the Sun different? It may be impossible to know for sure, but we speculate that the young Sun may have had an unusually high level of angular momentum. We noted above that we suspect that Li abundances converge more rapidly than do rotation rates as stars spin down, because that would help account for the small dispersion in Li in the Hyades, for example. It is also telling, we feel, that the proportions of Li-rich to Li-poor stars near 1 $M_{\odot}$ in M67 is very nearly the inverse of the proportion of fast rotators to slow rotators in the Pleiades. In other words, it is plausible to infer from the relative numbers of stars that the Pleiades ultrafast rotators will be Li-poor stars by the time they are as old as the Sun, and that the slow rotators in the Pleiades will look like the Li-rich stars in M67 when they are the Sun's age. This speculation is buttressed by the models (Pinsonneault 1997) and holds the promise of allowing some inference of behavior in the distant past of a star from surface conditions that prevail today. However, such a deduction is still risky, as shown by the contrary conclusion of Li & Collier Cameron (1993). They studied distributions of angular momentum in solar-type stars in clusters and suggested that the early Sun rotated very slowly if their model with weak core-envelope coupling was valid. Yet it is intriguing that a comparison to other stars may provide insight into the Sun's initial conditions.

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